Probabilistic seismic indoor injury estimation

T.Z. Yeow, G.A. MacRae, R.P. Dhakal, B.A. Bradley

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

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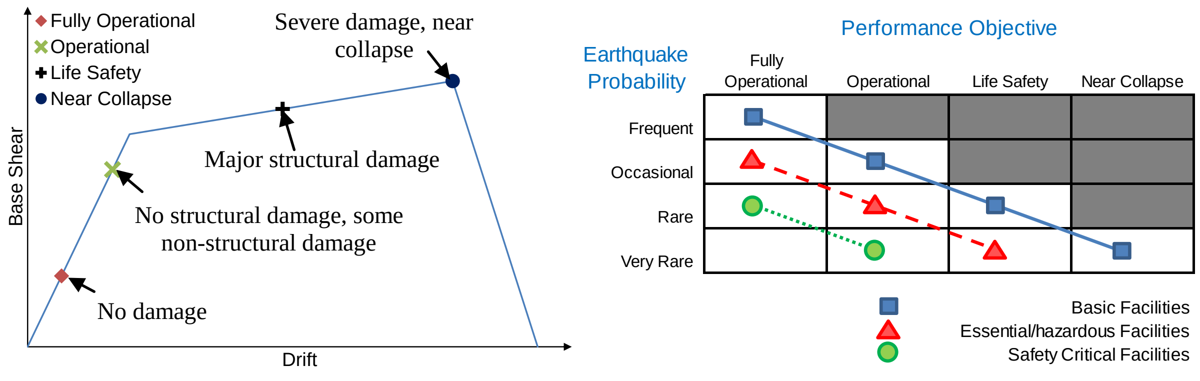
ABSTRACT: Most injury models in existence either estimate injuries at a regional level and/or focus only on fatalities. In regions with good engineering practice, the likelihood of building collapse is rare and hence fatality risk is also correspondingly low. Research has shown that in such situations non-fatal injuries are likely to result in larger economic loss than fatalities due to their higher incidence, despite non-fatalities having lower consequence. A new building-specific method of indoor injury estimation is proposed in this paper. Injuries are considered due to: (i) occupants being struck by toppling contents; and (ii) occupants losing balance and falling. This model considers the spatial distribution of occupants in the building, time-occupancy relationships, and the severity of injury to occupants. A simple room layout is used to demonstrate the application of the model.

1 INTRODUCTION

Death and non-fatal injuries are one of the three components of loss following a disaster (the other two being damage induced economic loss and business disruption/downtime). Most seismic design guidelines have performance objectives to reduce fatalities by limiting the drifts which a structure is likely to undergo. An example from SEAOC (1995) is shown in Figure 1. Figure 1a represents a pushover analysis and the drifts corresponding to the different limit states, while Figure 1b shows the target performance for ground motions of varying occurrence probabilities based on building importance. For example, life safety criteria must be met for basic facilities up to rare events, while more important facilities must satisfy life safety in very rare events as well.



(a) Limit state definitions (b) Performance objective for each limit state

Figure 1. Structural Performance Objective (SEAOC, 1995)

With modern structural design according to contemporary seismic design guidelines, building collapse rarely occurs for modern buildings, even in maximum considered earthquake shaking. In the 22 February 2011 Christchurch earthquake, for example, only two tall buildings suffered complete collapse; the Canterbury Television building (115 fatalities) and the Pyne Gould Corporation building (18 fatalities) (New Zealand Police, 2012). These two building collapse accounted for majority of the 185 fatalities resulting from the earthquake. However, there were over 6,000 non-fatal injuries as a direct result of the Canterbury Earthquakes (Gawith and CHIAPP, 2012).

International research (e.g. (Seligson and Shoaf, 2006)) has also shown that non-fatal injuries are generally more costly to society than fatalities, especially in regions with good seismic engineering practice. Porter et al. (2006) attempted to quantify the value of non-fatal injuries by assigning dollar values to each type of injury resulting from the 1994 Northridge Earthquake. Porter et al. showed that approximately 96% of the costs incurred due to all injuries are associated with non-fatalities. This illustrates that the neglect of non-fatal injuries in many seismic injury estimation methods will yield a substantial under-estimation of this aspect of seismic risk and must be accounted for.

