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Seismic Vulnerability Assessment of Non-structural Components using Bow-Tie Analysis

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Abstract: The importance of failure of non-structural building components during earthquake has generated considerable attention from decision makers. Non-structural components can be categorized into architectural, mechanical and electrical components. This paper will present a bow-tie based earthquake risk assessment analysis for mechanical and electrical non-structural component failure in buildings. Bow-tie approach integrates a fault tree and an event tree to represent causes, threats (hazards) and consequences in a common platform. Fault tree will investigate the scenarios (such as, site specific seismic hazard and non-structural component vulnerability) leading to failure. The event tree quantifies the sequence of events in the consequence analysis. The output of that bow-tie analysis is the consequence or outcome event probabilities. These probabilities will represent probability of losses due to mechanical and electrical non-structural components damage for a seismic event. The proposed bow-tie framework has been implemented for two case study buildings with different heights and seismic code design levels.

1. Introduction

Recent earthquakes, for example, 2006 Hawaii earthquake, 2003 Mexico earthquake, 2001 Nisqually earthquake, 1994 Northridge earthquake, highlighted vulnerability of different structural and non structural damages in reinforced concrete (RC) buildings (ATC-69 2008; Filiatrault et al. 2004). Different earthquake reconnaissance reports shows that even if the building meets the expected structural performance level, failure of non-structural components (e.g. architectural, mechanical, or electrical) may result injuries, fatalities, property and financial loss (ATC-69 2008; Mosqueda et al. 2009; Whittaker and Soong 2003). ATC-69 (2008), FEMA-356 (2000) has grouped non-structural elements into three categories: *architectural*, *mechanical* and *electrical,* and *other* contents (Table 1). Recent earthquakes in US shows the major cost of damage in buildings are due to the vulnerability of non-structural systems (Filiatrault et al. 2011). This is attributed to three-quarters of the construction cost of a typical building is related to the non-structural components.

HAZUS-MH MR3 (2003) has grouped the different non-structural components as “acceleration sensitive” and “drift sensitive” in order to assess their damage due to seismic load, which are a function of floor acceleration and inter-story drift, respectively. Furthermore, the mechanical and electrical components are mostly acceleration sensitive and a few of them are secondary cause of damage for drift sensitivity (HAZUS-MH MR3 2003). The damage states described in HAZUS-MH MR3 (2003) are *slight*, *moderate*, *extensive* and *complete* and in FEMA-356 (2000) are *hazard reduced*, *life safety* and *immediate occupancy*. The damage descriptions between HAZUS-MH MR3 (2003) and FEMA-356 (2000) are similar.

Table 1: Classification of non-structural components

Type	Item
Architectural	Cladding, glazing, partitions, ceilings, Parapets and ornamentation, canopies & marquees, chimneys and stacks, stairs and fire escapes, light fixtures, doors.
Mechanical and Electrical	Elevators, HVAC equipment, ducts, piping, fire sprinkler systems, fire alarm systems, emergency lighting, electrical distribution equipment, and plumbing.
Other Contents	Computer systems, manufacturing equipment, desktop equipment file cabinets, book shelves, hazardous materials, art objects.

This study is used to quantify the seismic risk induced damage and consequence (hence risk) of non-structural (mechanical and electrical) components due to an earthquake. A risk assessment framework has been developed by using a bow-tie (e.g., Shahriar et al. 2011; Cockshott 2005). The 'bow-tie' analysis can be used in a decision making process to prevent, control and mitigate undesired events by developing a logical relationship between causes and consequences of an undesired event (Duijm 2009; Dianous and Fievez 2006). Construction of a bow-tie diagram requires linking the Fault tree (FT) and event tree (ET) by a Critical event (CE). FT investigates the scenarios leading to failure whereas the ET models the known consequence scenarios. The ET scenarios are developed following the possible non-structural damages for different damage states described in FEMA-356 (2003). The vulnerability of non-structural components has been predicted accordingly. Quantifications of the damage states are vague and subject to uncertainties, and in this paper, fuzzy linguistics has been used to quantify the damage probabilities of events.

