11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 1760. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DESCRIPTION FOR INDOOR SPACE DAMAGE DEGREE OF BUILDING IN EARTHQUAKE

Shigeyuki OKADA

Department of Architectural Engineering, Hokkaido University
N13W8, Kita-ku, Sapporo 060 JAPAN

ABSTRACT

We should note different extent of casualties in destroyed buildings that are classified as having the same structural damage degree. For quantitative estimation of indoor space damage degree controlling casualty potential in damaged building, an idea of Spatial Vulnerability Analysis by means of W-Function was proposed. The case study of Chinese buildings proved the availability of W-Function for building damage classification that is relevant to the casualty potential.

KEYWORDS

indoor space damage; casualty; mortality; building typology; vulnerability.

INTRODUCTION

More than 70% of the earthquake fatalities worldwide can be attributed to building collapse (Coburn et al., 1992a). The severity of seismic damage to buildings is usually defined by assigning a damage degree to the main structural elements, such as column, beam and/or load-bearing wall. However we often observe different extent of casualties even in buildings classified as the same structural damage degree. This fact induces us to consider a new index for building damage classification that is relevant to observed damage and should be universally applicable. This research can be used for future actions envisaging strategies for a global earthquake casualty reduction.

The resistance of various building types to earthquake loads can be defined by the use of "Vulnerability analysis". The vulnerability of a building is one of the principal factors affecting the occurrence of casualties in earthquakes. Nevertheless past experience has shown that the probability of casualty occurrence depends very much on the loss of indoor space in affected buildings. The former should be called "Structural vulnerability analysis" and has been vigorously discussed, for example at the special session of the international conference on seismic zonation in France in 1995; while the latter might be called "Spatial vulnerability analysis". In this paper, I try to define a new index for indoor space damage estimation in order to progress vulnerability analyses, by which the probability of casualty for inhabitants in a building unit can be discussed and some damage patterns for various structural building types can be characterized, on the basis of a probabilistic approach.

INDOOR SPACE DAMAGE ESTIMATION CRITERIA

The method for estimation of indoor space damage degree associating with cause of death and injury is proposed in this chapter. Krimgold(1989) classified the cause of mortality in destroyed RC buildings in case of the 1985 Mexico earthquake as follows: Penetration wounds (13.38%), Fractures (16.18%), Crush (3.52%), Amputation (8.45%), Contusion (35.31%), and Dehydration (22.53%). The indoor space damage inducing the above cause of death is described by several indices Wi (i=1 to n) which mean functional deterioration of the living space in buildings. In this paper, 4 types of indices Wi are adopted, that is, plan buildings to 1.0 for buildings that suffered a total loss of the space function.

Definition of Index W1 : Plan Loss

W1 describes the space loss in plan of buildings, and is given by the ratio of A1 to A as follows:

$$W1 = A1/A,$$

where A1 is the floor area occupied by debris and A is the total floor area (Fig.1). W1 is related to human casualty risk during an earthquake due to the fall of disintegrated stones, bricks and/or concrete particles of roof and slab which are supposed to cause death or such injuries as multiple contusions, multiple fractures, and flowing wounds.

Definition of Index W2 : Section Loss

W2 describes the space loss in section of buildings, and is given by the ratio of B2 to B as follows:

$$W2 = B2/B,$$

where B2 is the sectional space loss due to the fall or collapse of a heavy structural material such as concrete beam, column, wall or floor slab, and B is the total sectional area (Fig.2). W2 is related to the factor causing crush wounds, amputation, and loss of blood.

Definition of Index W3 : Volume Loss

W3 describes the void index or the volume loss of survival space, and is given by the ratio of C3 to C as follows:

$$W3 = C3/C,$$

where C3 is the volume of debris and C is the space capacity beneath 2 meters from floor level which is called "Survival space" capable of containing survivors in a collapsed building (Fig.3). W3 is related to the factors causing suffocation and controlling whether population expose to an event are entrapped by a collapsed building (entrapment ratio).

Definition of Index W4 : Amount of Dust

W4 describes the amount of dust as a result of collapse of building (Fig.4). W4 is the casualty risk related to asphyxiation and should be scaled by the rubble size of debris. The finer rubble size is, the higher dust potential becomes.

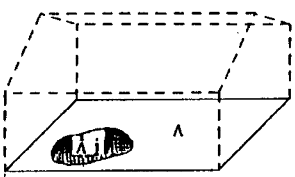


Fig.1. Definition of plan loss (W1).

