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Analysis for preliminary design of a class of torsionally coupled buildings with horizontal setbacks

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Abstract

Simplified method of analysis of a special class of torsionally coupled buildings with horizontal setbacks is developed that can be executed with a plane frame analysis by means of a personal computer. Since most buildings may not exactly satisfy all the classification criteria, it is shown that an averaging technique may be used in such cases up to a certain limit. Perturbation analysis is carried out in determining such a limit, and numerical examples are presented to validate this. As a whole, the proposed simplified analysis may be used as a convenient and offhand tool at the preliminary stage of design.

Keywords: Special class of buildings; Torsional coupling; Seismic analysis; Proportional stiffness; Horizontal setbacks; Dynamic analysis; Preliminary design

1.0. Introduction

Buildings are, hardly ever, truly symmetric. Consequently, lateral vibration of buildings during seismic excitation is always coupled with torsional vibration. A number of studies have been reported in the literature addressing the issue of lateral–torsional coupling ([3,6–8,10–13,15,17] and many more). Further, most seismic codes often suggest an equivalent static analysis against a specified lateral load profile for regular and nominally irregular buildings taking into account the torsional effects. Therefore, behavior of asymmetric buildings under monotonic or equivalent static loading has also received adequate attention ([1,2,4,5] and many more). On the other hand, when irregularity exceeds certain nominal limit, for example, building with horizontal setbacks, complete dynamic analysis is a must according to most seismic codes.

Instead of complete dynamic analysis, simplified dynamic analysis is often preferred, especially, at the stage of preliminary design. In this connection, a special class of torsionally coupled buildings has been reported in the literature [7,8,11,12] wherein the lateral stiffness and mass are distributed throughout the building in a specific way. Kan and Chopra [11, 12] reported that a multi-story building belongs to the category of a special class if (i) the center of mass (CM) of all the floors lie on one vertical line and radius of gyration about the vertical axis passing through the CM is the same for all the floors, (ii) principal planes of all the lateral load-resisting elements form an orthogonal grid system and (iii) lateral stiffness matrices of all the lateral load-resisting elements oriented along either of the two orthogonal directions are proportional to a characteristic lateral stiffness matrix along that direction; however, these two characteristic lateral stiffness matrices may not be identical. Further, it has been shown [11,12] that the response behavior of such a shear building may be obtained through appropriate combination of the results calculated from the analysis of two smaller systems, namely, (a) corresponding torsionally uncoupled building and (b) equivalent one-story torsionally coupled building. Hejal and Chopra [7,8] extended the concept of this simplified analysis to buildings comprising moment-resisting frames (MRFs) with the imposition of an additional constraint, which states identical characteristic lateral stiffness matrices along both the orthogonal directions. In other words, lateral stiffness matrices of all the lateral load-resisting elements are proportional.

However, conditions of the existence of the special class of buildings are hardly, ever, truly satisfied in practice, e.g., (i) lateral stiffness matrices of the constituting frames may not be exactly proportional and (ii) CM of all the floors may not

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be located exactly on a single vertical line. None of the two previous studies [11,12,7,8] has investigated the applicability of the simplified procedure in such cases. In the first study [11, 12], shear building is assumed and the existence of which is in itself questionable. In the second study [7,8], numerically proportional lateral stiffness matrices for the MRFs are directly assumed. This is because MRFs do not, in general, yield to exactly proportional lateral stiffness matrices. Furthermore, in order to proportion the MRFs so as to yield proportional lateral stiffness matrices, Hejal and Chopra [7,8] made an attempt by introducing a factor, called the 'joint rotation index', which is based on the assumption of uniform story height and uniform bay width, but these conditions are hardly, if ever, met in practice. Surprisingly, in both the previous studies, orthogonality of the building was assumed and that seems to be superfluous.

