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Ductility demands and residual displacements of pinching hysteretic timber structures subjected to seismic sequences

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ABSTRACT

Building structures constructed of timber components are characterized by a pinching-type hysteresis that indicates degraded stiffness and strength. Owing to the significant effect of their loading history, these types of structures may be more prone to failure when subjected to sequential seismic excitations. This study investigates the effect of seismic ground motion sequences on the ductility demands and residual displacements of building structures with pinching hysteretic models. A single-degree-of-freedom (SDOF) structure is considered, and is modeled with the hysteretic model consisting of a slip element and a bilinear element. The seismic ground motion sequences are simulated by repeating ground motion records with differing intensities. Through dynamic time history analysis, the effect of the seismic intensity, ductility level, hysteretic parameters, and site conditions are investigated. The results indicate that the seismic sequences amplify the ductility demands of pinching hysteretic structures, and this effect is more significant for short period structures. The pinching hysteretic structures have ductility amplification factors that are higher than those of bilinear hysteretic structures. The residual displacement shows a relatively strong correlation to the maximum displacement, and the ratio of residual displacement to maximum displacement approximately obeys an exponential probability distribution. Based on the numerical results, empirical formulas for estimating the ductility demand amplification and the probability density distribution of the residual displacement are proposed.

1. Introduction

A large earthquake can be followed by smaller aftershocks, and may also be preceded by foreshocks. The foreshock-mainshock or mainshock-aftershock sequences can lead to ground acceleration sequences at specific sites, causing the engineering structures constructed on these sites to experience repeated seismic excitations in a short period of time. The time interval between sequential earthquakes varies widely, from several minutes to several years. During very short time intervals within which the repair of damaged structures cannot be performed, repeated seismic excitation of these damaged structures can result in an undesirable accumulation of damage, and a structure that would survive a single excitation may fail under the effect of a seismic sequence.

While seismologists are trying to determine the correlation between the foreshock, mainshock, and aftershocks, at present it is still difficult to predict the occurrence of foreshocks or aftershocks [1,2]. However, for engineering design, structures are expected to suffer repeated earthquake excitations over a short period of time, particularly in areas where large numbers of sequential earthquakes have previously occurred. For example, foreshocks were observed during the 1975 Haicheng earthquake, the 1995 Kozani-Grevena earthquake [2], and the 2016 Kumamoto earthquake, while aftershocks have occurred in many major earthquakes, including the 2008 Wenchuan earthquake, the 2010 Haiti earthquake, the 2011 East Japan earthquake, the 2011 Christchurch earthquake, the 2016 Kumamoto earthquake, and the 2016–2017 Central Italy earthquakes. The number of aftershocks can vary from a few to hundreds. The 2008 Wenchuan earthquake had a mainshock of magnitude 8.0, followed by five aftershocks with magnitudes greater than 6.0 [3]. The 2010 Haiti earthquake had a mainshock of magnitude 7, which was followed by 14 aftershocks with magnitudes of 5–6.1 [4]. The 2011 East Japan earthquake had a mainshock of magnitude 9.0, which was followed by more than 7000 aftershocks over the next year. From August 2016 to January 2017, the central Italy was hit by an earthquake sequence, within includes 9 Mw5+ earthquakes and multiple aftershocks following these major shocks [28].

In current seismic codes, however, design earthquakes are usually defined as single event, and the effect of seismic sequences is not taken into account. A number of studies have investigated the influence of ground motion sequences on various types of structures. Amadio et al.

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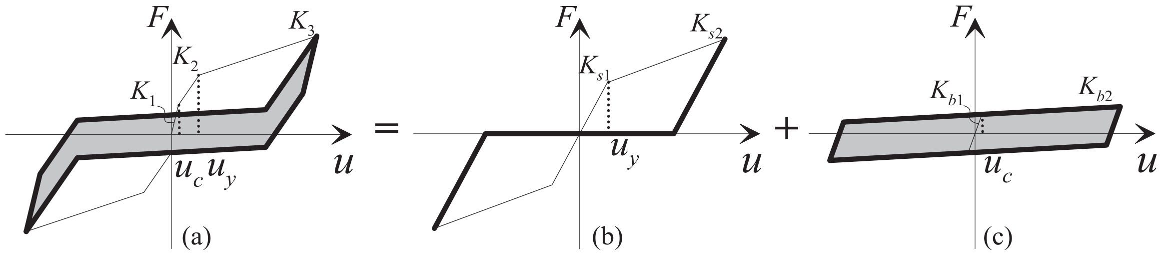

Fig. 1. Pinching hysteretic model.

