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SEISMIC RISK COMPARISON BETWEEN 1- AND 2-STORY HOUSES FOR PERFORMANCE-BASED EARTHQUAKE ENGINEERING

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ABSTRACT

In regional seismic risk assessments, the building stock is typically divided into a number of building categories, where, for each category, an index structure is used to represent the performance of the whole group. Thus, grouping buildings with significantly different seismic performances into a single class may result in important over- or underestimations of the regional risk. Historically 1- and 2-story single-family dwellings have been grouped into a single category for both insurance purposes, and regional risk assessments. This paper evaluates the relative seismic risk between 1- and 2-story houses using simple models and first principles. For this purpose, simplified lumped-mass models are used to assess the influence of the fundamental period of vibration, lateral stiffness in each story, mass distribution, and nonlinear effects, on the seismic response of 1- and 2-story houses. Results demonstrate that, in practically all cases, 2-story houses concentrate lateral deformation demands on their first stories, and that these demands are significantly larger than those in 1-story dwellings. Therefore, there are significantly higher probabilities of damage and expected losses in 2-story houses than in 1-story houses. This conclusion is perfectly consistent with the damage observed after different historical earthquakes, where 2-story houses have exhibited poorer performance than their 1-story counterparts. This work suggests that grouping 1- and 2-story houses into a single class, as has been typically done for many years, is conceptually wrong. Consequently, future building classification systems for regional risk assessments should separate these types of structures.

Keywords: PBEE; Loss estimation; Residential construction; Relative risk

1. INTRODUCTION

Light wood-frame houses constitute the majority of the structures in many seismic prone regions such as United States, Canada, and Japan. According to the U.S. Census Bureau (DADS 2010), there are more than 133,000,000 housing units in the U.S, of which 61.6% correspond to individual dwellings (also referred to as single-family houses). Moreover, there are more than 13,800,000 units only in California, where 58.1% are individual dwellings (DADS 2010). Therefore, an accurate estimation of the seismic risk in single-family houses is fundamental for estimating the regional risk of urban areas. The objective of a regional risk study is to estimate damage and losses in a large number of buildings within a geographical region. Ideally, this could be done by analyzing every building using complex multi-degree-of-freedom nonlinear models, and then aggregating the results. This approach is unfeasible in terms of computational effort, therefore simplified models of different types of structures are typically implemented. In this context, lumping buildings, in terms of their expected seismic performances, with an efficient classification system is a key phase in regional risk estimations. Buildings are usually classified based on a combination of construction characteristics (e.g., structural system, height or number of stories) and by type of occupancy (e.g., residential structures, hospitals, offices, schools). Traditionally, the insurance industry have lumped 1- and 2-story single-family houses together (Freeman 1932; Steinbrugge 1982). The insurance practice also served as a basis for regional risk studies. Investigations for the Department of Housing and Urban Development, during the 1970s, suggested a building classification system with a single class for wood-frame residential construction of three stories

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or less (Steinbrugge et al. 1969; Rinehart et al. 1976; Algermissen et al. 1978). Years later, the ATC-13 project, entitled Earthquake Damage Evaluation Data for California, was the first large-scale study in the U.S. focused on estimating seismic risk of structures (ATC 1985). It provided motion-damage relationships in the form of expert-opinion matrices for 78 classes of structures, relating Modified Mercalli Intensities (MMI) with levels of damage. As commented by King (2002), the building classification system of ATC-13, which lumped together 1- to 3-story wood-frame structures, was selected based on the expected stock distribution of California, and expected uniqueness in their classes' seismic performances. More recently, FEMA funded a project for developing a methodology for regional loss estimations, GIS-based (Geographic Information System) and nationally applicable, known as HAZUS® (Kircher et al. 1997; NIBS 1997; Whitman et al. 1997). Since its early versions and despite various updates, it continues to classify wood light-frame structures having one or two stories, as Class W1. Therefore, although methodologies for earthquake regional risk estimations have had a gradual evolutionary development in time, building classification systems have been somewhat stationary, especially when classifying residential construction, which represents the majority of the building stock of urban areas. Classification systems are based, in most of the cases, on previous studies and common practice from the insurance industry. However, a problem arises when lumping structures that may present dissimilar seismic performances. In this sense, 1- and 2-story dwellings have historically had different seismic performance levels. Poorer performance of 2-story houses has been consistently observed in different historic events, such as the 1971 San Fernando earthquake (McClure 1973; Steinbrugge et al. 1971), the 1984 Morgan Hill earthquake (Strykowski 1985), and the 1994 Northridge earthquake (Andreason and Rose 1994; Schierle 2003).

In 2015, 41.5% of the individual dwellings in the United States corresponded to 1-story structures, while 36.1% had two stories and 22.4% had three or more stories, according to the American Housing Survey (AHS) (U.S. Census Bureau 2016). From these statistics, it is clear than 1- and 2-story dwellings represent almost 80% of all individual dwelling in the U.S. and therefore it is important to evaluate correctly their seismic risk.. The objective of this paper is to evaluate the relative seismic risk between 1- and 2-story dwellings. This relative risk is demonstrated with simple models and using well established principles of structural dynamics for assessing the influence of the fundamental period of vibration, mass and stiffness distributions in height, and nonlinear effects. Both the past experience and the theoretical results, suggest that lumping 1- and 2-story houses in a single building class is conceptually wrong, as their seismic performances are significantly different.

