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A NEW CAUSALITY MODEL FOR EVALUATING THE PROBABIITY OF HUMAN DAMAGE FROM INJURY TO DEATH IN COLLAPSED BUILDINGS

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Abstract

A recent challenge for seismic damage evaluation, which forms the basis of risk management for reducing the death toll in damaged buildings, is expanding the technical capabilities from rough estimation of regional damage in municipal units to minute damage estimation for individual buildings. With this in mind, we proposed the related numerical functions with structural parameter of the load-carrying capacity for buildings in 13th World Conference on Earthquake Engineering (WCEE) of 2004. In this paper, we discuss the method of estimating human casualties in damaged buildings by expanding these previous studies.

As a method for estimating human casualties in various structural building types throughout the world, a universal model is set up with a causal scenario as follows: In the first stage of damage scenario, structural elements of buildings are damaged in accordance with the severity of ground motion. The degree of structural damage in an individual building can be quantitatively estimated on the damage scale from 0.0 (No Damage) to 1.0 (Total Collapse) by a Damage Index Function defined by the authors. In the second stage, the surviving interior space of building is reduced in proportion to the damage severity index and characterized by damage pattern of building. As for the deterioration of space, one of the authors defined the deterioration of surviving interior space as the volumetric reduction of a collapsed building in the 11th WCEE of 1996, and in the 16th WCEE an advanced numerical function for this volumetric reduction, defined by the Weibull probability distribution, is discussed in a different paper. In the third and final stage of the scenario, inhabitants trapped within the debris of the damaged building sustain serious injury corresponding to the volumetric reduction.

In order to handle human casualties quantitatively in modeling, we introduce the Injury Severity Score (abbreviated as ISS), which is devised to classify earthquake victims with multiple trauma. Using various data on damage that occurred in the 1995 Kobe Earthquake, we compiled a statistical database of wooden frame building damage scaled by the Damage Index, and of human casualties ranked by severity according to the ISS and using GIS technology to match a map of Kobe with building lot numbers. By applying Bayesian methods to the database, we successfully functionalized the stochastic relation between the building damage index and the ISS for each of casualties.

As a case study based on the Nankai Trough Quake, we calculated the assumed casualties at 0.5% of the population in Kochi Prefecture, Japan (about 731,000), only due to collapse of buildings and without taking into account tsunamis. These assumed victims break down as 2,386 people lightly injured (ISS scale range of 1 to 8), 603 people heavily injured (ISS scale range of 9 to 15), 535 people in critical condition, and 369 people killed instantly. The information obtained by this method is useful for indicating the amount of supply and demand on seismic countermeasures in each region.

Keywords: loss estimation, volumetric reduction of building, injury severity score

. Introduction

More than 70% of the earthquake fatalities worldwide can be attributed to building collapse. From a mitigation policy point of view, estimation of death toll occurring in damaged buildings is the basis of risk management for reduction of death, and the most essential matter in the field of earthquake engineering. The representative method for estimation, which is discussed in papers previous World Conferences on Earthquake Engineering (abbreviated to WCEE), incorporates such parameters as population exposure and building fragility into the equation for earthquake fatality rate. Estimations have successfully been expressed in terms of the probability of collapse rate over a large area the size of a town or district.

However, it is desired to improve seismic damage evaluation techniques from a rough estimation of regional damage in municipal units to more minute damage estimation of individual buildings. With these issues in mind, the authors proposed the related numerical functions available to estimate special fatality statistics at the building level or the household unit based on structural parameters of the load-carrying capacity for buildings in 13th WCEE of 2004 [1]. In this paper, we describe a method of estimating human casualties in damaged buildings by expanding on the work of these former studies.

The purpose of our study is to construct a model which can estimate not only the fatality rate but also casualty injury scale statistics to express more accurately and precisely the symptoms and needs of each human target at the building or household level.

2. Human Casualty Model

2.1 Adoption of the Injury Severity Score

In the field of disaster medicine, an Injury Severity Scale (abbreviated to ISS) is used generally to describe the degree of injury. The ISS is an established medical score, which ranges from 1 to 75, to assess patients with multiple traumatisms [2]. “Minor” injuries are scored as 1 to 8, “Moderate” as 9 to 15, “Moderate or Severe” as 16 to 24, “Severe or Critical” as 25 to 40, and “Critical or Injury Death” as 41 to 75. In addition, the ISS has a good correlation with the age-specific mortality as shown in Fig. 1.

