



## GROUND MOTION DURATION EFFECTS ON THE SEISMIC RISK ASSESSMENT OF WOOD LIGHT-FRAME BUILDINGS

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### Abstract

Wood construction comprises a large portion of building stocks of several countries across the globe with high preparedness for earthquakes including Japan, Canada, and the United States. Built environments of these countries are prone to long-duration ground shakings due largely to the proximity of subduction faulting systems. However, the current seismic design requirements do not adequately emphasize this key feature of ground motions. This study evaluates the impact of long-duration ground motions on seismic risk characteristics of code-conforming wood light-frame buildings. To this end, a study matrix of wood light-frame buildings is developed incorporating with two different heights (i.e., 1-story and 4-story) and two distinct occupancies (i.e., multi-family and commercial) designed for a very high seismic region according to the latest pertinent design requirements of the United States. The seismic performance of these buildings is assessed through incremental dynamic analysis (IDA) in accordance with FEMA P-695 recommendations. Each building is analyzed using three sets of ground motions, i.e., far-field FEMA P-695 ground motions ensemble, an ensemble of short-duration ground motions, and an ensemble of long-duration ground motions. For each building, structural responses are obtained, and collapse fragility for these three sets of ground motions are derived. Next, the structural analysis results are relayed to a component-based loss assessment framework developed based on performance-based earthquake engineering principles in order to predict the seismic risk characteristics of the adopted buildings including the vulnerability function, risk curve, and average annual loss (AAL). The loss assessment is conducted separately for the structural and nonstructural components as well as the content of the buildings. The study reveals the considerable effect of ground motion duration on the seismic vulnerability of light-frame wood buildings, specifically in the case of 4-story wood light-frame building which reveals approximately a mean increase of 140.0% in the predicted losses.

*Keywords: seismic risk assessment, wood light-frame construction, ground motion duration, earthquake insurance*



## 1. Introduction

Modern seismic design codes do not adequately emphasize the significance of the duration of ground motions. The recent strong ground motions distinguished by their long durations, including Maule 2010 and Tohoku 2011 earthquakes, have drawn the attention of practitioners and researchers to the influence of the duration of ground motions on the seismic performance of buildings. Subduction faulting systems are known to generate long duration ground motions and the built environments of countries with high-preparedness for earthquakes, e.g., United States, Canada, and Japan, are prone to long-duration earthquakes.

There are a limited number of studies available in the literature devoted to studying the influence of the ground motion duration on the seismic performance of structural systems. Van de Lint and Goh showed through simple models that the duration of earthquakes may have a significant influence on the reliability index of structural systems [1]. The results of analytical studies on reinforced concrete and steel structures show the substantial impact of the ground motion duration on the predicted collapse risk and damage index for these systems [2-5].

Wood is one of the primary construction materials in countries with high earthquake preparedness, e.g., the United States, Canada, and Japan. Wood construction is also more encouraged in recent years on environmental grounds to reduce the carbon footprint of the construction industry [6]. In particular, wood light-frame construction is a prevalent structural system in North America. A series of numerical studies are conducted at the University of British Columbia (UBC), Vancouver, to investigate the structural behavior of wood light-frame buildings exposed to the long-duration ground motions. The study is conducted through detailed 3D finite element analyses using the Clemson University in-house program called Timber3D. It is found that the median collapse capacity of a two-story residential wood light-frame building can reduce by 26-61 % depending on the building sheathing configuration for long-duration ground motions relative to short-duration ground motions [7]. Additionally, it is found that the median collapse capacity of NEESWood six-story residential wood light-frame archetype can reduce by 18% for long-duration ground motions compared to short-duration ground motions. It is also observed that the median of Park and Ang damage index at the MCE level for the same building is 36% higher for long-duration ground motions [8].

An exhaustive literature review conducted by the authors as briefly presented above reveals the significant influence of time-characteristics of ground motions on the performance of structural systems, specifically wood light-frame buildings. However, the literature lacks studies to explicitly investigate the influence of ground-motion duration on the seismic risk evaluation of structures. This study is undertaken to address the identified gap in the body of knowledge and is derived by the need within the earthquake insurance industry to account for the time-characteristics of ground motions which are typically ignored by the public or proprietary earthquake catastrophe loss models.

