EARTHQUAKE DAMAGE AND THE AMOUNT OF WALLS IN REINFORCED CONCRETE BUILDINGS

by

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SYNOPSIS

From the analysis of the observed damage to low-rise reinforced concrete buildings around Hachinohe City in 1968 Tokachioki earthquake by evaluating the two parameters, wall area ratio and average shear stress in walls and columns, it is concluded that damaged and undamaged buildings could be significantly distinguished by these two parameters.

Based on the relation of earthquake damage to wall ratio and nominal shear stress in columns and walls, the probability distribution of the earthquake resistant capacity of existing buildings was estimated and the prediction of the extent of earthquake damage was made.

EARTHQUAKE DAMAGE AND WALL AREA

From the observation that, in the event of 1968 Tokachioki earthquake, most of the severely damaged reinforced concrete buildings had only small amount of walls, an investigation was undertaken on the relation between the extent of earthquake damage and the amount of walls in reinforced concrete low-rise buildings located in the eastern part of Aomori Prefecture, e.g., Hachinohe City and Misawa City, where damage to buildings were most severe. Most of the buildings investigated were three-story school buildings.

Nakagawa et al. made valuable investigation on the relation between damage and the amount of wall in reinforced concrete buildings for 1923 Kanto earthquake (Ref. 1). The analysis by the author differs from Nakagawa's approach in that it considers, in addition to wall amount, nominal average shear stress in the first floor columns and walls expected to have been experienced during earthquake.

Wall-Area Index, Column-Area Index and Average Shear Stress in Walls and Columns

Wall-Area Index : $A_w/\Sigma A_f$ (cm^2/m^2)

Wall-area index is defined as the ratio of the wall area in the first floor in a direction (transverse or longitudinal), A_w(cm^2), to the total floor area above the ground floor, ΣA_f(m^2). Reinforced concrete walls of which length are greater than 60 cm are all taken into consideration. For walled columns, the full areas of side walls are into account irrespective of their lengths.

Column-Area Index : $A_c/\Sigma A_f$ (cm^2/m^2)

Column-area index is defined as the ratio of the column area in the first floor, A_c(cm^2), to the total floor area above the ground floor, ΣA_f(m^2).

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Average Shear Stress in Walls and Columns : $W/(A_c+A_w)$ (kg/cm^2)

Average shear stress in walls and columns is defined as the ratio of nominal building weight above the ground level, $W=1000\Sigma A_f(kg)$, to the sum of cross-sectional areas of walls and columns, (A_w+A_c) (cm^2), in the first floor in a direction. This value can be interpreted as the nominal average lateral shear stress in columns and walls, under the assumption that the weight per unit floor area of the building is 1000 kg/m^2 and the lateral base shear coefficient is 1.0. In evaluating the total floor area, areas of canopies, balconies and penthouses are all taken into account.

Classification of Damage Level

The levels of damage are classified under the symbols and definitions indicated in Fig. 1. It is intended that the characteristic patterns of damage in walls and columns are easily identified by using these classifications.

Results of Investigation

Fig. 1 shows the values of wall-area index, column-area index and average shear stress in walls and columns defined in the previous section, which were calculated based on the structural dimensions and building data collected by the author as well as the building data described in the Report on Building Damage in 1968 Tokachioki Earthquake by Architectural Institute of Japan (Ref. 2). Values for transverse and longitudinal directions are plotted simultaneously in Fig. 1. A group of curves indicating the relation between wall-area index and average nominal shear stress for various values of column-area index are shown in Fig. 1, so that the relation among these three parameters can be easily understood. Also shown are the ranges of required wall areas specified in the Structural Standard for Reinforced Concrete Walled Structures by Architectural Institute of Japan.

Discussions on the Results

The following could be deduced from Fig. 1.