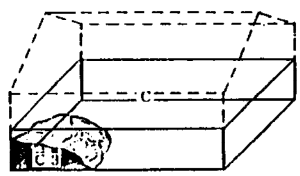
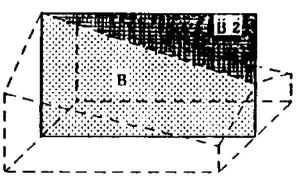
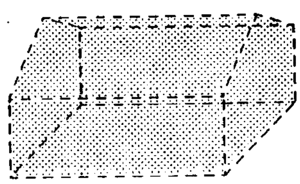


Fig.3. Definition of volume loss (W3)





BUILDING COLLAPSE PATTERN DESCRIPTION APPLYING THE NEW INDEX

Though damage patterns of buildings have been generally discussed in structural damage, jointly using with the proposed indoor damage indices may turn out to be more applicable in case of studying about mortality in damaged buildings. Because building collapse patterns are strongly related to structural building types specified by construction methods and materials, the definition of worldwide standard building types should be made in advance.

Classifications of Structural Building Types

In order to systematically classify almost all the structural building types over the world, the classification criteria is defined based on the definition of MSK intensity scale. That is, buildings are classified into Engineered Building Type D or Non-Engineered Building Type which is further divided into three categories: Masonry Type A (Weak Masonry), Masonry Type B (Loadbearing Unit Block Masonry), and Building Type C (Frame Structure). The MSK scale is commonly used in the world. This is a reason why the MSK is adopted as the first logical order in the tree structure of classification. The second logical order (Main Structural Classification) is defined by main structural material with referring to the Model Buildings developed by the Applied Technical Council (ATC-14, 1987). In the final logical order buildings are classified into 24 types. The list is shown in Table 1. Coburn and Spence (1992b) proposed a little different building typology modified from this table.

Table 1. Classifications of structural types of seismic vulnerability

	MSK Intensity Scale Definition	Main Structural Classification		Building Type	
Non Engineered Buildings	Masonry Type A Weak Masonry	AE	Earthen	AE1 AE2	Rammed earth construction Composite earth with timber or fiber
		AR	Rabble Stone	AR1	Rabble stone masonry in mud mortar
		AA	Adobe	AA1	Adobe sun-dried earth brick in mud mortar
	Masonry Type B Loadbearing Unit Block Masonry	BB	Unreinforced Brick	BB1 BB2	Unreinforced fired brick masonry in cement mortar Brick masonry with horizontal reinforcement
		BC	Concrete Block	BC1	Concrete block
		BD	Dressed Stone Masonry	BD1	Squared and cut stone masonry
	Building Type C Frame Structures	CC	RC Frame Cast In-situ	CC1	Reinforced concrete frame, in-situ
		CT	Timber Frame	CT1 CT2	Timber frame with heavy infill-masonry Timber frame with timber cladding
Engineered Buildings	Building Type D Engineered Structures	DB	Reinforced Unit Masonry	DB1	Reinforced brick masonry
		DC	In-Situ RC Frame	DC1 DC2 DC3	In-situ RC frame with non-structural claddin In-situ RC frame with infill masonry In-situ RC frame with shear wall
		DP	Precast RC Structures	DP1 DP2 DP3	Precast RC frame with infill masonry Precast RC frame with concrete shear walls Pewcast large panel structures
		DS	Steel Frame Structures	DS1 DS2 DS3 DS4 DS5	Light steel fame Steel frame, moment-resistant Steel frame with infill masonry Steel frame, braced Steel frame with RC shear wall or core
		DH	Hybrid or Composite	DH1	Composite steel frame with in-situ RC casing Steel/RC Structures

Structural Damage Estimation Criteria

As each damage of structure and indoor space characterizes damage patterns of buildings, the relation between them should be discussed in viewing various building damage patterns. It is well known that structural damage can be described by vulnerability functions designating the probability of damage of various building types under the same level of seismic motion. For example, vulnerability functions (V-

$$\text{V-Function} = 1/\left(\sqrt{2\pi}\sigma\right)\int_0^I \exp\left[-\left(I'-I_0\right)^2/\left(2\sigma\right)^2\right]dI',$$

where, V-Function shows cumulative damage rate expected in a dwelling area. For discussing the building damage pattern with relation to indoor damage indices, structural damage degree is necessary to be treated as an index, by which structural damage degree for a building unit can be described. D level classification from D0 to D5 as defined in the MSK scale can be useful for describing building structural damage degree. However, D level classification is not a scale capable of quantitatively estimating damage degree but it is a sort of raking. In order to estimate the structural damage degree for each building, structural damage index ranging from 0 to 1.0, which is a continuously numeric scale describing the damage degree for a building unit on the damage level from D0 to D5, is introduced instead of V-Function.