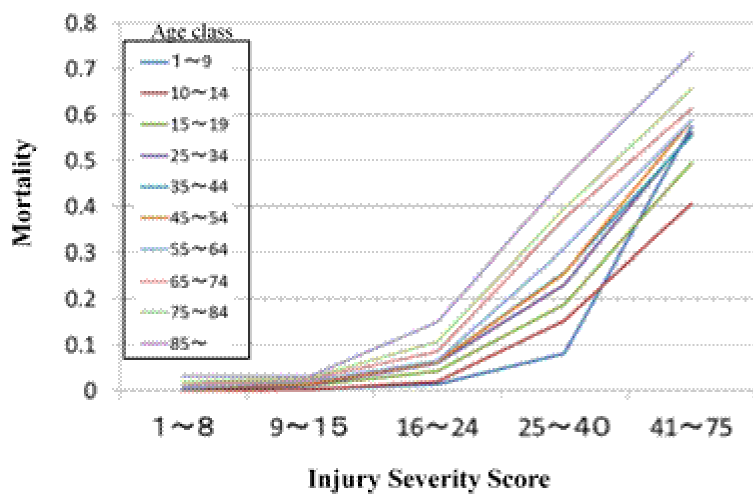


Fig. 1-Relation between the death rate by age class and Injury Severity Score

As the final goal of assessment of earthquake-caused human injury, we focus on the assessment of ISS probability distribution of residents trapped in a collapsed building with seismic structural damage defined in terms of Damage Index, ranging from 0.0 (No damage) to 1.0 (Total collapse). That is, the purpose of our study is to functionalize the relationship between the injury state of trapped residents and the damage state of the building. While Japanese local governments generally estimate only the number occurrences of two categories (the dead and injured) in a seismic human damage assessment, our purpose is to assess the lifetime remaining up to rescue for people trapped and injured in a collapsed building, and better predict the required medical practice and medical facilities through estimation of the ISS distribution.

2.2 Basic equations

The following is a typical scenario for seismic-related human casualty: A target area experiences seismic strong ground motions described by hazard index *s* such as seismic intensity *I* or peak ground motion *PGV*. At that time, the damage probability $P(s,x)$ of Damage Index *x* for a wooden frame structure building at this location can be assessed using the probability distribution $L(I_w)$ of load-carrying capacity value I_w of wooden buildings which is a function of building age.

$$P(s,x) = \int_0^{I_w} L(w) \cdot dw \tag{1}$$

where, $L(I_w)$ is determined by the following equation with the probability distribution of load-carrying capacity value I_w per each building age class *q* and the frequency distribution of I_w of wooden buildings located at a target area.

$$L(I_w) = \sum_q g(q, I_w) \times T(q) \tag{2}$$

$$I_w = \left(\frac{s - a(x)}{b(x)} \right)^{1/c(x)} \tag{3}$$

where, *a*, *b*, and *c* are parameters with different values depending on Damage Index *x*. The Index *x* is a type of cumulative probability distribution with the Weibull density function:

$$x = 1 - e^{-\left(\frac{s}{\eta}\right)^m} \tag{4}$$

where, *s* is an index of ground motion severity as *I* or *PGV* [cm/sec], and *m* and η are parameters of the Weibull distribution [2]. Figure 2 shows the relation between Eqs.(3) and (4) linking among ground motion severity *s*, Damage Index *x*, and load-carrying capacity I_w. The variable $T(q)$ refers to the frequency rate of each building age class *q*. The distribution of $L(I_w)$ is shown in Fig.3. The variation $g(q,I_w)$ refers to the average curves of the load-carrying capacity I_w of wooden buildings estimated by building age class *q* and is shown in Fig.4.

When seismic ground motion severity *s* collapses a wooden dwelling with a value of load-carrying capacity I_w or a probability distribution of load-carrying capacity $L(I_w)$, the degree of injury experienced by the inhabitants can be obtained by the following equation:

$$M_{ISS}(\theta) = \kappa_x \cdot f''_x(\theta) \tag{5}$$

where, $M_{ISS}(\theta)$ is the probability of ISS θ, and can therefore $M_{ISS}(\theta)$ can be considered as the number of inhabitants experiencing ISS θ. The parameter κ_x defines the population exposed to space at risk of being covered by debris inside a damaged building with Damage Index *x*, and is given by the following:

