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Volumetric Loss Estimation for Collapsed Buildings during Earthquakes

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Abstract

The severity of seismic damage to buildings is usually defined by assigning a damage degree to the main structural elements, such as columns, beams or load-bearing walls. Nevertheless, past examples of earthquake disasters have suggested that the probability of casualty occurrence strongly depends on the loss of indoor space in affected buildings. From the previous point of view, the purpose of this paper is to define the deterioration of survival space of a collapsed building as volumetric loss and to propose a new numerical function of volumetric loss for the wooden frame structure building type, which is the most common type in Asia. In addition, this paper discusses the relation between volumetric loss and casualties. Using the results of this study, we have constructed a numeric relation between the volumetric loss index and the damage index, representing the structural damage of a building as the W-Function of a wood frame structure. As the study progressed, methods were developed to promote the strengthening of vulnerable building structure, reduce casualties in collapsed buildings, and to support search and rescue activities.

Keywords: human casualty; wood frame building; volumetric loss of building; Beta distribution function

1. Introduction

As regards to a macro model for human loss estimation, conventional wisdom suggests that the estimation model should incorporate population exposure in some type of fragile building and earthquake fatality rate. For example, the earthquake death toll caused by wooden frame buildings collapsed in Japan is roughly estimated by the following empirical formula, which H. Kawasumi proposed in 1954 [1]:

$$\mathrm{D} = \alpha \times H^{\beta} \qquad (1)$$

D: Number of deaths
H: Number of collapsed buildings
α and β: empirical coefficients (0.01 and 1.3, respectively).

By following the above type of equations with a proportional relation of casualties and number of damaged buildings, the estimated loss is only available at the country level or a grid cell of not more than 10 km x 10 km. The reason why such types of equations have low precision for loss estimation is that the severity of seismic damage to buildings is usually defined by assigning a damage degree to only the main structural elements, such as columns, beams or load-bearing walls, despite the fact that we often observe a different extent of casualties in destroyed buildings of the same type classified as having the same damage degree. This fact caused us to consider a new index for building damage classification that is relevant to observed damage and can be universally applicable.

From the above point of view, one of the authors defined the deterioration of survival space of collapsed building as volumetric loss and proposed a new numerical function of volumetric loss for the type of masonry structure in the 11th World Conference on Earthquake Engineering (WCEE) [2]. The purpose of this paper is to propose the same type of volumetric loss function for wooden buildings, which are the most common in Asia, and to discuss the relationship between volumetric loss and casualties.

By using the idea of volumetric loss for buildings, we can propose a new causality model for evaluating the probability of human damage from injury to death in collapsed buildings (Refer to our different paper in the 16th WCEE [3]). In the paper, the degree of injury is described in terms of an Injury Severity Scale θ, which is regularly adopted in the field of disaster medicine. The proposed equation, available at the building level or household unit, is as follows:

$$M_{ISS}(\theta) = \kappa_{\Delta x} \cdot f''_{\Delta x}(\theta) \qquad (2)$$

where, the dependent valuable $M_{ISS}(\theta)$ is probability of injury level of θ on inhabitants in each specified building. The first term on the right side of the above equation $\kappa_{\Delta x}$, which is given by Equation (3), is the population exposed in the risky space of a building space that is observed to have a high value of volumetric loss, and the second term $f''_{\Delta x}(\theta)$ is the probability of injury to inhabitants within the building at a damage level of Δx.

$$\kappa_{\Delta x} = \sum_{\Delta x=0.6}^{1.0} \sum_{I=0}^{7.4} M_f(I) \cdot P(I, \Delta x) \cdot W_{\Delta x} \qquad (3)$$

where, the variable I is the seismic intensity of the relevant region in Japanese Meteorological Agency scale, the variable $M_f(I)$ is the population exposed in wooden buildings built in each region shaken in seismic intensity I, and the functional variable $P(I, \Delta x)$ is the fragility curve on building type of wood frame structure, giving the exceedance probability which means that the damage done to building in seismic intensity I exceeds a building damage degree Δx. The variable $W_{\Delta x}$ is the volumetric loss index of building collapsed in damage degree Δx, which is described in detail as follows.