Most existing models estimate injury at a regional level or focus on fatalities only. A new injury model for estimating non-fatal injuries for a building specific case is proposed in this paper. The model is developed within a probabilistic framework and focuses only on indoor non-fatal injuries in the event of non-collapse. A case study is used to demonstrate the application of the model.

2 BACKGROUND ON INDOOR INJURY ESTIMATION

Ohta et al. (1986) lists the following as the four main factors influencing indoor injury due to seismic action; (i) seismic intensity, (ii) indoor-space safety, (iii) time factor and (iv) demographic of occupants. Similar factors were also highlighted in Tierney (1990). Despite the above qualitative factors known to affect injury frequency, the actual development of indoor injury models is sparse. Those which are known to the author (e.g. Yeo and Cornell (2003) and Okada et al. (2012)) generally do not consider the time or demographic factors. Most of the focus has been on the indoor-space safety factor, in particular the modelling of the spatial distribution of building occupants.

Yeo and Cornell (2003) modelled the spatial distribution of occupants by dividing the total floor area into grids, each with a population density. The methodology allows for variation of population density in different areas of the floor. However it does not account layout of building contents (e.g. bookshelves) which makes it difficult to estimate injury due to occupants falling onto contents or vice versa. Okada et al. (2012) assumes that the occupants are evenly distributed around the occupiable floor area (i.e. area not taken up by furniture) to allow for simple calculation of the probability of injury due to toppling of contents. However, it is not possible to calculate injury due to occupants falling. Also, even distribution of occupants is rare. In offices, for example, an occupant is more likely to be seated at his/her desk than anywhere else around the room. Alternatively, occupants may move around the room to find a secure spot to take shelter during the initial period of seismic shaking.

A more flexible spatial distribution model would be to use a coordinate system, where certain coordinates are more likely to be occupied than others. More details on this model will be described in the following section.

3 PROPOSED INDOOR INJURY MODEL

3.1 Case study room

The plan layout of the case study room, which will be used to demonstrate the revised injury model, is shown in Figure 2, and is loosely based on a postgraduate office room at the University of Canterbury. The interior dimension of the room is 3.2m in the North-South direction and 5.4m in the East-West direction. There are four L-shaped desks located around the room, two bookshelves along the north wall, two mobile drawer units along the east wall, and three filing cabinets along the south wall. The furniture dimensions are given in Table 1. It is assumed that none of the furniture is anchored.

Table 1. Furniture dimensions

Item	Outer N-S width (m)	Outer E-W width (m)	Height (m)
L-shaped desks (0.65m depth) [$D_1,\ldots,D_4$]	1.20m	1.80m	0.75m
Bookshelves [BS_1, BS_2]	0.35m	0.90m	1.80m
Mobile drawers [MD_1, MD_2]	0.40m	0.65m	0.55m
Filing cabinets [FC_1,FC_2,FC_3]	0.65m	0.39m	1.65m