Despite of a lot of references, no structural damage estimation criterion has been uniquely confirmed. For example, the MSK-81 (1981) gives the definition of damage degree of single storey buildings. In Japan, 4 level categories for wooden houses are adopted as "No damage", "Partial damage", "Heavy damage", and "Major damage". And Architectural Institute of Japan (1980) proposed the damage estimation criteria for reinforced concrete frame buildings for the purpose of damage surveys after the 1978 Miyagi-ken Oki Earthquake. While Coburn (1989) explains the progression of damage in Turkish stone masonry buildings. The Chinese researchers (Yang et al., 1981) give clearly the definition of damage degree of multistorey buildings. Applied Technology Council (ATC-29, 1989) describes in detail the damage state of structural damage estimation criteria. Table 2 shows the relationship between D level damage classification on the MSK scale and the structural damage index proposed here, comparing with various damage estimation criteria proposed by others. Instead of D level damage classification, the central damage index is used as the scale of structural damage of buildings in this paper.

Table 2. Building structural damage estimation criteria

Damage Class	Damage State	Building Type:Not specified Single Storey MSK-81 (1981)	Building Type:Adobe Single Storey Coburn (1987)	Building Type:Brick Masonry Multi-storey Yang et al. (1981)	Structural Damage Index	Central Damage Index
D0	None	None	None	None or Fine cracks in corner	0	0
D1	Slight Damage	Fine cracks in plaster Fall of small piecies of plaster	Fine cracks in walls	Fine cracks in walls	0-0.2	0.1
D2	Moderate Damage	Small cracks in walls Fall of fairly large pieces of plaster Pantiles slip off Cracks in chimneys Parts of chimneys fall down	Cracks in walls	Cracks spreading diagonally in wall Parts of incidental structures such as chimneys and parapets fall down	0.2-0.4	0.3
D3	Heavy Damage	Large and deep cracks in walls Fall of chimneys	Corner failure	Corner failure Fair gaps on walls	0.4-0.6	0.5
D4	Destruction	Gaps in walls Parts of buildings may collapse Separate parts of the buildings lose thier cohesion Inner walls and filled-in walls of the frame collapse	Midwall collapse Panel of non-loadbearing wall collapse	Panel of non-loadbearing wall collapse A part of upper storey of the buildings totally collapse 1-3 quarters of the building collapse	0.6-0.8	0.7
D5	Total Damage	Total collapse of buildings	Roof collapse	Total pancake collapse Disintegrfarion Parts of upper storey of the building totally collapse Over 3 quarters of the building collapse	0.8-1.0	0.9

CASE STUDY FOR CHINESE MASONRY BUILDINGS

Structural and spatial vulnerability analyses were made on the basis of the available photographic evidence about damaged buildings in China to characterize the damage pattern of masonry buildings in order to examine the applicability of the new indices Wi. The data source of photographs about damaged buildings in China is the Photo Album of Eight Strong Earthquake Disasters in China (Institute of Geology, State Seismological Bureau, 1981). This photo album treats with 8 earthquakes; the 1975 Haicheng Earthquake, the 1976 Tangshan Earthquake, the 1966 Xingtai Earthquake, the 1976 Songpan Earthquake, the 1974 Zhaotong Earthquake, the 1970 Tonghai Earthquake, the 1973 Luhuo Earthquake, and the 1976 Longling Earthquake. The total number of damaged buildings taken the photographs is 111, of which breakdown is described in Fig.5. According to this figure, most of Chinese houses are classified into Unreinforced Brick Masonry (BB1) or Timber Frame with Heavy Infill-Masonry (CT1). For this analysis, 49 buildings which belong to building type BB1 or CT1 were selected in the end.

