17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SEISMIC FRAGILITY OF BUILDINGS RESTING ON HILL SLOPES UNDER MAIN SHOCK-AFTERSHOCK SEQUENCES

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Abstract

Earthquakes are paramount among the natural hazards owing to their potential to cause severe fatalities to the living beings and the infrastructure. Disastrous consequences after occurrence of several earthquakes across the world have inspired the researchers and practicing engineers to explore the seismic performance of structures. With rapid growth of urbanization, building construction is expanded to mountainous regions giving rise to step-back and set back-step back configurations of hill buildings. However, post-earthquake reconnaissance survey reports have revealed that the buildings resting on hill slopes are more susceptible to seismic damage than the buildings located in plain terrain. In general, foundations of hill buildings rest on different elevations causing the shorter columns on uphill side getting attracted to higher force and sustaining more damage during earthquakes. Hill buildings exhibit higher degree of irregularity as the centre of mass and the centre of stiffness are neither concurrent at any storey nor vertically collinear for different storeys resulting in torsional behavior in the buildings during earthquakes. Consequently, it is of utmost significance to delve deep into the seismic response pattern and seismic design philosophy of hill buildings with an objective of building a seismic resilient nation. The dearth of adequate literature on the seismic vulnerability of buildings resting on hill slopes is the primary motivation behind this study so as to contribute to the fulfillment of the research gap. Fragility functions represent the conditional probability of a structure surpassing a particular damage state under seismic excitations. Therefore, characterization of structural performance and enumeration of different damage states are performed so as to construct the seismic fragility functions of hill buildings at different seismic intensity levels. Apart from that, it can be well perceived that the hill buildings are not only prone to seismic damage under mainshock earthquakes, but also may be affected by aftershock earthquakes. At the instance of the structural response of hill buildings being highly impaired by mainshock events, occurrence of high intensity aftershock events pose severe detrimental effects to the structures and thus cannot be neglected in the seismic vulnerability evaluation. Hence, a simplified methodology is proposed in this research to incorporate aftershocks along with the main shocks in the seismic analysis and design of hill buildings. The comparison study of the seismic analysis results of hill buildings under only main shock and mainshock-aftershock sequences has revealed that the traditional approach of omission of aftershocks in seismic vulnerability evaluation, can underestimate the true seismic risk. Substantive findings from this research would enlighten the engineering community to initiate their academic venture in development of seismic fragility functions of hill buildings under the main shock-aftershock sequences with further refinement.

Keywords: Hill Buildings; Seismic; Fragility; Mainshock; Aftershock.

1. INTRODUCTION

Earthquake is one of the most disastrous natural calamities due to its unpredictability and the huge power of devastation. Earthquakes do not affect people directly but due to the destruction of structures, they are more vulnerable. During severe earthquakes, structures got collapsed and cause severe loss of human lives and property.

A major portion of the Indian subcontinent comes under the hilly region. The Scarcity of flat ground in the hilly region compels the construction activity in this sloping ground. Due to economic growth and rapid urbanization in this region, the rapid construction of multi-story reinforced concrete buildings on a hilly slope has become very necessary and demandable. To suit the hill slope geometry the structural configuration of the building situated in hilly regions are different from the buildings which are present in the flat topography due to their irregularity and asymmetry in both horizontal and vertical planes. The centre of mass of different floors and the centre of stiffness of different stories of the building does not lie on the same vertical axis. Two types of column provide support of these types of buildings at different levels where one type of column are situated on the sloping ground and the other type resting on the floor below. Between these two columns which are shorter in length are stiffer and can attract more forces and are prone to more damage when they are subjected to an earthquake. So for this type of irregularity and asymmetry in the structures of a hilly area, they are subjected to severe torsion in addition to lateral forces under the action of an earthquake. Several Past seismic events had occurred in this region such as the 1905 Kangra earthquake (Mw 7.8), 1934 Bihar and Nepal earthquake (Mw 8.0), 1950 Assam earthquake (Mw 8.6), 1988 Bihar and Nepal earthquake (Mw 6.9), 1991 Uttarkashi earthquake (Mw 6.8), 1999 Chamoli earthquake (Mw 6.8), 2011 Sikkim earthquake (Mw 6.9), 2015 Nepal earthquake (Mw 7.8) and most recent 2016 Manipur earthquake (Mw 6.8) which have shown major faults and drawbacks in the design and construction of failed and damaged RC buildings. Hence utmost care should be taken for making these structures earthquake resistant. Several configurations of buildings on the hilly slope are present but out of them the common geometric configurations of multi-storeyed reinforced concrete (RC) framed buildings on hill slopes are shown in Fig. 1. It can be observed that the foundation structure more or less follows the natural shape of the slope.