As seen from Fig. 1, buildings which suffered no or slight damage have apparent characteristics in terms of wall-area indices or nominal average shear stresses. Namely, undamaged buildings have (1) the wall-area index of more than 30 cm^2/m^2, or (2) the average shear stress of less than 12 kg/cm^2. Some undamaged buildings have the average shear stress greater than 12 kg/cm^2, which may be explained from the fact that these buildings are of C-type standard school buildings with the bay width of 3 m in the longitudinal direction having a number of rather slender columns and hence the shear failure in columns was not likely occur.

As the critical value of average shear stress dividing the damaged and undamaged buildings in case the wall-area index equals zero, it is inferred that the nominal ultimate stress of columns (stress for shear failure in short columns, in view of the failure pattern of damaged buildings) is 12 kg/cm^2. On the other hand, from the fact that the critical wall-area index dividing damaged and undamaged buildings is 30 cm^2/m^2, the nominal ultimate stress of wall is inferred as 33 kg/cm^2, by considering the case of column-area index equal to zero.

Using these two critical values, the nominal ultimate base shear of the building is calculated as $12A_c+33A_w$(kg). Equating this ultimate base shear strength to the nominal lateral force $1000\Sigma A_f$(kg), a curve can be defined indicating the condition that the nominal ultimate strength is equal to the nominal lateral force (corresponding to the total weight), as shown by the solid curve in Fig. 1.

Buildings with ✕ mark (shear failure in walls and columns) seem to be scattered along this curve. Most of buildings with ⊗ mark (failure in walls) are also along this curve.

The results obtained from Fig. 1 may be used as simple criteria for judging roughly the level of expected damage to buildings induced by earthquake motions.

In the analysis of the damage in 1968 Tokachioki earthquake, buildings could be classified into three zones, A, B and C on the plot of Fig. 1.

(1) In zone C, buildings are not damaged or very slightly damaged.

(2) In zone B, buildings with walls suffer more or less shear cracks in walls, especially heavy shear cracks in case the average shear stress is large, whereas buildings with no or very little walls may suffer shear failure in columns in case of short columns.

(3) In zone A, walls are heavily cracked and columns are heavily damaged in shear in case columns are short and shear failure precedes bending failure.

It is considered that, in the evaluation of the earthquake resistant capacity of the building, the buildings which fall in zones A and B require more detailed analyses including the consideration of column failure pattern and torsional behavior due to the eccentric arrangement of walls.

DISTRIBUTION OF EARTHQUAKE RESISTANT CAPACITY OF EXISTING BUILDINGS

Distribution of Earthquake Resistant Capacity

In the calculation of nominal average shear stress in Fig. 1, the nominal lateral force W is assumed to be $1000\Sigma A_f$(kg), by assuming that the building weight per unit area is 1.0 ton/m^2 and the base shear coefficient is 1.0.

From the response analysis using the ground motions recorded in Hachinohe in Tokachioki earthquake, the base shear coefficient for low-rise buildings is estimated to be 0.7 to 0.8. The average weight per unit area of actual reinforced concrete buildings is approximately 1.3 ton/m^2. Therefore, the response shear in the event of Tokachioki earthquake is estimated to be $(0.7\sim 0.8)\times 1.3\Sigma A_f(ton)=(0.9\sim 1.0)\Sigma A_f$(ton), which is almost equal to the nominal lateral shear used in the previous analysis.

This means that the estimated ultimate shear stresses of columns and walls, 12 kg/cm^2 and 33 kg/cm^2, as well as the ultimate base shear, $(12A_c+33A_w)$ (kg), are considered to be realistic, not nominal, values.

Here, we define a simple index for the earthquake resistant capacity, C_Y, as follows.

$$C_Y \times (1300\Sigma A_f) = 12A_c + 33A_w$$

Fig. 2 shows the distribution of C_Y calculated for the existing reinforced concrete buildings. Table 1 lists the location, the use and the number of stories of analysed buildings. Total number of buildings treated is 245, i.e., 52 buildings in Fig. 1 plus 193 buildings newly investigated for this purpose (Ref. 3). Most of the buildings analysed have been designed before the revision of the AIJ Standard for Structural Calculation of Reinforced Concrete Structures and the Building Standards by Japanese Ministry of Construction. In Fig. 2, the smaller value of C_Y for the transverse and longitudinal directions is plotted for each building. Values for one to five story buildings are simultaneously plotted in Fig. 2.