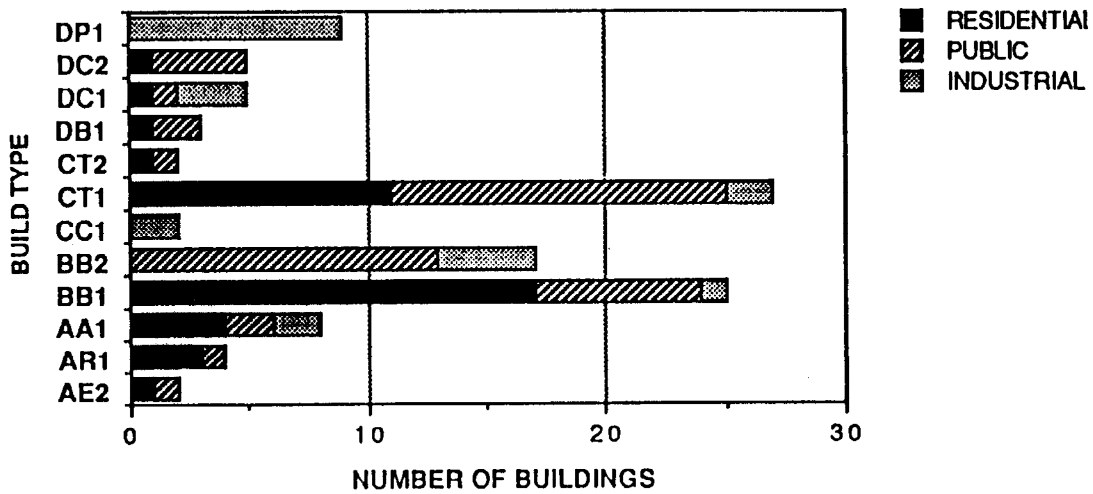


Fig.5. Breakdown of building types for Chinese buildings.

Estimation of Structural and Spatial Vulnerabilities

Coburn (1986) illustrated the typical damage pattern of masonry buildings in an intelligible figures (Fig.6). From the structural damage standpoint, Fig.6 (a) to (d) are classified as moderate damage (D2), heavy damage (D3), total damage (D5), and total damage (D5), respectively. The indoor damage indices Wi (i=1 to 4) corresponding to each damage are also shown in these figures. The scores of indices are measured with the eye. Though the damages in Fig.6 (c) and (d) are classified into the same damage level D5 (total damage) from the structural damage point of view, one in Fig.6(c) is less severe with section loss W2 and volume loss W3 than in Fig.6(d). In spite of the roof of a house in Fig.6 (c) fell down, three walls remain standing with preserving a slight survival space in the damaged house. While a house in Fig.6 (d) is totally disintegrated without a survival space. It is able to distinguish a different damage pattern between them by introducing the indoor damage indices. On the basis of the Photo Album, damaged Chinese masonry buildings were scored in structural damage (central damage index) and indoor space damage (indoor damage indices) for each floor.

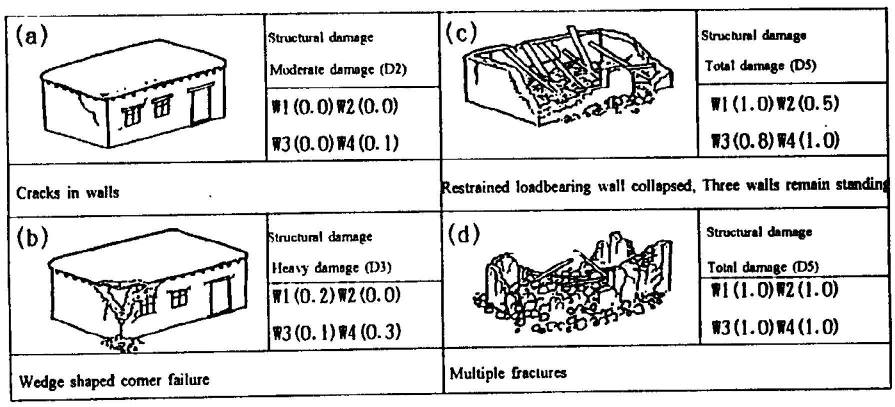


Fig.6. Typical damage pattern of masonry buildings described in Coburn (1986), and the indoor damage indices Wi and structural damage level D corresponding to each damage.