In this paper, a study on wood light-frame buildings incorporating with two different heights (i.e., 1-story and 4-story) and two distinct occupancies (i.e., multi-family and commercial) designed for a high seismic region according to the latest pertinent design requirements of the United States is undertaken. The seismic performance of these buildings is assessed through incremental dynamic analysis (IDA) using three sets of ground motions, i.e., the ensemble of far-field FEMA P-695 ground motions, an ensemble of short-duration ground motions, and an ensemble of long-duration ground motions. For each building, structural responses are obtained and collapse fragility for these three sets of ground motions are derived. Next, the structural analysis results are relayed to a component-based loss assessment framework developed based on advanced performance-based earthquake engineering principles in order to predict seismic risk characteristics of the adopted buildings including the vulnerability function, risk curve, and average annual loss (AAL). The loss



assessment is conducted separately for the structural and nonstructural components as well as the content of the buildings. In order to meet the specific needs of the earthquake insurance industry, the results are also presented in the form of the so-called secondary modifiers which can be directly employed by catastrophe loss earthquake models.

## 2. Seismic Risk Assessment

This section briefly reviews the seismic risk assessment procedure for four different reference models designed for the very high seismic design category ( $1.5D_{max}$ ) with  $S_s=2.25g$  and  $S_1=0.9g$  representing a typical modern wood construction at downtown Los Angeles, CA. The lateral load resisting system is wood light-frame shear walls. There are two building heights (1-story and 4-story) and two occupancies (commercial and multi-family). Further details about these archetypes can be found elsewhere [9]. The seismic risk assessment for these buildings is carried out using FEMA P-58 provisions [10].

Incremental dynamic analysis (IDA) using a nonlinear response history procedure is employed to quantify the engineering demand parameters (EDPs) needed for performance modeling, i.e., peak inter-story drifts, peak floor accelerations and peak inter-story residual drifts of the building under different hazard levels using Timber 3D [11]. An ensemble of 22 far-field pairs of bi-axial far-field ground motions developed as part of the FEMA P-695 project was utilized in this study [12]. The IDA was carried out by scaling the median of the FEMA P-695 response spectrum at the fundamental period of the building to the target hazard levels. Moreover, the two ensembles of ground motions representing long-duration ground motions and short-duration ground motions are employed as discussed elsewhere [3] to study the influence of the ground motion duration. Collapse fragility for each IDA is fitted to Weibull distribution and adjusted for spectral shape and 3-D modeling effects. The time history analyses were performed on the computer clusters at Clemson University (Palmetto Cluster).

Structural modeling results are relayed to the performance model to predict the financial losses in the format of the vulnerability function, AAL (average annual loss), and risk curve. The building is assumed to be located in downtown Los Angeles, CA. In this study, a MATLAB toolbox is developed to conduct vulnerability assessments, as discussed elsewhere [13-17]. The reparability check is ignored for all analyses. Structural and nonstructural vulnerable components are determined in accordance with FEMA P-58 recommendations. Content vulnerable components are assumed to be unanchored and determined in accordance with the recent work of authors [18].

## 3. Results

The risk assessment is carried out separately for the building (structural and nonstructural components) and the content. This segregation is conducted in accordance with the common practices of the insurance industry.

### 2.1 Building Loss

Fig. 1 presents the vulnerability function developed for the studied buildings. Each plot presents the mean structural and nonstructural loss versus the spectral acceleration at 0.3 seconds. The spectral acceleration value at the DBE level is also shown on the plots. It can be observed that the long-duration ground motions typically provide higher mean losses, specifically at higher levels of spectral acceleration. However, the short duration and FEMA P-695 render similar losses. Fig. 2 presents the impact of adopting long-duration ground motions as a secondary modifier for each building. The secondary modifier in this context is defined as the mean loss ratio obtained from the long-duration ground motions over the mean loss ratio obtained from the FEMA P-695 ground-motions. This secondary modifier is called 'long duration ground motion modifier (LDGMM).' The mean increase of loss, defined as the difference between mean losses from the long duration ground motions and FEMA P-695 ground motions divided by the mean losses from the FEMA P-695 ground motions, is 49.0%, 43.0%, 144.0%, and 137.0 % for the 1-story commercial building, 1-story



multifamily building, 4-story commercial building, and 4-story multifamily building, respectively. Fig. 3 presents the risk curve for 4-story multifamily building for long, short, and FEMA P-695 ground motions. In this plot, AFE is the annual frequency of exceedance of the building. Finally, Fig. 4 presents the normalized building AAL for each archetype. Normalized AAL is defined as the ratio of the AAL over the replacement value of the building.