2. Proposed Framework using Bow-Tie

A schematic bow-tie framework is shown in Figure 1. The FT is placed on the left side of the diagram and it starts with the CE (damages) and diverges until the causes are described using logic gates (e.g., AND and OR gates). The right side of the bow-tie diagram corresponds to ET development, which begins from the CE as initiating event and follows the sequences of events (consequence) to reach to the possible outcome events (OE) (Aven 2008).

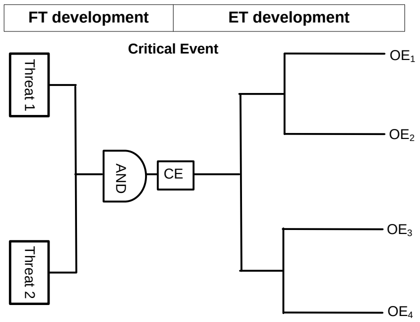


Figure 1: Schematic bow-tie framework

Both the FT and ET will be discussed further in the subsequent sub-sections for the proposed bow-tie framework.

2.1 Fault Tree

In the fault tree portion seismic hazard and building vulnerability converges to the top event "Damages". The top event branch out to different damage states adopted from HAZUS-MH MR3 (2003) (Figure 2). The probability of reaching each damage state by the acceleration sensitive non-structural components can be computed from the fragility curves. HAZUS-MH MR3 (2003) has developed the fragilities for different building types that will be used here as a case study. Figure 2 shows the steps associated with the calculation of damage probabilities.

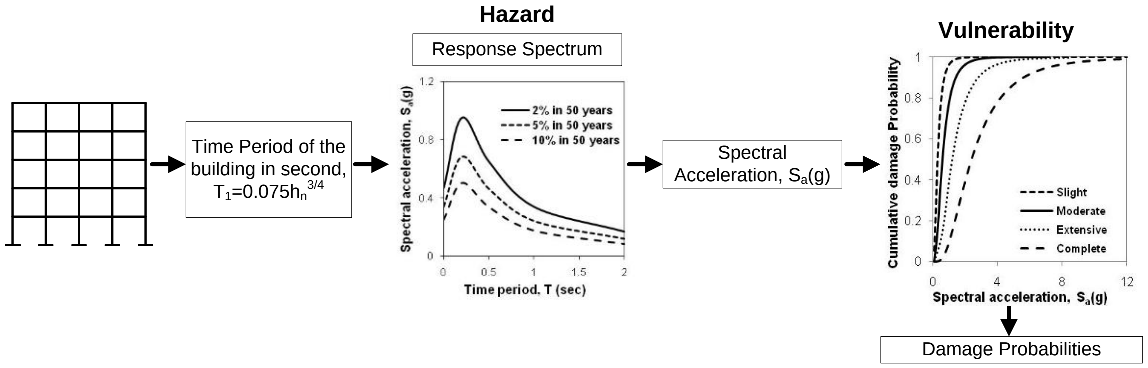


Figure 2: Steps associated with calculating outcome event probabilities

In designing the non-structural elements against seismic excitations involves the use of floor design spectra (Filiatrault et al. 2004; Shooshtari et al. 2010). Shooshtari et al. (2010) has developed floor design spectra for buildings in Canada having different heights and different lateral force resisting systems. In this study, Spectral acceleration (S_a) at the fundamental period of the structure is used as seismic hazard index. The uniform hazard spectrums with 5% damping has been used for Vancouver city. The design response spectra, is obtained at the building periods of 0.2, 0.5, 1.0 and 2.0 seconds, are used to quantify the seismic hazard. Figure 2 shows the design response spectrum for different hazard level (2%, 5% and 10% in 50 years) on firm ground conditions (NBC soil class C). Design spectral response acceleration could be found by multiplying the site coefficients and S_a. If the fundamental time period of a building is known, the design spectral response acceleration could be found from the response spectrum curves.