2. Calculation Method of Volumetric Loss Function

2.1. Definition of Damage Index of buildings

To follow an appropriate approach to quantitative estimation of human casualty from injury or death at the building level or household unit level, it is necessary to first confirm the empirical function specifying the damage degree of the building. That is, it is necessary to define the seismic structural damage state of an individual building in terms of the Damage Grade, from Grade 1 (No damage) to Grade 5 (Total collapse) (EMS-98 [3]). We already proposed the numerical scale of damage degree, from 0 (No damage) to 1.0 (total collapse), using visualized damage patterns of buildings so as to help field investigators classify building damage. The visualized damage patterns are shown in Fig. 2-1[4]. In this paper, we use this damage scale to describe the damage state of buildings.

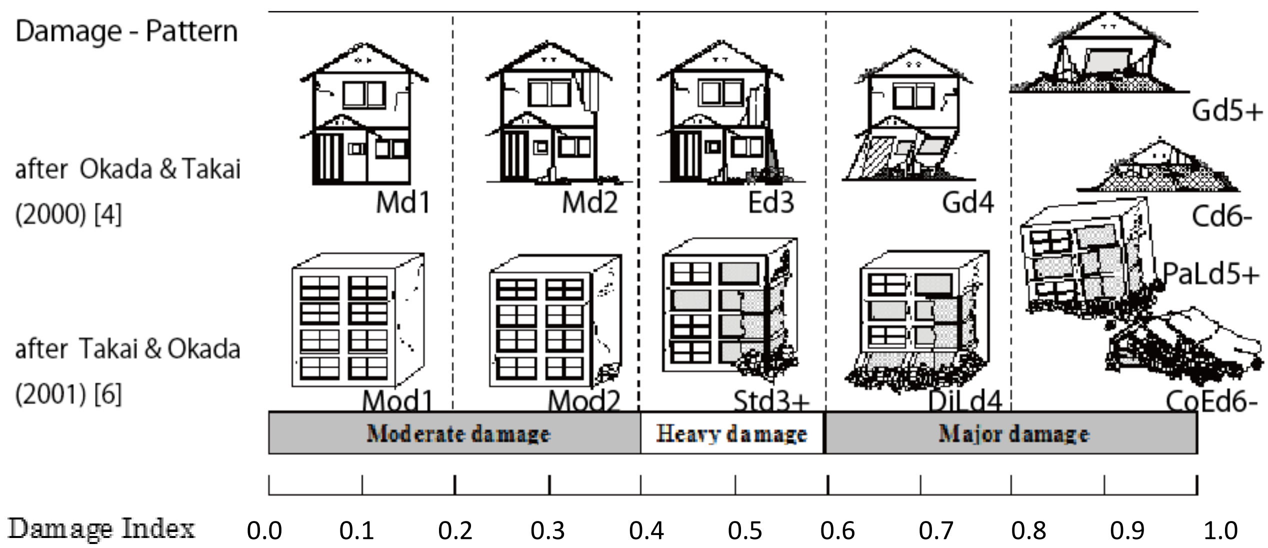

Fig. 2-1. Definition of damage index of building

2.2. Definition of indices of volumetric loss

We describe again the definition of indices of volumetric loss as follows [2]. The definition domain is commonly 0 to 1.0 in every index. Zero means no damage to the space of a building, and 1.0 means that the whole building is damaged. The numeric value of each volumetric loss index is called the "W-Value".

<u>Definition of Index W1: Plan Loss</u>

The volumetric space loss in the plan of a building referred to as "W1" is given by the ratio of A1 to A in each floor as follows (shown in Fig. 2-2):

$$W1 = A1/A \tag{4}$$

where A1 is the floor area occupied by debris, A is the total floor area, W1 is related to the human casualty risk while the building is shaking during an earthquake due to the fall of a disintegrated beam or column or particles of roof and slab, which may cause death or such injuries as multiple contusions, multiple fractures, or flowing wounds.

<u>Definition of Index W2: Section Loss</u>

The volumetric space loss in a section of a building referred to as "W2" is given by the ratio of B2 to B in each floor as follows (shown in Fig. 2-2):

$$W2=B2/B \tag{5}$$

where B2 is the sectional space loss due to the fall or collapse of a heavy structural material such as a beam, column, wall, or floor slab, and B is the total sectional area. W2 is an indirect index related to human casualty, but it is easier to judge the numerical value visually, only by the exterior of a damaged building, than for Index W1.