2. COMPARING 1 AND 2 STORIES

2.1 Displacement Demands

Simple lumped-mass models are used to illustrate the differences in displacement demands between dwellings with one and two stories. The basic parameters defining the models are shown in Figure 1. On one hand, the 1-story model has mass m_1, lateral stiffness k_1, fundamental period T_1, story height h_1, and roof displacement Δ_1. The interstory drift ratio of the 1-story model is simply, $IDR_1 = \Delta_1 / h_1$. On the other hand, the 2-story model is defined as having lower and upper masses, m_{2l} and m_{2u}, lower and upper lateral stiffnesses, k_{2l} and k_{2u}, lower and upper story heights, h_{2l} and h_{2u}, and a fundamental period T_2. Assuming that the response of the structure is dominated by the first mode of vibration the peak lateral displacements of the lower and upper floors, Δ_{2l} and Δ_{2u} (the latter is the roof displacement), can be used to estimate the interstory drifts in the lower and upper stories as follows:

$$IDR_{2l} = \Delta_{2l}/h_{2l} \quad (1)$$

$$IDR_{2u} = (\Delta_{2u} - \Delta_{2l})/h_{2u} \quad (2)$$

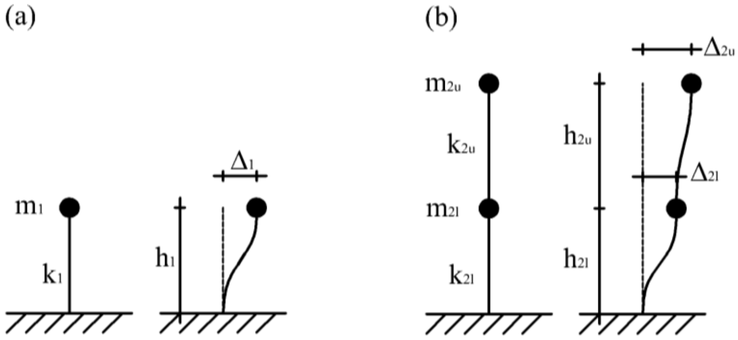

Figure 1. Simplified lumped mass models. (a) 1-story model; (b) 2-story model.

Miranda (1997; 1999) proposed an approximated method for estimating peak roof displacements and the maximum interstory drift ratios in multistory buildings, using a reference single-degree-of-freedom (SDOF) system and three modifying coefficients. These coefficients are defined as: (1) the ratio between the roof displacement and the displacement of the SDOF system; (2) the ratio between the maximum interstory drift ratio and the roof drift ratio (a measure of the degree of concentration of interstory drift demands at a certain story of the structure); and (3) the ratio between the peak inelastic displacement of the SDOF and the peak elastic displacement of the SDOF. Note that this last coefficient is equivalent to an inelastic displacement ratio, broadly studied in the literature (Miranda 2000; Miranda 2001; Ruiz-García and Miranda 2003; Akkar and Miranda 2004; Chopra and Chintanapakdee 2004; Ruiz-García and Miranda 2007, among many others) and that is referred to as coefficient C_1 in ASCE-41 (ASCE 2016). Miranda's notation is adapted for the case of the 2-story model in the present work, and is the basis for evaluating the concentration of displacement demands. The three modifying coefficients are given by:

$$\beta_1 = \Delta_{2u}/\Delta_i(T_2, C_{y,2}) \quad (3)$$

$$\beta_2 = \max(IDR_{2l}, IDR_{2u}) \cdot (h_{2l} + h_{2u})/\Delta_{2u} \quad (4)$$

$$\beta_3 = \Delta_i(T_2, C_{y,2})/S_d(T_2) \quad (5)$$

where $S_d(T_2)$ is the elastic spectral displacement of a SDOF system with period T_2, and $\Delta_i(T_2,C_{y,2})$ is the inelastic displacement of a SDOF system with period T_2 and normalized yield strength $C_{y,2}$ (i.e., the lateral yielding strength, F_y, normalized by the total weight of the structure, W). Rearranging, the maximum interstory drift ratio in the 2-story house can be computed as:

$$\max(IDR_{2l}, IDR_{2u}) = \beta_1 \cdot \beta_2 \cdot \beta_3 \cdot S_d(T_2)/(h_{2l} + h_{2u}) \quad (6)$$

Note that in the 1-story model, the coefficients β_1 and β_2 are equal to 1.0. The maximum IDR, thus, is estimated simply as $\beta_3 \cdot S_d(T_1) / h_1$. The coefficient β_3 depends on the fundamental period and the strength of the system, thus it is different for 1- and 2-story houses.

Three cases will be analyzed to illustrate the influence of the fundamental periods, the mass and stiffness distributions, and the nonlinear effects, on the displacement demands. First, a linear elastic case with uniform mass and stiffness distributions illustrates the influence of the fundamental period. Second, a linear elastic case, but with non-uniform mass and stiffness distributions is presented to study the influence of these distributions on the concentration of displacement demands at the first story of 2-story houses. Finally, an inelastic case with non-uniform mass and stiffness distributions is shown to analyze the influence of the nonlinear behavior.