Fragility curves will be used here to represent the vulnerability of mechanical and electrical non-structural components (Figure 2). According to Schultz et al. (2010), fragility curves are functions that describe the probability of failure, conditioned on the load, over the full range of loads to which a system might be exposed. Here the seismic demand is S_a found from the design response spectrum for different hazard level. HAZUS-MH MR3 (2003) has developed fragility curves for buildings in terms of the structural systems, story height (low, medium, high) and codes (high code, moderate code, low code and pre-code). Each fragility curve is characterized by median value of demand parameter (e.g., spectral acceleration) and lognormal standard deviation (β) values. Spectral acceleration is the parameter which has been used for calculating non-structural damage to acceleration-sensitive components.

The conditional probability of being in or exceeding, a particular damage state, ds_a, given the spectral acceleration, S_a, (or other seismic demand parameter) is defined by equation:

[1] $$P\left[ds_a \middle| S_a\right] = \Phi\left[\frac{1}{\beta_{ds_a}} \ln \frac{S_a}{\overline{S}_{a,ds_a}}\right]$$

where, β_{ds_a} is the standard deviation of natural logarithm of spectral acceleration for damage state ds_a, $\bar{S}_{a,ds_a}$ = is median value of spectral acceleration at which the building reaches the threshold of damage state ds_a and Φ is the standard normal cumulative distribution function.

For any given value of spectral acceleration, discrete damage-state probabilities are calculated as the difference of the cumulative probabilities of reaching, or exceeding, successive damage states. The probabilities of a building reaching or exceeding the various damage levels at a given response level sum to 100%.

2.2 Event Tree

Different accident scenarios may arise from a combination of different mechanical and electrical non-structural component damage and can lead to a significant threat to people and property (e.g., casualty, economic loss due to induced structural and non-structural damage). Figure 3 shows the damage propagation in ET. The ET considers the different damages and sequence described in Table 2, and corresponding fuzzy linguistics (Table 3) developed to propagate the events until it reveals all possible OEs (Table 4) in the 'bow-tie' diagram. The branch probabilities should sum up to 1.

