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A PROBABILISTIC CASUALTY MODEL TO INCLUDE INJURY SEVERITY LEVELS IN SEISMIC RISK ASSESSMENT

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Abstract

Despite the increasing adoption of Performance-Based Earthquake Engineering (PBEE) in seismic risk assessment and design of buildings, earthquakes resulted in around 1.8 million injuries (three times the number of fatalities) over the past two decades. Several existing PBEE-based methodologies use rudimentary models that may not accurately estimate earthquake-induced casualties. Even when models are suitable for predicting the total number of fatalities and critical injuries, they may fail to adequately differentiate between different levels of injury severity. This paper draws attention to the importance of extending the seismic casualty assessment method by broadening the perspective on injury severity. To this cause, a probabilistic model is developed to predict fatalities and injuries due to earthquakes. The proposed model adopts the FEMA P-58 framework for risk assessment and considers six injury severity levels (minor, moderate, serious, severe, critical and fatal), in accordance with the Abbreviated Injury Scale (AIS). The aforementioned framework evaluates the casualty risk with five modules: seismic hazard analysis, structural analysis and response evaluation (using incremental dynamic analysis), building collapse simulation, detailed casualty assessment caused by structural, nonstructural, and content components of the building, and injury severity assessment.
The injury severity assessment module assumes two modes of injury: occupants falling on the floor resulting in injury and injuries caused by unstable building contents hitting occupants as a result of sliding or overturning. The framework uses an occupant-time location model to predict the number of injuries and a set of building content fragility curves for sliding and overturning failure modes, developed by the incremental dynamic analyses. The proposed model was applied to a case study of a reinforced concrete, moment-frame office building furnished with 21 different content objects. The results show that the frequency of injuries resulting in hospitalization can be up to 30 times more than that of the fatal injuries at low shaking intensity levels and may amplify by 20 times at high intensity shaking.

***Keywords**: Performance-Based Design, Building Contents, Abbreviated Injury Scale, FEMA P-58, Casualty Model.*

1. Introduction

Seismic performance of buildings has been the focus of many researchers for the last two decades. Fatality and severe injuries that result in death are being studied and taken into account in modern performance-based frameworks; however, many of these performance-based methodologies fall short in terms of injury severity assessment. Experience from the previous earthquake events shows that fatality and injury can result from building collapse; however, the majority of injuries result from occupants being hit by building contents (falling or shifted objects) or falling on the floor. 55% of injuries from the 1994 Northridge earthquake (M_w = 6.7) were caused by falling objects, 22% by people falling on the ground, and 15% by jumping out of windows. On the other hand, only 1% of injuries were caused by structural damage [1]. Also, 19% of injuries from the 1987 Whittier Narrows earthquake (M_w = 5.9) were associated with occupants falling on the floor and 50% with falling objects and wall hangings. In the 1989 Loma Prieta earthquake (M_w = 6.9), 55% of injuries were due to falling on the floor, and 10% were caused by nonstructural components [2].

The seismic performance of structural and nonstructural components has been investigated in detail; however, the seismic performance of contents is overlooked despite its importance. For instance, the FEMA P-58 (P-58) [3] document provides a limited number of building content components for which the provided fragility functions are not paired with casualty consequence functions. Additionally, there is no documentation of estimating such losses under future earthquakes.

Limited studies discussed content-triggered injury at the building level. Okada et al. [4] proposed a methodology to find the probability of people getting injured due to furniture overturning using a binomial distribution model. The authors suggested four different situations of dealing with furniture risk in order to consider the aleatory and epistemic uncertainty. However, Okada et al. considered one failure mode, which is overturning, and did not classify the severity of injuries. Additionally, Yeow [5] developed a building-specific methodology to predict the number of injuries after earthquakes using Monte Carlo Simulation (MCS). Yeow considered two failure modes (sliding and overturning) of one damage state and classified injuries based on the Association for the Advancement of Automotive Medicine, which was expressed as the Abbreviated Injury Severity (AIS) code. However, Yeow's framework is coordinate-based, and the user may need to provide the room layout and contents coordinate within the layout to predict the number of injuries. Any change in the content configuration within the room will materially affect the results. Moreover, the detailed analysis is time-consuming.

This paper aims to expand the existing seismic casualty estimation framework to include injury estimation due to different sources (contents failure modes and falling on the ground) using a probabilistic model. The proposed methodology is divided into four parts: (1) content fragility functions and damage, (2) collapse simulation and collapse casualty, (3) probabilistic assessment of non-collapse fatality and injury, and (4) injury severity assessment. For demonstration, the framework is applied to a four-story office building consisting of a reinforced concrete moment frame system designed for high seismic region per ASCE 7.

