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Short communication

# Effects of multiple earthquakes on inelastic structural response

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ABSTRACT

The basic approach for seismic design of structures utilizes a single loading scenario and a single performance criterion; usually life-safety. In recent years, social and economic considerations have necessitated that more than one performance criterion is used, and also more than one level of earthquake intensity. This multiple load-and-limit state seismic design is the current best practice. There are a few locations around the world that warrant an alternative approach. These locations are affected by more than one earthquake within a relatively short period of time due to their special seismo-tectonic setting. Few existing studies simply assume that the first earthquake will impose the maximum damage. An opportunity has presented itself to study the effect of multiple strong earthquakes on structures as a consequence to the exceptionally rich set of records obtained from the earthquake sequence of Tohoku (Japan), starting on March 2011. In this technical note, five stations are selected to represent a set of sites subjected to multiple earthquakes of varying magnitudes and source-to-site distances. From the tens of records captured at these five sites, three are selected for each site to represent scenarios of leading and trailing strong-ground motion. A leading set is where the first earthquake has the largest peak ground acceleration (PGA) in the sequence of three, while a trailing set has the second or third records as its highest PGA signal. A short list of earthquake response parameters is selected, and the records are treated in two different manners. Inelastic constant ductility spectra for acceleration response are examined, alongside force reduction factor spectra. The final part of the technical note is a reinforced concrete (RC) frame analysis subjected to the same set of ground motions used for the response spectra. The inelastic response and force reduction factor spectra, alongside the inelastic response of the RC frame, not only confirm that multiple earthquakes deserve extensive and urgent studies, but also give indications of the levels of lack of conservatism in the safety of conventionally-designed structures when subjected to multiple earthquakes.



## 1. Introduction

There is substantial field evidence showing that the sequence of seismic events characterized by an earthquake with moderate intensity, followed by aftershocks with comparable or even higher magnitude, may occur in several hazard-prone regions world-wide ([7,8], among others), e.g. in California (Mammoth Lakes, 1980; Coalinga, 1983; Whittier Narrows, 1987; Northridge 1994), Italy (Friuli, 1976; Irpinia, 1980; Umbria-Marche, 1997; L'Aquila, 2009), Japan (Kobe, 1995; Niigata, 2004; Tohoku, 2011), New Zealand (Darfield, 2010; Christchurch, 2011) and Turkey (2011 Van Earthquakes,), among many others. Although researchers have yet to agree on the fundamental differences in characteristics between a main shock and major afore- and after-shocks [17], there is a renewed interest in assessing the effects of seismic sequences on the structural response of new and existing buildings and bridges. Early analytical investigations carried out by Mahin [18] showed that the displacement ductility demand of elastic–perfectly plastic single-degree-of-freedom (SDOF) systems may slightly increase at the end of the aftershock with respect to the main shock. Similar results were found by Aschheim and Black [4]. They examined the effects of prior earthquake damage on SDOF stiffness degrading structures and concluded that prior ductility demand has a very minor influence on peak displacement response. It was, however, assumed that prior displacement demands were less than those that would result if the structure was initially undamaged. Elnashai et al. [10], assessing an updated database of seismic records from Europe, California and Japan, observed that the ductility demand required by multiple earthquake ground motions can be remarkably higher than that required by a single event. This finding has been confirmed lately by extensive analytical work on SDOF systems and multi-storey steel buildings [3,12]. However, the latter numerical studies were neither exhaustive nor conclusive, since they examined only one natural and two artificial far-fault ground motions. More recently, extensive inelastic analyses have been carried out on a large ensemble of as-recorded main- and after-shocks to investigate the effects of

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repeated earthquakes on inelastic displacement ratios [16,14,15]. Nevertheless, hysteretic elastic plastic (bilinear) models were utilized for such nonlinear analyses. It is worth noting that the previous work focused primarily on idealized SDOF systems; additionally it was clearly stated that real sequential earthquakes were not examined as they were considered to render the numerical analyses extremely complex and not leading to transpicuous and practically conclusions, thus highlighting the limitation of the research targets.

The present study discusses the results of an ongoing research aimed at investigating the effects of as-recorded multiple earthquakes on the inelastic response of structural systems. Advanced hysteretic models with stiffness and/or strength degradation were considered to reliably simulate the seismic response of reinforced concrete (RC) structures under earthquake loadings. Inelastic constant ductility spectra are examined, alongside force reduction factor spectra. The results of the inelastic response for a sample RC frame subjected to a suite of multiple natural records are also presented to emphasize the lack of conservatism of the modern seismic codes. The results discussed hereafter are the outcomes of the preliminary analyses carried out on the effects of multiple earthquakes; such results provide some first insight of the inelastic behavior of structural systems that exhibit stiffness deterioration and strength degradation, e.g. existing non-ductile RC buildings.