Spatial Probability Density Function by Beta Distribution

An example of the frequency distribution of scores of indices Wi is shown in Fig.7 that means such a probability density distribution of indoor space damage degree. This distribution can be idealized as a likelihood function on indoor space damage under a certain structural damage degree that is indicated by the central damage index. A score of indices Wi is a random variable distributing non-symmetrically in an interval of finite length from 0 to 1. A familiar probability density distribution satisfying the above conditions is the beta distribution f(x;q,r,A,B), as follows:

$$f(x;q,r,A,B) = \frac{1}{B-A}\frac{G(q+r)}{G(q)\times G(r)}\left(\frac{x-A}{B-A}\right)^{q-1}\left(\frac{B-x}{B-A}\right)^{r-1} \quad \text{for } A \le x \le B, \text{ otherwise} = 0$$

where, G(α) is the gamma function defined by

$$G(\alpha) = \int_0^{\infty} x^{\alpha-1}e^{-x}dx.$$

The case of A=0 and B=1 gives the standard beta distribution. Here, the standard beta distribution is adopted as a probability density function of indoor space damage degree (called to W-Function). In Fig.7, the doted line shows the W-Function, that is, the beta distribution obtained through a curve fitting method.

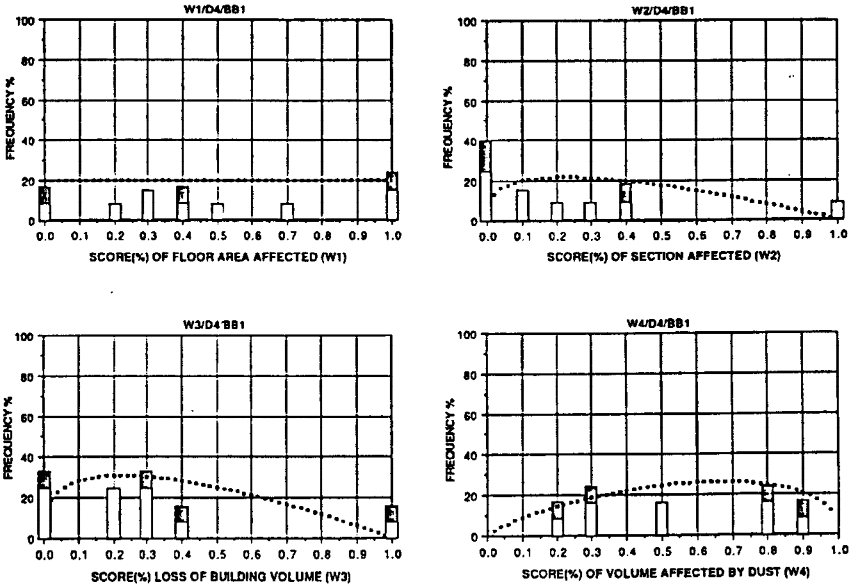


Fig.7. Frequency distribution of scores of W-Functions for building type BB1 (Unreinforced Brick Masonry) on the damage level D4. Square dots mean the standard beta distribution fitted.

Characterization of Collapse of Masonry Buildings

In order to scrutinize the characteristics of W-Function for Chinese buildings, the W-Function is simplified by means of 3 factors such as mean value, standard deviation and range which characterize the shape of W-Function as shown in Fig.8. Fig.9 is an explanatory graph showing the relation between structural damage degree (structural damage index) and indoor space damage degree (indices Wi) by use of the mean value of W-Function, for understanding the preservation of indoor space function dependent on each structural building type. From such a graph, it is able to judge the building capacity sparing inhabitants in a serious earthquake. A building, which belongs to the structural building type with W-Function being on the upper left hand corner in this figure, has higher preservation of indoor space function than one which belongs to the structural building type with W-Function being on the lower right hand corner.

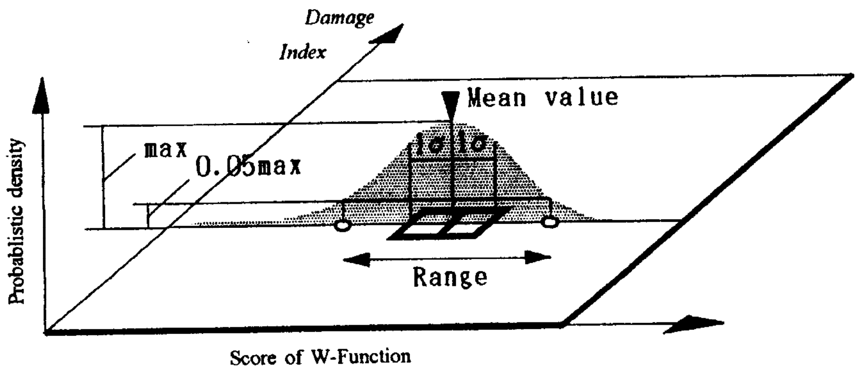


Fig.8. Simplified expression of W-Function by means of mean value, standard deviation, and range.