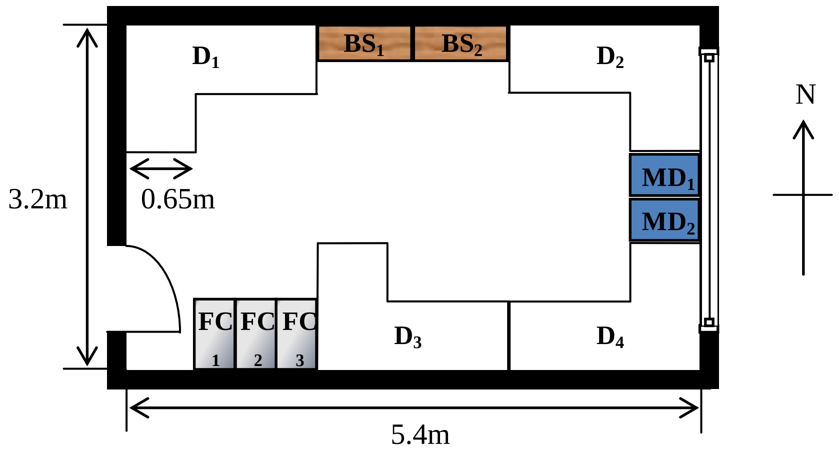


Figure 2. Case study room layout

3.2 **Outline of methodology**

The proposed methodology utilizes Monte Carlo simulation to obtain the final probabilistic distribution of injury losses. The steps for a single Monte Carlo trial are shown in Figure 3. Each step will be discussed in more detail in the following sections.

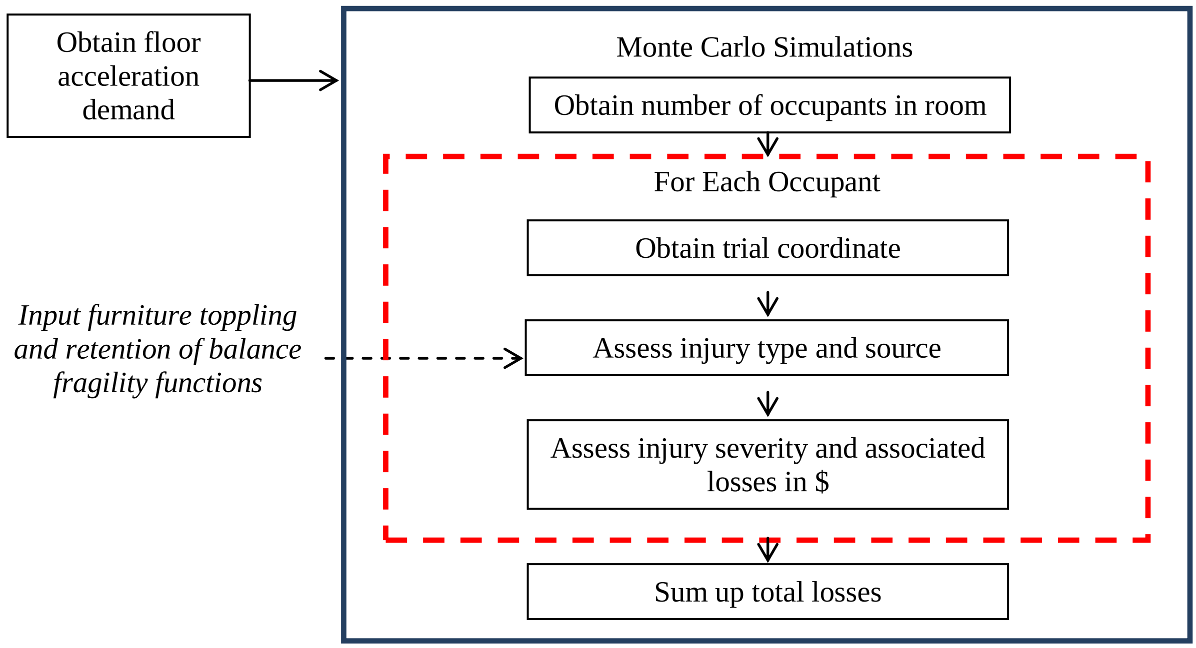


Figure 3. Flowchart of overall methodology

3.3 **Obtaining number of occupants in room**

The first step in the methodology is to obtain the number of occupants in the room. In reality, the number of occupants in the room is time dependent. For example, in office type rooms, it is unlikely that anyone will be located in the room at 3am, while most occupants would be present at 2pm in the afternoon. There are many ways of obtaining the probability mass distribution for the number of people in the room. One method is to monitor the number of people over a timespan. The probability that *n* people are in the room would simply be the ratio of the number of hours which there are *n* people present to the total number of monitored hours. For the purpose of this case study, the probability mass distribution for the number of people located in the room is assumed and is shown in Table 2.