2.1.1 Elastic response, uniform mass and stiffness distributions

The difference in the fundamental periods of 1- and 2-story dwellings is the first factor that causes a difference in displacement demands. To estimate the period difference, two coefficients easily obtained from floor plans are presented, linking the mass and lateral stiffnesses properties of 2-story houses with an "equivalent" 1-story house. Note that the term "equivalent" is used here in terms of occupancy: the idea is to link the properties of a 2-story house to those of a 1-story house with similar occupancy characteristics (floor area, number of bedrooms and bathrooms, etc.). Equations 7 and 8 show the equivalent stiffness and equivalent mass coefficients, λ_k and λ_m:

$$\lambda_k = A_{w,int,u}/A_{w,tot,u} \tag{7}$$

$$\lambda_m = m_{eq1st}/(m_{2u} + m_{2l}) \tag{8}$$

where $A_{w,int,u}$ is the plan area of interior walls in the upper story of the 2-story house, $A_{w,tot,u}$ is the total plan area of walls in the same upper story, and m_{eq1st} is the mass of a 1-story house with the same area as the 2-story house. Note that m_{eq1st} and m_{2u} + m_{2l} are similar, but not exactly equal. The term m_{eq1st} is generally smaller for two reasons: (1) the lower mass in the 2-story model, m_{2l}, lumps the mass of the diaphragm, plus one half of the mass of the lower level walls, and one half of the mass of the upper level walls, while m_{eq1st} does not consider the latter portion; and (2) m_{2l} considers the mass of the floor diaphragm between two levels, which is heavier than roof diaphragms, while m_{eq1st} considers all the diaphragm mass portion as roof diaphragm. As a rough approximation, let us take an "equivalent" 1-story house (again, in the sense of occupancy) with a mass m_{eq1st} and a stiffness equals to $k_{2l} + \lambda_k \cdot k_{2u}$. Thus, considering a uniform mass and stiffness distribution ($m_{2l} = m_{2u} = m_2$; $k_{2l} = k_{2u} = k_2$), the ratio between the fundamental period of a 2-story house and its equivalent 1-story model is:

$$\frac{T_2}{T_1} = \sqrt{\frac{1+\lambda_k}{\lambda_m(3-\sqrt{5})}} \tag{9}$$

To estimate the order of magnitude of this ratio, Table 1 presents the mean, standard deviation, coefficient of variation (COV), and 95% confidence interval of the mean of λ_k and λ_m, for a set of ten floor plans of 2-story houses of different developers, with a variety of floor areas and located in different regions of California. Typical gravity loads were used for computing the equivalent mass and stiffness coefficients (NIBS 2012). As can be seen, these coefficients are quite stable, with COV values smaller than 10%. Using the mean values of λ_k and λ_m, a first order approximation of the ratio T_2/T_1 is 1.783. Although this is quite a rough estimate, it is easily obtained from floor plans, and gives an idea of the difference of the fundamental periods of 1- and 2-story houses. Even more, Camelo (2003) measured fundamental periods of 1- and 2-story wooden structures. The mean fundamental period of the measured 1-story structures was 0.103 seconds, while that of the measured 2-story houses was 0.193 seconds. Therefore T_2/T_1 is, as a first order approximation, 1.874, which is merely 5% larger than our rough estimation. These periods are consistent with those measured by other authors (Filiatrault et al. 2002; Kharrazi and Ventura 2006; Filiatrault et al. 2010). Consequently, this period ratio is translated into different spectral displacement demands $S_d(T)$, values that are proportional to the pseudo-spectral

Table 1. Statistical estimators for 2-story distribution coefficients.

Estimator	λ_m	λ_k	α_m	α_k
Mean	0.63	0.53	0.62	1.39
95% C.I.	[0.63 , 0.64]	[0.51 , 0.55]	[0.60 , 0.64]	[1.33 , 1.45]
Standard Deviation	0.01	0.04	0.02	0.13
COV	0.01	0.07	0.04	0.09

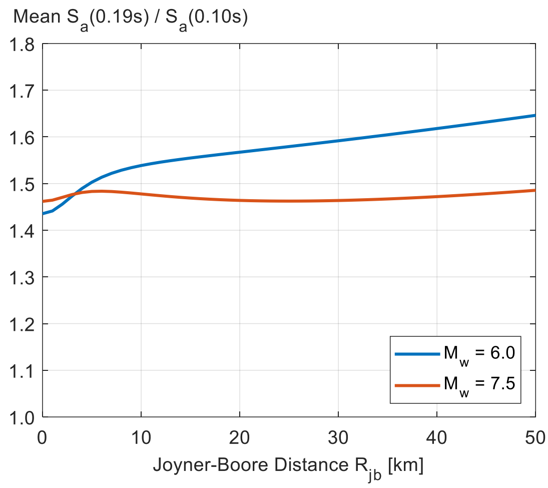

Figure 2. Median ratio between spectral ordinates at 0.19s and 0.10s as a function of M_w and R_{jb}, according to the GMPM developed by Boore et al. (2014), with V_{s30} = 250 m/s.

