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Estimating number of simultaneously yielding stories in a shear building subjected to full-sine pulse velocity base excitation

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ABSTRACT

Past research has shown that seismic force demands in the columns of lateral load resisting systems depend on the number of simultaneously yielding stories (N_{SYS}) above the column considered. Current design procedures for steel frames (e.g., those in AISC-341) typically specify that all stories are considered to be yielding. Time history analyses show that this assumption may be overly conservative for tall buildings. No systematic procedure exists for estimating this N_{SYS}. Concepts of wave propagation theory are used here in seeking such a procedure. As a first step towards that goal, research was conducted to investigate the N_{SYS} due to an incident wave in a shear-type building subjected to full-sine velocity base excitation, to understand the relationships between input excitation, inter-story drifts, story forces, and hence to formulate a procedure to estimate the N_{SYS} along the building height. Story yielding capacity of a base excitation was found to depend on the magnitude of its velocity record. Accordingly, a parameter v_y was defined that determines the minimum magnitude of the velocity wave required to yield a story. Mathematical expressions were derived to predict the beginning and end of story yielding due to the incident wave. With this, N_{SYS} values at any instant as the incident wave propagates up the building could be determined. This estimation procedure was found to provide good estimates of the actual yielding for structures considered here that have v_y values decreasing with height, with the estimated values being on the conservative side.

1. Introduction

In design procedures based on capacity design principles, such as the AISC 341-10 Seismic Provisions for Structural Steel Buildings [1], the axial force demand in columns of a seismic force resisting system (SFRS) is often specified to be obtained by considering that all the ductile members along the height of the SFRS have yielded simultaneously. However, time history analyses show that although occurrence of simultaneous yielding over the entire height of a building may occur in low-rise structures, it is not necessarily the case for mid to high-rise structures. Studies on seismic demands in columns have been done and techniques for estimating column demands have been proposed in the past (e.g., by Redwood and Channagiri [2], Tremblay and Robert [3], Lacerte and Tremblay [4], Richards [5], to name a few). Many of these studies report that maximum column axial forces occur when the plastic yielding mechanism is developed over multiple consecutive stories above the level under consideration. For example, for braced frames, Redwood and Channagiri [2] proposed that the axial force demand in the column at a particular level be obtained by adding the vertical component of the ultimate brace forces immediately above that story, to the SRSS of vertical forces from all the other braces above that level, while Lacerte and Tremblay [4] proposed a method that considered the forces in critical braces as 1.0 and 1.2 times the expected brace capacity in tension and compression, respectively, and brace forces in all the other floors as those obtained when brace buckling initiates in these stories. Richards [5] investigated the demands on seismic columns of various types of braced frames considering four different system strengths and three different structural heights and reported that performing capacity design assuming simultaneous yielding over the entire height of tall buildings was in some cases overly conservative. These studies have typically been empirical, relying on nonlinear time history analysis of a number of typical frames. While these have provided valuable (but limited) insights on seismic demand in columns, there is much to gain by developing a

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systematic and generalized way to estimate the expected number of simultaneously yielding stories (N_{SYS}) in building frames, because this is an essential step towards being able to determine column forces from a modified capacity design perspective. In absence of such a procedure, the capacity-design approach as implemented in current design procedures could severely overestimate the actual axial demands on columns, resulting in overdesigned and economically inefficient columns.

Towards the above goal, the authors undertook to investigate whether wave propagation theory could be used to develop a systematic procedure for estimating the number of simultaneously yielding stories, and, eventually, axial force demand in columns. Three essential steps are envisioned for this purpose: First, a procedure must be developed for estimating the number of simultaneously yielding stories in a simple shear building subjected to velocity-pulse base excitation; Second, this procedure must be adapted as necessary for shear buildings subjected to actual earthquake excitations, in the perspective that earthquakes can be represented as a series of pulses, and; Third, a procedure must be formulated to estimate the axial force demand in columns considering the force transferred from the simultaneously yielding stories and the other non-yielded stories above the column under consideration.