The distribution of C_Y seems to have the peak at $C_Y = 0.8{\sim}1.0$. The probability density function of C_Y could be modelled by a log-normal distribution as shown by the smooth curve of $f(C_Y)$ in Fig. 2.

Prediction of Earthquake Damage

Let the response shear coefficient of building be C_B. Then, the probability of failure of building can be expressed,

$$P_f = P(C_Y < C_B) = P(C_Y/C_B < 1)$$

Though the response shear C_B should also be considered as a random variable which is the function of the dynamic properties of buildings, C_B is tentatively assumed to take a definite value in the following discussion, due to the lack of information. It is considered logical to assume that for low-rise buildings C_B is independent of the number of stories, i.e., the period, as they will belong to the constant response acceleration range.

The probability of failure can be obtained from the probability density of C_Y as follows.

$$P_f = \int_0^{C_B} f(C_Y)dC_Y$$

Fig. 3 shows the curve of P_f calculated from the modelled $f(C_Y)$ in Fig. 2. Looking at Fig. 3, the value of P_f is not so large, about 5 % at most, until the response shear reaches 0.5 . However, it increases rapidly as C_B becomes greater than 0.5, resulting in 25 % for C_B of 0.8, which would interprete the percentage of building damage around Hachinohe City in 1968 Tokachioki earthquake.

CONCLUSIONS

The relation between damage to reinforced concrete buildings caused by 1968 Tokachioki earthquake and the amount of walls was investigated. Also studied was the distribution of earthquake resistant capacity of existing reinforced concrete buildings.

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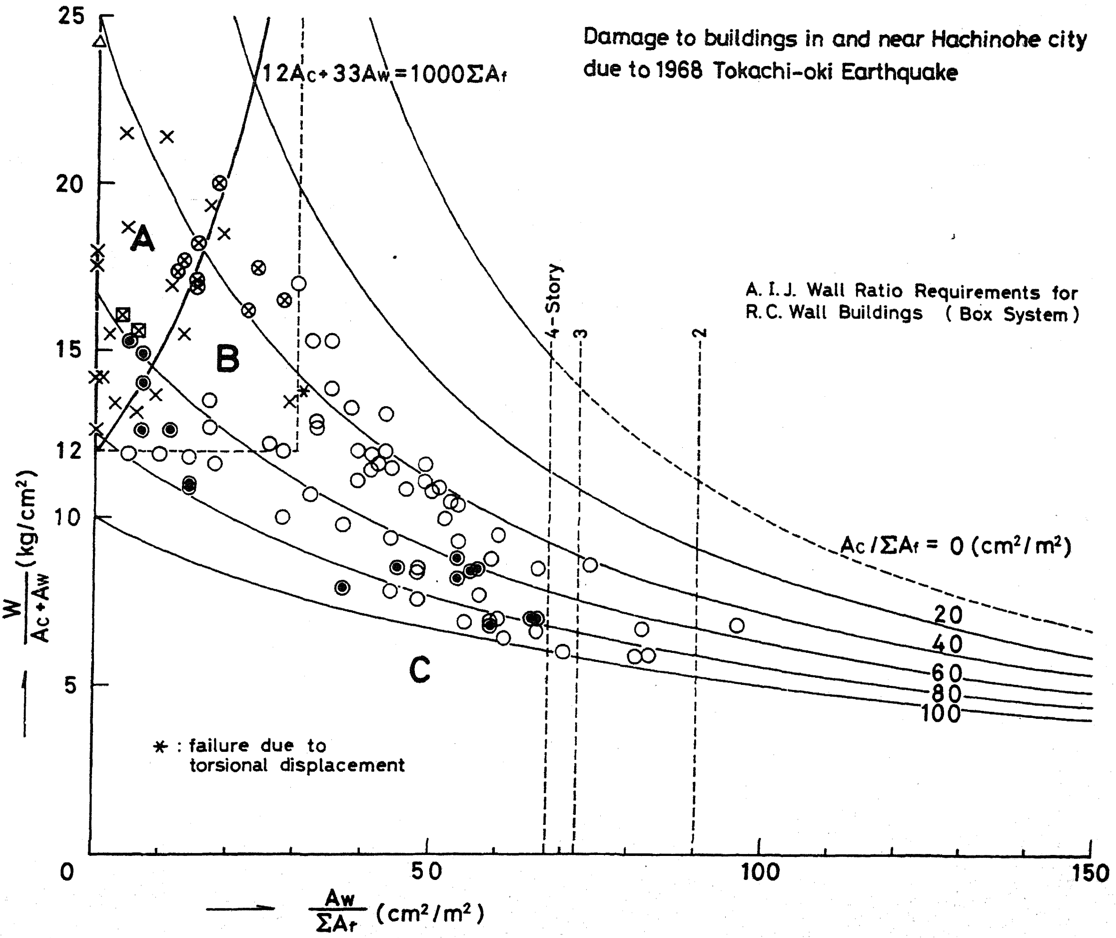