acceleration ordinate, $S_a(T)$, and the square of the fundamental period, T. Even if $S_a(T_1) \approx S_a(T_2)$, the spectral displacement of a 2-story house would be approximately $1.783^2 = 3.18$ times larger than that of its equivalent 1-story model. However, $S_a(T_1)$ is, in general, different than $S_a(T_2)$. This depends on the periods T_1 and T_2, and the spectral shape (which can be measured through ground motion prediction models, GMPMs). As an example, Figure 2 shows the ratio of the median values of $S_a(T_2 = 0.19s)$ and $S_a(T_1 = 0.10s)$, for two magnitudes and as a function of Joyner-Boore distance, according to the GMPM developed by Boore et al. (2014). As can be observed, the mean ratio is, for different combinations of magnitude and distance, around 1.50. The total ratio between displacement spectral ordinates $S_d(T_2)$ and $S_d(T_1)$ is then, on average, $S_d(T_2) / S_d(T_1) \approx 1.783^2 \cdot 1.50 = 4.77$. This means that spectral displacement demands in 2-story houses are approximately five times larger than those in 1-story houses.

As previously demonstrated, spectral displacement ordinates of 2-story houses are significantly larger than those of 1-story houses. But what are the differences in IDR demands? To compute the coefficients β_1 and β_2 (note that in this elastic case, $\beta_3 = 1.0$), the modal shapes ($\Gamma_i\{\phi_i\}$ for the i-th mode) are computed for the 2-story model. The first mode controls the displacement demands for two reasons: (1) the spectral displacement ordinate of the second mode is significantly smaller than the one of the first mode (because of the period difference); and (2) the modal shape of the second mode, $\Gamma_2\{\phi_2\}$, is significantly smaller than that of the first mode, $\Gamma_1\{\phi_1\}$. Therefore, β_1 and β_2 could be accurately estimated using merely the first mode information. For a 2-story model with uniform mass and lateral stiffness distributions, the modal shape of the first mode is $\Gamma_i\{\phi_i\} = \{1.171, 0.724\}$. Considering a constant story height ($h_{2l} = h_{2u}$), $\beta_1 = 1.17$ and $\beta_2 = 1.24$. The first story has the maximum IDR (note, from the modal shape, that 62% of the total roof displacement is concentrated at the lower story). Comparing IDR_{2l} with the IDR of its equivalent 1-story model, and assuming a constant story height in the models ($h_{2l} = h_{2u} = h_1$):

$$\frac{IDR_{2L}}{IDR_1} = (\beta_1\beta_2)_2 \cdot \frac{S_d(T_2)}{S_d(T_1)} \cdot \frac{(\beta_3)_2}{(\beta_3)_1} \cdot \frac{h_1}{h_{2L}+h_{2U}} = 1.45 \cdot \frac{S_d(T_2)}{S_d(T_1)} \cdot \frac{1}{1} \cdot \frac{1}{2} \approx 3.46 \quad (10)$$

where the ratio $S_d(T_2) / S_d(T_1)$ was taken as approximately 4.77, as shown before. Equation 10 demonstrates that elastic IDR demands at the lower story of 2-story houses with uniform mass and stiffness distributions are, on average, 3.46 times larger than those at 1-story equivalent dwellings.

2.1.2 Elastic response, non-uniform mass and stiffness distributions

The previous case analyzed 2-story models with uniform mass and stiffness distributions along the height of the models, but in general, houses are expected to have non-uniform distributions. In order to quantify the distributions in 2-story houses, two coefficients are introduced: the mass distribution coefficient, α_m, and the stiffness distribution coefficient, α_k, defined as follows:

$$\alpha_m = m_{2u}/m_{2l} \tag{11}$$

$$\alpha_k = k_{2u}/k_{2l} \tag{12}$$

Table 1 includes estimations of the mean, standard deviation, coefficient of variation (COV), and 95% confidence interval of the mean of α_m and α_k, for a set of ten floor plans of 2-story houses. Typical weights of wooden houses (NIBS 2012) result in roof masses being approximately 62% of the lower level masses. Also, modern architecture of 2-story houses introduces large spaces (such as living rooms, dining rooms, garages) on the first story, while most bedrooms and bathrooms are on the second story. This occupancy distribution results, as a general trend, in 2-story houses with approximately 39% stiffer second stories, compared to their first stories.

The period ratio between 2- and 1-story houses is computed for different combinations of mass and stiffness distributions. Mean values of λ_m and λ_k are used in the computations, and these period ratios are shown in Figure 3. As shown, the period ratio is not strongly affected by the mass and stiffness distribution coefficients, varying merely between approximately 1.7 and 2.0 for a set of realistic distribution coefficients or approximately 8% from its mean value. Using the mean values of α_m and α_k for a first order approximation, the period ratio is roughly 1.76 (therefore $S_d(T_2) / S_d(T_1) \approx 1.76^2 \cdot 1.50 = 4.65$, using $S_a(T_2) / S_a(T_1) \approx 1.5$, as before).

