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A MODEL FOR EVALUATING LIFE SPAN CHARACTERISTICS OF ENTRAPPED OCCUPANTS BY AN EARTHQUAKE

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SUMMARY

An attempt of modeling was made to estimate life span characteristics of entrapped occupants under collapsed dwellings in a devastated earthquake, applying Weibull function known effective at the mathematical formulation of the reliability of machinery systems. Kobe city was selected as a testing area of modeling in consideration of the 1995 Hyogoken-nanbu earthquake with M=7.3. First, learned from the field investigations, causes of death were classified into 5 major modes in terms of remaining life span or time length changing from 5-6 minutes for suffocated occupants to several days for either starved or dehydrated occupants with no injury. Second, life span characteristic function was described for each mode in use of Weibull function with mode-dependent shape and location parameters. Third, by summing up all the characteristic functions while taking into consideration of weighted coefficients proportional to the existing rates of entrapped occupants by mode, we obtained a unified life span characteristic equation as the one equivalent to the survival rate function for entrapped occupants. The unified equation make clear that in the early times as immediate state after the earthquake, the life span characteristic (=survival rate) decays quickly and comes down to 80% within one hour. With increasing times it decreases as low as 50% in half a day and, in a few days, it approaches to the worst state that almost no occupants are alive.

A brief analysis was made to evaluate the efficiency of SAR (Search And Rescue) activities by different groups. The groups considered are families and neighbors, local-to-regional fire brigades and national self-defense forces and it was found that the SAR activities by people living near-by was most efficient.

We are in the belief that the mathematical modeling and regarding simulation of life span characteristics after an earthquake are fundamentally important so as to provide key-note information for exploring better SAR strategies and operations.

INTRODUCTION

In the field of medical insurance, studies on life span characteristics have long been conducted, applying a mechanical failure model which employs Weibull distribution function. Among those, there is an approach of formulating the human's life span characteristics as the weighted summation among three

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different modes of "initial failure for infants", "random failure for adults" and "wear failure for aged occupants ", and has been known as a leading theory in epidemiology specific to the care for aged people.

This is a study to apply the above-mentioned theory for estimating the remaining life span of the occupants entrapped under damaged dwellings by an earthquake. There is, however, some certain differences between our study and that in medical insurance. The time length considered in the medical insurance is over several 10 years. But, in our case the origin time to start counting of the remaining life span for entrapped occupants is at the occurrence of an earthquake and so it is at most several days. One more significant difference is the characteristic of failure mode. In our case a single mode of "wear failure", corresponding to the aged people in medical insurance, would be reasonable, since unusual features to human body may occur under various physical damages to building itself and household contents etc during strong seismic shaking. In fact, occupants who are entrapped under heavily damaged dwellings are nothing but candidates to deaths, if they can not escape by themselves nor they are extricated in a certain short time. What we aim at is to develop a model by which remaining life time span characteristics can be estimated even roughly. We believe that our study will produce fundamental information for optimal initiation and execution of emergency responses as SAR (Search And Rescue) activities.

METHOD OF MODELLING

Fundamental Equations

In order to obtain life span characteristics of occupants entrapped under damaged dwellings we need to introduce a few assumptions. The first one is to set the starting time point at the occurrence of an earthquake. The adopted mode in our case is just one type of "wear failure" in machinery mechanics or the one for the aged people in insurance medicine. We also assume that the health conditions of occupants are different from person to person depending on what kind of injury and to what extent they suffered, that is, the remaining life span is controlled by the severity levels of injury and by the body part where injured. In this meaning there are several numbers of "wear failure" having different characteristics and so let each of failure states rewrite as "each of mode". Then, the equation for the unified life span characteristic following an earthquake, equivalent to the survival function, can be given as follows.

$$L(t) = P_1 \cdot W_1(m_1, T_0, t) + \cdots + P_n \cdot W_n(m_n, T_{0n}, t) \tag{1}$$

$$W_i = \exp\{-(t / T_{0i})^{mi}\} \tag{2}$$

Hence, $[1 - W_i]$ is the function corresponding to the original Weibull function and P_i indicates existing probability ratios by mode. Parameters (m, T_0) are the ones named shape and location respectively and relations with the mean remaining life span (= time length) and the dispersion are expressed as follows.