○ : Small or no damage in columns and shear walls

(◉ = C type school building)

△ : Collapse

× : Shear failure in most 1st-story columns

☒ : Bending failure in about a half of 1st-story columns, shear failure in some 1st-story columns and slight shear cracks in shear walls

⊗ : Shear cracks in most 1st-story shear walls and slight damage in columns

Fig. 1 Wall-Area Index, Column-Area Index and Average Shear Stress in Walls and Columns

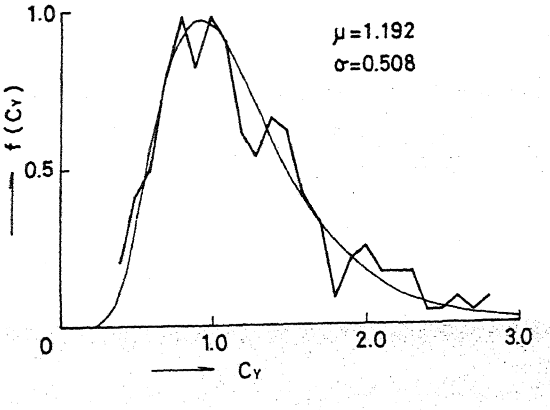

Fig. 2 Distribution of Earthquake Resistant Capacity

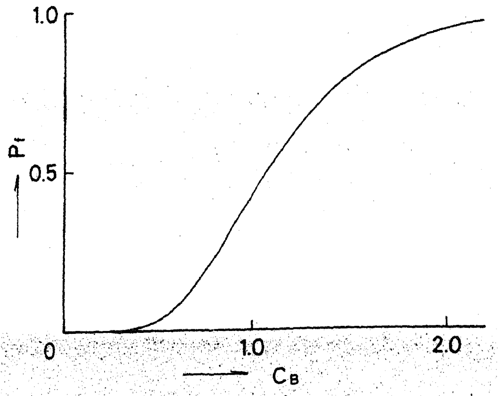

Fig. 3 Probability of Failure of Buildings

Table 1 The Location,The Use and The Number of Stories of Analysed Buildings

	Number of Stories					Total
	1	2	3	4	5	
Office Bldg.		28	29	18	8	83
School Bldg.	2	15	58	8	2	85
Apartment House		1	7	7	3	18
Hospital Bldg.		2	6	5	4	17
Others	3	15	10	9	5	42
Total	5	61	110	47	22	245
Fukushima Pref.		3	7	10	13	23
Miyagi		21	20	12	4	57
Iwate		4	5	7	4	20
Aomori	4	15	57	9	6	91
Akita		7	8	6	2	23
Yamagata	1	10	11	2	3	27
Niigata		1	2	1		4