Figure 4 shows the variation of the coefficients β_1 and β_2 as a function of the mass and stiffness distribution coefficients, using the first mode information (as explained in the previous section), and constant story heights. It can be seen that the influence of α_m on β_1 is negligible, and β_1 slightly decreases when increasing α_k. This is because as α_k increases, the system tends to a flexible first story with a rigid second story, with a similar behavior as a SDOF system. Consequently, the coefficient β_1 tends towards 1.0 when α_k increases. On the other hand, the influences of α_m and α_k on β_2 are larger than the case of β_1. Lower α_m (lower roof mass) and larger α_k (stiffer second story) are related, once again, to a flexible first story with a rigid second story, where the lateral displacements at both levels are almost equal ($\Delta_{2l} \approx \Delta_{2u}$). Therefore, β_2 tends towards the value $(h_{2l} + h_{2u})/h_{2l}$. In this case, with constant story heights, β_2 tends towards 2.0. The multiplication $\beta_1 \cdot \beta_2$ also tends towards the value $(h_{2l} + h_{2u})/h_{2l}$ when decreasing α_m and increasing α_k, as a consequence of the tendencies of β_1 and β_2. Using the mean values of α_m and α_k, a first order approximation for $\beta_1 \cdot \beta_2$ is 1.74. This value is 20% larger than that of the previous case with uniform mass and stiffness distributions. The total ratio between IDR demands in 2- and 1-story houses (see Equation 10) is then approximately $IDR_{2l} / IDR_1 \approx 4.06$, 17% larger than the uniform mass and stiffness distribution case.

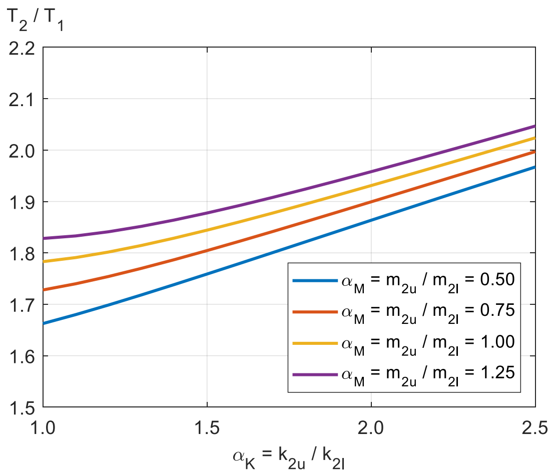

Figure 3. Variation of the period ratio between 2- and 1-story houses as a function of mass and stiffness distribution coefficients.

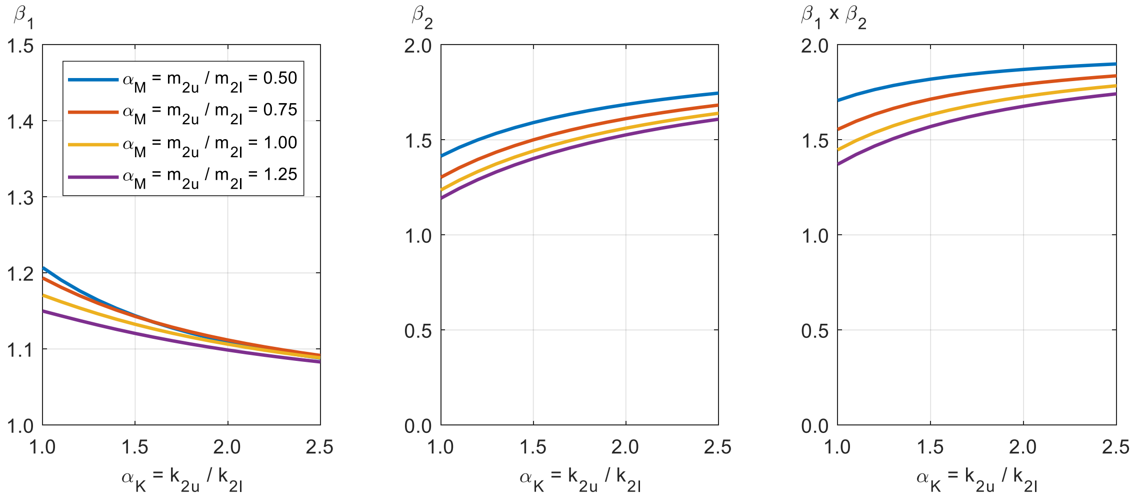

Figure 4. Variation of β_1, β_2, and $\beta_1 \times \beta_2$ in 2-story models, as a function of their mass and stiffness distribution coefficients, using the first modal shape and constant story heights.

2.1.3 Inelastic response, non-uniform mass and stiffness distributions

The previous sections demonstrated the concentration of IDR demands on the first story of 2-story houses with elastic behavior. In order to study the influence of the nonlinear behavior, 2-story models (with varying period, yield strength, and mass and stiffness distribution coefficients) are subjected to a set of ground motion records. These records were selected from nine different U.S. earthquakes with moment magnitudes ranging between 6.5 and 7.3, Joyner-Boore distances between 0 and 90 km, and peak ground accelerations between 0.10g and 0.69g (0.23g on average). Record pairs in two perpendicular horizontal directions were taken from 102 stations (a total of 204 ground motion records) on soils with average shear wave velocity at the top 30 meters between 190 and 359 m/s (NEHRP site class D).