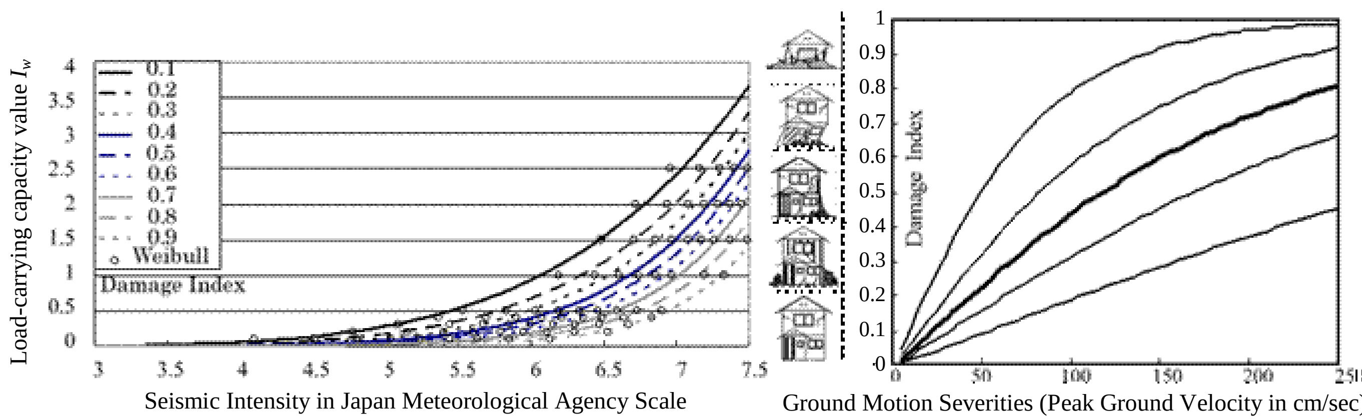
$$\kappa_x = \sum_{x=0.6}^{1.0} \sum_{I=0}^{7.4} M_f(I) \cdot P(I,x) \cdot W_x \tag{6}$$

where, the index *I* is seismic intensity on the Japanese Intensity Scale with the defined range of 0 to 7.4 at intervals of 0.1 step at the target area representing the seismic hazard severity *s*. $M_f(I)$ is the inhabitant population living in wooden dwellings exposed to seismic intensity *I*. $P(I,x)$ is the probability distribution of the Damage Index *x* for a wooden frame structure building located in the area and is given by Eq. (1). The index W_x is called the “W-Value”, and describes the deterioration of survival space of a collapsed building. The range of volumetric loss is 0 to 1.0. Zero means no damage to the space of a building, and 1.0 means that the whole building is damaged and contains no remaining survival space. The numeric value is obtained by the following function, which we propose for Japanese wooden frame building in a different paper, presented at 16th WCEE [3].

$$W_x = \frac{1}{B(p,q)} \int_0^x x^{p-1}(1-x)^{q-1}\,dx \quad \begin{cases} p = 24.53,\ q = 7.17 \text{ for } 1^{st} \text{ floor} \\ p = 27.57,\ q = 4.26 \text{ for } 2^{nd} \text{ floor} \end{cases} \tag{7}$$

$$B(p,q) = \int_0^1 x^{p-1}(1-x)^{q-1}\,dx \tag{8}$$

where the index x is Damage Index. The variable $B(p, q)$ is the Beta function defined in Eq. (8). The parameters p and q are the parameters of the Beta function, which are given as fixed values.



(1) In case of Seismic Intensity as ground motion severities (2) In case of PGV as ground motion severities

Fig. 2-Relation among Ground Motion Severity, Damage Index, and Load-Carrying Capacity

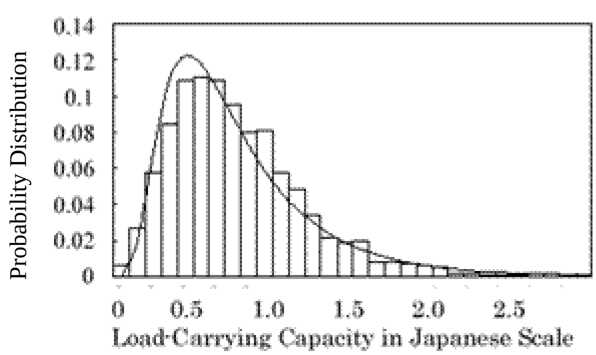


Fig. 3-Frequency distribution of the Load-carrying capacity of Japanese wooden buildings