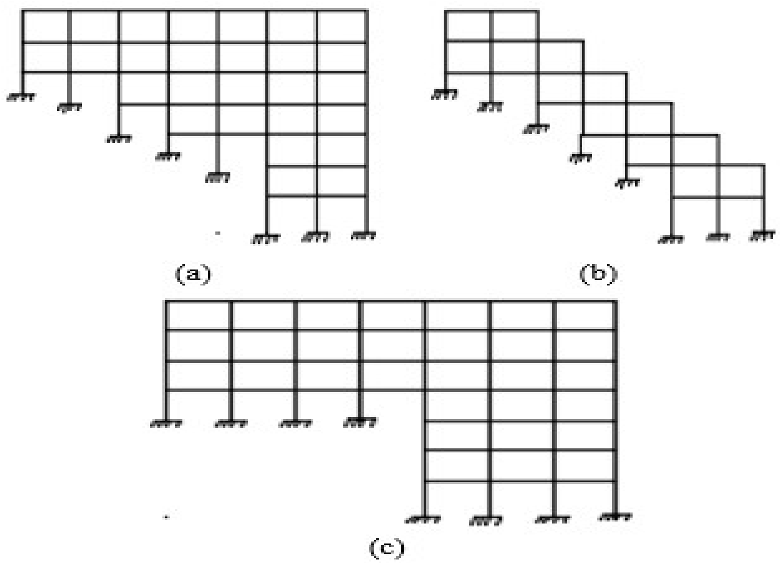


Fig 1. Hill building configuration (a) Step-back building (b) Setback-Step back building (c) Floors at two different levels [Source-De *et al.* (2018)]

Seismic Fragility function plays an important role in the seismic vulnerability analysis of an earthquake phenomenon by indicating the probability of structural components exceeding different damage states under seismic loading. So fragility curves are one of the most efficient tool for probabilistic assessment of structures. In this study fragility relationship for RC buildings situated on a slope is currently generated based on an initially undamaged building condition that is subjected to only mainshock and mainshock-aftershock sequences. A Complex fault system can cause multiple earthquakes in any region around the world. Because when the first rupture takes place these fault systems are not able to relieve all accumulated strains. Therefore, sequential ruptures occur at different locations until the fault system gets completely stabilized. The sequential ruptures along the fault segments lead to multiple earthquakes which are often hard to distinguish them as foreshock, mainshock and aftershock or a sequence of earthquakes. So an attempt has been made in this study to perform fragility analysis of Step-back building configuration under mainshock and mainshock-aftershock sequences.

2. LITERATURE REVIEW

The existing literature in the area of performance of hill buildings under seismic sequences is quite scarce. The substantive findings from the existing relevant literature are summarized below.

Kumar and Paul (1998) performed three-dimensional dynamic analyses of hill buildings based on the transformation of stiffness and mass of various components about a common arbitrarily chosen reference axis.

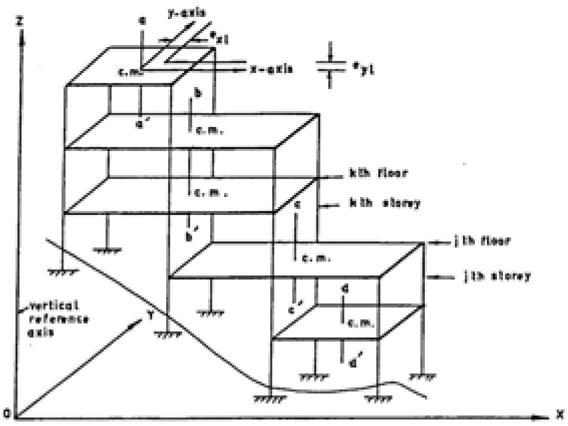


Fig 2.1 Idealized multi-storey Step-back and Set back building [Source-Kumar and Paul (1997)]

Sarkar *et al.* (2010) proposed an empirical formula for estimating the fundamental time period of Setback-Step back building which was expressed as the function of regularity index based on modal analysis and pushover analysis of setback buildings.