2. Content fragility functions and damage

Fragility function is defined as the probability of failure when the component demand exceeds its capacity. In this paper, two failure modes are considered for a free-standing building content: sliding, and rocking. Fragility functions are derived based on Majdalaweyh et.al. [6]. The demand parameter used for the sliding model fragility function is the sliding displacement, while the damage states are limited sliding and excessive sliding. In the case of the rocking model, the demand parameter is the rotational angle with overturning being the damage state.

3. Collapse simulation and collapse casualty

In this study, a casualty loss estimation framework is performed using the MATLAB toolbox developed by [7–9]. First, the entire building is modeled and subjected to 22 far-field ground motions provided by FEMA P-695, then an Incremental Dynamic Analysis (IDA) is performed on the building to determine the building

Engineering Demand Parameter (EDP) such as the peak inter-story drift, or peak floor accelerations. Multiple realizations of EDP are then generated to examine the building damage. At each realization, the building is checked for collapse using the building collapse fragility curve. If collapse is realized, the collapse mode is determined (next section). The flowchart of the performance-based loss assessment procedure adopted from FEMA P-58 is shown in Fig. 1.

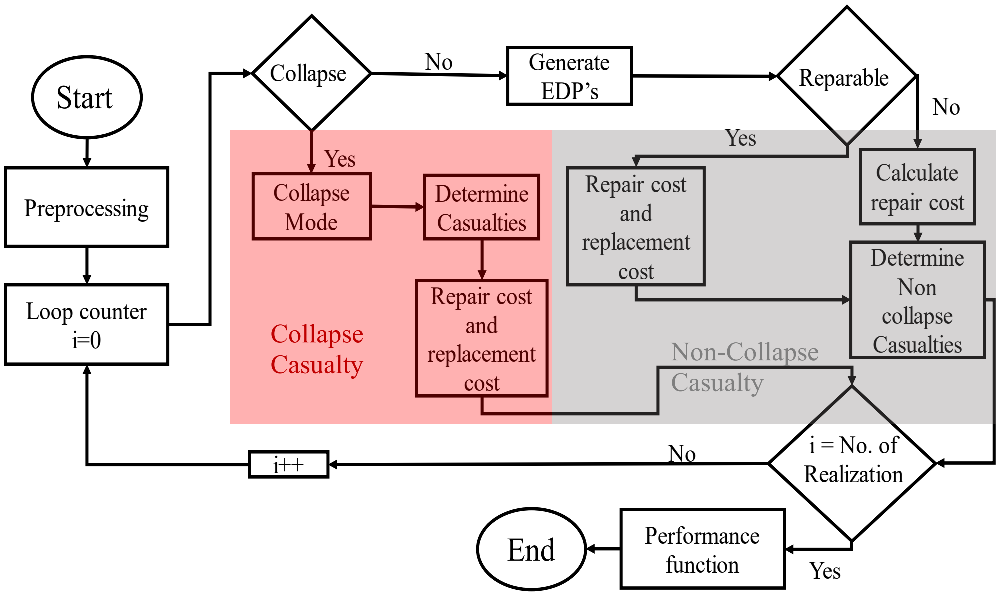

Fig. 1 - The flowchart of the performance-based loss assessment procedure in the current version of FEMA P-58

3.1 Collapse modes

P-58 defined collapse modes as "the ways in which a building would be expected to collapse, ranging from partial to complete collapse. Possible collapse modes are single-story, multiple story, and total collapse." In order to find structure collapse modes, collapse triggers are tracked throughout IDA. However, this methodology is inefficient in terms of time and impractical because collapse modes are sensitive to different variables such as building modeling, ground motion characteristics, and etc.

In this paper, a methodology is proposed to predict building collapse modes using Monte-Carlo Simulation (MCS). The steps of analysis are as follows:

1- Extract the peak inter-story drift of incipient collapse from the IDA results.
2- Fit the peak inter-story drift of incipient collapse into a lognormal distribution.
3- Simulate random variables from the peak inter-story drift fitted distribution.
4- Perform MCS to find the probability of failure of each floor. The probability of failure can be found by comparing the generated demand (EDP, inter-story drift) with the simulated random variables.
5- Count the number of collapsed floors in each simulation to find the collapse mode of the building. Fig. 2 shows the probability of the number of collapsed floors corresponding to the intensity level for an office building.