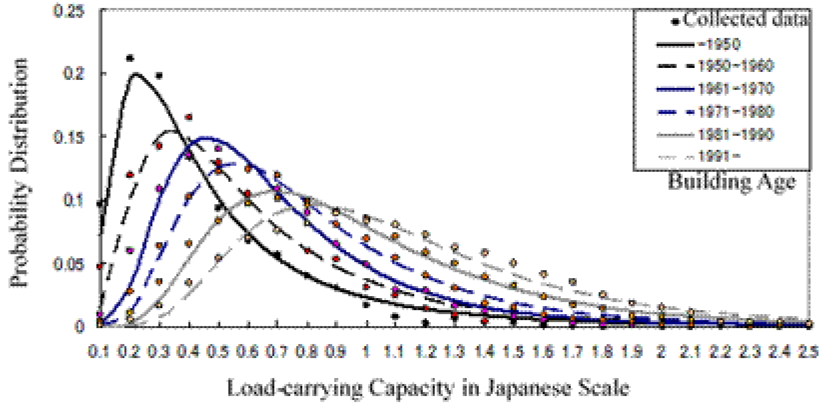


Fig. 4-Average curves of the Load-carrying capacity of wooden buildings estimated by building age

The function $f''_x(\theta)$ in Eq. (5), which gives the number of inhabitants experiencing ISS θ in each specified building, is the probability of injury to inhabitants within the building at a damage index of *x*. It is very difficult to functionalize $f''_x(\theta)$, in that so far few cases have been observed that reliable and detailed database information is available on injury caused by housing collapse. Therefore, in the present study we apply a method through a Bayesian approach to combine a priori subjective probability provided by experts with some observed data in the form of a likelihood function, which allows for future updates of factual data on human casualties. We can get the following distribution $f''_x(\theta)$ by using the posterior probability distribution $f''_\Lambda(\theta)$ obtained in the Bayesian approach:

$$f''_x(\theta) = \int_{-\infty}^{\infty} \frac{f''_\Lambda(\lambda)}{\sqrt{2\pi}\sigma\varsigma\theta} \exp\left[-\frac{1}{2}\left(\frac{\ln(\theta)-\lambda}{\varsigma}\right)^2\right] d\lambda \tag{9}$$

In this paper, we adopt the expression of notation for the Bayesian approach, for example, single quotation means anterior probability distribution, and double quotation means posterior probability distribution.

In a general Bayesian estimation, the posterior probability distribution $f''(\theta \mid \varepsilon)$ is given by the following equation:

$$f''(\theta \mid \varepsilon) = k \cdot l(\varepsilon \mid \theta) \cdot f'(\theta) \tag{10}$$

where, the distribution $l(\varepsilon \mid \theta)$ is a likelihood function with average value μ and standard deviation ς, and in our study variable ε means idealized data, on which Damage Level of building collapsed and ISS of inhabitants were observed in 65 cases in the 1995 Kobe Earthquake, fitted by the Lognormal distribution $LOGNORM(\lambda, \sigma)$ with the average value $\mu = \lambda$ and the standard deviation $\varsigma^2 = n\sigma$. The number *n* is the number of data, *n* = 65 in this study. The distribution $f'(\theta)$ is the anterior distribution of the average value λ of ISS, and in this study, we assume that the distribution is the normal distribution $N(\mu', \sigma')$. The posterior probability distribution $f''(\theta \mid \varepsilon)$ is equivalent to the distribution $f''_\Lambda(\lambda)$, which is the distribution of the average value depicted in Eq. (9) in our study, and described by the following normal distribution $N(\mu'', \sigma'')$:

$$f''_\Lambda(\theta) = \frac{1}{\sqrt{2\pi}\sigma''} \exp\left[-\frac{1}{2}\left(\frac{\lambda-\mu''}{\sigma''}\right)^2\right] \tag{11}$$

where,

$$\mu''=\frac{\mu(\sigma')^2+\mu'\left(\varsigma^2/n\right)}{(\sigma')^2+\left(\varsigma^2/n\right)} \tag{12}$$

$$\sigma''=\sqrt{\frac{(\sigma')^2\left(\varsigma^2/n\right)}{(\sigma')^2+\left(\varsigma^2/n\right)}} \tag{13}$$

In addition, the variable κ of Eq. (10) is a normalization coefficient and is given by the following:

$$\kappa=\left[\int_{-\infty}^{\infty} l(\theta)\cdot f'(\theta)\cdot d\theta\right]^{-1} \tag{14}$$