Random number generators can be used to obtain the number of people in the room for each Monte Carlo simulation trial. If for example a random number of 0.713 was generated, this would correspond to four people being present in the room at the time of the earthquake based on the cumulative probability (P(number $\leq n$)) in Table 2. Similar methods can also be used in other steps in the methodology, but will not be discussed in detail in following sections.

Table 2. Probability of *n* number of occupants present in room at time of earthquake

Number of Occupants (n)	P (number = n)	P (number $\leq n$)
0	0.5	0.5
1	0.03	0.53
2	0.1	0.63
3	0.07	0.7
4	0.25	0.95
5	0.03	0.98
6	0.02	1

3.4 Obtaining trial coordinate of each occupant

As mentioned previously, a coordinate system will be used to model the spatial distribution of each occupant within the room. For this case study, it will be assumed that more than one occupant located at the same coordinate is possible. From the floor plan of the room shown in Figure 2, it can be seen that the occupiable floor area (area not occupied by furniture) is irregular in shape. As such, the occupiable area will be divided into smaller grids called sub-areas, as illustrated for example in Figure 4, where the occupiable area was divided into 8 sub-areas. A smaller number of sub-areas could have been used (i.e. areas 2 and 3 could be combined together). However, an advantage of having more sub-areas is that different probabilities can be assigned to each.

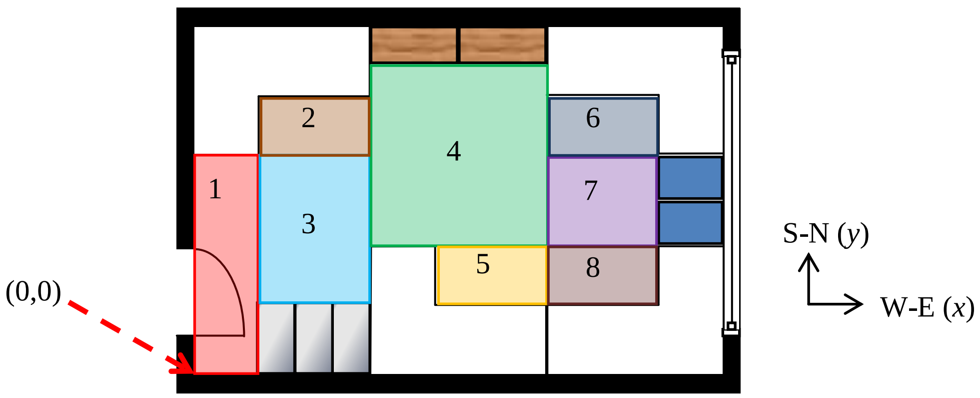


Figure 4. Subdivided occupiable areas

For example, the probability that a person is located near their desk (sub-areas 2, 5, 6 and 8) is considerably higher than in other areas round the room (sub-areas 1, 3, 5, and 7). In this case study, it will be assumed that a single occupant has 70% probability that he/she will be seated at his/her desk and 30% probability that he/she will be in other areas around the room. Note that possible movement around the room is ignored at this stage of the model development, and will be considered in future versions. This probability can then be further distributed assuming uniform spatial distribution among the sub-area group. For example, sub-areas 1, 3, 4 and 7 have a total area of 6.74m^2 while sub-area 1 alone has an area of 1.3m^2. Thus the probability of an occupant being located in sub-area 1 is 0.3(1.3m^2/6.74m^2) = 5.8%. Table 3 shows the location, dimensions and probability of occupancy for each sub-area for the considered example, which can be directly used in Monte Carlo simulation.