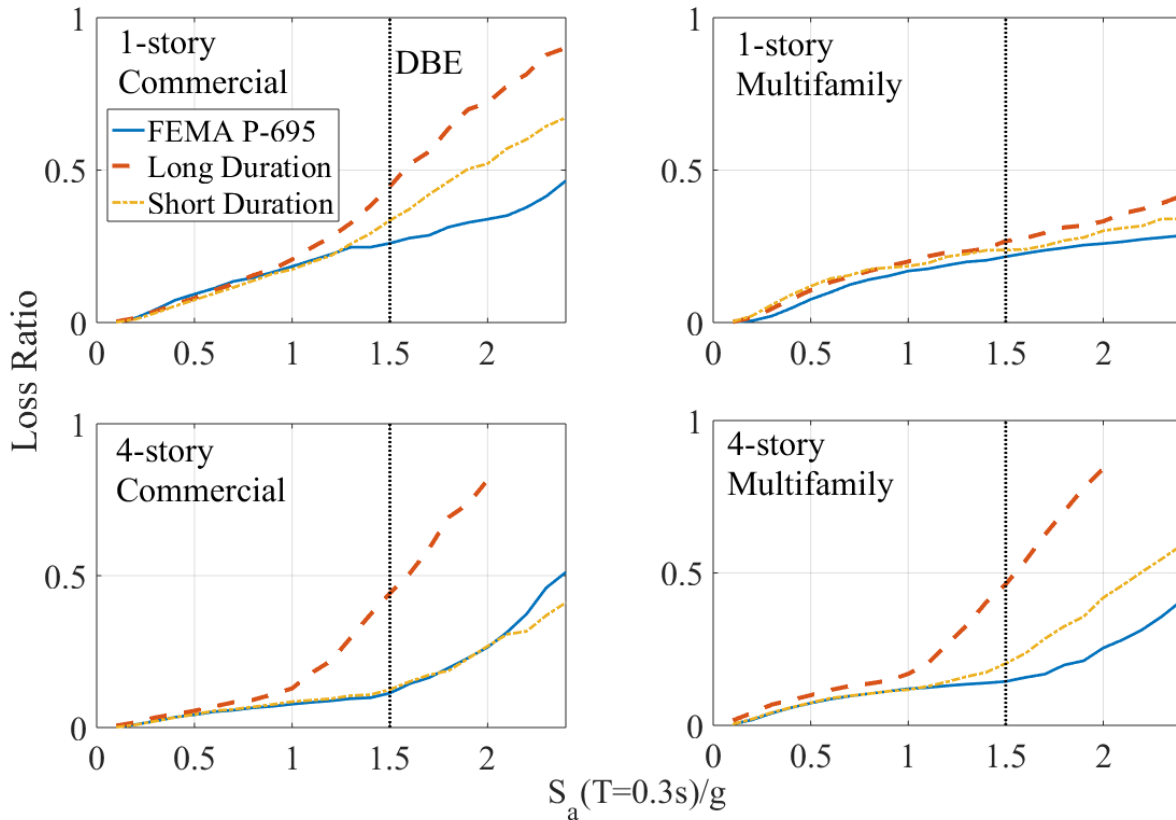


Fig. 1 – Building vulnerability function

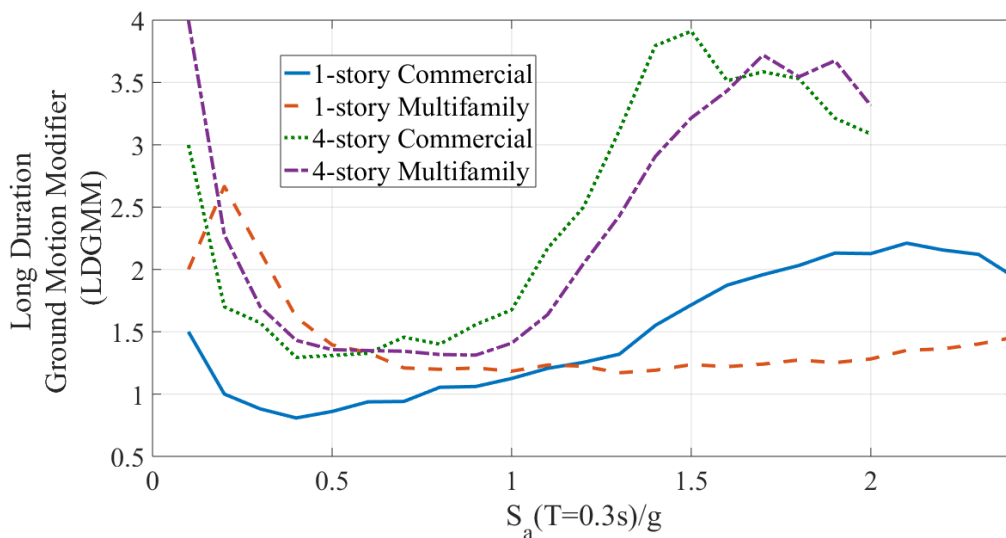


Fig. 2 – The impact of adopting the long-duration ground motions on building vulnerability functions presented as a secondary modifier called the long duration ground motion modifier (LDGMM)

