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Parametric study of the non-linear seismic response of three-dimensional building models

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Abstract

The behavior of buildings when subjected to severe seismic events, that force them to enter in the non-linear range is studied. Using simple three-dimensional models of structures, the influence that several parameters have on the seismic response can be evaluated, namely: the number of resistant planes parallel to the earthquake action, the degree of torsional coupling (Ω_θ), the uncoupled fundamental vibration period (T_{Y1}), the normalized static eccentricity (e/r), the uncoupled lateral frequencies ratio (ω_{X1}/ω_{Y1}), the torsional stiffnesses ratio (γ_X), and the overall ductility of design (μ).

Two horizontal components of four acceleration records of the ground motion recorded during the earthquake of 3 March 1985 in the central zone of Chile were used as seismic excitation. The records were normalized to have the Peak Ground Acceleration (PGA) equal to $0.4g$. The non-linear dynamic analysis was carried out using the time history response (THR) method and subjecting each structural model to a ground motion represented by each of the eight normalized seismic records, through which we obtained eight values for each relevant response. Due to the fact that the non-linear behavior of the structure is sensitive to the particularities of the seismic excitation, it is considered advisable to average the responses over the set of seismic records used.

Finally, the main conclusions obtained were: (i) the displacements at each floor level do not vary with the number of resistant planes parallel to the direction of seismic action in structures with moderate static eccentricity ($e/r \leq 0.50$) and low overall ductility of design ($\mu \leq 4$), which is the opposite effect as that observed for the displacements and ductilities of each frame; (ii) the relevant parameters in this type of study are identified.

Keywords: 3D Modeling; 3D Non-linear seismic analysis; Asymmetric buildings; Uni-directional earthquake; Uni-directional seismic design; Seismic design criteria

1. Introduction

In countries of large or high seismicity, it is very important to have codes and a practice of earthquake-resistant design, in order to adequately predict the behavior of a real building during a severe seismic motion that it will have to withstand without collapsing at least once during its service life.

Therefore, studying the behavior of the model in the non-linear situation that precedes collapse allows the detection of inelastic deformations in many of its resistant elements. It will be possible to confirm that in such circumstances not only are the forces (like the shear forces at each floor level) of great importance for the seismic design of the building, but also the deformations and especially the ductility demands on buildings.

Doing this type of analysis in usual buildings normally exceeds the technical-economic capabilities of structural engineering offices due to the multiple questions on the seismic excitation that must be considered, the non-linear characteristics of the structure, and the difficulty in interpreting the results.

Recent studies of the non-linear response of three-dimensional (3D) structures that show in-plan torsion effects due to eccentricity in mass or stiffness [1–5] allow one to acquire a better understanding of the problem; nevertheless, it is very difficult to generalize such results as design guides that are applicable to most structures, because the non-linear response has been shown to be very dependent of the unique characteristics of each model and of the applied seismic excitation.

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Notations

Ω_θ	Degree of torsional coupling.
T_{Y1}	Uncoupled fundamental vibration period.
e/r	Normalized static eccentricity.
ω_{X1}/ω_{Y1}	Uncoupled lateral vibration frequencies ratio.
γ_X	Torsional stiffnesses ratio
μ	Overall ductility of design.
PGA	Peak ground acceleration.
THR	Time history response method.
ρ	Relative stiffness beam–column ratio.
CM	Center of mass.
CS	Center of stiffness.
S	Direction of the seismic excitation.
L	Span of the beams.
h	Height of the columns.
EI_b	Flexural stiffness of the beam.
EI_c	Flexural stiffness of the column.
A/B	Aspect ratio.
M_y	Yield bending moment.
$\omega_{\theta j}$	j-th torsional vibration frequency.
ω_{Yj}	j-th lateral vibration frequency.
$C_{\theta R}$	Value proportional to the torsional stiffness of the structure measured with respect to its center of stiffness
C_Y	Value proportional to the lateral (translational) stiffness provided by the resisting planes oriented in the Y-direction.
r	Radius of gyration of the plan (uniform mass distribution).
Y_i	Location of the i-th frame parallel to the earthquake action S (with respect to the CM).
(u, v, θ)	Degrees of freedom located in the CM of the floor slab.
C	Damping matrix (Rayleigh type damping).
R	Reduction factor for earthquake induced loading.
μ_θ	Maximum local ductility of rotation.
$\mu_{\theta ac}$	Accumulated local ductility of rotation.
θ_m	Maximum rotation at the end of an element.
θ_p	Rotation of the plastic hinge.
θ_{ac}	Cumulative sum of the plastic rotations (positive or negative).
θ_y	Yield rotation (rotation at the end of an element when the bending moment at this end is equal to M_y).
M_{yb}	Yield moment at the ends of the beams.
θ_{yb}	Yield rotation at the ends of the beams.
M_{yc}	Yield moment of a column.
$M_{\max}$	Maximum moment that is generated when the maximum rotation θ_m is reached at the end of the column.
θ_{yc}	Yield rotation at the ends of the columns.
R_m	Ratio of bending moments in the ends of the columns.
R_v	Ratio of lateral displacement (drift) to displacement due to rotation, at the ends of the columns.
M_t, M_b	Bending moments at the ends of the columns (top and bottom, respectively).
δ_t, δ_b	Lateral displacements at the ends of the columns (top and bottom, respectively).
θ_t, θ_b	Joint rotations at the ends of the columns (top and bottom, respectively).
θ_{yc}^1	Yield rotation at the base of the first story column
θ_{yct}^n	Yield rotation at the top of the column of any story.
θ_{ycb}^n	Yield rotation at the bottom of the column of any story.
N	Number of floor slabs.
$\Delta 2-1$, $\Delta 3-1$	Percentage differences of the results obtained from models 2 and 3 with respect to those of model 1.
$R_{\text{mod }1}$, $R_{\text{mod }2}$, $R_{\text{mod }3}$	Average maximum seismic responses in each one of the three models in this study.

The linear elastic behavior of one-story systems with eccentricity in only one direction can be completely defined using only three parameters: the uncoupled fundamental vibration period, the torsional coupling degree, and the normalized static eccentricity [6]. Nevertheless, for the study of the non-linear response it is necessary to specify other details of the structural model, such as the location in-plan and the load–deformation behavior of the resistant planes. In addition to such parameters, multi-story systems have the added difficulties of calculating the variations across the height of the characteristics of mass and stiffness in the elastic range, and additionally of strength in the inelastic case. Therefore, an important disadvantage that appears in the study of the non-linear response of buildings is the large number of parameters that are required to define the model.

In view of the complexity of the typical 3D models that represent real buildings, this paper proposes a methodology for studying the influence on the non-linear response of a multi-story simple model, with different number of resistant planes parallel to the direction of the seismic action, of some of the parameters which describe its elastic behavior [7].

2. Methodology

2.1. General characteristics

The general model corresponds to a five-story building with identical rectangular floor plans that are symmetric in the direction perpendicular to the seismic action. It has a resistant system formed by massless frames with a relative stiffnesses beam–column ratio $\rho = 0.125$ in the story closest to the mid-height of the frame [8] and with lateral stiffness matrices proportional to each other [9]. These resistant planes are located on an orthogonal grid and connected in each floor level by a rigid diaphragm, in whose center of mass (CM) the mass of the building is concentrated.