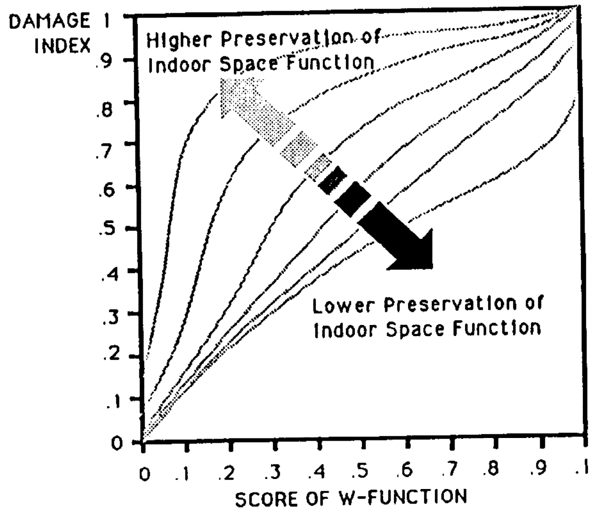
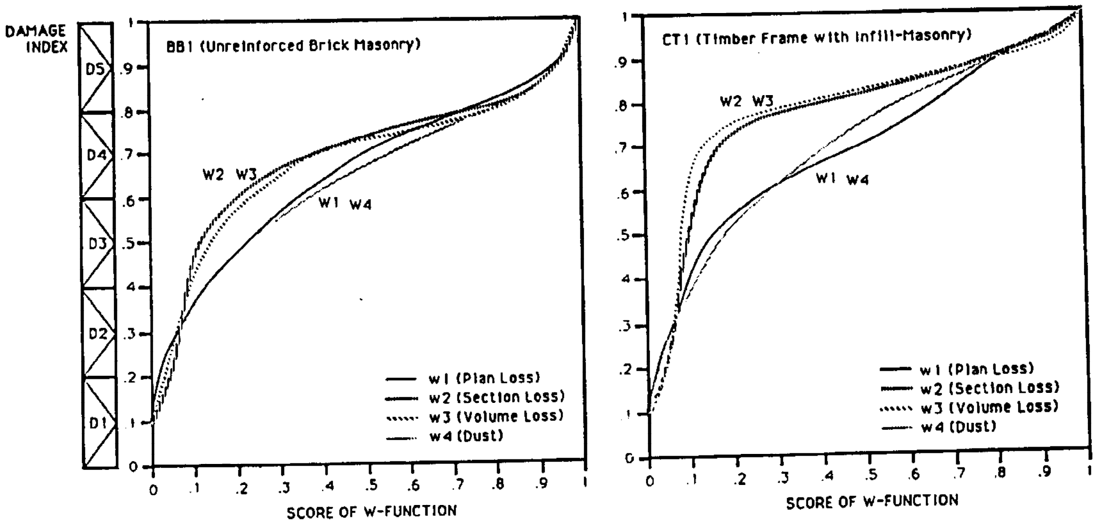


Fig.9. Explanatory graph for understanding W-Function.

The mean values of W-Functions for Unreinforced Brick Masonry (BB1) and Timber Frame with Heavy Infill-Masonry (CT1) are compared in Fig.10. The fall of bricks, which is major material of buildings of Type BB1, controls all of the indoor space functions related with W1 to W4. On the structural damage level D4 (0.6<structural damage index<0.8), the score of indices W2 and W3 related to the cause of heavy injury distribute almost uniformly from 0.2 to 0.8. It means that the indoor space of building of this type has the same probability of becoming the state of slight damage (Wi=0.2) to total damage (Wi=0.8) on the D4. Structural damage on the D4 level is characterized by the collapse of the non-loadbearing wall. Whether a masonry wall falls down inwards or outwards must be accidental, but must be a vital matter to occupants. As shown in the probability distribution, an accident conclusively controls the indoor space damage degree which is relevant to casualty potential. On the D5 damage level, the scores of all W-Functions of this type of buildings is characterized by the collapse of roof. The inside space of building type BB1 is a jumble of debris as a result of collapse of heavy roof elements.



(a) (b)

Fig.10. Comparison between the mean values of W-Functions for BB1 (Unreinforced Brick Masonry) and CT1 (Timber Frame with Infill-Masonry).

