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Estimating number of simultaneously yielding stories in a shear building subjected to earthquake excitation

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ABSTRACT

A procedure for estimating the number of simultaneously yielding stories (N_{SYS}) in a shear type building subjected to seismic ground excitation is proposed. Proper estimation of N_{SYS} values will lead to more accurate estimation of axial force demand in columns which will result in economical design of columns. In this procedure, the main pulse of the velocity record responsible for causing the maximum number of stories to yield simultaneously was identified and isolated to idealize it by a full-sine velocity pulse, as an extension of the procedure for estimating the N_{SYS} for a full-sine pulse velocity base excitation developed previously by the authors. A set of eighteen earthquake records sorted into three categories of earthquakes were considered, namely: earthquake excitations having (i) a single dominant pulse (ii) multiple distinct pulses, and; (iii) no distinct pulses in their velocity record. Since most of these earthquakes have relatively long duration main pulses, another set of eighteen earthquake records was obtained by condensing their acceleration time scale and was used to study the proposed procedure for earthquakes that have shorter duration main pulses. The estimated maximum value of N_{SYS} obtained from the proposed procedure was found to be adequately close to the actual value observed from OpenSees analysis for the structures and earthquakes considered.

1. Introduction

To achieve an economical design of columns in lateral-load-resisting systems, it is desirable to estimate the number of simultaneously yielding stories (N_{SYS}) as this directly impacts the axial force demands in columns (particularly given that such forces are currently often specified considering that all stories are yielding). In absence of proper estimation of the number of simultaneously yielding stories and hence axial force demand in columns, the capacity-design approach as implemented in current design procedures could severely overestimate the actual axial force demands on columns, resulting in overdesigned and economically inefficient columns. In an attempt to derive a systematic procedure for estimating the number of simultaneously yielding stories and use it to find axial force demand in columns of shear-buildings subjected to ground excitation (other than by empirically analyzing a large number of archetype structures), three essential steps were envisioned: 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 vertical force transferred from the simultaneously yielding stories and the other non-yielded stories above the column under consideration. The first step of the procedure that is focused on pulse-base excitations was presented in Shrestha and Bruneau [1].

The research work presented here focuses on the second of the above listed steps which is: investigation of a proposed procedure to estimate the N_{SYS} values for a shear building subjected to earthquake excitations, developed by extending the previous procedure for full-sine pulse velocity base excitation. The proposed procedure postulates that the maximum number of stories yielding simultaneously due to an earthquake excitation could be caused by the biggest pulse in its velocity record (an assumption based on observations from response to selected individual earthquake records). Accordingly, in the proposed procedure, the main pulse of the velocity record is isolated and idealized by a full-sine pulse, so that

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the estimation procedure developed previously for full-sine pulse base excitation could be applied.

The idea of representing ground motions either by equivalent pulses, series of equivalent pulses, or dominant pulses, has been around for decades. Techniques for representing near fault pulses vary from use of simple pulses like rectangular, triangular, trigonometric (sine, cosine) functions to more advanced techniques that uses wavelet analysis. Early procedures considered simulating earthquake excitations using simple pulse shapes (e.g. Hall et. al. [2]; Bruneau and Wang [3], [4]). Some recent works considered more advanced techniques for simulating and extracting the near fault pulse of the earthquake record. Based on wavelet analysis, Mavroeidis and Papageorgiou [5] used a modified form of Gabor wavelet to propose a step-by-step procedure to define amplitude A, frequency f_p (or pulse duration T_p), phase ν, and oscillatory character γ as needed parameters to represent near field ground motion. Baker [6] presented a method to classify a ground motion as "pulse-like" or "non-pulselike". Wavelet analysis using Daubechies wavelet was adopted in his procedure. Vassiliou and Makris [7] conducted wavelet analysis to extract the most energetic pulse from the acceleration record of an earthquake. Different types of wavelets were used in their work, including a cosine type B cycloidal pulse, a symmetric Ricker wavelet, an Antisymmetric Ricker wavelet, a Type C1 cycloidal pulse, a Type C2 cycloidal pulse, a Gabor wavelet modified by Mavroeidis and Papageorgiou [5] and referred to as the M&P wavelet, and a time derivative of the Gabor signal.