T=0.075 1-2(1-и) (2и-1)] (1)

и=regularity index

h=overall height of the building

Garcia (2012) examined the ground motion characteristics of 184 real mainshock-aftershock data and studied the response under artificial sequences which were very different from that of real sequences particularly when the approach of repeating the real mainshock data with identical ground motion features as an artificial aftershock was employed.

Singh *et al.* (2012) conducted a linear and nonlinear time history analysis of Step-back RC frame buildings on a slope and identified a considerable amount of torsional effects under cross slope excitations.

Tesfamarian *et al.* (2013) noticed an increase in average maximum inter-story drift ratio for six-story ductile RC frames on being subjected to mainshock–aftershock sequences relative to the mainshock alone. This increase was not observed when the frame had brittle unreinforced masonry infill.

Surana *et al.* (2015) assessed the seismic fragility function of Step-back hill buildings by incremental dynamic analysis procedure which disclosed that the buildings resting on slope designed as per the existing code provisions for buildings situated on flat topography exhibit a higher susceptibility to damage and failure during earthquakes.

Vijaya Narayanan *et al.* (2015) conducted nonlinear dynamic analyses on hill buildings with different restraints at column bases to conclude that the buildings with smaller plan dimensions were best suited for construction along steep hill slopes.

Raghunanadan *et al.* (2015) proposed aftershock collapse fragility of ductile reinforced concrete (RC) framed buildings in California by conducting incremental dynamic analysis and concluded that aftershocks may result in the collapse of a structure which was not seriously damaged in the mainshock.

Abdelnaby (2016) suggested damage control fragility curves for various mainshock-aftershock events. For that purpose, the response of various buildings such as gravity designed frame, capacity designed frame and moment-resisting frame buildings were considered which showed the severity of the damage potential of all these frames for subsequent aftershock events as compared to mainshock event. Multiple earthquakes offer significantly more vulnerability to the structures as compared to one major design earthquake.

Mohammad *et al.* (2017) presented a parametric study of hilly buildings which were geometrically varied in height and length and they were subjected to seismic forces along and across hill slope direction and analysed by using Response Spectrum Method and from that, it could be concluded that Setback-Step back buildings perform better than Step-back configuration buildings when they were subjected to seismic loads.

Surana *et al.* (2018) categorized different buildings such as SC-A (regular), SC-B (Setback-Step back) and SC-C (Step-back) which include all features which primarily control seismic fragility of the buildings. From these fragility curves, it was observed that the buildings having Step-back configuration were more vulnerable as compared to other building types.

Surana *et al.* (2018) identified the effects of building height (2 story, 4 story and 8 story), seismic zone (zone IV & V), and near and far-field sites on the collapse fragility of RC frame hillside buildings of 3 different structural configurations such as flat land (FL), Split Foundation (SF) and Step-back (SB) structural configurations using incremental dynamic analysis (IDA) procedure and it was observed that the story just above the uppermost foundation level was the most vulnerable location in the SF and SB hillside buildings. To plot fragility curves using normalized intensity measure, the $S_{a,avg}$ (maximum considered earthquake [MCE]) has been obtained from site-specific seismic hazards analyses.