Mean value:

$$\mu_i = T_{0i} \cdot \Gamma\{(m_i + 2)/m_i\} = T_{0i} \cdot \Gamma\{1 + 1/m_i\} = T_{0i} \cdot 1/m_i \cdot \Gamma\{1/m_i\} \tag{3}$$

Dispersion:

$$\sigma^2 = (T_{0i})^2 \cdot \Gamma\{(m_i + 2)/m_i\} - (T_{0i})^2 \cdot \Gamma\{(m_i + 1)/m_i\}^2 \tag{4}$$

Here, Γ is Gamma function. Since we assume that the Weibull distribution good for the "wear failure" , m_i is naturally larger than unity. Incidentally, the original Weibull distribution function and density distribution function are as below.

$$W_i = 1 - \exp\left\{-\left(t / T_{0i}\right)^{mi}\right\} \tag{2-1}$$
$$W_i = \left(t / T_{0i}\right) * \left(t / T_{0i}\right)^{mi-1} * \exp\left\{-\left(t / T_{0i}\right)^{mi}\right\} \tag{2-2}$$

Simply, we can say that the major objective of this study is to get an expression for remaining life span characteristic of entrapped occupants using Eqs (2-1) and (2-2) and to examine through numerical calculations. If we can somehow assume [σ_i / μ_i] as known quantity, we can get Eq (5) by eliminating [T_{0i}].

$$\sigma_i / \mu_i = \left[\Gamma\{(m_i + 2)/ m_i\} - \Gamma\{(m_i + 1)/ m_i\}^2\right]^{1/2} / \Gamma\{(m_i + 1)/ m_i\} \tag{5}$$

Death Cause Modes and Remaining Life Span

Based on the established knowledge in the disaster medicine we are able to fix "remaining life span" of human being suffered injury as is listed in Table 1. From this table we learn that there are 2 major groups in death causes.

Table 1 Death Modes and Remaining Life Span

Death Modes		Life Time Length
Mode 1	Suffocation	5 - 6 min
Mode 2	Injuries - Head, Chest	2 - 3 hours
Mode 3	- Abdomen	3 - 24 hours
Mode 4	- Limbs	24 hours or more
Mode 5	- no injury	Around 3 days

One is the suffocation and crush symptom group and the other is the group belonging to surgical injuries. The former is the one with a very short remaining time so as to be said "instant death or fatal injury", and the latter is the one of which life span changes according to the seriousness of diseases between several 10 min to several 10 hours. Guided by the above table, we will discuss remaining life span characteristics for all the entrapped occupants while classifying death causes into 5 modes. Taking in mind of the classification as above and associated characteristics by mode, we determined 2 essential parameters attributed to the Weibull function. Those are mean remaining life span (μ) and its standard deviation (σ) for each of 5 modes. For the mean remaining life span we fixed through field experiences, but there is no much valid information for the standard deviation. So, for the simplicity's sake we assumed a certain value of 0.3 for all the modes. Table 2 summarizes all the parameters used for the following derivations.

Table 2 List of Parameters for each of 5 Modes

Parameters / Mode	Mean Time Length (μ)	SD (σ)	T_0 (hour)
1	5 min	1.5 min	0.092
2	3 hours	0.9 hour	3.32
3	12 hours	3.6 hours	13.3
4	1.0 day	0.3 day	26.6
5	2.5 days	0.75 day	66.5

Then, equations describing the remaining life span characteristics by mode are written as

$$W_1 = \exp\left\{-(t/0.092)^m\right\} \quad (6\text{-}1)$$

$$W_2 = \exp\left\{-(t/3.324)^m\right\} \quad (6\text{-}1)$$

$$W_3 = \exp\left\{-(t/12.30)^m\right\} \quad (6\text{-}1)$$

$$W_4 = \exp\left\{-(t/26.59)^m\right\} \quad (6\text{-}1)$$

$$W_5 = \exp\left\{-(t/66.48)^m\right\} \quad (6\text{-}1)$$

Hence, we adopted m =3.71 for all the modes. It is nothing but assuming (σ_i / μ_i)=0.3, regardless of modes. The summation of the above equations from (6-1) to (6-5) with specific weighting factors of which values differ from mode to mode gives the unified life span characteristic equation and is the same to Eq (1).