Table 3. Probability of occupancy of a single person in each sub-area

Sub-area	Southwest co-ordinate (m)	E-W length (m)	N-S length (m)	Area (m^2)	Probability of occupancy	Cumulative Probability
1	(0,0)	0.65	2	1.3	0.058	0.058
2	(0.65,2)	1.15	0.55	0.63	0.175	0.233
3	(0.65,0.65)	1.15	1.35	1.55	0.069	0.302
4	(1.8,1.2)	1.8	1.65	2.97	0.132	0.434
5	(2.45,0.65)	1.15	0.55	0.63	0.175	0.609
6	(3.6,2)	1.15	0.55	0.63	0.175	0.784
7	(3.6,1.2)	1.15	0.8	0.92	0.041	0.825
8	(3.6,0.65)	1.15	0.55	0.63	0.175	1.000

Assuming that the spatial distribution of a single occupant within each sub-area is also uniformly distributed, the co-ordinate of an occupant's location can be estimated using the following equation

$$Coordinate_x = rand_x \times length_x + WCoordinate_x \quad (1)$$

where $Coordinate_x$ refers to the x coordinate which the occupant is occupying, $rand_x$ is the random number generated for the x direction, $length_x$ is x component of the sub-area length and $WCoordinate_x$ is the x coordinate of the west side of the sub-area which the occupant is occupying. A similar approach may be used to obtain the y coordinate. This equation can be directly used in Monte Carlo simulations. Note that this equation is applicable to rectangular shaped sub-areas only, though similar equations can be derived for other sub-area shapes.

3.5 Modelling of injury sources

Only two types of injury are independently considered for this paper: (i) injury due to being struck by contents; and (ii) injury due to losing balance and falling. Furthermore, type (i) injuries will be limited to contents which have toppled over. Sliding of furniture or contents falling will be considered in future advancements of this methodology. Of the furniture present, it is assumed that only the bookshelves and filing cabinets pose a threat from toppling, and can only fall in the N-S direction for simplicity. If an item of furniture is to topple, and the occupant's coordinate lies within the fall zone of the item of furniture, he/she have a specific probability of being injured. In this initial study, the probability is taken as unity. In further studies, the effectiveness of mitigation measures such as "Drop, Cover and Hold" will be evaluated, and injury occurrence fragility functions will be developed.

Several empirical equations exist to estimate the fragility functions (i.e. lognormal mean ($\lambda_{toppling}$) and dispersion ($\zeta_{toppling}$)) of floor acceleration which causes toppling of contents. The one which will be considered in this study is loosely based off Kaneko and Hayashi (2004). $\lambda_{toppling}$ can be obtained using Equation 2, where D and H are the depth are height of the furniture, and g is the acceleration of gravity. For simplicity, it will be assumed that $\zeta_{toppling} = 0.5$.

$$\lambda_{toppling} = \ln\left[\frac{D}{H} g \left(1 + \frac{D}{H}\right)\right] \quad (2)$$

For type (ii) injuries, occupants may lose balance and fall to the floor or onto another object. This aspect of injury is perhaps where the coordinate method of spatial distribution is most advantageous. Using simple trigonometry and assuming a falling occupant height of 1.7m, the probability that an occupant would fall to the floor or onto another object given that they have lost balance can be estimated. Consider the case shown in Figure 5, where the shaded area represents obstacles which result in occupants injuring themselves when falling. The obstacles are located 1.3m north and 0.9m east of the occupant. Assuming the occupant's fall radius is the same as his/her height, the angle between top left dotted line and the vertical arrow, θ_1, is 40.1°. The angle between the bottom right dotted line and the horizontal arrow, θ_2, is 58.0^o. This leaves the small angle between both dotted lines, θ_3, to be 172^o. As θ_3 represents the angles which leads to the occupant falling away from the obstacles, the probability of falling to the floor is therefore 48% (172 ^{o}/360^o). This is the method to obtain the conditional probability that an occupant will fall to the floor given that they have fallen, *P*(*floor*|*fall*). Note that the fall radius is likely to be different than the occupant height due to the possibility that the occupant may not be standing or that the occupant may take a few steps before falling. This will be considered in further studies, which will also take into account varying occupant height.