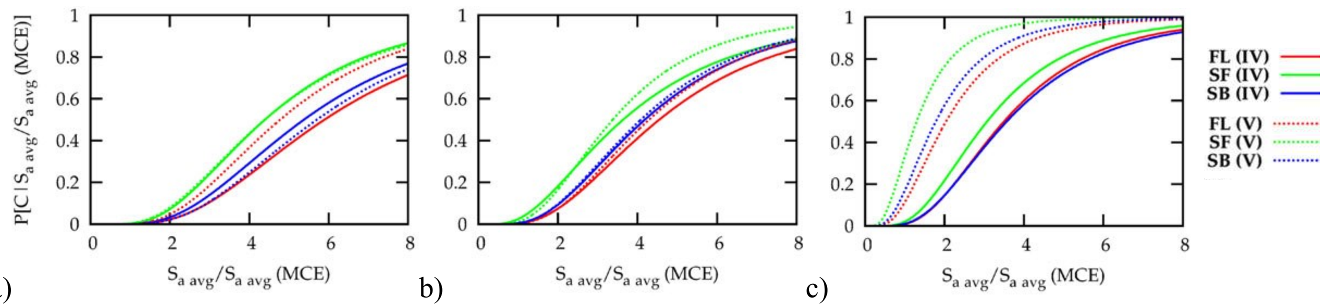


Fig 2.2 Effect of seismic zone (IV&V) on collapse fragility of considered flat land (FL), split-foundation (SF), and step-back (SB) structural configurations: (a) two-story buildings, (b) four-story buildings, and (c) eight-story buildings. [Source-Surana *et al.* (2018)]

De *et al*. (2018) modified the empirical equation specified in the code for the computation of fundamental time-period based on regression analysis results of four hundred seventeen setback frames with varying ground slope, story number and span number.

$$T=0.042\, h_{eqv}\, 0.97\theta^{-0.06} \tag{2}$$

h_{eqv}= equivalent height, θ =degree of slope.

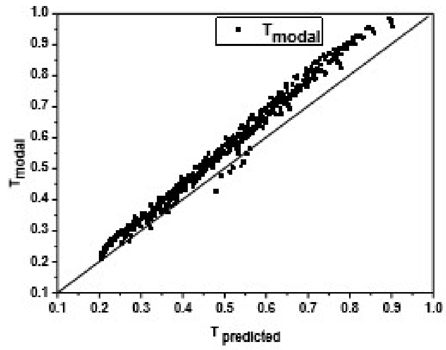
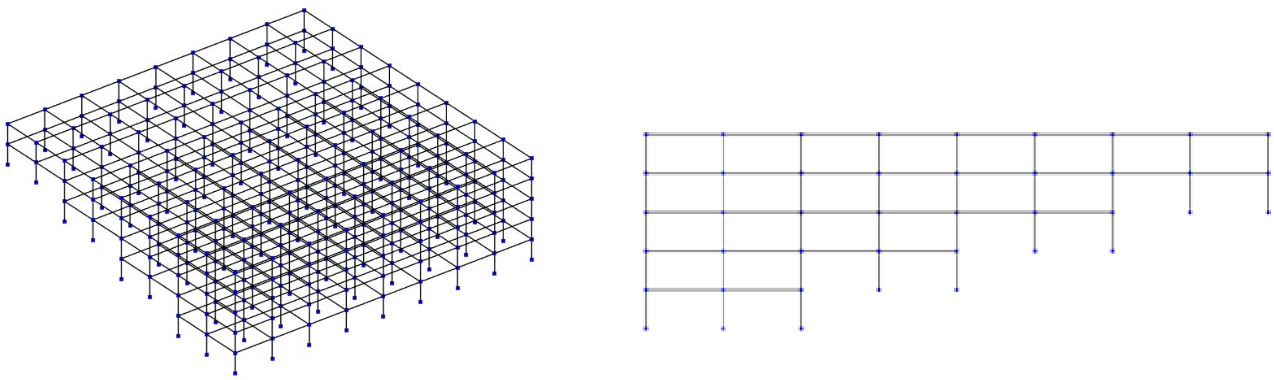


Fig 2.3 The comparison of actual and predicted fundamental time periods. [Source De *et al.* (2018)]

Surana *et al.* (2018) performed a numerical study where for the Step-back and Split-foundation hill-side buildings, simple floor spectral amplification functions were proposed and validated. The proposed spectral amplification functions considered both the building's plan and elevation irregularities which could be used for seismic design of acceleration sensitive non-structural components.