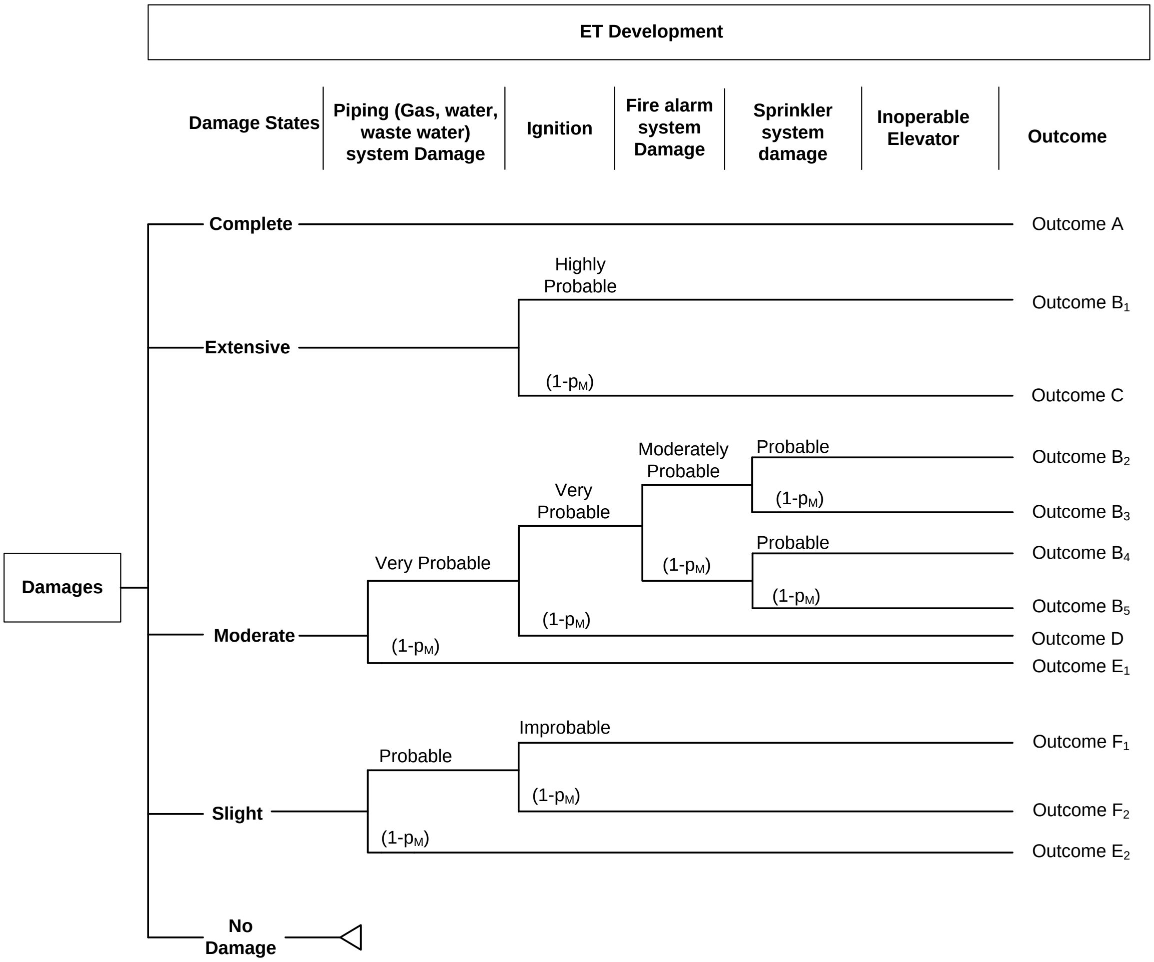


Figure 3: Proposed bow-tie framework

Table 2: Nonstructural Performance Levels and Damage—Mechanical and electrical systems/components (adopted from FEMA-356 2000)

System/Components	Non-structural performance level		
	FEMA-356 (2000)/ HAZUS-MH MR3 (2003)		
	Hazard reduced/Extensive	Life safety/Moderate	Immediate occupancy/Slight
Elevators	Elevators out of service.	Elevators out of service.	Elevators operable; can be started when power available.
Piping	Some lines rupture. Some supports fail. Some piping falls.	Minor damage at joints, with some leakage. Some supports damaged, but systems remain suspended.	Minor leaks develop at a few joints.
Fire Sprinkler Systems	Many sprinkler heads damaged by collapsing ceilings. Leaks develop at couplings. Some branch lines fail.	Some sprinkler heads damaged by swaying ceilings. Leaks develop at some couplings.	Minor leakage at a few heads or pipe joints. System remains operable.
Fire Alarm Systems	Ceiling mounted sensors damaged. System nonfunc-tional.	May not function.	System is functional.

Table 3: Linguistic Probabilities

Linguistic	Symbol	Probabilities (p_M)
Very Improbable	VI	0.01
Improbable	IP	0.05
Moderately Probable	MP	0.3
Probable	P	0.5
Very Probable	VP	0.8
Highly Probable	HP	0.95

In ET development, different accident scenarios have been shown (e.g., piping system damage, ignition, and fire system damage). For complete damage, the entire structure will be collapsed, so no branch has been made for that. For extensive damage, different mechanical and electrical components will behave differently (Table 2). The fuzzy linguistics has put in the branches depending on the possible damages that have been stated in FEMA-356 (2000). For extensive damage, the possibility of different component damage is high, so probability of damage of each component is assumed to be 1. Only one branch has been made for the event “ignition” to incorporate the uncertainty for that event. For moderate damage states, the event “Inoperable elevator” propagates with a probability of 1, as the elevator system will be inoperable at that damage state (Table 2). For slight damage state, there will not be any severe damages. Some minor damages have been predicted in the piping.

Finally each of the branches is ended up in an outcome. The symbolic outcome presented in Figure 3 is described in Table 4.