Definition of Index W3: Volume Loss

The void index, or the volume loss of survival space, referred to as "W3" is given by the ratio of C3 to C in each floor as follows (shown in Fig. 2-2):

$$W3=C3/C \tag{6}$$

where C3 is the volume of debris, and C is the space capacity 2 meters below the floor level, which is called the "survival space" and is capable of containing survivors in a collapsed building. W3 is related to the factors causing suffocation and controlling whether a collapsed building entraps populations exposed to an event.

Definition of Index W4: Amount of Dust

The amount of dust in each floor as a result of a building collapse is defined as "W4". This index may be related to the casualty risk due to asphyxiation and should be scaled by the rubble size of debris. The finer the rubble size, the higher the dust potential becomes. Even though this is an important factor in the risk of building space, we do not discuss it further in this paper because it is difficult to determine the value of W4 by using the photos of damaged buildings.

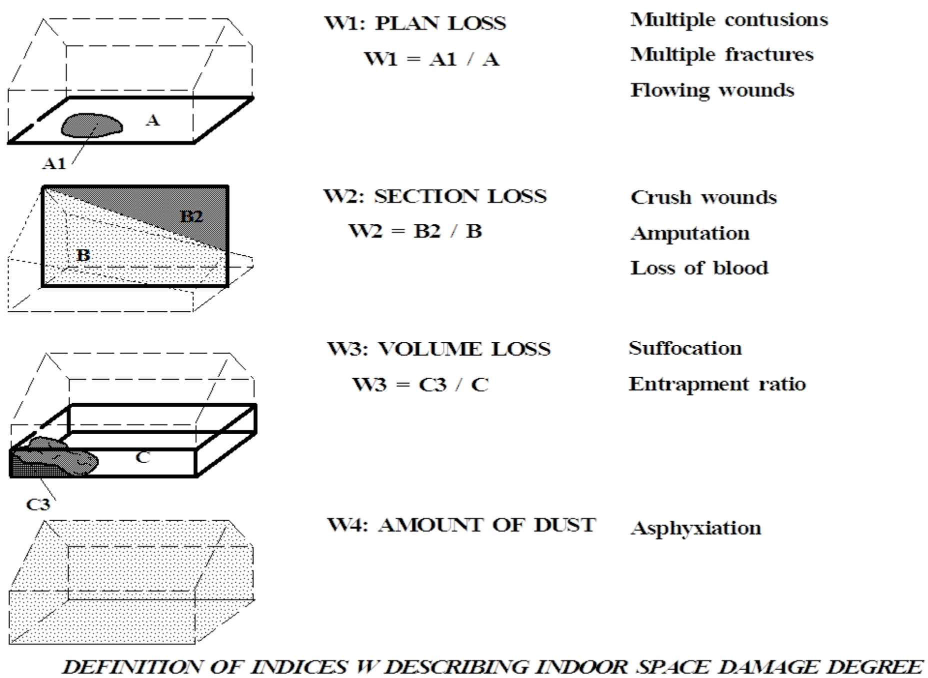

Fig. 2-2. Definition of W-Value Index

2.3. Data on wooden buildings

In Japan, we recently experienced some destructive earthquake disasters of which the main cause was seismic ground motions; for example, the Noto Hanto Earthquake and the Niigataken Chuetsu-oki Earthquake, both in

2007. We obtained the photos of damaged buildings and the related data on the Damage Index of buildings described in Chapter 2.1. Their damage patterns are illustrated in Fig. 2-1, along with the injury conditions of the inhabitants. The total number of building samples in the above two earthquakes is 5,163.

2.4. Judgment of volumetric loss

In order to verify the error in each judgment, four investigators, including one of us, judged the volumetric loss of space on each floor of the damaged buildings for W1, W2, and W3 using the photos. Examples of the judged photos are shown in Fig. 2-3.

Figure 2-3(1) and (2) show examples of damaged two-storied buildings. In Fig. 2-3 (1) we cannot find distinguished evidence of damage in the exterior view of the house, but the foundation of the house marked with a circle in this figure is cracked. Since the foundation is one of the extremely vital elements of building structure and is destroyed, the degree of structural damage should be rated more severely than the class of “Heavy Damage”, that is Damage Pattern Ed3, in Fig. 2-1. We finally decided that the damage index is 0.5. On the other hand, we have no damage to include in an estimation of volumetric loss for this house. That means all of the W-Values for every floor are 0.0.