3.2 Number of fatalities and injuries due to building collapse

In order to find the number of fatalities and injuries due to building collapse or building components damage, first, the number of people inside the building is estimated according to P-58 peak population model [3]. The total building peak population is given by Eq. (1):

$$Total\ Building\ Peak\ Population = Number\ of\ stories \times Peak\ Population \times footprint\ area \quad (1)$$

The daily population model is also provided in FEMA P-58, based on the time of the day, day of the week and month of the year. Fig. 3 presents a sample of the daily population model for two occupancy types: multi-residential, and commercial.

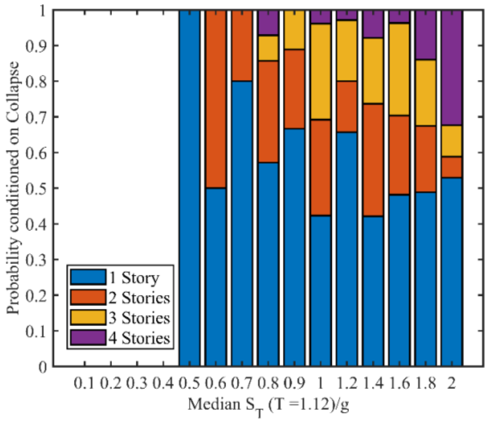

Fig. 2 - Probability of number of collapsed floors corresponding to the intensity level for an office building

The normalized number of fatalities and injuries due to collapse can be calculated by Eq. (2):

$$Normalized\ Number\ of\ Fatality\ or\ injury = \ \ldots$$

$$\frac{P_{fatality\ or\ injury} \times Peak\ Population \times P_{day}(time\ and\ day) \times P_{month}(month\ of\ the\ year) \times \#of\ collpased\ floors}{Total\ Peak\ Building\ Population} \quad (2)$$

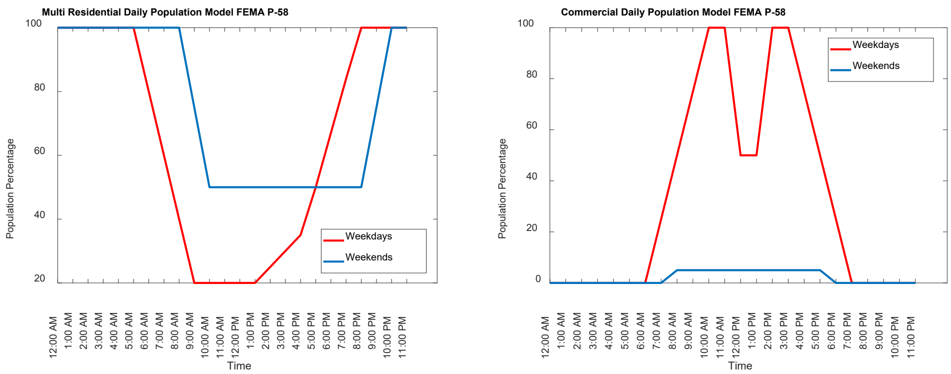

Fig. 3 - Probability of the number of collapsed floors corresponding to the intensity level.

4. Probabilistic assessment of non-collapse fatality and injury

Non-collapse fatality and injury are derived from three sources: 1) structural and nonstructural components, where the consequence and fragility functions can be found directly from the P-58 database, 2) building contents, and 3) occupants falling. Yeow [5] reported that contents and occupant falling contribute more to minor and moderate injuries in comparison with structural components which are the cause of fatalities and fatal injuries. The proposed methodology used in this study to estimate injuries due to content and falling is summarized in Fig.4.

