Engineering Structures 90 (2015) 48–60

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Duration effect of spectrally matched ground motions on seismic demands of elastic perfectly plastic SDOFS

Hetao Hou [a,b,1], Bing Qu [a,c,*]

[a] Sichuan Province Key Laboratory of Seismic Engineering and Technology, Southwest Jiaotong University, Chengdu 610031, China
[b] School of Civil Engineering, Shandong University, Jinan, Shandong Province, China
[c] Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, United States

ARTICLE INFO

Article history:
Received 5 August 2014
Revised 10 February 2015
Accepted 11 February 2015
Available online 2 March 2015

Keywords:
Ground motion duration
Ductility
Hysteretic energy
Seismic demands

ABSTRACT

Although ground motion duration is generally perceived to influence structural response, it has not been explicitly considered in current seismic design practice. This paper investigates duration effect of ground motions on ductility and hysteretic energy dissipation demands on structures. Spectrally equivalent ground motions were first generated from historical records to decouple the effect of duration from those caused by other characteristics of ground motions. The spectrally equivalent ground motions were then grouped into the Short-Duration (SD) and Long-Duration (LD) suites based their significant durations for Response History Analyses (RHA) of elastic-perfectly plastic Single Degree of Freedom Systems (SDOFS). Results from RHA show that ground motion duration has a negligible influence on the central tendency of ductility demands but a significant impact on that of hysteretic energy dissipation demands. Statistical evaluations and hypothesis tests further demonstrate that the LD ground motions lead to higher hysteretic energy dissipation demands but exert similar level of ductility demands on structures in comparison with the SD ground motions. With the result database from RHA, an empirical model was developed to consider the effect of ground motion duration on hysteretic energy dissipation demands. The empirical model was then integrated into the Park–Ang damage index for determination of the required ductility capacity for a system. Results from parametric analyses show that the empirical model provides reasonable estimates of required ductility capacity. Results from RHA were also used to evaluate adequacy of the FEMA 461 quasi-static cyclic loading protocol for seismic performance evaluation. It was found for elastic-perfectly plastic SDOFS that the FEMA 461 quasi-static cyclic loading protocol is sufficient to exert the hysteretic energy dissipation demands due to SD ground motions but may be inadequate for consideration of the hysteretic energy dissipation demands due to LD ground motions.

1. Introduction

The characteristics of earthquakes which have the greatest importance for structural responses are intensity (amplitudes of displacement, velocity and acceleration), frequency content, and duration of earthquake ground motions. Intensity and frequency content of a ground motion record affect amplitude and shape of its response spectrum, respectively. These two factors can be directly considered through the use of idealized seismic design spectra or response spectra generated using ground motion records in determination of the seismic demands on a given structure. Although it is generally perceived that duration of ground motions also influences structural response and some analysis and design methods tend to indirectly account for this factor through proper selections of ground motion records and hysteretic models [1,2]; the effect of ground motion duration has never been explicitly taken into account as a parameter in current seismic design provisions [3], performance assessment [4,5], and loading protocols used for testing of structural components, assemblies, and systems [6]. There are many factors leading to the ignorance of the effect of earthquake ground motion duration in the earthquake engineering design community. The major reasons are briefly listed below.

First, the past research has produced inconclusive and even controversial results on the effect of earthquake ground motion duration on structural damage due to the use of different measures of earthquake duration and structural damage indices [7]. Conceptually, ground motion duration correlates to the energy released from an earthquake to a structure and consequently affects its damage

---

* Corresponding author at: Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, United States. Tel.: +1 805 756 5645; fax: +1 805 756 6330.

E-mail addresses: houhetao@sdu.edu.cn (H. Hou), bqu@calpoly.edu (B. Qu).

[1] Tel.: +86 13969036483; fax: +86 531 88392672.

http://dx.doi.org/10.1016/j.engstruct.2015.02.013
0141-0296/Published by Elsevier Ltd.

resulting from the earthquake. Prior experimental studies of reinforced concrete and steel components [8–15], investigation of historical earthquake records [16,17], earthquake reconnaissance field studies [18], and numerical studies using cumulative damage measures [19–23] have reported that duration of ground motions (or the higher number of cyclic loading cycles caused by long-duration ground motions) is positively correlated to structural damage. However, analytical studies using maximum displacement or drift as a measure of damage contradict these findings and generally find no correlation between ground motion duration and increasing damage [22,24–29] unless the models can capture stiffness and strength degradations caused by excessive damages and the destabilizing action of gravity loads [7].

In addition to the use of different measures of duration and structural damage, challenges exist to decouple the effect of ground motion duration from those caused by other ground motion characteristics. For example, differences in response spectral amplitude and spectral shape can also result in different damage levels in a given structure. While different measures have been proposed to separate peak response from cyclic response [2,30], it is not straightforward to isolate the effect of duration from other characteristics.