3. Case Study

In a case study based on the Nankai Trough Quake as the earthquake input, we try to estimate the damage done to wooden frame buildings and the human damage occurring inside the damaged buildings in Nankoku City, which is a bed town of Kochi City in Shikoku Island, Japan. According to the report by the Cabinet Office, government of Japan [4], there are 4 types of the assumed source fault zone. We selected the nearest zone to the Shikoku Island (Fig. 6), which is estimated as having the severest earthquake ground motion (Fig. 7) caused by faulting motion. The Cabinet Office roughly calculated human loss in the above case by following the conventional type of equation with a proportional relation of casualties and number of damaged buildings:

$$D=t_w\times H\times\frac{P_w}{P_0} \tag{15}$$

where, the index D is the number of humans damaged, t_w is empirical coefficient (t_w=0.0676 in case of death, t_w=0.177 in case of injury), the index H is the number of collapsed wooden buildings, the index P_w is the number of residents in wooden buildings in a target area, and the index P_0 is the population in a target area. The reported human damage is listed in Table 1.

The estimated result we calculated by the equations (5) through (14) is shown in Table 1 for comparison. Although both results are comparable as to the number of deaths, it is apparent that our method improves upon the conventional method, with the capability of estimating injuries from each damage grade of ISS.

TABLE 1-The list of estimated human damage

<table>
<tr><th></th><th colspan="4">This Study</th><th>Estimation by
The Cabinet Office</th></tr>
<tr><td>Number of dead</td><td colspan="4">369</td><td>440</td></tr>
<tr><td>Number of
light injured</td><td rowspan="6">Number of
injured by
ISS</td><td>1-8
Minor</td><td>2,386</td><td>2,386</td><td>1,200</td></tr>
<tr><td rowspan="5">Number of
heavy injured</td><td>9-15
Moderate</td><td>603</td><td rowspan="5">1,138</td><td rowspan="5">1,600</td></tr>
<tr><td>16-24
Moderate or Severe</td><td>316</td></tr>
<tr><td>25-40
Severe or Critical</td><td>171</td></tr>
<tr><td>41-75
Critical or D2,386eath</td><td>48</td></tr>
<tr></tr>
<tr><td>Total number of
injured</td><td colspan="4">3,524</td><td>2,800</td></tr>
</table>

Compared to the rough estimation at a municipality unit level or a grid cell of not more than 10 km x 10km, our model can provide the quantitative estimation of human casualty from injury or death at the building level or household unit level. Fig. 8 shows the map of seismic intensity on Japanese Intensity Scale in Koch prefecture in case of the assumed Nankai Trough Quake. Fig. 9 describes our observed result on the number of deaths in Nankoku City at the small grid cell of 250m x 250m.

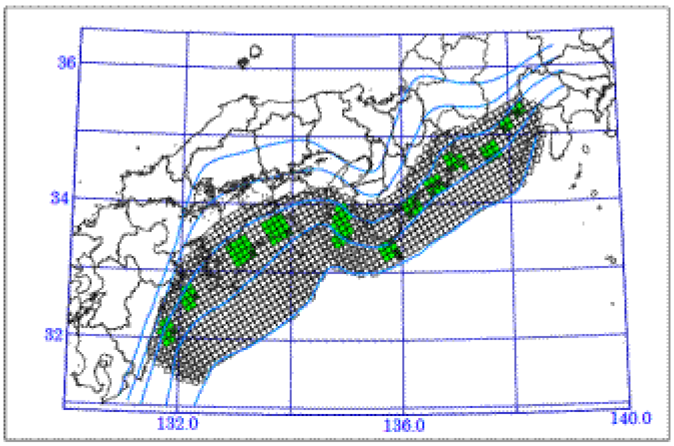


Fig.6-The nearest fault zone to Shikoku Island of the assumed Nankai Trough Quake