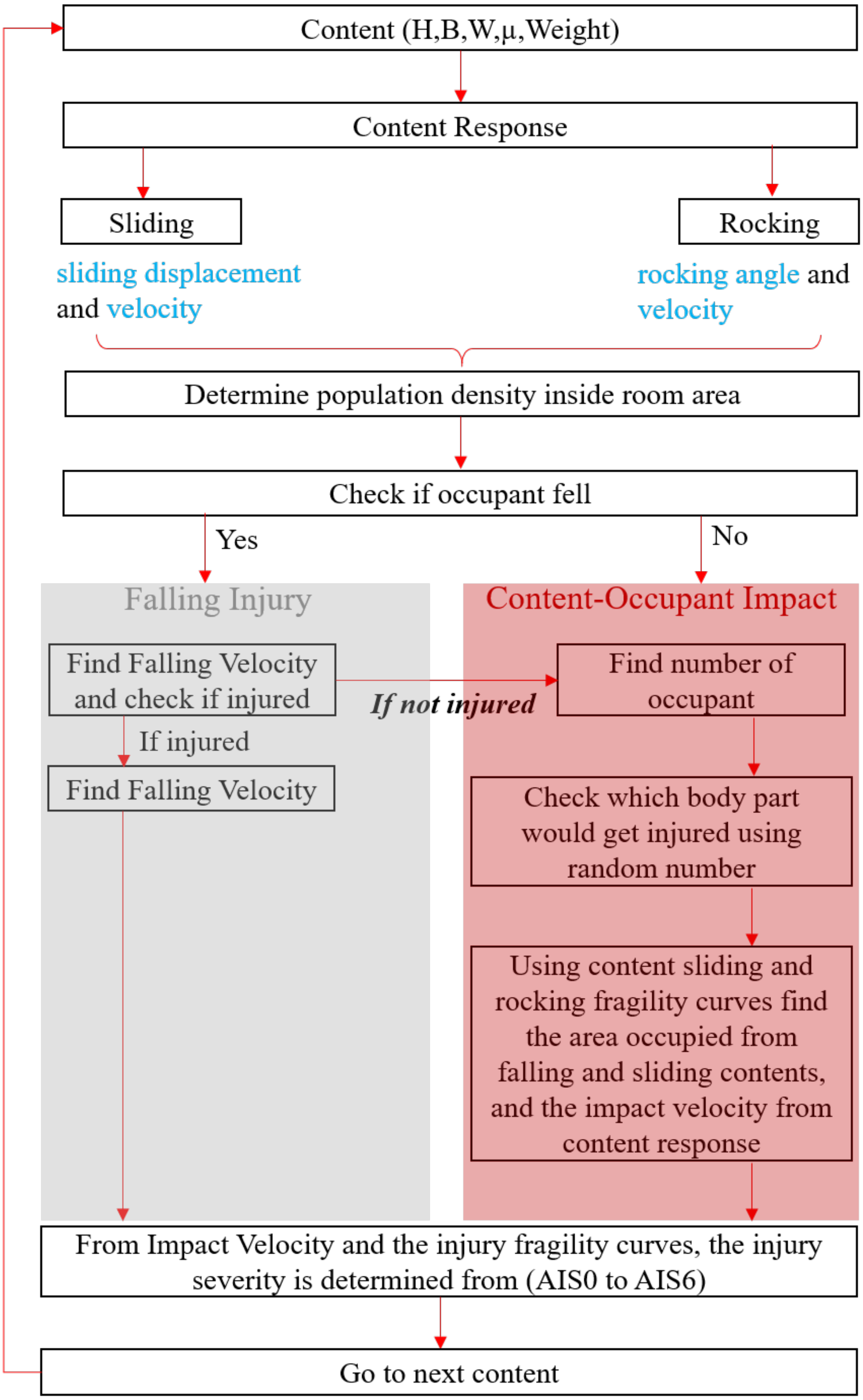

Fig. 4 - The proposed methodology for injury estimation

The input required for the analysis is content characteristics (width, length, height, mass, friction coefficient, and weight). The analysis begins with finding the content EDP for each simulation. In the case of sliding, the EDPs are the sliding relative displacement and velocity, which can be determined at each intensity level from IDA results. In the case of rocking, the EDPs are the rocking angular displacement and velocity. Next, the population density inside the office is calculated from the peak total population in the building and the population model. Finally, using MCS, the model predicts whether the occupant is injured, the cause of the injury, and the injury severity level. This study considers the following two types of injuries: 1) injuries due to falling on the floor, and 2) injuries due to content-occupant impact.

4.1 Falling Injury

In the event of strong ground motion, occupants inside the building might lose balance, fall and get injured. The occupant falls if the floor acceleration is higher than the acceleration limit of falling. The falling acceleration limit is estimated using a lognormal distribution of a median equal to 0.17g and 0.69 dispersion [5]. Falling may injure the upper limb (shoulders) or the pelvis. The injury severity at the upper limb and pelvis can be found by using the falling velocity which is given by Eq. (6). This equation models the falling person as an inverted pendulum where the center of mass located at 60% of the occupants' height (H) from the bottom of his feet while standing [5].

$$V_i = H_{IO}\sqrt{\frac{16g\left(1-cos\left(\theta_{body}\right)\right)}{4.7H}} \qquad (3)$$

Where V_i is the impact velocity, H_{IO} is the impact height and in this case, it is equal to H, and θ_{body} is the body's angle with respect to the vertical line.