## 2. Earthquake input

The Tohoku earthquake was a magnitude $M_w = 9.0$ undersea mega-thrust earthquake that occurred on 11 March 2011 off the coast of Japan. The epicenter was approximately 70 km s East of the Oshika Peninsula of Tohoku and the hypocenter at an underwater depth of approximately 32 km s (e.g. [22]). Following the main quake of March 11, there has been a large number (about 1000 up to now!) of moderate-to-high magnitude after-shocks. Five seismic stations are selected to represent a set of sites subjected to multiple earthquakes of varying magnitudes and source-to-site distances. From the tens of records captured at the five seismic sites, three are selected for each site to represent scenarios of leading and trailing strong-ground motions. A leading set is where the first earthquake has the largest peak ground acceleration (PGA) in the sequence of three (FKS016), while a trailing set has the second (IBR003 and MYG004) or third (FKS010) records as its highest PGA signal. A station with a sequence of records exhibiting similar values of PGAs was also considered. The properties of the sample records are summarized in Table 1. The North–South components of the strong motions were utilized. The values of moment magnitude $M_w$ for the sample earthquakes range between 5.8 (FKS010-1; FKS016-2 and IBR003-1) and 9.0 (FKS016-1); the PGAs vary between 0.100 g (IBR003-3) and 1.138 g (FKS016-1). The earthquake records were downloaded from the database of K-Net available on the website http://www.k-net.bosai.go.jp/k-net/quake/index_en.html.

The sample ground motions were firstly corrected employing a linear baseline correction and a Butterworth band-pass filter (Freq1 = 0.1 Hz, Freq2 = 25 Hz, Order 4). The frequency content of the afore-, main and after-shocks is measured by the predominant ($T_p$) and the mean ($T_m$) periods of the ground motions. The values of $T_p$ and $T_m$ are lower than 0.3 s; $T_m$ is generally higher than $T_p$. It is observed that no direct correlations exist between the predominant and mean period of the main shocks and the counterpart values of the afore- and after-shocks. The records selected for the present study were generated by different seismo-genetic faults. They are of high interest from an engineering seismology standpoint as they are representative of real earthquake records. Further selections of seismic sequences from existing world-wide earthquake records may be misleading as they can be biased in terms of the ground motions properties, e.g. frequency content, amplitude, $T_p$ and $T_m$, and also of the sequence of the strong/weak pulses. In the present study the intensity measure (IM) used to describe ground motions and their sequence is the PGA; however, energy-based IMs, can also be utilized to quantify cumulative damage potential. The use of the latter IMs is beyond the scope of the present technical note.

## 3. Inelastic spectral response

### 3.1. Hysteretic models

Three piecewise hysteretic models were considered to evaluate the inelastic response spectra: the elastic–perfectly plastic, the elastic plastic with linear hardening and the modified Clough model. The elastic plastic model is the simplest hysteretic model and can be employed to simulate the response of framed systems in which the plastic collapse is caused by the simultaneous onset (elastic–perfectly plastic) or the progressive formation (elastic plastic with hardening) of plastic hinges. However, bilinear models do not account for cyclic degradation. The modified Clough model was also utilized because it incorporates stiffness deterioration under reversal loading ([19,13], among others). In the modified Clough model the amount of stiffness degradation is a function of the peak deformation. Strain-hardening is introduced by assigning a positive slope to the post-yield portion of the primary envelope. Three values of hardening were considered, namely 5%, 10% and 15%. An increase of the hardening value in the modified Clough model delays the amount of stiffness degradation. Inelastic acceleration and displacement response spectra were derived through nonlinear dynamic analyses performed by assuming an equivalent viscous damping ratio of 0.5%. Three values of constant ductility $\mu$, namely 2, 4, and 6 were utilized. These ductility levels are commonly related to specific seismic damage states whether designing a new structural system or assessing an existing one in earthquake-prone regions (e.g. [5,6,1,2]; among others).

### 3.2. Acceleration response

The inelastic acceleration response spectra derived for the sequence of earthquake records with similar values of PGAs (see Table 1), i.e. the triad of time histories relative to Funehiki Station (FKS008), are provided in Fig. 1. The computed results are for the stiffness degrading hysteretic model with 5% post-yield hardening. The response spectra for the single event refer to the first record in the sequence. The results are expressed in terms of spectral accelerations and spectral amplification factors. Fig. 1 shows that the inelastic spectral demand for the multiple events is higher than that of the single record. The variations are remarkably dependent on the period of vibration and the level of ductility. The maximum difference between single and multiple events is found at very low periods, i.e. less than 0.1 s. For $\mu = 2$, the inelastic spectral response for multiple records can be twice that relative to a single event (0.58 g *vs.* 0.29 g at 0.1 s). As the $\mu$-value increases, the maximum difference is found for shorter periods: 0.06 s (for $\mu = 4$ and $\mu = 6$) *vs.* 0.1 s for $\mu = 2$. Moreover, the effects of sequence of earthquakes tend to become negligible for high ductile systems. Acceleration spectra estimated for high ductility and single events tend to match the response spectra for multiple earthquake records. It can thus be argued that modern capacity-designed structures, i.e. with accurate seismic details, hence exhibiting adequate local and global ductility, may withstand safely the seismic demand induced either by a single or a sequence of earthquake loading. Multiple records spectra tend to be smoother than the single event