DENSITY AND DISTRIBUTION FUNCTIONS

Characteristic Curves

Substituting actual values of parameters (m, T0) as is listed in Table 2, to Eq (2-2), we can get a density distribution functions of remaining life span. In Fig.1 we depicted 5 characteristic curves in relation with elapsed time after an earthquake. Hence, the scale in the ordinate is arbitrary as usual. As is seen in this figure, we can recognize a general tendency that life span characteristics expand to longer one with increasing number of mode. It is also easy to see the times corresponding to the maximum points of curves approximate the mean values (μ) by mode.

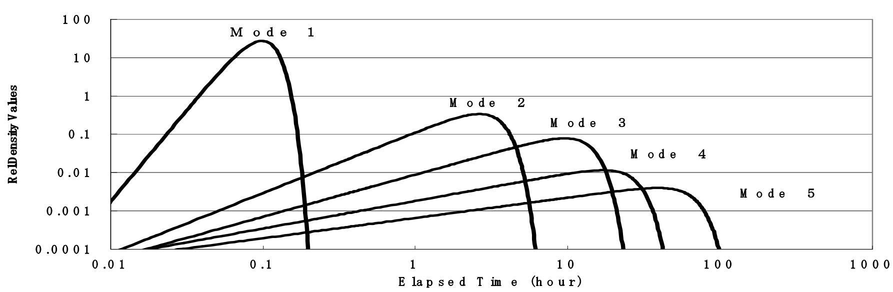

Fig. 1 Density Distribution Curves for Each of 5 Modes.

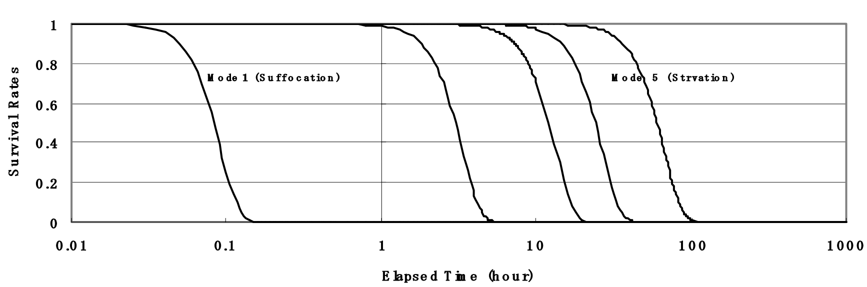

Fig. 2 Remaining Life Span Characteristic Curves for Each of 5 Modes.

Likewise, we can get characteristic curves of distribution functions of remaining life span by mode. It is shown in Fig. 2. Hence, the survival rates at given times for each mode are shown as the relative value as the one having 1.0 at t =0 (immediate time after an earthquake). From this figure we also see that each of the curves, regardless of modes, decreases with increasing times. The curve for the mode 1, corresponding to either suffocation or fatal crush symptom, locates in the extreme left part and decreases sharply so as to come down to zero within 10 min after the end of seismic shaking. The best one, mode 5, for the occupants who suffered no injury tells that they can live longer but within a few days they are oblige to be dead. The major causes are believed either starvation or dehydration and often combined symptoms of both effects.

To know the total life span characteristic of entrapped occupants, we should get a summation of those for each of 5 modes with some weighting factors. But, prior to conducting the summation there are two matters we should know more. One is the relation of the mode number to the severity levels of injury and the other is to give actual values for weighting factors. In the following section we discuss to get answers for these two questions.

TOTAL LIFE SPAN CHARACTERISTICS

Assimilation of Modes to Severity Levels of Injury

If we have much data regarding to the above two questions, we will be able to get reasonable answers to some extent. Such field data is unfortunately very limited and so we should overcome this difficulty somehow introducing an alternative way. Suggested by the key information that the increasing mode number gives the increasing life span remaining, we attempted to equate the difference of modes to the difference of severity levels of injury. This is nothing but correlating each of modes to simplified anatomic "ISS (injury severity scores)". After all, we adopted one-to-one relation between two independent variables as shown in Table 3.