4.2 Content-occupant impact injury

An occupant may get hit by building contents at any body part. Records from the 1994 Northridge earthquake show that 11.2% of injuries to the head and 68.4% to the lower and upper limbs. The Whitter Narrow earthquake records indicate that 40.5% of injuries were to the head [2]. Therefore, the variability of the impacted body part is modeled by dividing the occupants' body into four main parts: head, upper limb, pelvis, and lower limb. The length of each body part according to the schematic in Fig. 5 is used to estimate the probability of the part being impacted by a content component at each simulation.

After picking the impacted body part, the area that the falling or sliding content occupied is found using the content dimensions, while the impact velocity is found using the estimated EDPs from IDA. The impact velocity is consequently used to determine the injury severity.

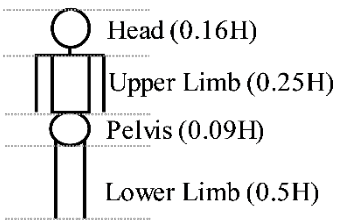

Fig. 5- Sketch of an occupant's body parts [5]

5. Injury severity assessment

Injury severity is classified according to a classification system developed by AIS code. This system is developed for injuries due to vehicular accidents; however, this system can be applied to other types of injuries [1]. AIS is a scoring system that depends on the body structure; it has seven levels ranging from 0 representing no injuries to 6 representing fatal injuries. Table 1 lists the description for each AIS level and provides an example for each level. The injury fragility functions are subsequently used to determine the injury severity based on the impact velocity of the content (Fig. 6).

Table 1- AIS levels [1]

AIS level	Example
1 Minor	Scalp contusion
2 Moderate	Head injury (unconscious < 1 hour), scalp laceration > 10 cm long.
3 Serious	Head injury (unconscious 1-6 hour), Femur fracture
4 Severe	Lung laceration, with blood loss >20% by volume
5 Critical	Cervical spine cord laceration
6 Fatal	Injuries that immediately or ultimately result in death

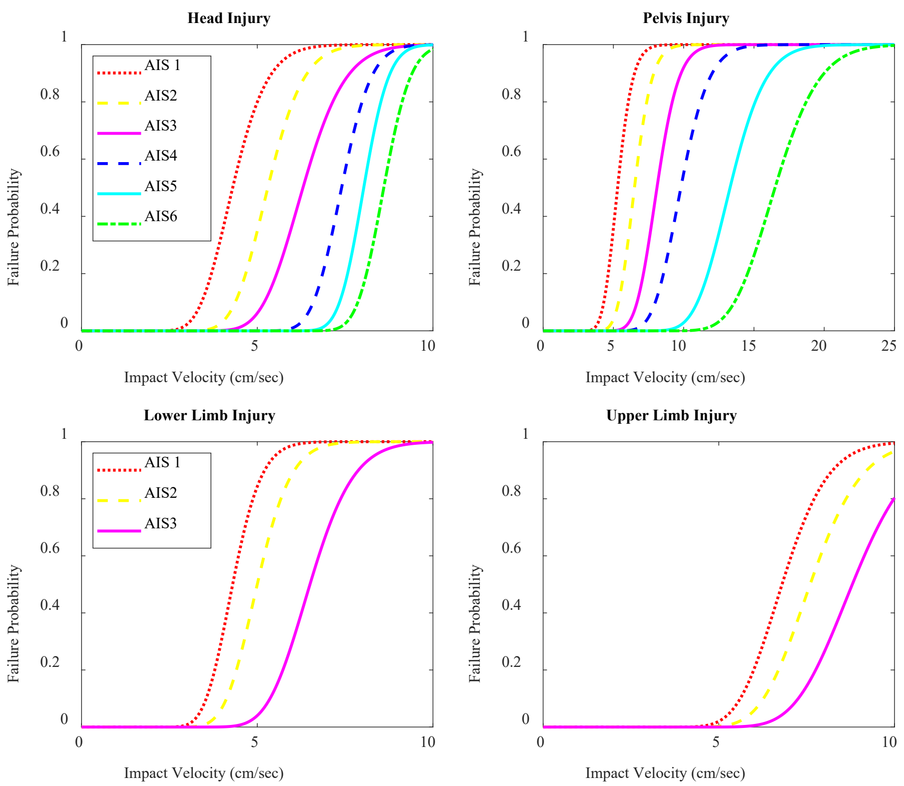

Fig. 6 - Injury fragility curves [5]

7. Case Study

To illustrate the application of the proposed earthquake casualty model, a case study is performed on a 4-story office building located in a high seismic hazard zone. The structural system of this building is a reinforced concrete moment frame. The structural characteristics of the reference model are summarized in Table 2. Peak population per 1000 square feet is 4 and the building floor area is 21600 square feet; therefore, the total peak population is around 346 across the four stories. The mean occupants' height is estimated as 68 inches with 0.06 dispersion. The nonlinear time-history analyses are conducted on Clemson University's high-performance computing platform (Palmetto Cluster). The fragility functions for building collapse are anchored on peak floor accelerations derived from IDA of the building at multiple ground spectral acceleration values during each run.