3. CONFIGURATION OF BUILDING MODEL

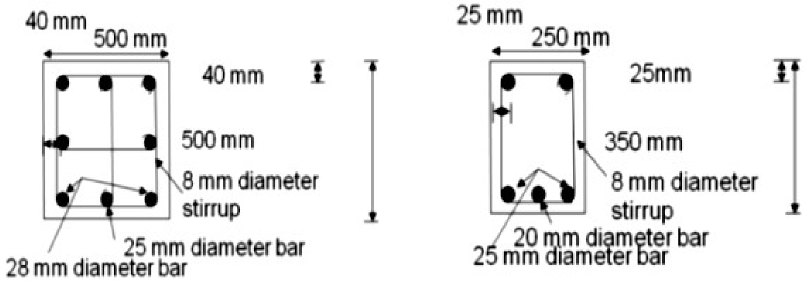
A 5 story RC hill building with Step-back configuration is modelled in Opensees Navigator (v 2.5.8) (http://opensees.berkeley.edu).Each building has 8 bays in each plan directions with typical bay width as 6 m and typical story height as 3 m. The isometric view and front elevation of the step-back building model are shown in Figure 3.1. A strong column weak beam philosophy is utilized for the design of buildings.M25 grade concrete and Fe 415 grade steel reinforcement are used throughout the building. The thickness of the slab is considered 0.15 m in this study.



(a) (b)

Fig 3.1 Isometric View (a) and Front Elevation (b) of Step-back Building

The typical cross-sectional dimensions of the columns and beams of the Step-back building are considered as 500 × 500 mm and 250×350 mm respectively. The reinforcement detailing of the beams and column are presented in Figure 3.2.



(a) (b)

Fig 3.2 Column (a) and Beam (b) Cross-sectional Details of Step-back Building

As material property Concrete 04 is utilized in the current study which is based on Popovics concrete material model (1973) with degraded linear unloading/reloading stiffness. For reinforcement material, Steel MPF is used to construct uniaxial material which represents the uniaxial constitutive nonlinear hysteretic material model for steel proposed by Menegotto and Pinto (1973), and extended by Filippou et al. (1983) to include isotropic strain hardening effects. Fiber sections are used where patches are created for both core concrete and cover concrete and layers are generated for left rebar, middle rebar and right rebar. Aggregator section is included to reduce torsional effects on column. Nodal masses are provided at the C.G of each story because the building is irregular in configuration so centre of gravity (C.G) changes accordingly. In this study, transformation method is adopted as a constraint handler which performs a condensation of constrained degrees of freedom. For numbering the degrees of freedom in the domain RCM is adopted which renumbers the degrees of freedom to minimize the matrix band-width using the Reverse Cuthill-McKee algorithm. Sparse Symmetric is used as a non-linear equation solver which is a direct solver for symmetric sparse matrices. Energy increment is adopted as Convergence Test type which specifies a tolerance on the inner product of the unbalanced load and displacement increments at the current iteration. For iteration from the last time step to the current step Kryolev Newton algorithm is adopted which uses the tangent at the first iteration to iterate to convergence. Newmark integrator is used which determines the next time step for analysis including inertial effects.

4. EARTHQUAKE GROUND MOTIONS

In this study, the mainshock and its corresponding aftershock ground motions of the 2011 Sikkim earthquake are assembled from the Center for Engineering Strong Motion Data (CESMD) ⟨http://www .strongmotioncenter.org/⟩. The magnitudes of mainshock event and aftershock event for the Gangtok station are 6.9 and 5.7 respectively in moment magnitude scale. The soil type for the site located at an elevation of 1536 m corresponds to rocky or hard soil. The seismic sequences have peak ground accelerations (PGA) of 1.491 m/s^2 and 0.70 m/s^2 for the mainshock and aftershock respectively in the east-west directions. At first, the building is subjected to ground accelerations from main-shock event and the storey level responses are recorded. Thereafter, the same building is subjected to mainshock-aftershock sequence so as to capture the cumulative damage in the building. The methodology adopted for analyzing the hill buildings under seismic sequences is schematically presented in Figure 4. In this approach, the mainshock-damaged building is kept at rest for 30 seconds and thereafter, the aftershock ground motions are applied to it. Subsequently, the storey level responses are recorded for seismic vulnerability evaluation.