The 2-story lumped-mass model is adapted to account for nonlinear behavior. For this, bilinear hysteretic models are included in both stories, with a 5% post-yield stiffness coefficient. For every record, the yield strength of the lower story, $F_{y,2l}$, is computed as a function of the strength ratio, R, as shown in Equation 13.

$$F_{y,2l} = S_a(T_2) \cdot (m_{2l} + m_{2u})/R \qquad (13)$$

The height distribution of the yield strength is assumed to be equal to the stiffness distribution (α_k). The damping ratio for all the models is taken equal to 8%, being consistent with the measurements performed by Camelo (2003) in 2-story houses. Figure 5 presents the variation of β_1 and β_2 as a function of the fundamental period and strength ratio, for the 204 records. Mean values of α_m and α_k were used, however using other values results in similar tendencies. Once again, the story height was taken constant in this example. Each point represents the result of one ground motion record, and the solid lines show the median values of the 204 records for every model. As shown the influence of the fundamental period is negligible on both coefficients, for periods larger than 0.10 seconds, which is consistent with periods of vibration measured by Camelo (2003) in 2-story houses. Figure 5 also shows that the influence of the strength ratio on β_1 and β_2 is also negligible once the system behaves nonlinearly (R larger than 1). Once the first story yields, it forms a soft story and inelastic displacements are strongly concentrated at the lower level. This behavior results in β_1 tending to 1.0 and β_2 tending to $(h_{2l} + h_{2u})/h_{2l}$ (which equals 2.0 for constant story heights) when increasing the strength ratio R. Moreover, Figure 5 also shows the correlation between β_1 and β_2. As can be observed, there is strong negative correlation between these coefficients. In other words, when β_1 decreases, β_2 tends to increase, which is expected, as explained before.

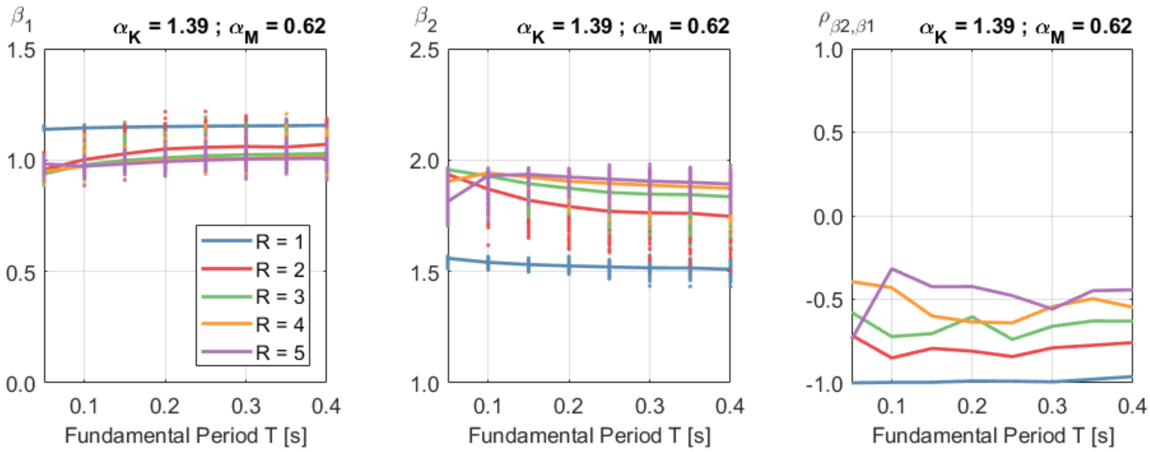

Figure 5. Variation of β_1 and β_2 in 2-story models as a function of their fundamental period of vibration and R, using α_K = 1.39, α_M = 0.62, and constant story heights. Results of individual records are presented as points, and their geometric means as solid lines.

The resulting product $\beta_1 \cdot \beta_2$, as a function of the fundamental period and strength ratio, is presented in Figure 6. As explained before, while β_1 decreases, β_2 increases, therefore the product $\beta_1 \cdot \beta_2$ is very stable. The negligible dispersion of $\beta_1 \cdot \beta_2$, shown in Figure 6 as well, is explained by the small dispersions of β_1 and β_2, along with their negative correlation which further reduces its variability. A constant representative value of $\beta_1 \cdot \beta_2 = 1.88$ can be chosen for 2-story houses with nonlinear behavior. This value is 8% larger than the one obtained for the elastic case with non-uniform stiffness and mass distributions. The robustness of this representative value represents a valuable result for future regional risk estimations.

The last ratio that has to be addressed is the ratio between β_3 coefficients for the 1- and 2-story models: $(\beta_3)_2 / (\beta_3)_1$. To estimate this ratio, SDOF models with bilinear hysteresis behaviors are subjected to the same set of 204 ground motion records described above. For the 2-story models, three periods T_2 are used (0.15s, 0.20s, and 0.25s), while the strength ratio R_2 (subscript 2 for referencing the 2-story models)