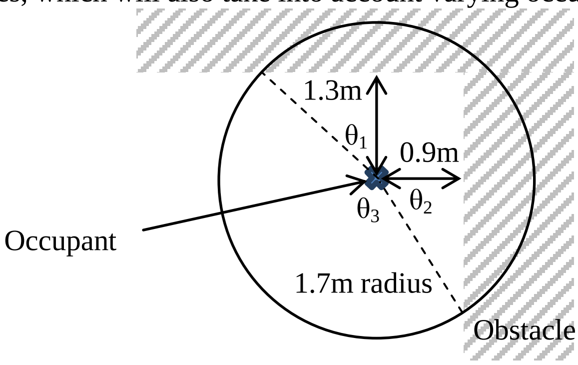


Figure 5. Method to obtain probability of a person falling to the floor/obstacle given than he/she has fallen

The fragility function which will be used to model the retention of balance is based on Graaf and Weperen (1997). The lognormal mean acceleration value which causes loss of balance, $\lambda_{falling}$, is 0.08g, while the dispersion, $\zeta_{falling}$, is 0.25. Note that for the purpose of this case study, it is assumed that loss of balance always leads to falling for this case. This can be used to obtain the probability that an occupant will fall, *P*(*fall*), which can be combined with *P*(*floor*|*fall*) to obtain the probability of an occupant falling onto the floor, *P*(*floor*), as per Equation 3. Similar equations can be used to obtain probability of occupant falling onto obstacles.

$$P(floor) = P(floor \mid fall)P(fall) \tag{3}$$

For both types of injury, if the acceleration demand, a_{demand}, is greater than the acceleration "capacity", $a_{capacity}$, then the furniture has toppled or the occupant has fallen, depending on which injury source was investigated. A random number generator can be used to obtain $a_{capacity}$ from the fragility functions for use in Monte Carlo simulation.

3.6 Severity of injury

Previous research has been conducted on estimating severity of injury due to being struck by contents (i.e. Takahashi et al. (2012)), however no fragility functions were defined. Such research results do indicate that a person being struck by heavy toppling furniture usually end up with serious injuries. As such, it will be assumed that any occupants struck by toppling furniture will have serious injury. At the time of writing this paper, the authors are not aware of any research linking a person falling to injury severity. For the purpose of this study, it will be assumed that a person falling to the floor results in insignificant injuries while a person falling onto content will have minor injuries.

Using the cost per accident estimates from New Zealand Transport Agency (2010), the losses for each severity of injury are as \$325,000, \$17,000, \$1000 and \$0 for serious injury, minor injury, insignificant injury and no injury respectively. For example, if one person was injured due to contents toppling and two were injured due to falling onto the floor, the total injury loss would be \$327,000.

4 APPLICATION OF MODEL USING MONTE CARLO SIMULATION

For the case study of the room in Figure 2, it is assumed that the maximum acceleration floor demand, A_{max}, has a lognormal mean of 0.12g and a dispersion of 0.8. Monte Carlo simulations with 100,000 trials were used. It was checked that 100,000 trials provided sufficient convergence.

4.1 Probability of injury to a single occupant

The probability of injury to a single occupant is shown in Table 4, and is deaggregated based on the injury source or type. It can be seen that probability of injury due to toppling of contents is significantly less than the probability of injury due to loss of balance, or the probability of no injury occurring. This is because: (i) the acceleration required to cause toppling of contents, particularly the filing cabinets, are high; and (ii) the probability that an occupant will be located in the fall zone is low due to the distribution of occupants. The probability of injury due to loss of balance is higher than the probability of no injury occurring. This is because the lognormal mean value of acceleration that triggers loss of balance is lower than the lognormal mean value of the acceleration demand, so majority of the occupants not injured due to content toppling will be injured due to loss of balance.