Table 3 Comparison of Death Modes to Injury Severities

Death Modes		Injury Severities
Mode 1	Suffocation	Instant Death / Fatal
Mode 2	Injuries - Head, Chest	Serious
Mode 3	- Abdomen	Moderate
Mode 4	- Limbs	Light
Mode 5	- no injury	Non

Next, we should figure out the frequency distribution of entrapped occupants incorporated with the severity levels of injury. To get the frequency distribution in terms of actual values in percentage actually, we confined our scope only for Kobe city at the 1995 earthquake and we got each of frequencies for different injury levels.

The essential idea is to introduce an assumption that entrapped rates are simply determined by two major factors of the degree of dwelling itself and the severity of injury of occupants (Refer to the Appendix for detail).

Thus the adopted values finally in percentage for each of modes are

P_1 =0.02 (2%), P_2 =0.11 (11%), P_3=0.23 (23%), P_4 =0.30 (30%) and P_5 =0.34 (34%).

And, substituting these values into Eq (1), we get the unified "remaining" life span for entrapped occupants whose severity levels of injury change step-wisely.

Examination of Derived Model

A unified life span characteristic curve obtained as above is plotted in Fig 3, in comparison with individual curves for each of 5 modes. As is seen here this unified curve approximates the first mode curve with the shortest remained life span and with increasing elapsed times it comes closer to the 5th mode curve with the longest mean life span. In the relation with diseases, these can be summarized as follows; in the immediate state following an earthquake the deaths due to either suffocation or fatal crush are dominant - it is essentially the same to “instant deaths” -

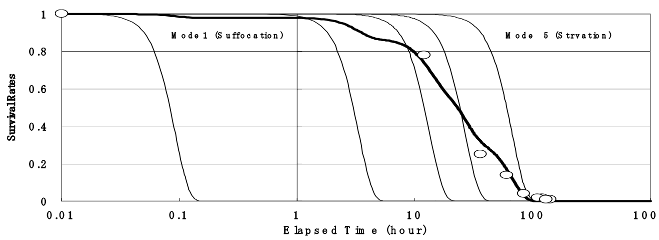

Fig. 3 Comparison of Unified Characteristic Curve with Field data.

and some may even die during seismic shaking. On the other hand, with increasing elapsed times deaths due to surgical injuries from lighter to heavier ones become dominant. And, the remaining life spans are dependent on both of where injured and how injured. Generally we see that the remaining times increase from injury of head, chest and abdomen to limbs as is from the upper part to the lower part of a body, although with wider dispersion of remaining times in reflection of the severity levels of injuries even if the same part of a body was attacked. While tracing such complicated processes it comes to the occupants who suffered no injury. They are gotten to deaths due to the starvation and dehydration in the worst circumstance with no enough circulation of fresh air and much dust under totally collapsed dwellings.

Incidentally, field data on remaining life span is very limited. Only the data we have is the one by the Kobe city fire station. One of authors (H. MURAKAMI) made an energetic collection of the data on how many occupants were extricated while alive or dead. This data allows us a comparison with the model developed here. Plotted open circles in Fig 3 are data by MURAKAMI. This comparison suggests our model developed here is satisfactory at least for Kobe case.

TOWARDS REDUCTION OF FATALITIES

Comparison with SAR activities

As is explained in the Appendix a very big number of occupants in Kobe as many as 200,000 were seemed entrapped under damaged dwellings. Some may say such number is too big to be real. In Hokudan-cho area of Awajishima island locating very near to Kobe, however, we have a field data suggesting that more than 20% of occupants were entrapped at the immediate situation when the earthquake attacked. We are in belief that several hundreds of occupants in Kobe were just candidates of deaths if there was no escape by themselves or SAR activities in the following times. The characteristic curve we obtained here can be defined as the one showing a natural trend of time-dependent survival rates. It was our fortune that some effective SAR activities got into practice within a short time. Again using the data by MURAKAMI we made Fig. 4. This figure demonstrates when and what kinds of SAR activities were got into operation and suggests that the efficiency of activities differ among 3 different SAR groups.