Moreover, although progressively collected data tend to increase diversity of the ground motion records [31], compared with the abundant database of earthquake records having short and moderate durations, the limited number of long-duration ground motion records explains in part the lack of interest to incorporate ground motion duration as a parameter into seismic design practice. The long-duration ground motions can be caused by near-fault earthquakes with backward directivity [32,33] and more likely by the large subduction zone earthquakes [34,35]. Although the data of large subduction earthquakes are very limited, geological evidence and investigations since 1980s provided compelling evidence that such earthquakes have occurred at regular, though widely spaced, time periods in the past in the world. Taking North America as an example, such earthquakes could happen in the future with magnitude and duration comparable to those of the 1960 Chile and 1964 Alaska subduction earthquakes, perhaps even reaching magnitude 9.5 and lasting for 4 min [35–37]. The recent earthquake events (such as the M9.0 Tohoku, Japan Earthquake) clearly highlight the potential of having the earthquakes of larger magnitude and longer duration than any earthquakes experienced in modern times. The severe building damages observed from these long-duration earthquakes have called into the following question: whether the current seismic provisions and design practice, which do not appropriately account for the effect of ground motion durations, can produce acceptable structural response in the event of a severe long-duration earthquake.

Furthermore, the design lateral strength prescribed in modern seismic design provisions for structures are typically lower and in some cases much lower than the lateral strength required to maintain a structure in the elastic range in the event of severe earthquakes. Strength reductions from the elastic strength demand are commonly accounted for with the response modification factor, i.e., the R factor. Many analytical models have been proposed to quantify the R factor based on the ductility capacity of a specific system [38–46]. However, several researchers have expressed their concerns about the lack of rationality in determination of the R factors, which only takes into account ductility capacity of a system. As explicitly specified in the 2003 NEHRP Recommended Provisions and Commentary for Seismic Regulations for New Buildings and Other Structures [47], structural systems with larger hysteretic energy dissipation capacity should be assigned higher R values, resulting in design for lower forces than systems with relatively limited hysteretic energy dissipation capacity. It is necessary to check whether the hysteretic energy dissipation demand on a system is lower than its hysteretic energy dissipation capacity for successful achievement of satisfactory seismic performance in the system. However, analytical models quantifying the hysteretic energy dissipation demands, which can be significantly affected by earthquake ground motion durations, remain missing.

As discussed above, crucial knowledge gaps exist in understanding and quantifying the effect of earthquake ground motion duration on seismic response of structures. It is an impediment to the widespread acceptance of the current seismic design provisions for structures for mitigating the catastrophic effects of earthquakes. Therefore, the objectives of this investigation are (1) to generate spectrally equivalent ground motions with short and long durations for isolating the effect of duration from the effects of other ground motion characteristics; (2) to investigate the effect of earthquake duration on ductility and hysteretic energy dissipation demands of structures through extensive Response History Analyses (RHA) of representative nonlinear Single Degree of Freedom Systems (SDOFS); (3) to develop analytical models for quantification of hysteretic energy dissipation demands on structures; (4) to discuss the implication of the results for seismic design of structures based on a damage index that combines both ductility and hysteretic energy dissipation; and (5) evaluate whether the current loading protocol recommended by Federal Emergency Management Agency (FEMA) [6] is adequate to impose the hysteretic energy dissipation demands associated with short- and long-duration earthquakes in quasi-static cyclic tests on structural specimens, respectively.

2. Ground motion database

2.1. Measure of ground motion duration

It should be noted that the total recorded time of an accelerogram is not a scientific measure of ground motion duration for the problems addressed in this investigation since the total length of the accelerogram may vary depending upon the recording device; and more importantly only the strong motion portion of an accelerogram may cause nonlinear behavior and hence damage in a structure. More than 30 metrics have been defined in literature to quantify the duration of ground motions for different purposes [48]. The most widely used measures for hazard quantification and ground motion selection [49] include the following four definitions: *bracketed duration*, *uniform duration*, *significant duration*, and *effective duration*. *Bracketed duration* represents the time elapsed between the first and last excursions of the accelerogram above a certain acceleration threshold (e.g., 0.1 g). *Uniform duration* represents the total time during which the acceleration is larger than a certain acceleration threshold (e.g., 0.1 g). *Significant duration* represents the time interval over which a specific percentage of the total Arias Intensity is accumulated (commonly used ranges are 5–95% and 5–75%). The total Arias Intensity, I_A, is defined as

$$I_A = \frac{\pi}{2g} \int_0^{t_{\max}} a^2(t)dt \tag{1}$$

where $a(t)$ = ground acceleration time-history; $t_{\max}$ = length of accelerogram; g = gravitational acceleration.

Effective duration uses the same concept as *significant duration* except that the total Arias Intensity is replaced by the following Cumulative Absolute Velocity (CAV):

$$\mathrm{CAV} = \int_0^{t_{\max}} |a(t)|dt \tag{2}$$

It is important to recognize that the abovementioned four duration measures may not be identical even for the same ground motion. For comparison purpose, Fig. 1 illustrates the evolutions