5. CALCULATION FOR FRAGILITY ANALYSIS

Fragility functions represent the conditional probability of a particular structure surpassing a certain damage state when subjected to seismic excitations. Seismic fragility function can be mathematically expressed in terms of conditional probability as follows:

$$F(DS/IM = im) = \int_{EDP} F(DS/EDP) \cdot dF(EDP/IM = im) \tag{3}$$

Here F (DS/IM = im) represents the seismic fragility of a structure i.e. the conditional probability of exceeding a Damage State (DS) for a structure for a given Seismic Intensity Measure (IM) i.e. IM = im. Damage States (DS) represent the threshold levels of damages experienced by the structural components under a given loading environment. F (DS/EDP) indicates conditional probability of exceeding a particular DS for a specific Engineering Demand Parameter (EDP). An engineering demand parameter (EDP) is a scalar or a functional quantity that can define the seismic demand of a structural element at any point of the loading history. It is assumed that for a given EDP, DS is statistically independent of IM. Similarly, F (EDP/IM) indicates conditional probability of exceeding EDP for a given Seismic Intensity Measure (IM). Eventually, F (EDP/IM) requires structural response analysis while F (DS/EDP) requires structural damage analysis.

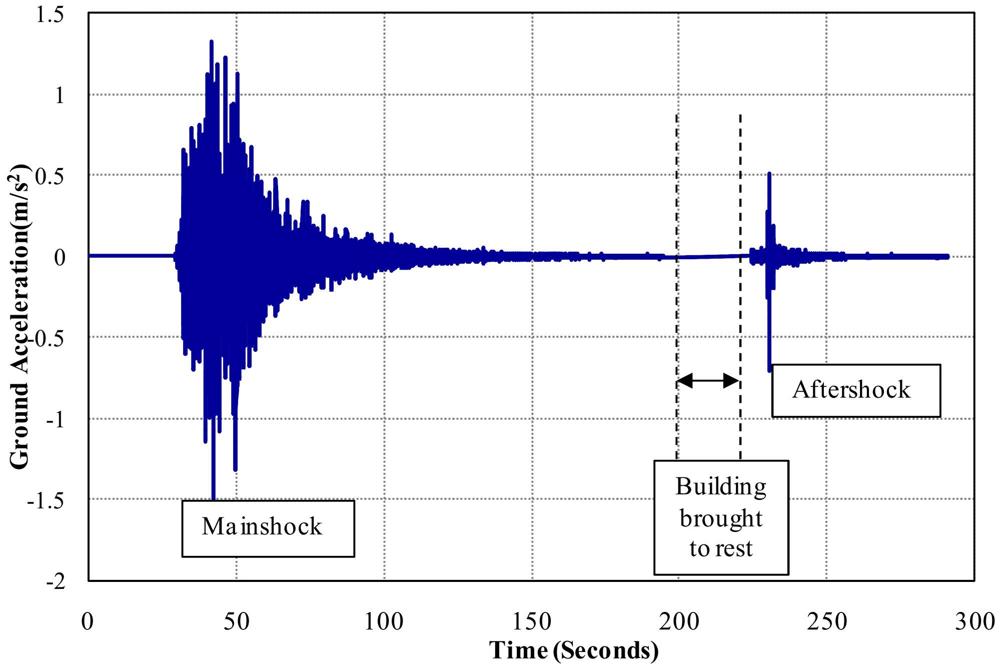


Fig 4 Analysis Scheme for mainshock-aftershock sequence on building

In order to obtain seismic fragility curves of step-back frame building, incremental dynamic analysis procedure is employed in OpenSees model. In this research, spectral acceleration (S_a/g) is selected as seismic intensity measure while maximum inter-storey drift ratio is chosen as the engineering demand parameter. Three damage states, i.e. Low Damage, Moderate Damage and Severe Damage are considered in this study for seismic fragility evaluation. A maximum inter-storey drift ratio of upto 1% corresponds to low damage while a maximum inter-storey drift ratio above 1.5% corresponds to severe damage. A maximum inter-storey drift ratio within 1-1.5% corresponds to moderate damage. Lognormal distribution, being one of the most widely used probability distribution, is utilized in this study for evaluation of seismic fragility functions.

The seismic fragility curves are developed for the step-back frame building for three damage states under only mainshock event and shown in Figure 5.1. Subsequently the, seismic fragility curves of the same building are constructed under mainshock-aftershock sequence as shown in Figure 5.2. From the comparison study between the seismic fragility curves under both case studies, it is quite evident that the effect of aftershock is not at all negligible.