Table 2 - The structural characteristics of the reference model

Reference Model	Model Dimension	Number of stories	Period (sec)	Analysis Platform	Source
Reinforced concrete moment frame	2D	4	1.12	OpenSees [10]	[11]

A total of 21 building contents (furniture and electrical appliances) are included in the generic office's assumed 750 ft^2 consequence area. The normative quantity of content, i.e., the quantity for each group of components per unit gross square area is estimated based on engineering judgment. Fig. 7 shows a sample of content configuration inside one consequence area in the office building. The position of each content specified to get a sense of the total content occupied area and the area where the occupants can be distributed, the black dots are the occupants.

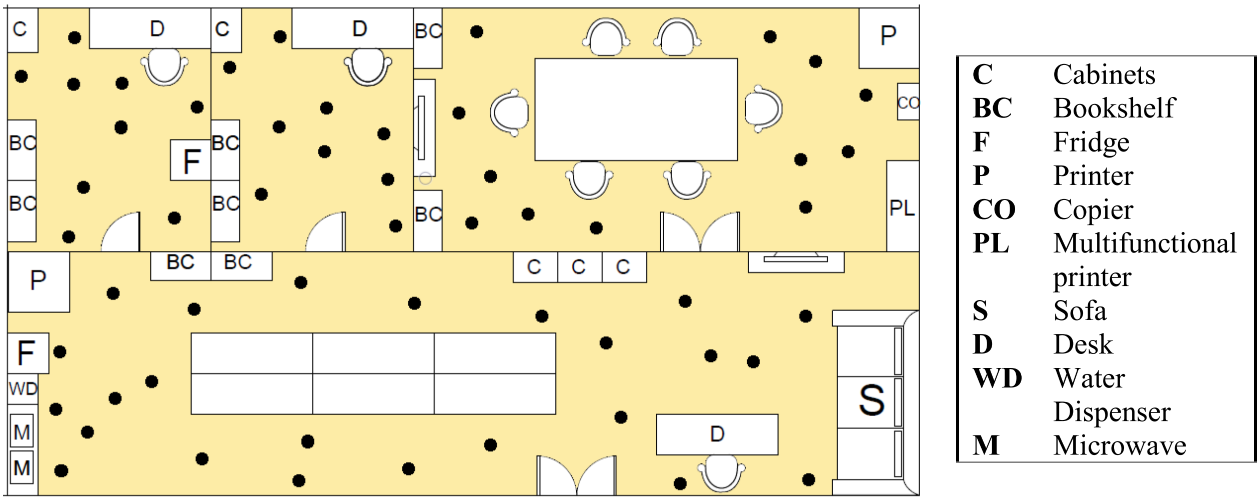

Fig. 7 - Contents configuration inside one consequence area and population density distribution within the consequence area in the office building.

7.1 Collapse Casualty Vulnerability

After checking for collapse, the collapse mode of the building is determined. The collapse fatality and injury rates are calculated using Eq. (2). The probability of fatality is assumed to be 90% and the probability of injury is assumed as 10% for all collapsed floors. Fig 8 shows the normalized number of fatalities and fatal injuries conditioned on the building collapse, which is the ratio of the number of fatalities and fatal injuries to the total peak population in the building.

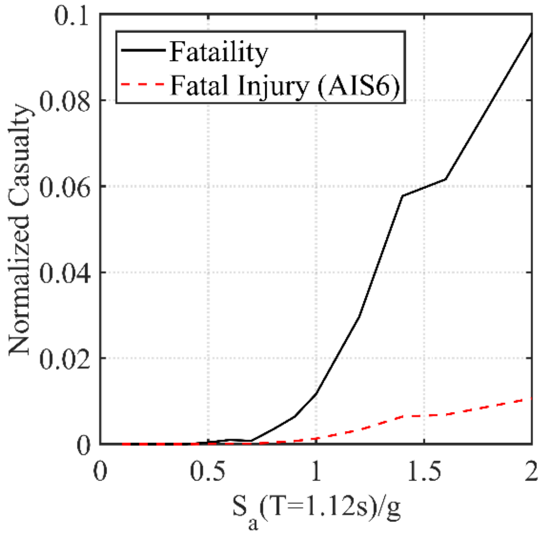

Fig. 8 - Normalized number of fatalities and fatal injuries after building collapse versus ground spectral acceleration