This paper focuses only on the first of these steps, by investigating the number of simultaneous yielding stories due to an incident wave in a tall shear type building subjected to full-sine velocity base excitation, to understand the relationships between input excitation, inter-story drifts, story forces, and hence to formulate a procedure to estimate the number of simultaneously yielding stories along the building height. Although some researchers have previously used wave propagation analysis or aspects of wave propagation theory to find or understand the response of structures due to pulses and earthquakes (e.g., Clough and Penzien [6], Humar [7], Safak [8], Hall et al. [9], Krishnan and Muto [10]) and for system identification and health monitoring (e.g. Sneider and Safak [11], Todorovska and Trifunac [12], Todorovska and Trifunac [13], Todorovska and Rahmani [14], Ebrahimian and Todorovska [15]), the concepts and approach presented here to obtain the number of simultaneously yielding stories and axial force demand in columns is novel.

Note that tall structures like those considered in the study presented here are also subjected to flexural deformations. However, in this initial work, buildings deforming only in shear are considered. Using such a simple model allows to investigate the validity and potential of the concepts before considering applications to more complicated structures.

2. Concepts of wave propagation to find number of simultaneously yielding stories

2.1. Magnitude of velocity wave required to cause story yielding

A ground displacement is taken here as an excitation at the base of a building, generating a traveling wave along its height. Based on classical wave propagation theory, for a shear building with uniform story height and mass, with no damping, and within elastic range, displacement at any point x and instant t can be expressed as a combination of forward and backward propagating displacement waves along the height of the building. Here, the forward and backward traveling displacement waves have been denoted as u_f and u_b, respectively, as shown in Eq. (1).

$$u(x,t) = u_f(x-ct) + u_b(x+ct) \tag{1}$$

where, c is the velocity of a propagating wave. Similarly, shear strain s at any point can also be expressed as a summation of forward and backward moving waves as shown in Eq. (2) and can be expressed in terms of displacement waves as shown in Eq. (3).

$$s = s_f + s_b \tag{2}$$

$$\frac{\partial u}{\partial x} = \frac{\partial u_f}{\partial x} + \frac{\partial u_b}{\partial x} \tag{3}$$

The corresponding velocity v, and forward and backward velocity waves v_f and v_b are expressed as in Eq. (4), and related to displacement and shear strain as per Eqs. (5) and (6), respectively.

$$v = v_f + v_b \tag{4}$$

or,

$$\frac{\partial u}{\partial t} = \frac{\partial u_f}{\partial t} + \frac{\partial u_b}{\partial t} \tag{5}$$

or,

$$\frac{\partial u}{\partial t} = -c\frac{\partial u_f}{\partial x} + c\frac{\partial u_b}{\partial x} = c(-s_f + s_b) \tag{6}$$

For buildings having shear-type lateral-load resisting systems (a.k.a. shear buildings or shear frames), the corresponding elastic shear force induced at a particular story in a building is determined by Eq. (7), where V is the story shear force, K is the shear stiffness, and $\frac{\partial u}{\partial x}$ is the shear strain at that story.

$$V = K \times \frac{\partial u}{\partial x} \tag{7}$$

Story yielding occurs when the story shear force reaches its yield capacity V_p. If the corresponding shear strain is represented as $\left(\frac{\partial u}{\partial x}\right)_y$, then the force deformation relationship, at the onset of story yielding, can be expressed as:

$$V_p = K \times \left(\frac{\partial u}{\partial x}\right)_y \tag{8}$$

or, rearranging Eq. (8),

$$\left(\frac{\partial u}{\partial x}\right)_y = \frac{V_p}{K} \tag{9}$$

Also, if k is the story stiffness and h is the story height, shear stiffness K can be expressed as:

$$K = k \times h \tag{10}$$

Then, Eq. (9) can be written as:

$$\left(\frac{\partial u}{\partial x}\right)_y = \frac{V_p}{kh} \tag{11}$$

Thus, $\left(\frac{\partial u}{\partial x}\right)_y$ is the shear strain required to yield a story with story stiffness of k and shear yield capacity of V_p.

Shear strain can also be expressed as a combination of forward and backward moving velocity waves expressed in Eq. (12).

$$\frac{\partial u}{\partial x} = \frac{1}{c}\left(-\frac{\partial u_f}{\partial t} + \frac{\partial u_b}{\partial t}\right) = \frac{1}{c}(-v_f + v_b) \tag{12}$$

Substituting Eq. (12) in Eq. (11) and rearranging the terms, one obtains:

$$(-v_f + v_b)_y = \frac{c}{h}\frac{V_p}{k} \tag{13}$$

The left hand side can be denoted as v_y since it gives a measure of the minimum magnitude of the linear combination of the forward and backward moving velocity waves required to cause yielding in the story and it depends on the structural property of