What we can read from this figure is not a few. First of all, we see that SAR activities by family members and neighbors are very effective as those started earlier as 10 min or less after the earthquake and so 80% of occupants were extricated while alive. However, their activities got less effective in half a day. The reason may be due to the fact that they had no powerful tools nor skills to let entrapped occupants extricate from under heavy loading by disintegrated building materials, though they had an advantage of the nearest position to the occupants who ask help.

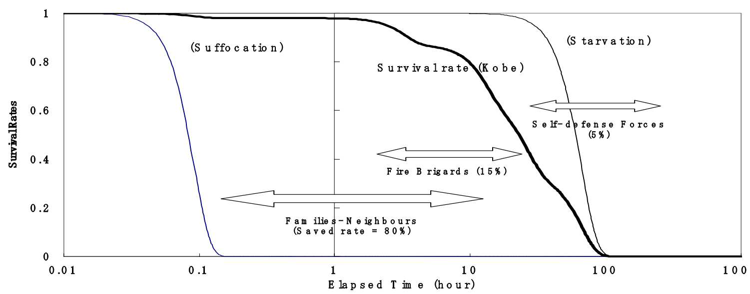

Fig. 4 Comparison of Unified Curve with Various SAR Activities.

The fire brigades, stationed near-by residential area, could come to the sites in a shorter time as 1-several hours and worked effectively using some special tools good for the extrication so as to get higher score as 50% of occupants were saved. The self-defense forces having camps somewhat far could not do much in the meaning of saving entrapped occupants although they had very well equipped. Actually, their arrival at the destination was late as one day or more was necessary until getting into the SAR activities.

Further Studies Requested

Suppose the remaining life span of a person under damaged dwelling as T_{life} and the time of initiation of SAR activity as T_{SAR}, then naturally a relation of $T_{life} > T_{SAR}$ should be hold. Otherwise it means mere extrication of the dead occupants. As stated above family members, neighbors and people living in near-by communities took very important role on the early stage of SAR activities. What we have learned to get better SAR activities are not a few. The first one is, probably, to encourage to be more familiar each other among local people in ordinary days, the second one is to let them brush up their knowledge and skills on SAR regarded activities through training, the third one is to let them keep somewhat powerful tools. In spite of such strengthening there still remain significant numbers of entrapped occupants whom no one can help. They are the occupants suffering either suffocation or fatal crush and so their remaining life span is as short as several minutes. Therefore SAR activities starting triggered by the occurrence of an earthquake gives no significant outcomes. The situation is similar to the case for the entrapped occupants who suffer severe surgical injury, as of head and/or abdomen, with remaining life span of less than a few hours. From this point of view we should stress the importance of prior countermeasures. The most effective one is, among those, to get better seismic performance for their dwellings. And, it is also necessary to develop the way of reducing fatalities even during the time period of seismic shaking. Otherwise, no significant reduction of earthquake fatalities can be expected.

In this paper we developed a simple model to describe remaining life span characteristics of entrapped occupants under damaged dwellings, applying well-known theory on mechanical failure in machinery mechanics. And, after having tested its validity using the field data in Kobe at the 1995 Hyougoken-nanbu earthquake in Japan, we discussed a way for sounding significant reduction of earthquake fatalities. However, there remain more studies to be made. One is to develop our model itself while increasing influential factors other than we considered in the simple model. Some of probable factors to be incorporated are season and time of occurrence of an earthquake even in one country of Japan. It is also necessary to expand our model good for earthquakes in different countries with different structural types over wooden-frame. Behavioral performance of occupants may differ by several factors as age, sex, health condition and so on. We are on the way of developing a more advanced model in consideration of some of the above mentioned factors.