Damage Index	W1 of 1st Floor	W3 of 1st Floor	W3 of 1st Floor	W1 of 2nd Floor	W2 of 2nd Floor	W3 of 2nd Floor
0.5	0	0	0	0	0	0

Fig. 2-3(1). Example photos of a heavily damaged wooden house and estimated values on volumetric loss

From the internal view of the house in Fig. 2-3(2), we notice that the pillars are tilted with an angle of 18 degrees in part of the first floor. On the other hand, the second floor keeps remained level; therefore, the Damage Pattern corresponds to a Gd4 in Fig. 2-1. We judged the damage index to be 0.75. The section loss, W2, is can be determined using the tilt angle of indoor space. The approximation criteria are given as follows: the value of W2 is estimated from 0 to 0.3 in case of a tilt angle less than 20 degrees, from 0.4 to 0.6 in case of a tilt angle of 20 to 30 degrees, and from 0.7 to 0.9 in case of little remaining the internal space of the floor. No elevated space on the floor is valued at 1.0. In this case, we estimated the W2 of the first floor to be 0.3 judging from the fact that the walls and pillars in the first floor were tilted at an angle of 18 degrees.

Damage Index	W1 of 1st Floor	W3 of 1st Floor	W3 of 1st Floor	W1 of 2nd Floor	W2 of 2nd Floor	W3 of 2nd Floor
0.75	0.3	0.3	0.4	0.2	0	0.1

Fig. 2-3(2). Examples of photos of a critically damaged wooden house and estimated values on volumetric loss

Damage Index	W1 of 1st Floor	W3 of 1st Floor	W3 of 1st Floor	W1 of 2nd Floor	W2 of 2nd Floor	W3 of 2nd Floor
1.0	1.0	1.0	1.0	-	-	-

Fig. 2-3(3.) Examples photos of a totally collapsed wooden house and estimated values on volumetric loss

Fig. 2-3(3) shows an example of a damaged single-storied building. It is apparent that this house is totally collapsed from both the damage degree of the exterior structure and the volumetric loss of interior space.

To examine the judgment error in decisions for W-Values, Fig. 2-4 shows the frequency distribution of W2-values decided by each of four investigators (Unless otherwise stated, hereafter W-value means W2-value.).

Each judgment was consistent among the investigators, and the average error among each judgment is within 0.03266. Therefore, the tiny differences in judgment on W-Values can be ignored.

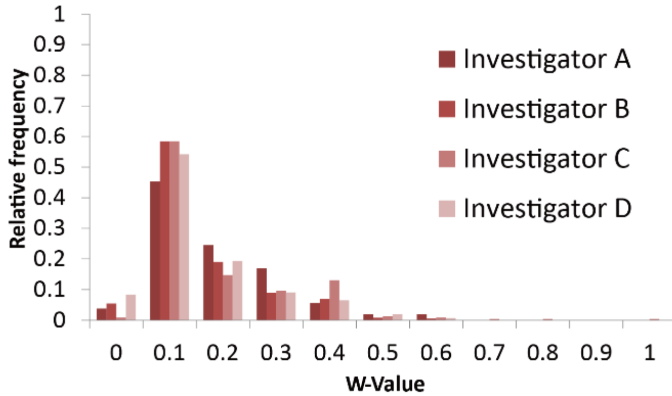

Fig. 2-4. Judgment errors for each investigator

2.5. Functionalization of W-value using the Beta Probabilistic Function

The volumetric loss is presumed to be strongly dependent on the damage pattern of the building, as shown in Fig. 2-5, which depicts that the peak frequency of W-values is increasing in proportion to the increase of the Damage Index, substituting numerically for the damage pattern of a building.