7.2 Non-Collapse Casualty Vulnerability

The non-collapse fatalities and injuries are due to nonstructural component and building content damage:

1) nonstructural components casualty vulnerability: Fig. 9 presents the nonstructural casualty vulnerability curve; it can be observed that the fatal injuries are higher than direct fatalities.

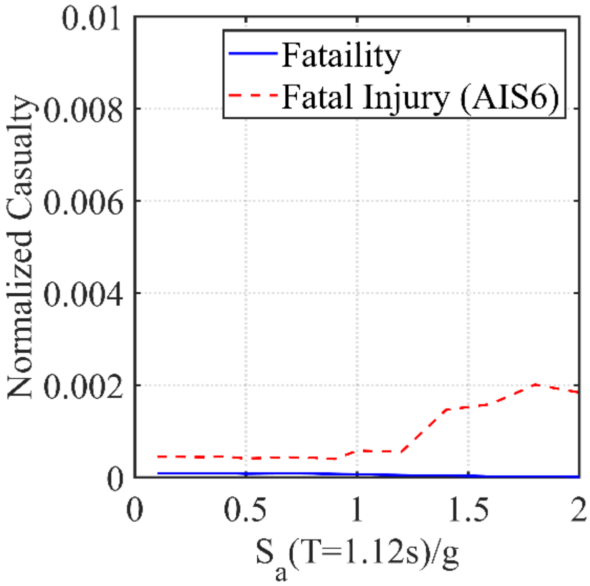

Fig. 9 - Normalized Casualty due to nonstructural component damage versus ground spectral acceleration

2) content casualty vulnerability: To find the injury and fatality rates due to contents, the framework suggested in Fig. 4 - The proposed methodology for injury estimation is used. Fig. 10 presents non-collapse free-standing content injury and falling injury for six levels of injury severity from AIS1 to AIS6. The Figure suggests that minor (AIS1) and serious injuries (AIS3) are more frequent than other injury severities. Also, the normalized number of casualties decreases after 1g because the building collapse will dominate.

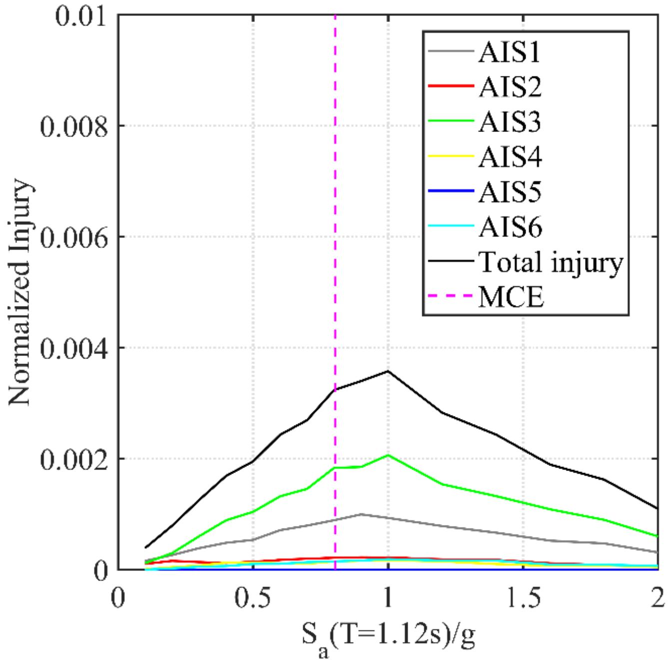

Fig. 10 –content and falling injury vulnerability for six levels of injury severity versus ground spectral acceleration. The vertical dashed line identifies the ground spectral acceleration value at the MCE level.

Total post-earthquake injuries can be simply put as the sum of injuries due to collapse and non-collapse cases. The total number of fatalities and fatal injuries are illustrated in Fig. 11, while Fig. 12 shows the normalized injuries due to building contents.