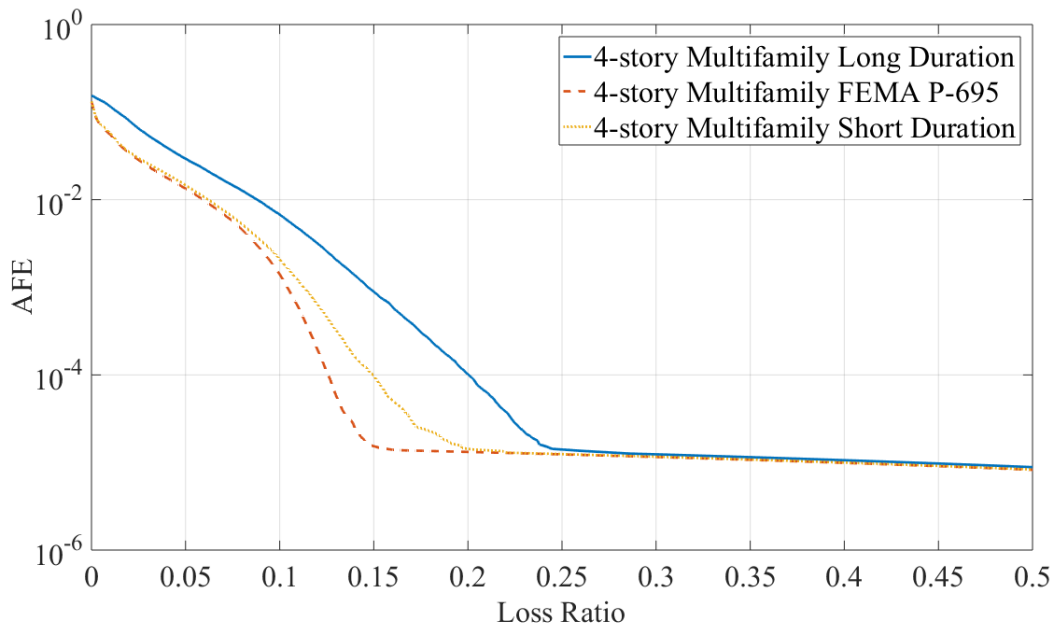


Fig. 3 – Building risk curve for the 4-story multifamily building

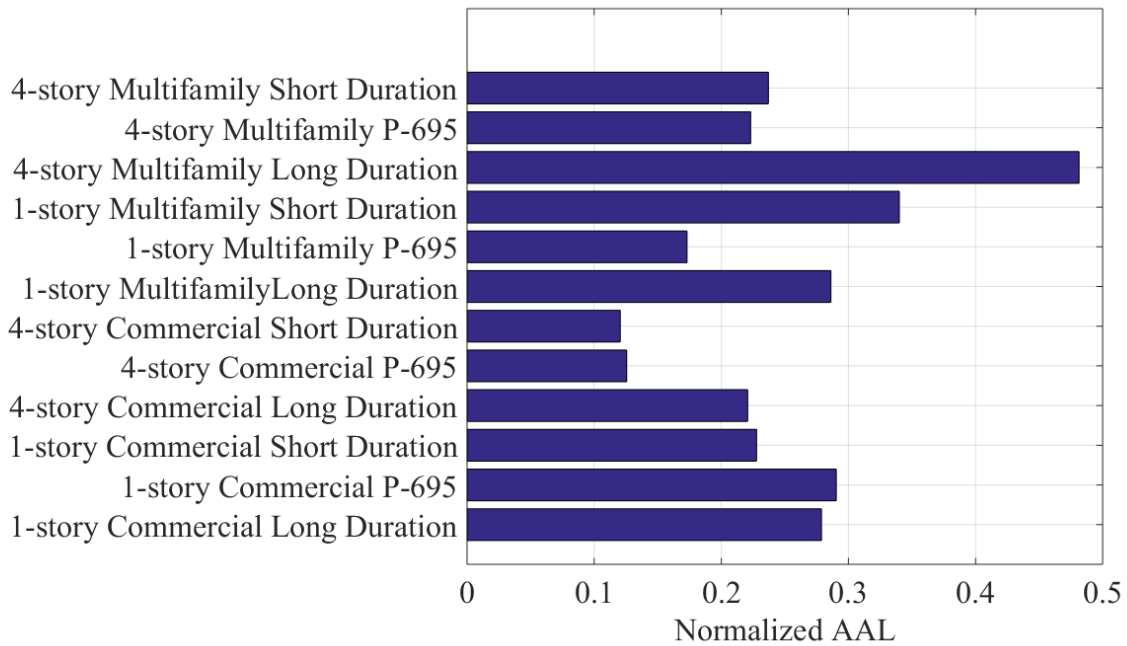


Fig. 4 – Comparison between building normalized AAL(%) for different buildings



## 2.2 Content Loss

Fig. 5 presents the content vulnerability function developed for the studied buildings. Each plot presents the mean content loss versus the spectral acceleration at 0.3 seconds. The DBE level is also shown on the plots. It can be observed that the long-duration ground motions typically provide higher mean losses, specifically at higher levels of spectral acceleration. However, the short duration and FEMA P-695 render similar losses. Fig. 6 presents the impact of adopting long-duration ground motions as a secondary modifier (long duration ground motion modifier, LDGMM) on the content losses for each building. Similarly, LDGMM is defined as the mean content loss ratio obtained from the long-duration ground motions over the mean content loss ratio obtained from the FEMA P-695 ground-motions. The mean increase of loss, which is defined as the difference between the mean content losses from the long duration and FEMA P-695 ground motions divided by the mean content losses from the FEMA P-695 ground motions, is 32.0%, -6.0%, 21.0%, and 56.0 % for the 1-story commercial building, 1-story multifamily building, 4-story commercial building, and 4-story multifamily building, respectively. Fig. 7 presents the risk curve for the 4-story multifamily building content for the long, short, and FEMA P-695 ground motions. Fig. 8 presents the normalized AAL for the content for each archetype.