Here, a simple approach is used: in the proposed procedure, the main pulse in the velocity record responsible for causing the maximum number of stories yielding simultaneously is used and the use of a simple full-sine pulse for idealizing this main pulse was observed in many instances to be sufficient for the intended purpose. Simple pulse models, such as the sinusoidal pulses used by Kalkan and Kunnath [8], the triangular wave trains used by Krishnan and Muto [9], and other similar simple pulses, have been reported adequate to satisfactorily capture the salient responses of structures. Furthermore, the corresponding mathematical simplicity inherent to simple pulse definitions makes them attractive for practical applications. This is consistent with the observation (by Kalkan and Kunnath [8]) that, although simple pulses may not fully capture the characteristic of original earthquakes, the more sophisticated methods of representing or extracting near-fault pulses using wavelets analysis may face some of the same limitations.

The work presented below describes the procedures followed to identify dominant pulses in ground motions, to represent them by equivalent full-sine pulses (consistent with those used in Shrestha and Bruneau [1]), and to predict number of simultaneously yielding stories in a shear-building subjected to earthquake ground motions. These predictions are then compared against results from non-linear analysis. Note that for the study conducted here, simple shear buildings have been considered as opposed to complete designs that may benefit from overstrength introduced by the design process (and that may not have "ideal" shear behavior). Nonetheless, the work presented here is a fundamental step in studying the relationship between story yielding in the building and the velocity waves traveling along the building height, such as to develop a procedure to estimate the number of simultaneously yielding stories due to an earthquake excitation.

2. Analysis parameters

2.1. Structure considered

The same elastic and inelastic systems with uniform and varying story stiffness, defined as Structures-I, -II, -III, and -IV in Shrestha and Bruneau [1], have been considered here. The structures have two percent viscous damping and variation of story yield capacity, V_p, based on the lateral force distribution prescribed by code procedures. The V_p value at the base is made equal to the maximum elastic force demand observed during the entire earthquake history for the case defined as response reduction factor R of 1.0. The V_p values at other stories were then calibrated with respect to the value at the base using the distribution of the V_p values over the building height. Note that the R values will not necessarily be 1 at the other stories. The corresponding four types of structural system are considered as illustrated in Table 1. A response reduction factor R of 4 is considered for the base story. The OpenSees analysis software was used for the dynamic analysis of the structures considered. The model characteristics and non-linear material properties used for the computer analyses were identical to those described in Shrestha and Bruneau [1].

2.2. Input excitation

The input earthquake excitations considered for the study have been categorized into three groups, depending on the pulse-like characteristic of their velocity record: (i) earthquake excitations having a single dominant pulse in their velocity record, (ii) earthquake excitations having multiple distinct pulses in their velocity record, and; (iii) earthquake excitations that do not have distinct pulses in their velocity record (i.e., non-pulse type earthquake velocity excitation). The three groups of earthquakes considered here, have been referred to as Category A, B, and C respectively. Earthquakes belonging to Categories A and B considered here represent pulse type earthquakes that occur near fault and are known to have more damaging effect on the structure. Six earthquake excitations have been considered in each group, resulting in the eighteen earthquakes listed in Table 2. The velocity time history for these earthquake records are shown in Fig. 1. Some of the earthquake records that have been considered include pulses that have large duration such that the wavelength of the pulse is longer than the height of the building. In such cases, the reflected wave may interfere with the incident wave even before the peak of the velocity wave enters the building. The span of the building over which

Table 1
Structural systems considered.

Case	Structure type				Story stiffness		Response		Damping	V_p variation over height
	I	II	III	IV	Constant over height	Varying over height	Elastic	Inelastic	2%	Code based
1	×				×		×		×	×
2		×			×			×	×	×
3			×			×	×		×	×
4				×		×		×	×	×