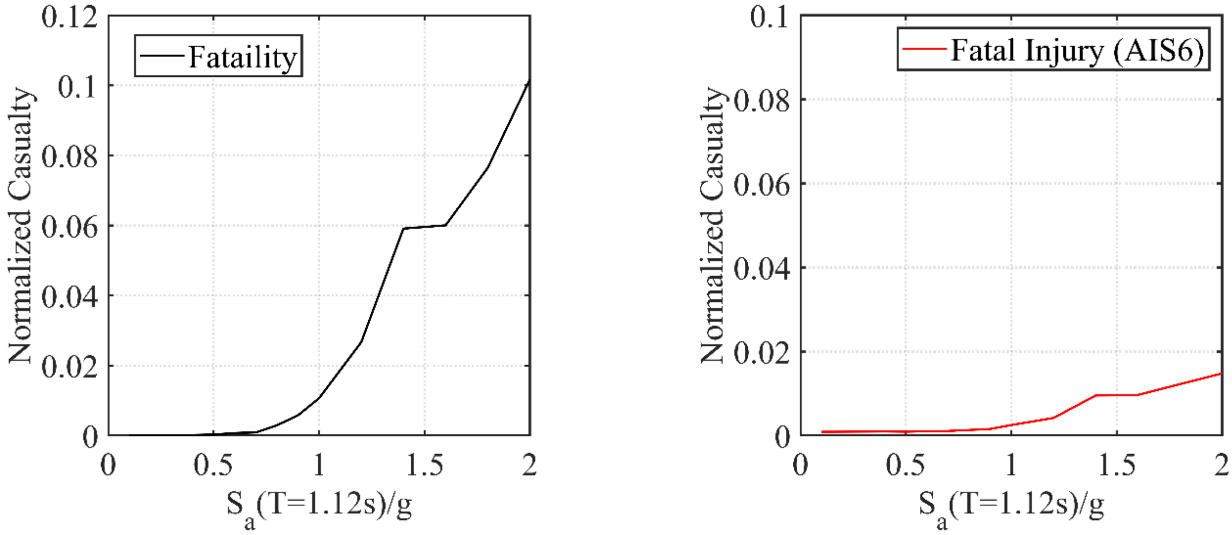

Fig. 11 - Total normalized injury for collapse and non-collapse

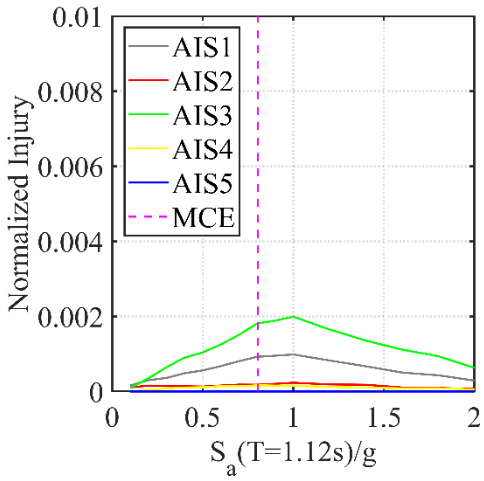

Fig. 12 - Total normalized injury for collapse and non-collapse due to building contents and occupant falling

This case study shows that impact by building contents and occupants falling are estimated to result in 75% of the total number of injuries at the MCE (Maximum Considered Earthquake) level, while serious injuries constitute 40% of the total number of injuries and minor injuries account for 20% of them. This case study signifies that the building contents can be a potential cause of injuries and highlights the importance of building contents injury assessment.

6. Conclusion

Historically, building contents and falling had a high contribution to earthquake injuries, however, reliable analytical models are lacking in the studies dealing with the content injury. This study presented a probabilistic approach to develop injury and fatality vulnerability functions for commercial buildings due to two main causes: content failure modes (sliding and overturning) and falling. A Monte Carlo Simulation is performed to predict the number of injuries in the building based on content fragility functions and the falling acceleration of occupants. The injuries are subsequently classified into six AIS levels based on the impact velocity. A case study of the four-story office building is presented in which the vulnerability functions are developed.

The conclusion can be summarized in the following points:

- Current performance-based frameworks fall short in predicting non-collapse injuries especially for building contents.
- The presented case study highlights the need for incorporating injury due to impact by building contents and falling into performance-based frameworks as they may account for 75% of total injuries.
- The proposed framework can be easily integrated within the FEMA P-58 framework and apply to commercial buildings as well as other occupancy types for risk estimation.
- Mitigation against injury from contents is critical to improving the building safety.

This model is flexible and can be applied to different occupancy types (multi-family, hospital, hotel, etc.) once the content fragility functions are provided. Further investigation is needed to study the effect of different building contents on injury vulnerability.

7.Acknowledgments

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