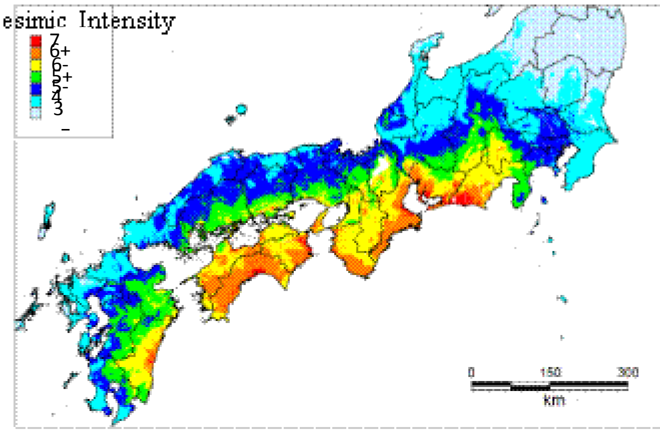


Fig.7-Seismic intensity distribution map reported by the Cabinet Office of Japan

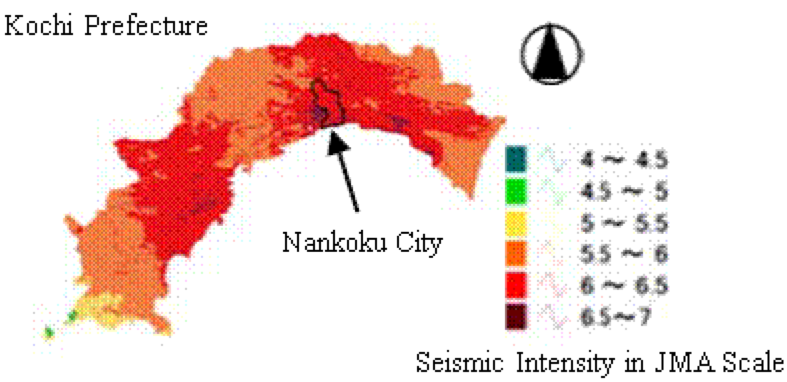


Fig. 8-Seismic intensity distribution map in Kochi prefecture

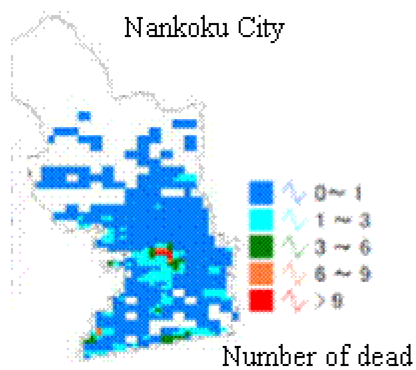


Fig.9-Estimated number of death in Nankoku City

We show an example of estimation at the building level in Fig. 10 cutting one block area in Nankoku City out of a satellite photo by Google Earth. Using Eq. (1) and the information about load-carrying capacity value (I_w =1.33) of Housing A, we can estimate the damage probability of building *P(s,x)* as shown in Fig. 11. As the building information we obtained is clear, the probability *P(s,x)* is simple such as deterministic value distributing only at 0.2 in Damage Index. Substituting this probability for Eq. (6) and using Eqs. (5) through (14), we obtained the probability of injury occurrence on the inhabitants as shown in Fig. 12. In case of Housing A, the building may not be destroyed at all because of its high load-carrying capacity, so that no injury may occur.

In case of Housing B, we obtained the building information that the house was built in 1990s, instead of the load-carrying capacity value. Following the same computation process, we can calculate the damage probability of the building as shown in Fig.13. As Housing B is relatively new, the probability of injury occurrence on the inhabitants in maximum for no injury, as shown in Fig. 14.

In case of Housing C, we obtained only ambiguous information on building age of 1920s through 1970s. Therefore, the damage probability of building peaks in the higher region of Damage Index as shown in Fig.15, and we obtained probability of injury occurrence on the inhabitants as shown in Fig. 16. On the basis of this probability, we can calculate the age-specific mortality per one person in Housing C with use of Fig. 1. Fig. 17 shows the result. For example, assuming that a couple of which ages are early 40s and a 6-year-old son live in House C, the probability of death occurrence over 1 person is estimated as follows:

The probability of death for 40s year-old person: 5.5% (=0.055) obtained from Fig. 17

The probability of death for 6 year-old child: 3.5% (=0.035) obtained from Fig. 17

The probability of death over 1 person = 1.0 – survival rate for all of the inhabitants

= 1.0 – ((1.0 - 0.055) x (1.0 - 0.055) x (1.0 - 0.035))

= 1.0 – (0.945 x 0.945 x 0.965)

= 0.138 (13.8%)

Fig. 10-A part of target area by the satellite photo and the location of examples of housing