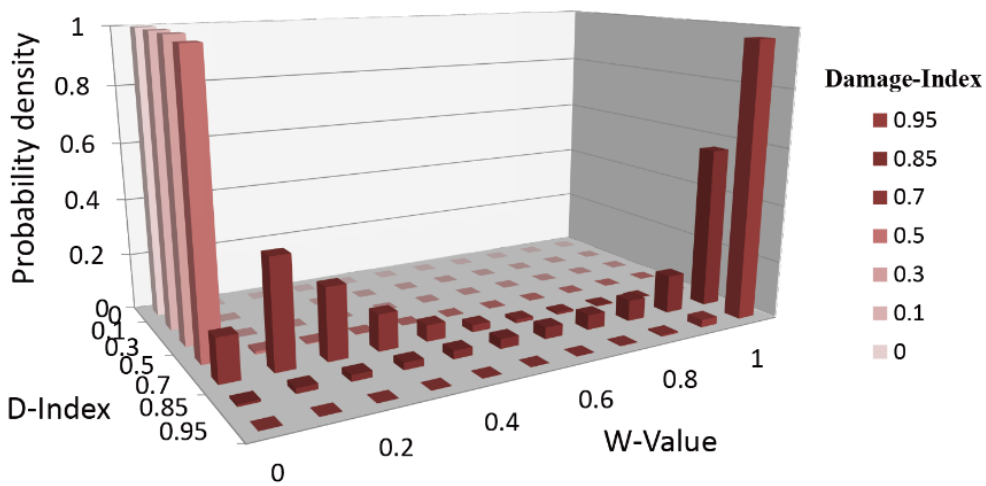

Fig. 2-5. Relationship between W-Value and Damage Index

For mathematical visualization of the two relationships, the frequency distribution of W-values estimated for each damage index is functionalized by the following Beta distribution, referring to the technique shown in Okada [2]:

$$f(x) = \frac{x^{p-1}(1-x)^{q-1}}{B(p,q)} \tag{7}$$

where *f(x)* is the frequency of the W-value, and *x*, p, and q are parameters of the Beta distribution with the defined ranges of $p > 0, q > 0, and\ 0 < x < 1$. *B(p, q)* is the Beta function as follows:

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

The average value, *E(x)*, and the standard deviation, *V(x)*, of the Beta distribution are given by Eqs. (9) and (10), respectively.

$$E(x) = \frac{p}{p+q} \tag{9}$$

$$V(x) = \frac{pq}{(p+q)^2(p+q+1)} \tag{10}$$

Although the Beta probability density function cannot be evaluated at the endpoints of $x = 0$ and 1, we use the following cumulative Beta distribution function through the parametric estimation technique instead of directly fitting the probability density function to the frequency distribution of the raw data on the observed W-values.

$$F(x) = \frac{1}{B(p,q)} \int_0^x x^{p-1}(1-x)^{q-1}dx \tag{11}$$

2.6. W-Function for Volumetric Loss of Buildings

For fitting the cumulative Beta distribution function given in Eq. (11) to the two dimensional plane of Damage Index and W-value, the peak of W-value to each Damage Index in Fig. 2-5 is plotted in Fig. 2-6 as the representative value of the W-value. In this figure, the fitted curve and the W1-values of wooden buildings observed in the case of the 1995 Kobe Earthquake are shown for reference. This figure shows that wooden buildings have a high quantitative consistency between plan loss, W1, and section loss, W2. This fact means that we can use the more easily countable W2-value instead of the W1-value for wooden buildings. From the above discussion, the following equations are adopted as the W-Function, meaning the volumetric loss of Japanese wooden-frame building:

$$F(x) = \frac{1}{B(p,q)} \int_0^x x^{p-1}(1-x)^{q-1}dx \quad \begin{cases} p = 24.53,\ q = 7.17 \text{ for 1}^{\text{st}} \text{ floor} \\ p = 27.57,\ q = 4.26 \text{ for 2}^{\text{nd}} \text{ floor} \end{cases} \tag{12}$$

where $F(x)$ and x are the values of the W-value and Damage Index, respectively. $B(p, q)$ 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.