Table 4: Possible outcomes arise from the mechanical and electrical non-structural damage

Outcome	Description
Outcome A	-casualty -economic loss -collapse of the whole building
Outcome $B_{i\ (i = 1,2,3,4,5,6)}$	-casualty -induced non-structural and structural damage -economic loss -collapse of the whole building due to fire outbreak
Outcome C	-induced non-structural and structural damage -economic loss
Outcome D	-induced non-structural and structural damage
Outcome $E_{i\ (i = 1,2)}$	-negligible damage
Outcome $F_{i\ (i = 1,2)}$	-induced non-structural and structural damage (minor)

3. Fuzzy Logic

Fuzzy linguistic variables have been used here to quantify the damage probabilities of non-structural components as the probabilities of various risk items is vaguely known or assessed. Reports from the past earthquake records show that the damage data is not adequate to generate meaningful statistics on overall losses from non-structural components and contents (ATC-69 2008).

Fuzzy logic provides a language with syntax and semantics to translate qualitative knowledge/judgments into numerical reasoning (Tesfamariam and Saatcioglu 2008; Ferdous et al. 2009). A fuzzy number describes the relationship between an uncertain quantity (e.g., event probability) and a membership function, which ranges between 0 and 1. In the proposed approach, the subjective judgment of event probability is assumed linguistic and described using a triangular fuzzy numbers (TFN). The fuzzy probabilities of initiating are then used to estimate the outcome event probability that is also estimated as a fuzzy number. The fuzzy-based approach used for ETA comprises the following three steps: (1) Define event probability using TFNs; (2) Determine outcome event probability as a TFN; and (3) Defuzzify outcome event frequency as a crisp number (point estimate).

3.1 Define event probability using TNFs (fuzzy members)

Linguistic expressions (such as moderately probable, probable, and improbable) have been used rather than numerical expressions to justify the probability of an event. An expert's linguistic judgment is assigned a TFN. The TFN (Figure 4), described with the three vertices, (p_L, p_M, p_R) represents the minimum, most likely and maximum values of event probability, whereas the α-cut level is a degree of membership μ_p (Ferdous et al. 2009). Here, fuzzification factor, Δ has been introduced to calculate the minimum and maximum values of the event probability (Tesfamariam and Sadiq 2006). So the TFN could be represented as (p_M-Δ, p_M, p_M+Δ). For a TFN, nested intervals can be generated by incrementally changing the α-cut levels as follows:

[2] $\tilde{P}_\alpha = \{\alpha_i, p_{Li}, p_{Ri}\}$; for i = 1, 2,..., n.

Figure 4 shows the TFN to represent the event probability.

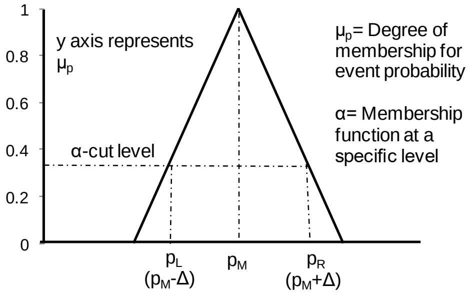


Figure 4: TFN to represent the event probability

Six fuzzy linguistics have been presented in Table 3. The corresponding fuzzy probabilities can be calculated as $\{p_L=\max(0, p_M - \Delta), p_M, p_R=\min(1, p_M + \Delta)\}$.

3.2 Determine outcome event probability as a TFN

Outcome event TFN is calculated by taking the minimum and maximum value of the multiplication of the TFN intervals (Tesfamariam and Sadiq 2006). In a TFN, the membership function uses the following relationship to determine the interval at the α-cut level:

[3] $$\underset{\alpha}{\tilde{P}} = \left[p_L + \alpha(p_M - p_L), p_R - \alpha(p_R - p_M)\right]$$

Fuzzy arithmetic operations are used to determine the outcome event probability. Here ETA requires fuzzy multiplication operation to calculate the outcome event probability. For event probabilities P_1 (p_{1L}, p_{1M}, p_{1U}) and P_2 (p_{2L}, p_{2M}, p_{2U}) (represented by two TFNs), the fuzzy multiplication result is (p_{1L} x p_{2L}, p_{1M} x p_{2M}, p_{1U} x p_{2U}) (e.g. Figure 5).