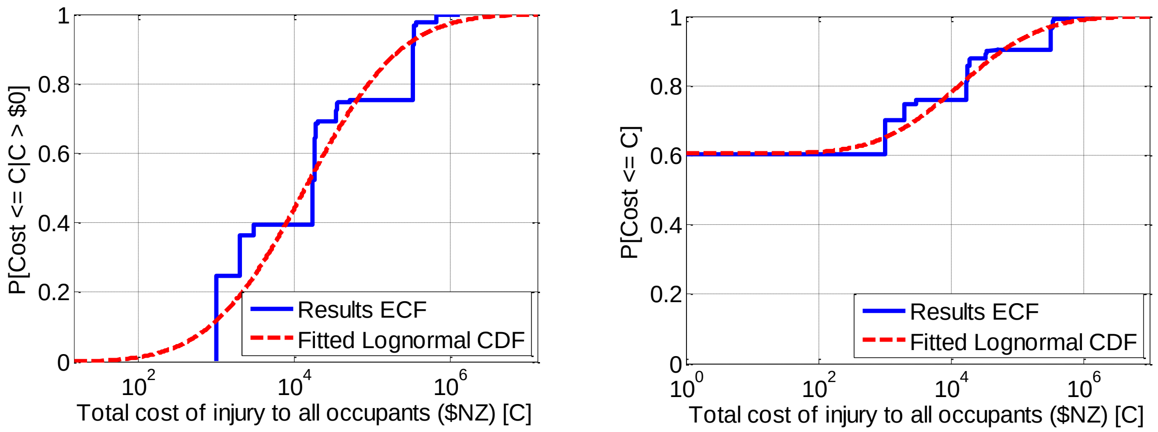
Table 4. Probability of injury to single occupant

Type	**Content Toppling**					**Loss of balance**		**No Injury**
Source	**FC1**	**FC2**	**FC3**	**BS1**	**BS2**	**FO**	**FG**	
P(injury from source)	0.0016	0.0015	0.0015	0.042	0.043	0.172	0.324	0.415
P(injury from type)	0.0896					0.496		0.415
FC – filing cabinet BS – bookshelf FO – fall onto object FG – fall onto ground								

4.2 Results considering multiple occupants and injury severity

From the Monte Carlo simulations, approximately 60% of the trials resulted in a total cost of injury of \$0 (i.e. no occupants were injured). The high probability of no injury occurring can be attributed to the probability distribution of the number of people in the room in Table 2, where 50% of the time there is no one present in the room, which instantly means no one will be injured at least 50% of the time. The other 10% are from cases where people were present in the room but none of them were injured.

Figure 6a shows the lognormal distribution of the total cost of injury to all occupants given that an injury has occurred, while Figure 6b shows the total distribution considering all cases. In cases where injury has occurred, the lognormal mean total cost is approximately \$14,000 with a dispersion of 2.2. As injury due to toppling of contents has large consequence (assumed \$325,000 per injury), anchoring contents likely to topple should result in significant reduction of total injury cost. Other mitigation measures (i.e. covering sharp corners of contents) may also lead to a reduction of these costs.



a) Only cases where cost > 0 b) All cases considered

Figure 6. Distribution of injury cost

Fragility curves such as the one shown in Figure 6 are the outputs of interest from the model. These can be used to assess the likely losses which might be incurred within a building due to injury. Further advancements of this model will be carried out to account for fatalities and other injury types.

5 CONCLUSIONS

A new method of estimating building-specific indoor injuries during a seismic event has been proposed in this paper. This model uses coordinates to model the spatial distribution of occupants around the room, and is beneficial when modelling injury due to an occupant losing balance and falling. This model has also included time-occupancy factors and links the sources of injury to injury severity, factors not previously included in existing indoor injury models.

A simple case study of a room was conducted to demonstrate the use of this model. It showed that approximately 60% of the time, no one will be injured in the room. In cases where injury has occurred, the lognormal mean cost of injury to all occupants is $14,000 with a dispersion of 2.2. Application of mitigation methods (i.e. anchoring furniture) should result in reduction of injury costs.

Although this model was developed for building-specific cases, generalized properties for typical building types (e.g. office, industrial) can be used as inputs to develop simpler models for use in regional loss assessment. Such models can then be used to estimate benefits of mitigation methods (i.e. fastening items of furniture) on a regional scale.

6 ACKNOWLEDGEMENT

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