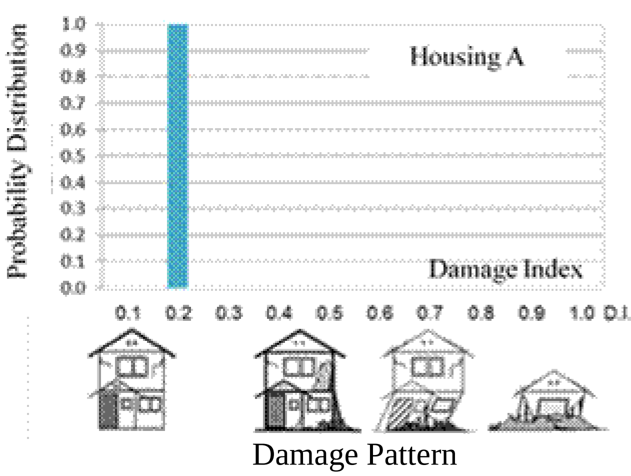


Fig. 11-Estimated damage probability of Housing A

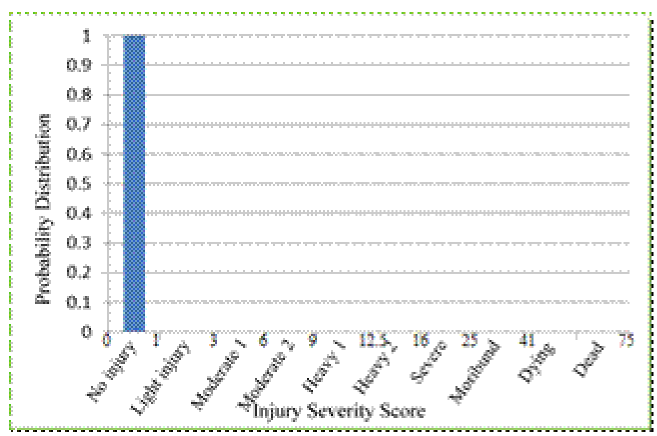


Fig. 12-Estimated probability of injury occurrence for an inhabitant of Housing A

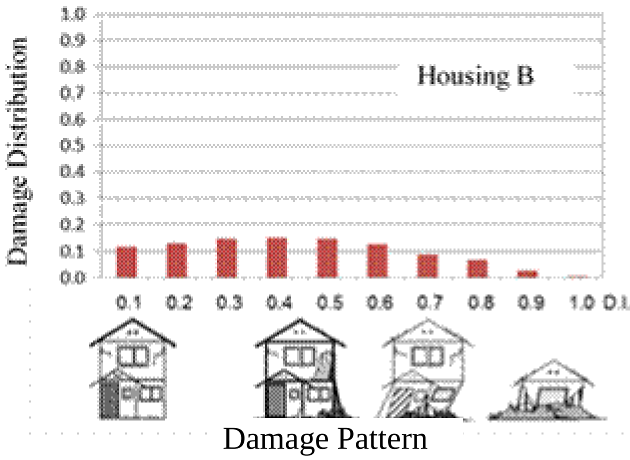


Fig. 13-Estimated damage probability of Housing B

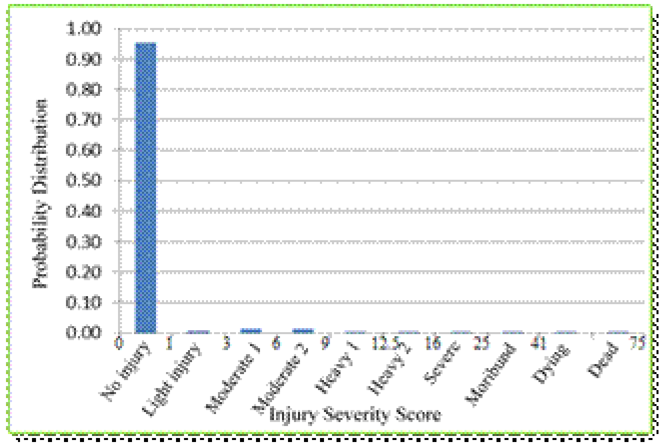


Fig. 14-Estimated probability of injury occurrence for an inhabitant of Housing B