3.3 Defuzzify outcome event probability as a crisp number (point estimate)

Defuzzification transforms a fuzzy number into a crisp value (Ross 2004). Centroid method has been used here to defuzzify the fuzzy numbers (e.g. Figure 5). The following algebraic expression is the representation of centroid method which has been used for defuzzification of outcome event probability or frequency:

[4] $$P_{out} = \frac{\int \mu_p(p).pdp}{\int \mu_p(p).dp}$$

4. Case Study

The proposed framework has been implemented to low code and high code RC moment resisting frame. For this case study only low and high rise building has been considered. The step-by-step calculation is outlined below.

Step 1: Acceleration demand from seismic hazard

Description of the building and fundamental period of corresponding buildings is given in Table 5. The period (T_1) is calculated using the empirical equation (shown in Figure 2) provided by NBCC 2005. The $S_a(T_1)$ have been computed from the response spectra (shown in Figure 2) and are summarized in Table 5.

Table 5: Description of buildings used in case study

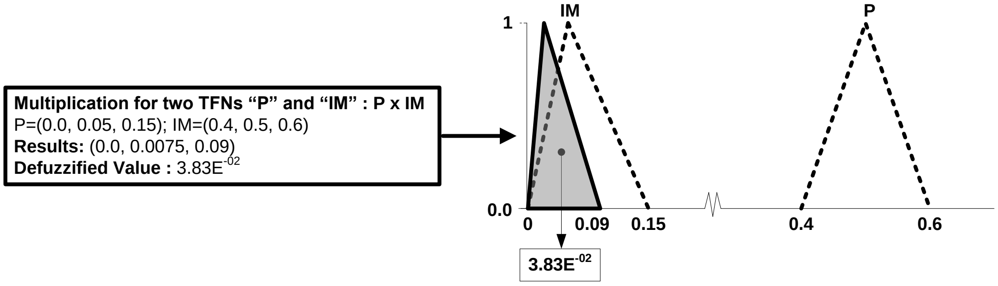
Label	Description	Height			Acceleration demand		
		Name	Stories (height)	Period, T_1 (sec)	Hazard Level		
					2%	5%	10%
C1L	Concrete moment resisting frame	Low-rise	2 (6)	0.288	0.862	0.619	0.453
C2H		High-rise	12 (37)	1.125	0.319	0.226	0.166

Step 2: Damage probabilities from building vulnerability

For C1L low-code building type, the damage probabilities are found from the fragility curves (Figure 2). Using the acceleration demand of 2% hazard as input, the cumulative probabilities of damage for slight, moderate, extensive and complete damage are, 0.939, 0.703, 0.311, and 0.063, respectively. Finally, the damage probabilities for no damage, slight, moderate, extensive and complete are, 0.060, 0.237, 0.392, 0.248, and 0.063, respectively.

Step 3: Outcome event probabilities by ETA

One sample calculation for F_1 outcome event probability will be shown here. The bold triangle in Figure 5 is representing the outcome event TFN. The path leading to the outcome event "F_1", shown in Figure 3, is followed by two events. The probabilities of these two events are linguistically expressed and assumed to be "Probable" and "Improbable". The linguistic probabilities are found according to Table 3 and the fuzzification factor Δ is taken as 0.1. These two variables are assigned TFNs and then the TFN for outcome event "F_1" has been calculated using fuzzy arithmetic operation rule for multiplication.