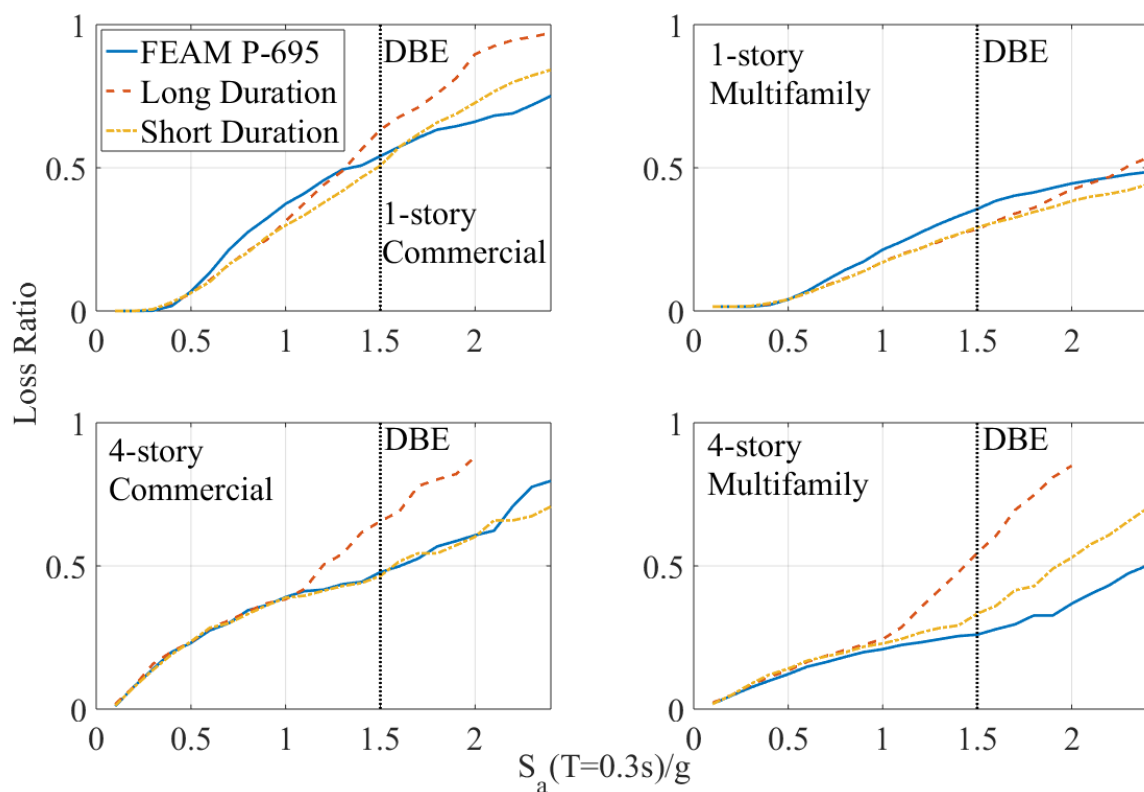


Fig. 5 – Content vulnerability function

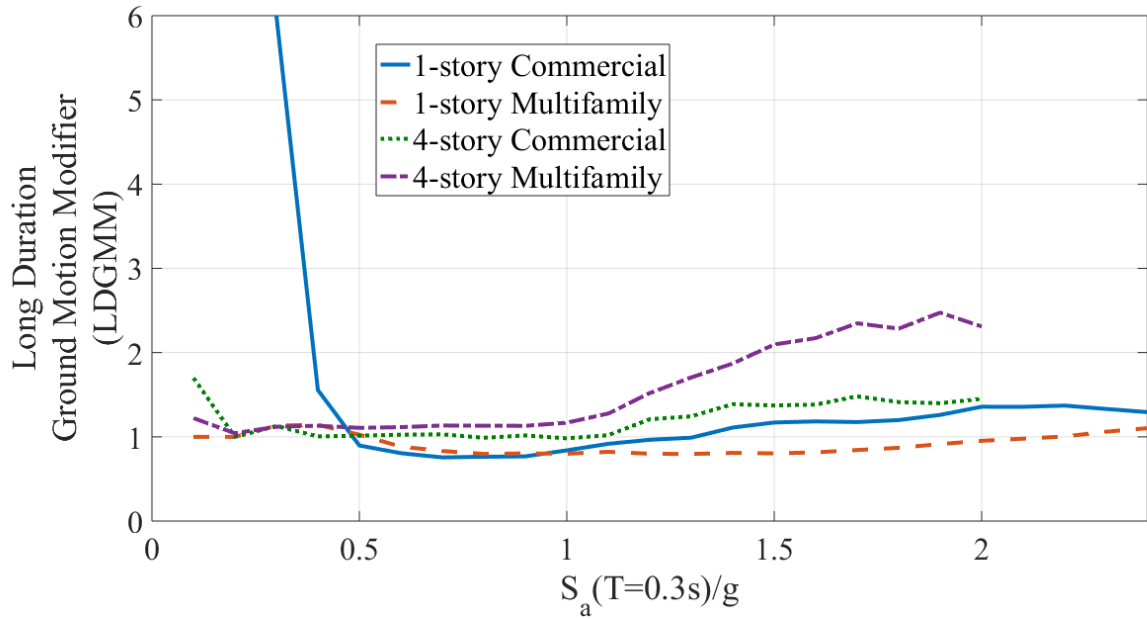


Fig. 6 – Content vulnerability function secondary modifier or long duration ground motion modifier