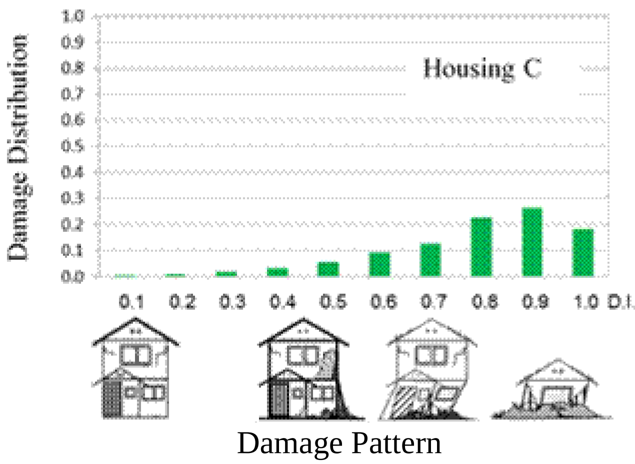


Fig. 15-Estimated damage probability of Housing C

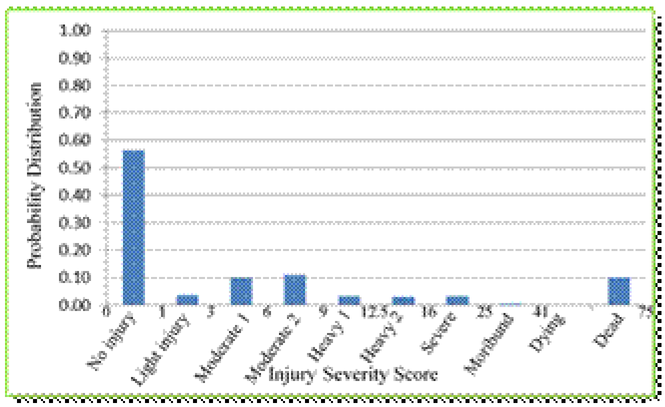


Fig. 16-Estimated probability of injury occurrence for an inhabitant of Housing C

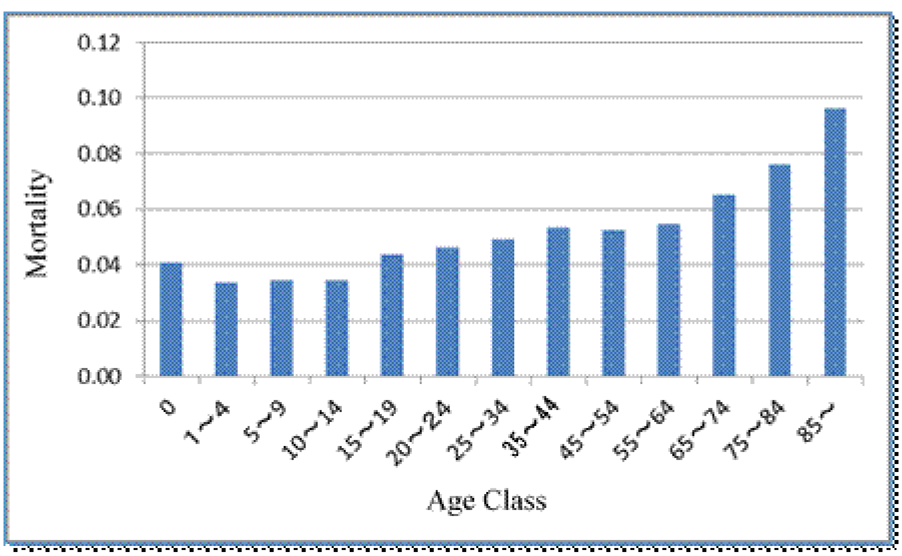


Fig. 17-Estimated death probability of inhabitants classified by age class in Housing C

For this case study based on the Nankai Trough Quake, we calculated the casualties at 0.5% of the whole population in Kochi Prefecture, Japan, around 731,000 people, only by the collapse of buildings and without the effect of tsunamis. These casualties break down as 2,386 people lightly injured (ISS scale range of 1 to 8), 603 people heavily injured (ISS scale range of 9 to 15), 535 people in critical condition, and 369 people killed instantly. The information obtained by this method is useful to plan supply and demand for seismic countermeasures in each region. In addition, we demonstrated that it is possible to estimate the probability of injury occurrence at building unit.

4. Conclusions

This study constructed a series of new constitutive equations available to estimate the number of casualties due to building collapse in the event of an earthquake. An original point of view not shown in previous studies is that the victims can be estimated on the scale of Injury Severity Score, which is universally used in the fields of disaster medicine and public health. By using the calculated results, we can promote the strengthening of vulnerable building structure as a proactive countermeasure against seismic disasters, and provide medical management with information usable to support search and rescue activities in the acute stage for medical service.

Although we proposed the methodology limited with wood frame structure in this paper, it seems to be easy to the methodology can be expanded to other types of buildings by indirectly using fragility curves.

5. References

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