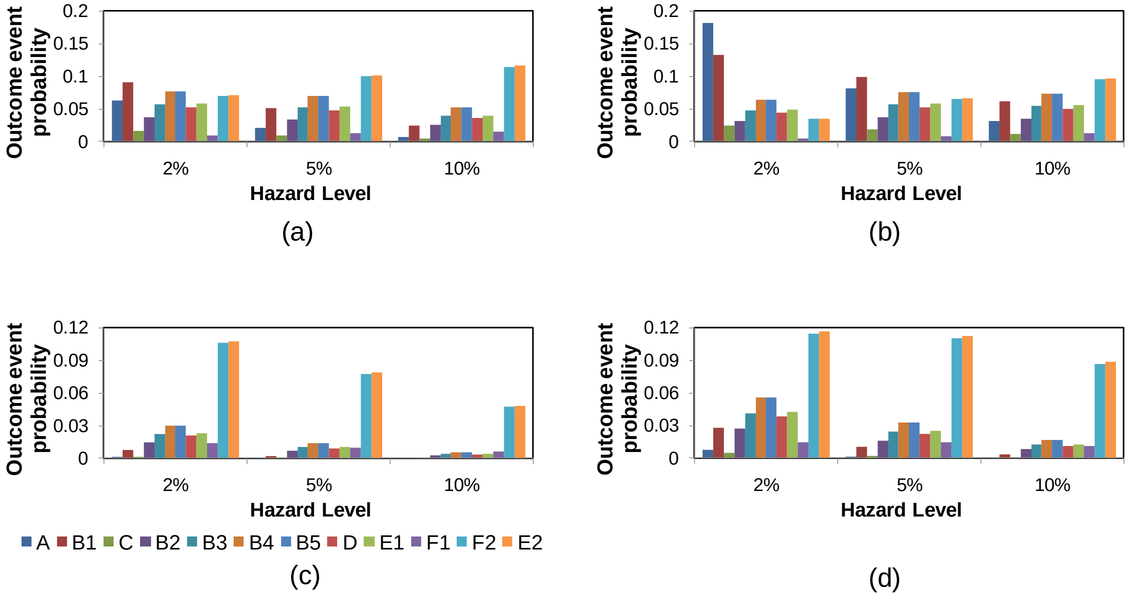


Multiplication for two TFNs "P" and "IM" : P x IM
P=(0.0, 0.05, 0.15); IM=(0.4, 0.5, 0.6)
Results: (0.0, 0.0075, 0.09)
Defuzzified Value : 3.83E^{-02}

Figure 5: Calculation of outcome event TFN

The results have been found for α-cut level 0. The TFN for the outcome events is defuzzified (Equation 4) to obtain the crisp probability for the event. Finally the defuzzified value is multiplied with the damage probability to get the outcome event probability for each damage state. So the outcome event probability for C1L low-code building with 2% hazard level is: 3.83E^{-02}*damage probability for slight damage=3.83E^{-02}*0.237=1.24E^{-02}.

Figure 6 shows all outcome event probabilities in bar charts. Discuss about the results…



(a) (b)

(c) (d)

Figure 6: Outcome event probabilities represented in bar charts (a) C1L High code building (b) C1L Low code building (c) C1H High code building and (d) C1H Low code buildings.

5. Conclusions

Damage resulting from non-structural components of the building may lead to a number of consequences (e.g., casualty, economic loss, induced structural and non-structural damage, fire outbreak, etc). The quantification of various outcome event probability associated with non-structural damage is the crucial part due to unavailability of damage data.

The final outcome of that bow-tie analysis is the outcome event probabilities. The proposed framework has been implemented to RC moment resisting frame with different heights and design consideration. The results found from the case study shows that,

- Almost all the outcome event probabilities are higher for the low-code buildings as the probability of being in different damage states is higher for low code buildings.
- When the damage probability is higher the outcome event probability is also found to be higher and it is observed for all the case study buildings.

The outcome event probabilities are representing the percentage of various types of loss. Those probabilities will be useful to find out the direct economic losses due to non-structural damage for an earthquake. Those results could be useful in decision making process also. The results presented in this study are based on expert elicitation. That framework could be implemented by using the field damage data from an earthquake which will make the results more reliable.

Acknowledgments

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