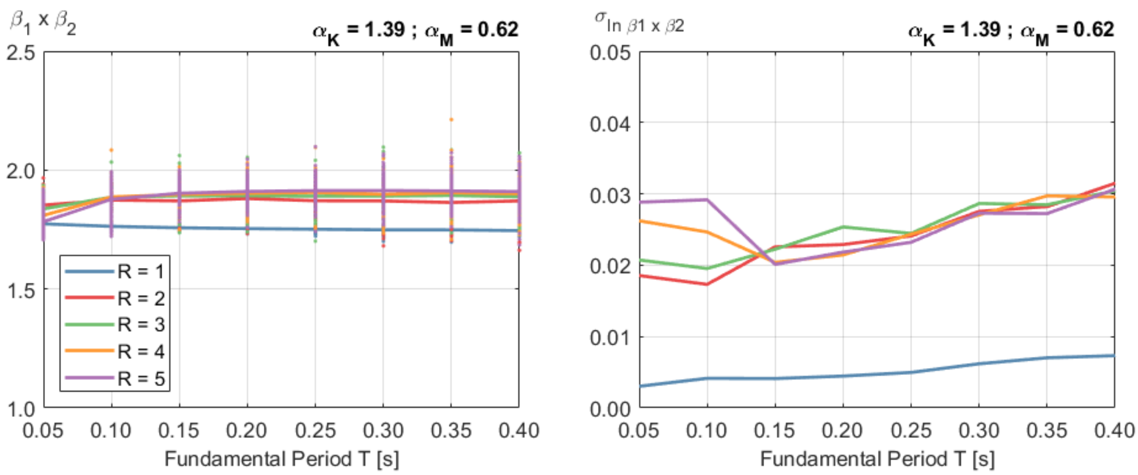

Figure 6. (a) Variation of β_1 x β_2 in 2-story models as a function of their fundamental period of vibration and R, using α_K=1.39, α_M=0.62, and constant story heights. Results of individual records are presented as points, and geometric means as solid lines. (b) Variation of the logarithmic standard deviation of β_1 x β_2 in 2-story models as a function of their fundamental period of vibration and R, using α_K =1.39, α_M =0.62, and constant story heights.

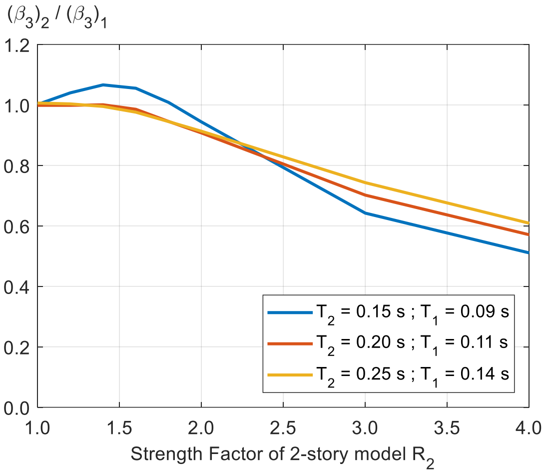

Figure 7. Variation of the median ratio $(\beta_3)_2 / (\beta_3)_1$ as a function of the strength factor and fundamental period of the 2-story model, with a constant ratio T_2 / T_1 = 1.76.

is varied from 1 to 5. For the 1-story models, two approximations are assumed: (1) the period ratio between the 2- and 1-story models is assumed constant, and equals to 1.76; and (2) the normalized strengths of 1-story models are assumed to be equal to those of 2-story models (this assumption is based on the fact that short-period structures are typically designed with a constant seismic coefficient and constant R factor, independent of their periods). Note that the effective strength ratios of 1- and 2-story models are not equal, because $S_a(T_1) \neq S_a(T_2)$. Figure 7 shows the variation of the median ratio $(\beta_3)_2 / (\beta_3)_1$ as a function of the 2-story fundamental period and strength factor, T_2 and R_2, respectively. Overall, the ratio $(\beta_3)_2 / (\beta_3)_1$ decreases when increasing R_2, and varies between 1.05 and 0.50 for the considered range of periods and strength factors.

Finally, the ratio of peak IDR demands in 2- and 1-story houses is estimated (see Equation 10). Using the values previously discussed, the ratio IDR_{2l} / IDR_1 varies roughly between 2.2 (for large R_2 values) and 4.6 (for R_2 values between 1 and 2) indicating that interstory drift demands are significantly larger in 2-story houses than in 1-story houses.

2.2 Probability of Damage and Expected Loss

The previous section compared the IDR demands in 1- and 2-story houses, demonstrating theoretically that these demands are concentrated on the first story of 2-story houses, reaching values between 2.2 and 4.6 times larger than those at 1-story houses. These differences in displacement demands are then