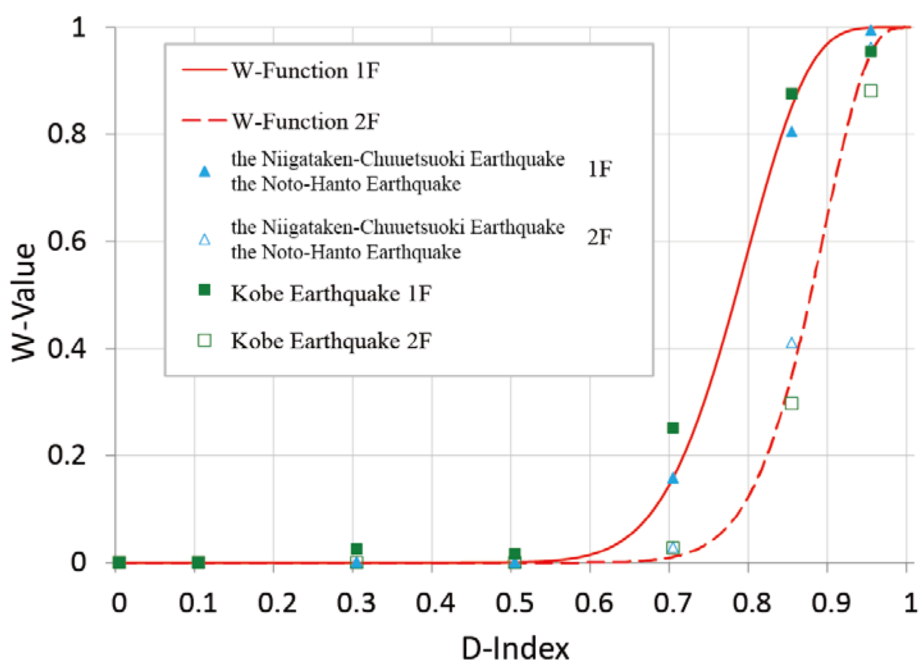

Fig. 2-6. W-Function curve estimated in this study

3. Characterization of Collapse of Wooden Frame Buildings

We discussed the characteristics of collapse for Chinese buildings, which are classified into Unreinforced Brick Masonry (Building Type BB1) and Timber Frame with Heavy Infill-Masonry (Building Type CT1) from the structural point of view, using the W-Function in the previous paper [2]. Herein, we try to scrutinize the characteristics of the W-Function for Japanese wooden buildings, classified as Timber Frame with Timber Cladding (Building Type CT2), in comparison with types of Chinese buildings.

The W-Functions of types of BB1 and CT1 for the single story buildings in China and of type CT2 for the two storied buildings in Japan are compared in Fig. 3-1. The fall of bricks, which is a major material in buildings of Type BB1 and CT1, controls the plan loss of the W1-value on the structural damage for Heavy and Major damages, depicted as over 0.6 in the Damage Index. As for the section loss of the W2-value, Type BB1 traces 0 to 0.8 on the structural damage scale, which is considered Heavy damage, and traces from 0.6 to 0.8 for the Damage Index. The W2-value of Type BB1 is characterized by the collapse of the non-loadbearing wall. However, the W2-value of Type CT1 does not even reach 0.5 because it incorporates a timber frame, which is characterized by ductility. For Major damage, from 0.8 to 0.9 on the Damage Index, the W2-value of CT1 is probably in the range of 0.4 to 0.6, which means that the elevated indoor space for Type CT1 is more likely to be preserved than for Type BB1, which is likely to experience a jumble of debris as a result of collapse of heavy roof elements.

On the other hand, the difference between W1- and W2-values for Type CT2 can be neglected as described in Chapter 2.4. The collapse of indoor space is characterized by the stories of a building. The ductility of a wooden frame helps to preserve the indoor space in buildings steadily without deformation or Heavy damage, as evidenced by the W-values on the 1st floor and 2nd floor being beneath 0.4 and 0.1, respectively. A remarkable characteristic of the W-Function for CT2 is a sudden brittleness, for example from 0.4 to 1.0 on the 1st floor, arising in the state of Major damage.