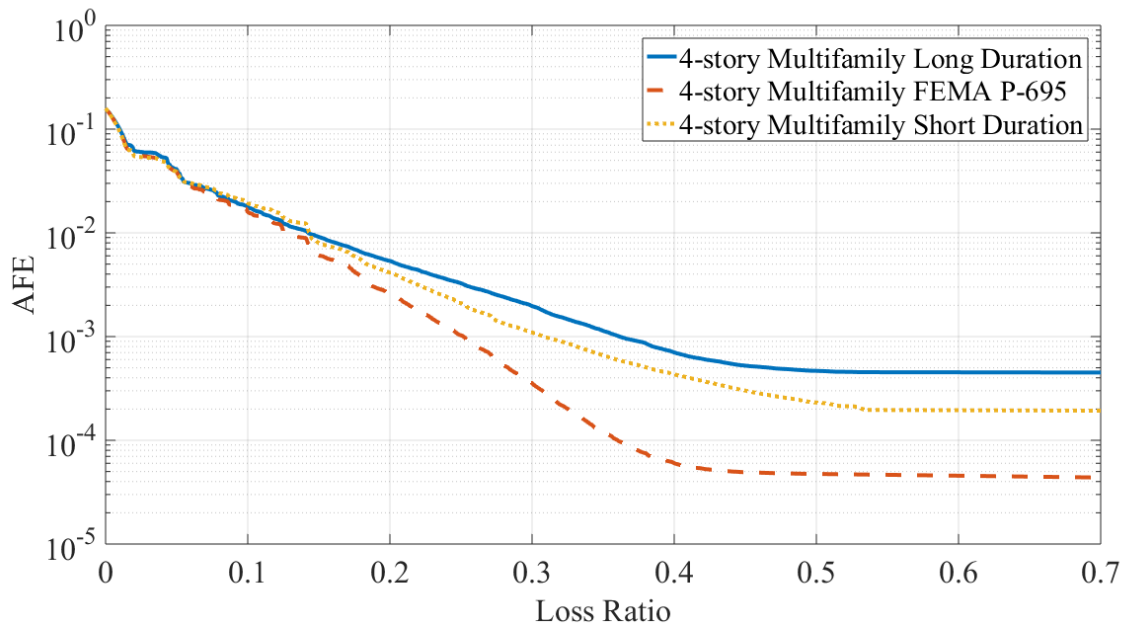


Fig. 7 – Content risk curve for 4-story multifamily building

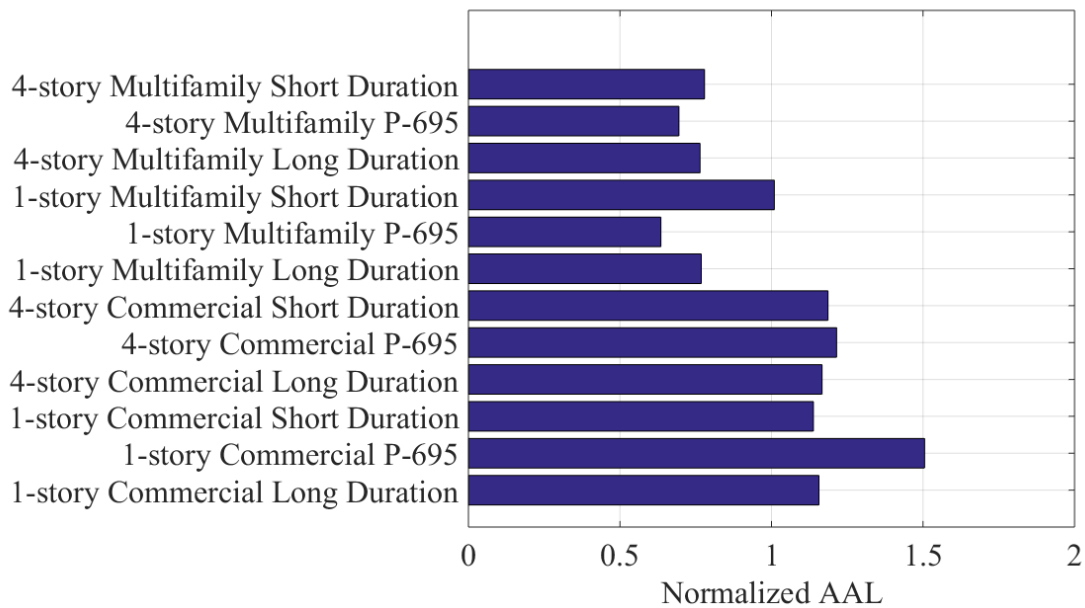


Fig. 8 – Comparison between content normalized AAL(%) for different buildings

#### 4. Conclusions and Summary

This paper presents the preliminary results of a study conducted jointly by the Clemson University and AIG on the seismic risk assessment of wood light-frame structures considering the ground motion durations. The following conclusions can be drawn:

- The impact of adopting long-duration ground motions is presented in the form of a secondary modifier called long duration ground motion modifier (LDGMM) to adjust the predicted losses, both for building and content.
- The content loss is less sensitive to ground motion durations compared with the building (structural and nonstructural components) loss.
- The ground-motion duration has lower effects at lower levels of shakings. This observation can be attributed to the fact that the building response is dominated by linear and elastic behavior at lower levels of shakings. More importantly, collapse loss also kicks in at higher levels of shaking.
- The building height appears to exacerbate the influence of adopting long ground motions. In other words, the additional damages inflicted by long duration ground motions appear to increase significantly by the increase of building the first period of the vibration.
- The building occupancy does not have a significant impact on the losses incurred for different ground-motion durations.