The preservation of indoor space for building type CT1 is summarized as follows: Because CT1 is a composite structure system of timber frame and brick masonry, the W-Functions of this type reflect the characteristics inherent to both of structural materials. On the D4 damage level, there is markedly a difference between BB1 (Fig.10(a)) and CT1 (Fig.10(b)). As for W1 and W4 the shape of W-Function of CT1 are similar to those of BB1 because of the fall of bricks mainly controlling W1 and W4. On the other hand, W2 and W3 do not reach even at 0.5 because they are under the control of timber frame also lower than BB1. The safety of timber frame is demonstrated.

From this figure, it can be pointed out that CT1 is similar in W1 and W4 to BB1, but type CT1 has higher preserving performance than type BB1 as to W2 and W3. The collapse of roof of building chiefly affects W1 of plan loss. W2 of section loss and W3 of survival space volume loss are affected by the collapse of wall in addition to roof. W4 of these building types is related to the amount of dust due to the fall of bricks. Therefore, the fall of brick seems to control every functional deterioration from W1 to W4 of building type BB1 made of unreinforced fired brick. Because CT1 designates timber frame buildings with infilled walls of unreinforced fired brick masonry, W1 and W4 of CT1 are mainly controlled by the fall of brick, and W2 and W3 are deeply concerned with the collapse of frame. As the results, W1 and W4 of CT1 resemble those of BB1 in less preservation of indoor space function and the characteristic is supposed to be attributed to brittleness of brick. Higher preservation of W2 and W3 for CT1 than for BB1 is seems to be ascribed to timber frame being more ductile than brick.

CONCLUSIONS

An idea of Spatial Vulnerability Analysis to quantitatively estimate indoor space damage degree in collapsed buildings was proposed. Examples were shown as values of W-Function for selected building types based on analysis of a photographic database of collapsed buildings in some Chinese earthquakes. As a result of this analysis, it was found out that W-Function method could systematically described structural and spatial damage pattern characterized by building types. Casualty in a building is more associated with indoor space deterioration than with collapse of main structural elements of building. It would become important to estimate indoor space damage degree by such an approach proposed in this paper.

As a next step of this research, the criteria of giving a score of W-Function to a damaged building should be completed so as to generalize the method of Spatial Vulnerability Analysis. Further, the W-Functions of all the 24 building types should be parameterized in order to theoretically link between structural vulnerability function and casualty potential, and to progress the sophisticated computer model for estimation of casualties in damaged building.

ACKNOWLEDGMENT

This research was achieved as a part of the collaborative study among Faculty of Engineering, Hokkaido University; Earthquake Research Institute, University of Tokyo; and The Martin Centre for Architectural and Urban Studies, University of Cambridge. The purpose of the study is to establish a computer model for estimation of casualties in a damaged building caused by an earthquake. I am deeply indebted to Prof. Y.Ohta, Prof. R.J.S.Spence, Dr. A.W.Coburn and Dr. A.Pomonis for their helpful discussion.

REFERENCES

Applied Technology Council (1987). Evaluating the Seismic Resistance of Existing Buildings (ATC-14). Redwood City. CA. 1-370.

Architectural Institute of Japan. (1980). Reports on the Damage Investigation of the 1978 Miyagi-ken oki Earthquake. 1-907. (in Japanese).

Coburn, A.W. (1986). Seismic Vulnerability and Risk Reduction Strategies for Housing in Eastern Turkey. *Ph.D Dissertation. University Cambridge.* 1-245.

Coburn, A.W., R.J.S.Spence, and A.Pomonis (1992a). Factors determining human casualty levels in earthquake: Mortality prediction in building collapse. *Proc. of Tenth World Conf. Earthq. Engg.* 5989-5994.

Coburn, A.W. and R.J.S.Spence (1992b). Earthquake Protection. John Wiley & Sons Ltd. 1-355.

Institute of Geology. (1981). The Photo Album of Eight Strong Earthquake Disasters in China. Seismological Press. China.

Krimgold, F. (1989). Search and Rescue in Collapsed Reinforced Concrete Buildings. *Proc from the 3rd U.S.-Mexico Workshop on 1985 Mexico Earthquake Research.*

Yang, Y. et al. (1981). Earthquake Destruction of Multi-Storey Brick Masonry Building in China. Seismological Press. China. (in Chinese).