A building is said to be with horizontal setbacks if there exists at least two points within its plan area when joined through a straight line, the line runs out of the plan area. In the absence of a stiff shear wall, the lateral stiffness matrices of the constituting frames of a building with horizontal setbacks closely satisfy the desired proportionality criterion of the special class of buildings. Consequently, any building without stiff shear walls may also be treated as satisfying all the classification criteria if the CM of all the floors lie on a single vertical line and the radius of gyration about this vertical line is the same for all the floors. The objective of this paper is two-fold: first, to explore the concept of this simplified analysis to the special class of buildings with horizontal setbacks and second, to investigate the applicability of the procedure where mass proportionality criteria of the special class are not exactly satisfied. In order to meet these objectives, first, the formulation presented in Hejal and Chopra [7,8] is extended to the special class of buildings with horizontal setbacks, as reported herein followed by a numerical example on a ten-storied C-shape building with MRFs. Second, a rigorous perturbation analysis is carried out in order to restrict the limit of the scattering of the floor CMs (from the vertical line passing through the average CM of the building) up to which the simplified analysis can be applied with an acceptable error for all practical purposes. Numerical example on the same C-shape-MRFs building, but with vertically-nonaligned CMs, is then presented to substantiate the results of the perturbation analysis. Finally, the same C-shape-MRFs building, but with another two sets of vertically-nonaligned CMs, are analyzed so as to assess the conservativeness in the limiting criteria derived from the perturbation analysis. In all the numerical examples presented, results of the simplified method are compared with that calculated using SAP2000 [14].

The methodology developed in this paper does not impose any constraint over the shape of the diaphragm and the orientation of the lateral load-resisting elements. Therefore, the proposed approach is equally applicable to buildings of V-, Y- etc. shape provided that the necessary conditions are satisfied. However, without losing the generality, C-shaped building is chosen for illustration. Further, 3D FEM analysis of the special class of torsionally coupled buildings with horizontal setbacks is no longer impossible in the present era of computer advancement. Consequently, one may argue against the utility of this simplified analysis in the present scenario. Nevertheless, such a simplified analysis may always be preferred to assess the design force resultants at preliminary stage of design; 3D FEM analysis may be carried out at the final stage of verification. Therefore, the proposed simplified analysis can be applied as a convenient and offhand tool with sufficient accuracy at the preliminary stage and requires only plane frame analysis.

2.0. Development of the methodology

To formulate the methodology presented in this paper, an arbitrarily shaped diaphragm of a typical floor of an N-story building comprising different wings is considered. CM of all the floors is assumed to be lying on the same vertical line; the radius of gyration about the vertical axis passing through the CM is assumed to be the same for all the floors. Defining the degrees of freedom at the CM of respective floors, mass matrix of the building can be expressed as the direct product of two smaller matrices as follows:

$$_{3N\times 3N}[M] = {}_{3\times 3}[\mathrm{CM}]_B \otimes {}_{N\times N}[m] \text{ where,} \tag{1}$$

$$[\mathrm{CM}]_B = \begin{bmatrix} 1 & 1 & r^2 \end{bmatrix}_{\mathrm{diag}}. \tag{2}$$

Here, $[m]$ is a diagonal matrix with elements as the lumped mass at the respective floor levels and may be considered as the mass matrix of the characteristic frame; r the radius of gyration of a typical floor about the vertical axis passing through the CM; and $[\mathrm{CM}]_B$ may be considered as the mass matrix of an equivalent one-story coupled building. Similarly, considering the proportionality of the lateral stiffness matrices of the constituting frames and assuming (i) ith frame of the qth wing with stiffness proportionality constant as C_{iq} is located at a distance d_{iq} from the geometric center of gravity of the wing and oriented at an angle α_{iq} in counter clockwise direction with respect to the longitudinal axis of the wing, (ii) qth wing of the building, comprising of NEQ number of frames, is located from the CM of the building at distances d_{Lq} and d_{Sq} along the longitudinal and transverse directions of the wings, respectively, and oriented at an angle β_q in counter clockwise direction with respect to the global X-axis and (iii) $[K^*]$ is the stiffness matrix of the characteristic frame while NW is the total number of wings, stiffness matrix of the building may also be expressed as the direct product of two smaller matrices as follows:

$$_{3N\times 3N}[K_B] = {}_{3\times 3}[CL]_B \otimes {}_{N\times N}[K^*] \quad \text{where,} \tag{3}$$

$$[CL]_B = \sum_{q=1}^{NW} \left([CL]_{qB}\right);$$
$$[CL]_{qB} = [T]_q^{\mathrm{T}}\,[CL]_q\,[T]_q; \tag{4a}$$
$$[CL]_q = \sum_{i=1}^{NEQ} \left([CL]_{iq}\right);$$