6. CONCLUSIONS

Derivation of fragility functions is one of the most prominent tools in seismic vulnerability assessment of structures. In this study, incremental dynamic analysis methodology is adopted to assess the performance of step-back buildings resting on hill slopes under the 2011 Sikkim Earthquake ground motion records. Seismic behaviour of step-back buildings is determined under only mainshock event as well as mainshock-aftershock sequence. This research also presents the seismic fragility curves of step-back buildings under only mainshock event and mainshock-aftershock sequence. Spectral acceleration (S_a/g) is chosen as the seismic intensity measure while maximum inter-storey drift ratio is selected as the engineering demand parameter. Three damage states, i.e. Low Damage, Moderate Damage and Severe Damage are considered in this study for seismic fragility evaluation. A maximum inter-storey drift ratio of upto 1% corresponds to low damage state while a maximum inter-storey drift ratio above 1.5% corresponds to severe damage state. A maximum inter-storey drift ratio within 1-1.5% corresponds to moderate damage state. Incorporation of aftershock in seismic fragility of step-back buildings represents higher seismic vulnerability in comparison with only mainshock seismic performance. Therefore, this research concludes that the traditional approach of omission of aftershock in seismic vulnerability assessment will underestimate the seismic risk of buildings resting on hill slopes.

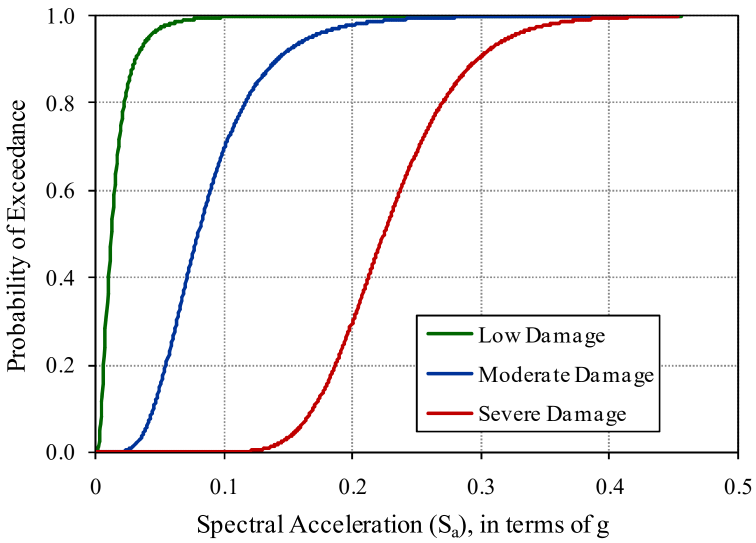


Fig 5.1 Seismic Fragility of step-back frame building under mainshock event only

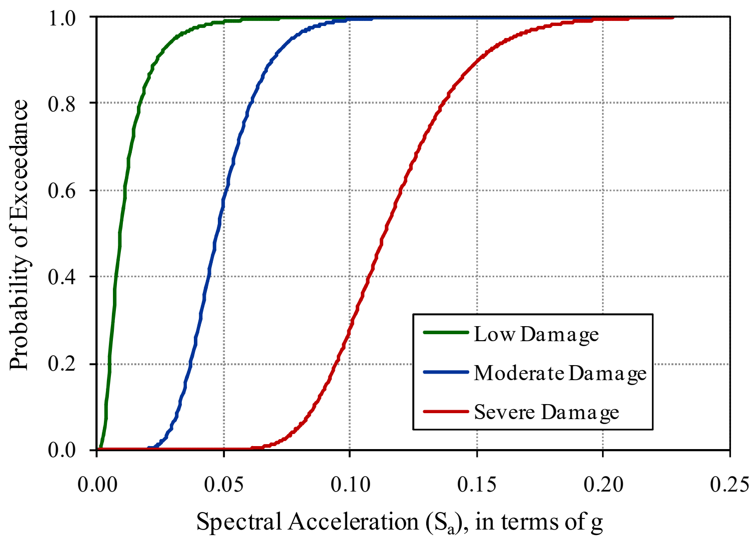


Fig 5.2 Seismic Fragility of step-back frame building under mainshock-aftershock sequence

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