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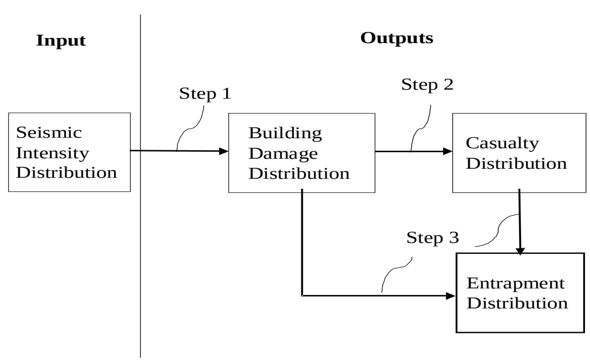
APPENDIX

Estimation Scheme of Entrapment Rates of Occupants

With an aim of providing fundamental information for better initiation of SAR (Search and Rescue) activities immediately after a devastated earthquake, a scheme to estimate entrapment rates of occupants in damaged dwellings was developed, in the scope of the situation in Kobe at 1995 Hyougoken-nanbu earthquake in Japan. The scheme is framed based on an assumption that the seismic intensity distribution in a model area is given as known data and the entrapment rates are derived via three major steps, as is seen in the figure below.



General Estimation Scheme for Entrapment Rates

The first step is to get damage distribution of dwellings in relation of seismic intensity distribution in the model area. The second step is to calculate casualty distribution of people living in the model area, having the damage distribution of dwellings as input information. The third step is to estimate the entrapment rates, combining thus obtained intermediate results via steps 1 and 2.

First step This is the step is to count for the damage distribution of dwellings in a suffered area. And it is the same to the well-known method. The distribution function of damage levels (x) of dwellings given as a function of seismic intensity (I) is written as $f(x) = B(x;\lambda)$. Hence, B means Beta function defined in a range of [0-1] and λ is a quantity expressed in relation of so-called structure-specific vulnerability function which relates directly to seismic input (I). As for structure types we simply assume that most dwellings in the model area are made of wooden. Then, by having seismic intensity distribution and by knowing vulnerability characteristic of the dominant dwellings in the model area, we can get $f(x)$ in numerical form.

Second step This is the step to figure out the distribution of casualty levels (x) for occupants in the model area, $g(y)$, in 4 classified severity levels from no injury, light injury, heavy injury and fatal injury or instant death, and for each of them increasing numerical values with increasing injury severity levels are assigned in a range [0-1] as well. The essential idea for the estimation of casualty distribution is to correlate to how and to what extent dwellings were damaged. That is, the most important input information is, at estimating $g(y)$, the damage distribution, $f(x)$, of dwellings obtained in the first step. The derived equation itself is somewhat complicated and so we can not write it down here. One note we keep in mind is in this scheme casualties due to earthquake fires are out of consideration.

Third step This is the final step, to figure out the entrapment rates by casualty levels at immediately after an earthquake and to apply for the case in Kobe. Before getting into the estimation, however, we need one more consideration. It is to evaluate the entrapment rate for a single person whose dwelling is damage as (x) and suffers injury as (y). Based on the field data we have got in Hokudancho, Awajishima island locating near to the epicenter of Hyougoken-nanbu earthquake, we modeled it by an equation as

$$z(x, y) = (k \cdot x + y - k \cdot x \cdot y)^m .$$

Here, constants k and m are parameters to control the difficulty of escape from damaged dwellings. In comparison with the field data, k^m=0.3 and m=2 seem probable. Using this equation with those obtained in the first and second steps, we are finally able to estimate probable numbers of entrapped people in Kobe area. The equation to describe entrapment rates, $S(y)$, is written as

$$S(y) = \int f(x) \cdot g(y) \cdot z(x, y) dx$$

and executing this integration between [0-x] we get the probability value for each of severity levels of injury.

Some results obtained by tan application of the above developed scheme to Kobe are as follows; Entrapment rates are 2% for fatally injured, 11% for heavily injured, 23% for moderately injured, 30% for lightly injured and 34% for non injured respectively. Also, the calculation tells that at the immediate situation people more than 200,000 were entrapped. That corresponds approximately to 15% of total population in Kobe, inclusive of around 100,000 people entrapped even with no injury. Readers might feel these figures are too big to be real. Our field data in Hokudancho gives that 19 percent of occupants were actually entrapped, This evidence supports that the above figures in Kobe area are probable. We are in belief that this scheme would be a tool to create the useful information for SAR activities.