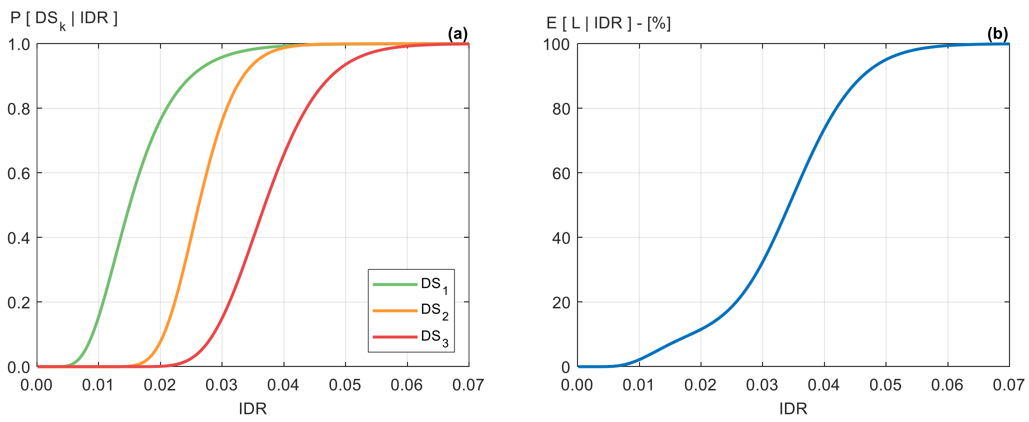

Figure 8. (a) Fragility curves; and (b) Expected loss ratio as a function of IDR, for interior structural walls (component number B1071.021 of ATC-58 project (Hamburger et al. 2004)).

(a) 1995 Kobe Earthquake, Japan (Michio Miyano)

(b) 2011 Christchurch Earthquake, New Zealand (John Kirk-Anderson)

(c) 2011 Christchurch Earthquake, New Zealand (Asher Trafford)

Figure 9. Examples of damaged 2-story houses. Considerable damage is concentrated in their first stories.

translated into even larger differences in probabilities that structural and drift-sensitive non-structural components are damaged, and consequently, significant differences in expected losses at 1- and 2-story houses. As an example of a drift-sensitive component, Figure 8a shows fragility curves, as a function of IDR, of wood interior shear walls with structural panel sheathing, gypsum wallboard, designed with hold-downs (component number B1071.021 for the ATC-58 project (Hamburger et al. 2004)). Figure 8b shows the expected loss ratio (defined as the percentage of the total loss of the component in its last damage state) as a function of IDR. As can be seen, a threefold difference in IDR can produce significant differences in the probabilities of damage and expected losses. For example, an IDR increment from 0.01 to 0.03 results in an increment in the probability of damage state 1 or higher from 15.5% to 95.8% (increased 6.2 times). Similarly, the probability of damage state 2 or higher increases from practically 0% to 76.2%. In the case of the expected loss ratio, a threefold increment in IDR demands from 0.01 to 0.03, is translated into an increment in the expected loss ratio from 2.2% to 32.5% (increased 14.6 times). Note that these are examples for a difference of merely three times, but as shown in the previous section, the IDR can be as much as 4.6 times larger in the first stories of 2-story houses, with respect to 1-story houses and therefore the difference in damage would be even larger.

These analytical differences between the seismic performances of 1- and 2-story houses have also been observed in past earthquakes. Figure 9 shows a set of examples of 2-story houses after two earthquakes. As can be seen, houses present significant damage on their first stories, with a second story remaining practically damage-free. These examples confirm that deformations and damage are heavily concentrated on the first story of 2-story houses, as demonstrated theoretically in the previous sections.

3. CONCLUSIONS

Earthquake regional risk estimations have had a gradual evolutionary development in time. However, building classification systems have been somewhat stationary, especially when classifying houses, which represent the majority of buildings. Historically, houses having one, two, and even three stories have been lumped into a single building class. Nevertheless, past experiences of different earthquakes have shown that 2-story houses present poorer performance than 1-story houses. This difference is the focus of this article, and is demonstrated to be a result of:

1. Difference in the fundamental period between 1- and 2-story houses. With simple models, 2-story houses are estimated to have, on average, periods about 1.8 times larger than those of 1-story houses. This difference is translated into larger spectral displacement ordinates in 2-story houses (approximately 4.7 times larger than 1-story houses).
2. Elastically, 2-story houses concentrate 62% of the roof displacement on their first story when the distribution of mass and stiffness is uniformly distributed along the height. With this, IDR demands on the first story of 2-story houses with uniform mass and stiffness distributions are more than 3.4 times larger than those in 1-story houses.
3. Typical architecture of 2-story houses results in a lower mass at the roof and higher stiffness at the second story. Consequently, higher concentrations of the roof deformations are presented on the

first story. Thus, 2-story houses with non-uniform (and more realistic) mass and stiffness distributions have IDR demands 4.0 times larger than those in 1-story houses.

4. A soft-story is formed once the first floor yields (nonlinear behavior), concentrating even more IDR demands. This results in displacement demands in 2-story houses with non-uniform mass and stiffness distributions and nonlinear behavior which can be up to 4.6 times larger than those in 1-story houses.
5. The relationship between increments in IDR demands and increments in expected losses or increments in the probability of drift-sensitive components being damaged, is strongly nonlinear. Therefore differences of, for example, three times in IDR demands, can lead into huge differences in risk.

As a general conclusion, lumping both systems in a single class with a unique seismic performance is demonstrated to be conceptually wrong. Although simplified models were used in this analysis, the goal is to reflect that the differences in risk between 1- and 2-story dwellings cannot be neglected. Even if more complex models were used, similar results are expected, where 2-story houses present worse seismic performance than 1-story houses. This work is a step towards an update on building classification systems for both the insurance industry and earthquake risk estimations. In these updated systems, houses having one and two stories must be assigned to different classes, each one considering their unique dynamic characteristics and seismic performances, being consistent with what we have historically seen in past earthquakes and demonstrated in this study.

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