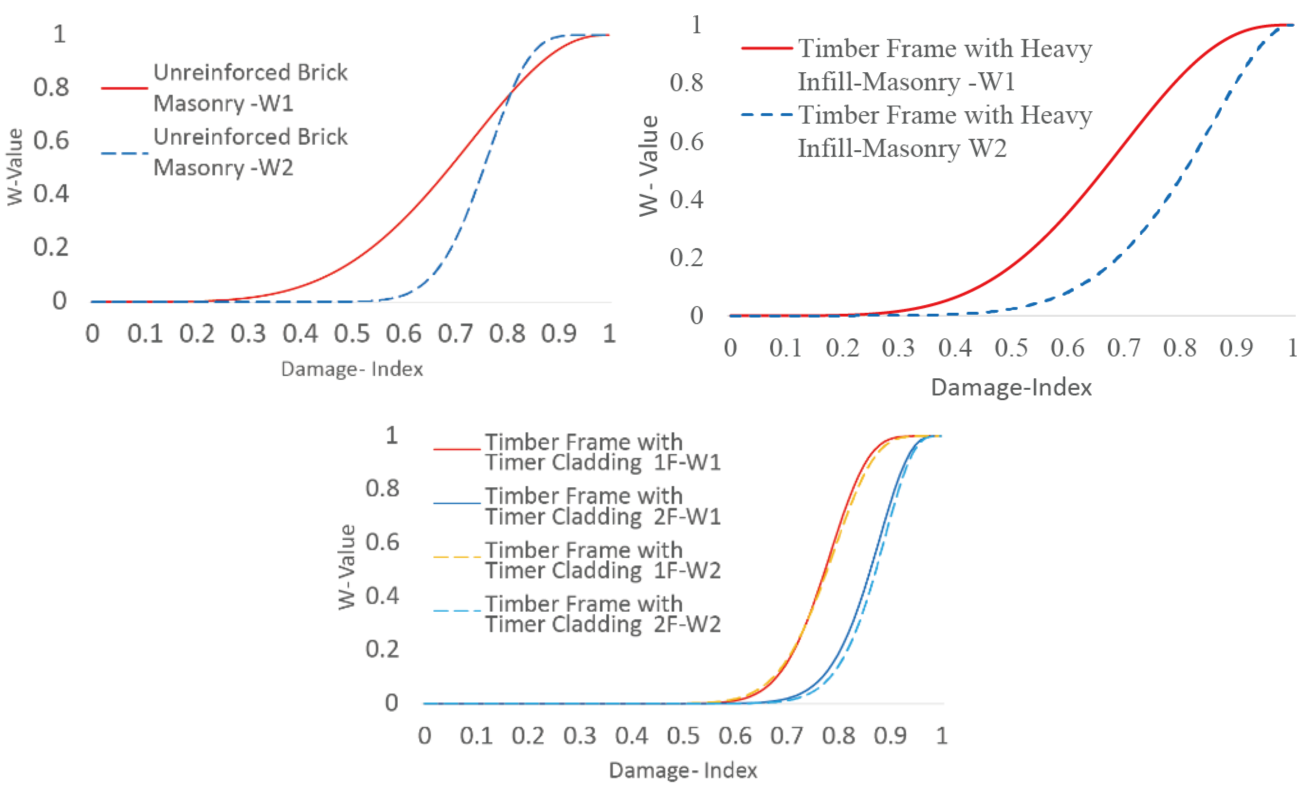

Fig. 3-1. W-Functions for each building type

From the comparison of different types of buildings, it can be pointed out that CT1 is similar in W1-value to BB1, but type CT1 has higher preserving performance than type BB1 for W2-value; furthermore, type CT2 is the most highly retentive of indoor space. The flattened layer of building due to collapse of the roof chiefly affects the W1-value of plan loss. The W2-value of section loss is affected by the collapse of a wall in addition to the roof. Therefore, the fall of brick seems to control functional deterioration for both W1 and W2 for building type BB1 made of unreinforced fired brick. Because CT1 designates timber frame buildings with infilled walls of unreinforced fired brick masonry, the W1-value of type CT1 is mainly controlled by the fall of brick, and the W2-value is deeply related to the collapse of frame; whereas the W-values of CT2, of which the main structure is made of timber frame without bricks, are controlled by the inclination of walls and columns. As a result, the W1-value of CT1 resembles that of BB1, with less preservation of indoor space function, and the characteristic is attributed to the brittleness of brick. Higher preservation of W2-value for CT1 than for BB1 is seems to be ascribed to timber frame being more ductile than brick. In addition, it becomes quite evident that type CT2 without use of bricks has the highest preserving performance among the three types, but this type of building is easily fragile at the moment of collapse.

4. Relation between W-Function and Mortality Rate in the 1995 Kobe Earthquake

We compare the W-Function proposed in this paper to the mortality rate in the 1995 Kobe earthquake [5] in order to demonstrate the actual use of this function. The W-Functions are expressed in the plane of Damage Index, and the W-value axes and the mortality rates are shown in the plane of Damage Index and mortality rate per household unit axes in Fig. 4-1. Though the data on mortality rate in the Kobe Earthquake is observed as a mixed form of the first and second floors, we can find a close correlation between the mortality rate and the W-Function. As a result, we will propose a new causality model for estimating human casualties through the W-Function in another paper [6] of this conference.