[5] simulated the effects of a seismic sequence on single-degree-of-freedom (SDOF) structures using a bilinear model, a degrading stiffness hysteretic model without pinching, and Clough's model. Three ground motions were used as earthquake inputs, and the base shear, ductility, and dissipated energy were investigated with a time history analysis. A parameter, q, is defined as the ratio between the maximum accelerogram that a structure can withstand without failure and the accelerogram at which yielding first appears in the structure. The results demonstrated that multiple earthquakes can induce considerable accumulation of damage and result in a consequent reduction in the q-factor. Following this research, Fragiacomo et al. [6] conducted extensive studies considering different types of steel frame structures. Hatzigeorgiou and Beskos [7] investigated the effects of multiple earthquakes on the inelastic displacement ratio of structures. A total of 112 ground motion records obtained at different types of sites were applied to structures simulated with a bilinear model. An empirical formula for the inelastic displacement ratio was proposed, which incorporated the effects of the structural period, damping ratio, post-yield stiffness ratio, and force reduction factor. Hatzigeorgiou [8] also investigated the ductility demand and strength of an inelastic structure subjected to repeated near- and far-fault earthquakes. Di Sarno [9] employed ground motion sets obtained during the 2011 earthquake in Tohoku, Japan. The inelastic spectral responses of the ground motion sets were derived, and a two-span two-story frame structure was subjected to multiple earthquake ground motions. It was recommended that the effects of stiffness and strength degradation due to sequential earthquakes should be considered in modern codes of practice. Zhai et al. [3,10–12] carried out a series of studies investigating the Park-Ang damage index, constant damage displacement ratio, and strength reduction factor of structures subjected to a mainshock-aftershock sequence. Ruiz-Garcia et al. [13] investigated the interstory drift and residual drift of reinforced concrete (RC) frame buildings under the excitation of seismic sequences, and determined that the building response depends on the ratio of the damaged period of vibration to the dominant period of the aftershock. Ruiz-Garcia and Aguilar [14] investigated the influence of modeling assumptions on the maximum and residual displacements of steel frame buildings subjected to mainshock-aftershock sequences, and highlighted the importance of the building model for the assessment of structural behavior induced by aftershocks. Very recently, Hosseinpour and Abdelnaby [15] investigated the effects of irregularity, earthquake direction, aftershock polarity, and vertical component of the earthquake on structural performance. Shin and Kim [16] demonstrated that the frequency contents play an important role in the response induced by aftershocks. Nazari et al. [17] examined the collapse risk of wood frame buildings, and determined that the effect of aftershocks on the damage states are more significant than their effects on collapse for low-rise buildings.

These previous studies have demonstrated that seismic sequences produce responses that differ from those that occur during a single event, and the effect depends on numerous factors, including the structural period, structural modeling approach, hysteretic model, damping ratio, and frequency contents of the ground motions. During repeated earthquakes, degradation of structures is of great concern [18], as the preceding earthquake causes reduction in the structural strength of stiffness, and the resulting change in structural performance may have unfavorable effects on the structural response. In the 2016 Kumamoto earthquake, a large number of timber structures, including many historical structures of great cultural value, failed as a result of the sequential excitations of foreshocks, mainshock, and aftershocks. This study focuses on timber structures, which have a very limited energy dissipation capability due to the pinching phenomenon in their hysteretic loops. These characteristics are substantially different from steel or concrete structures, which have been simulated by a bilinear model or modified Clough model in previous studies.

By employing a pinching hysteretic model, this study investigates the ductility demands and residual displacements of timber structures subjected to ground motion sequences. These ground motion sequences are modeled by replicating a specific ground motion record, and the intensities of the two sequential ground motions are adjusted to simulate foreshock-mainshock and mainshock-aftershock sequences. Based on the numerical results, some insights into the effect of sequential earthquake excitations on pinching hysteretic structures are presented.

2. Hysteretic model of the structure

Fig. 1(a) shows the force–displacement relationship curve of the structural model considered in this study. The skeleton curve is composed of three segments: the first represents the elastic stiffness, K_1; the second segment indicates the stiffness of the material after cracking, K_2; and the third indicates the stiffness, K_3, after reaching the yielding force, F_y. The stationary hysteresis is indicated by the thick lines. This model is characterized by a pinching phenomenon, which represents the typical hysteretic characteristics of timber systems, including X-lam buildings and light-frame walls [19]. The model can be decomposed into a slip element (Fig. 1(b)) and a bilinear element (Fig. 1(c)). The slip element has a bilinear skeleton curve, with the elastic stiffness and post-yield stiffness denoted as K_{s1} and K_{s2}, respectively. The slip element experiences slip-type hysteresis (thick line) after the virgin circle, with no energy dissipated in slip hysteresis. The yield displacement is denoted as u_y. The energy dissipation of the structure is contributed only by the bilinear element. Similar to the definitions established by Matsuda and Kasai [20], K_{b1} and K_{b2} denote the initial elastic stiffness and the post-yield stiffness of the bilinear model, respectively, and u_c is the displacement corresponding to the elastic limit of the bilinear element.

Matsuda and Kasai [20] presented a set of parameters for this hysteretic model: $K_1 = 0.44$ kN/mm, $K_{b1}/K_1 = 0.53$, $K_{b2}/K_{b1} = 0.0566$, $u_c = 4.5$ mm, and $u_y = 18$ mm. These parameters were obtained from experiments with typical polywood structures used in Japan. These parameters are adopted as benchmark values. In addition, some of these parameters are also adjusted to investigate their effect on structural response. In addition to the benchmark values, $K_{b2}/K_{b1} = 0.2$ and $K_{b1}/K_1 = 0.75$ and 1.0 are also considered. Note that when K_{b1}/K_1 is equal to 1.0, the structural model becomes a bilinear model. Fig. 2 shows the hysteretic curves with different parameter values. The structural mass is adjusted so that the elastic period, T, is 0.5 s, 0.8 s, 1.2 s, and 2.0 s. An inherent viscous damping ratio of 0.02 is assumed, and the damping coefficient is proportional to the tangent stiffness. This damping assumption is commonly used for dynamic analysis of timber structures in