Some aspects of the study are still under development, including a risk curve approach taking ground-motion duration into account and a more effective definition for the ground motion duration secondary modifier. The study is also being expanded for different structural systems.



## 5. Acknowledgments

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## 6. References

- [1] Van De Lindt JW, Goh G (2004): Effect of earthquake duration on structural reliability. *Engineering Structures*, **26** (11), 1585-1597.
- [2] Barbosa AR, Ribeiro FLA, Neves LA (2016): Influence of earthquake ground-motion duration on damage estimation: application to steel moment resisting frames. *Earthquake Engineering & Structural Dynamics*, **46**, 27-49.
- [3] Chandramohan R, Baker JW, Deierlein GG (2016): Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records. *Earthquake Spectra*, **32** (2), 927-950.
- [4] Fairhurst M, Babazadeh A, Ventura CE (2019): Effect of ground motion duration on reinforced concrete shear wall buildings. *Earthquake Spectra*, **35** (1), 311-331.
- [5] Raghunandan M, Liel AB (2013): Effect of ground motion duration on earthquake-induced structural collapse. *Structural Safety*, **41**, 119-133.
- [6] Rethink Wood (2013): Evaluating the carbon footprint of wood buildings. April.
- [7] Pan Y, Ventura CE, Finn WDL (2018): Effects of ground motion duration on the seismic performance and collapse rate of light-frame wood houses. *ASCE Journal of Structural Engineering*, **144** (8).
- [8] Pan Y, Ventura CE, Finn WDL, Xiong H (2019): Effects of ground motion duration on the seismic damage to and collapse capacity of a mid-rise woodframe building. *Engineering Structures*, **197**.
- [9] Ziaei E (2017): Seismic analysis of light-frame wood building with a soft-story deficiency. *Ph.D. Dissertation*, Clemson University, Clemson, USA.
- [10] FEMA P-58 (2012): Seismic performance assessment of buildings- methodology. Washington, D.C., USA.
- [11] Pang W, Ziaei E, Filiatrault A (2012): A 3D model for collapse analysis of soft-story light-frame wood buildings. *World Conference on Timber Engineering*, Auckland, New Zealand.
- [12] FEMA P-695 (2009): Quantification of building seismic performance factors. Washington, D.C., USA.
- [13] Safiey A, Pang W, Javanbarg M, Rokneddin K, Ziaei E (2017): Development of earthquake vulnerability functions and risk curves for low and mid-rise hotel buildings using a performance-based loss estimation framework. *16<sup>th</sup> World Conference on Earthquake Engineering*, Santiago, Chile.
- [14] Safiey A, Ziaei E, Gu M, Pang W, Rokneddin K, Javanbarg M (2018): Influence of irreparability fragility on seismic vulnerability assessment of buildings. *11<sup>th</sup> National Conference on Earthquake Engineering*, Los Angeles, USA.
- [15] Safiey A, Pang W, Ziaei E, Majdalaweyh S, Rokneddin K, Javanbarg M (2019): Rethinking treatment of irreparability in the context of performance-based earthquake engineering. *ASCE Structures Congress*, Orlando, USA.
- [16] Rokneddin K, Safiey A, Javanbarg M, Manghnani V, Pang W (2017): Analytical content vulnerability assessment methodology for earthquake catastrophe models. *16<sup>th</sup> World Conference on Earthquake Engineering*, Santiago, Chile.
- [17] Ziaei E, Safiey A, Pang W, Rokneddin K, Javanbarg M, Gu M (2018): Seismic vulnerability assessment of buildings using a statistical method of response prediction. *11<sup>th</sup> National Conference on Earthquake Engineering*, Los Angeles, USA.



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- [18] Majdalaweyh S, Pang W, Safiey A, Ziaei E, Rokneddin K, Javanbarg M, Prabhu S (2019): Seismic vulnerability assessment of anchored block type contents due to sliding and overturning. *12<sup>th</sup> Canadian Conference on Earthquake Engineering*, Quebec City, Canada.