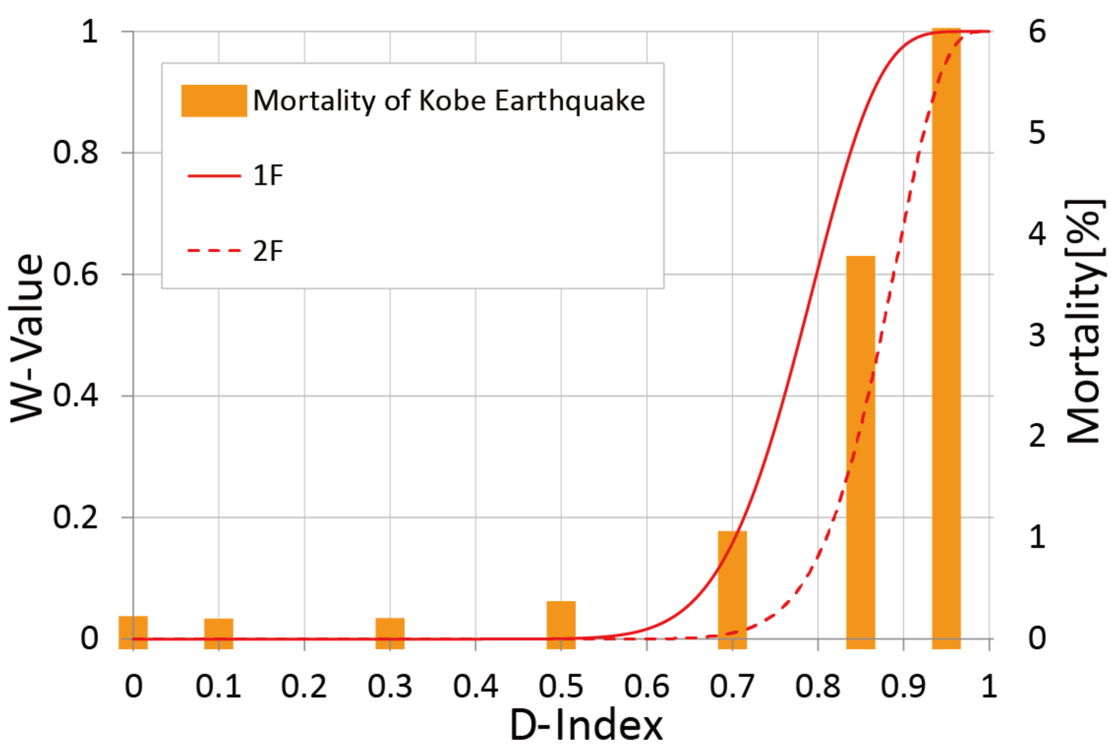

Fig. 4-1. Comparison of W-Function and seismic death risk function for casualties per house

5. Conclusions

The results of this study showed that volumetric loss of buildings can be measured successfully with high resolution by the use of W-values, regardless of the experience or judgment skill of investigators. In addition, positive correlation of W-Function and casualty rate was confirmed. As a result, we recognized that preservation of internal space of buildings limits the casualty rate, and the W-Function is informative to describe the state of volumetric loss of buildings as a probable phenomenon. Definitely, the survival space of buildings is relatively much preserved, and there are very few casualties caused by collapsed buildings not exceeding 0.7 in the Damage Index scale, which shows the structural damage of buildings; if W-Values rapidly approach 1.0, the survival space of buildings almost disappears.

We found that the wood frame structure of Japan and masonry structure of China are quite different from each other in terms of the relationship between W1 and W2. Moreover, we constructed the numeric relationship between the volumetric index and the damage index, representing the structural damage of buildings as each W-Function for different types of wood frame structures and masonry structures. In addition, applying the proposed functions to damage estimation for human casualties can be used to develop the probable density function of human injury, described by Injury Severity Score and used globally in the field of disaster medicine [6].

6. References

[1] Kawasumi H (1954): Intensity and magnitude of shallow earthquakes. *Bereau Central Seism. Intern.Ser.A, Trav, Sci.*, **19**, 99-114.

[2] Okada S (1996): Description of indoor space damage degree of building in earthquake. *11th World Conference on Earthquake Engineering,* 3/4 (CD-ROM) Paper No.1760.

[3] Grunthal G (1998): European Macroseismic Scale 1998. *Cahiers du Centre Europeen de Geodynamique et de Seismologie,* **15**, 1-99.

[4] Okada S, Takai N (2000): Classifications of structural types and damage patterns of buildings for earthquake field investigation, *12th World Conference on Earthquake Engineering*, Auckland, New Zeeland. Paper no.705.

[5] Tabata N, Okada S (2006): Seismic death risk function for casualties per house. *J. Struct. Constr. Eng., AIJ,* **605**, 71-78.

[6] Okada S, Nakashima T, Iida A, Kitahara M (2017): A new causality model for evaluating the probability of human damage from injury to death in collapsed building. *16th World Conference on Earthquake Engineering*, Santiago Chile.