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RELATIONSHIP BETWEEN SEISMIC CAPACITY AND DAMAGE OF REINFORCED CONCRETE SCHOOL BUILDINGS IN JAPAN THAT HAVE EXPERIENCED THE 2001 GEIYO EARTHQUAKE

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SUMMARY

After the 1995 Hyogoken-Nanbu earthquake, the seismic capacity evaluation of public buildings becomes prevalent in Japan. Since school buildings are used as local evacuation centers after disastrous earthquakes, the verification of their seismic capacity is a pressing need. However, due to the lack of supportive funds, many school buildings still remain unchanged. The relationship between the structural damage and seismic capacity has been identified from various pervious studies. However, there is no reliable relationship yet mainly due to difficulty to grasp information on damaged and undamaged buildings. In this study, the seismic capacity evaluation for the most school buildings in the affected area of the March 24, 2001 Geiyo earthquake, Kure City, Hiroshima Prefectur, was conducted. We found that the seismic indices of school buildings in Kure City are generally low compared with the results obtained for other prefectures in Japan. Therefore in this area, larger structural damage is expected than that of other regions for a same magnitude event. In the 2001 Geiyo earthquake, many old buildings were damaged. Many school buildings suffered from minor to moderate damages since the level of input motion was one in which the structures start to exhibit inelastic responses. Larger levels of damages were observed for the buildings constructed before 1971, especially for those having low concrete strengths. A good correlation between the seismic index (I_S) of structures and their damage grades is observed when the sites are classified by the predominant period.

INTRODUCTION

In the 1995 Hyogoken-Nanbu (Kobe) earthquake, the buildings designed by the old seismic code were severely damaged. Since the buildings designed by the present code suffered from only slight or no damage, the old buildings also need to have the same level of earthquake resistance as the present buildings do. Earthquake resistant capacity of reinforced concrete (RC) buildings can be checked by the method prescribed in Japanese standard for existing reinforced concrete buildings [1].

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In the past studies, seismic capacity evaluation was performed only for the buildings which suffered from high damage levels in order to develop the relationships between the seismic index and damage level [2-4]. Therefore, the earthquake resistant capacity of the buildings in that area was estimated generally lower than the actual one. It should be pointed out that the data for buildings that suffered from no to minor damages were rather scarce to evaluate their seismic resistance. Extensive seismic capacity evaluation for public buildings was carried out only after the 1995 Hyogoken-Nanbu earthquake, including evaluation for buildings with no damage.

Since the seismic performance of public elementary schools and junior high schools in Kure City had already been evaluated before the 2001 Geiyo earthquake, the relationship between the seismic index and actual damage level is analyzed in this study. First, the seismic index data for elementary and junior high school buildings in Kure City are collected. The damages data due to the Geiyo earthquake are also gathered. Microtremor observations are conducted at the sites of these schools in order to evaluate the difference in input seismic motion due to the difference in the soil condition. Using all these data, the relationship between the seismic index and actual damage level in the Geiyo earthquake is investigated.

SEISMIC CAPACITY EVALUATION METHOD

In our study area, Kure City, the seismic safety of school buildings is investigated based on the seismic capacity evaluation method in Japanese standard for existing reinforced concrete buildings [1]. In this method, the seismic index, I_S, is calculated by

$$I_S = E_0 S_D T \,, \tag{1}$$

where E_0 is the basic structural index for each story to a given direction, S_D represents the shape index, calculated from the plan of a structure, and T is the age parameter estimated from the decrepit condition of a building. The basic structural index, E_0, is defined by

$$E_0 = CF\phi \,, \tag{2}$$

in which C and F are the structural strength and ductility index, respectively, ϕ is a coefficient converting the base shear force to the story shear force of a corresponding story..

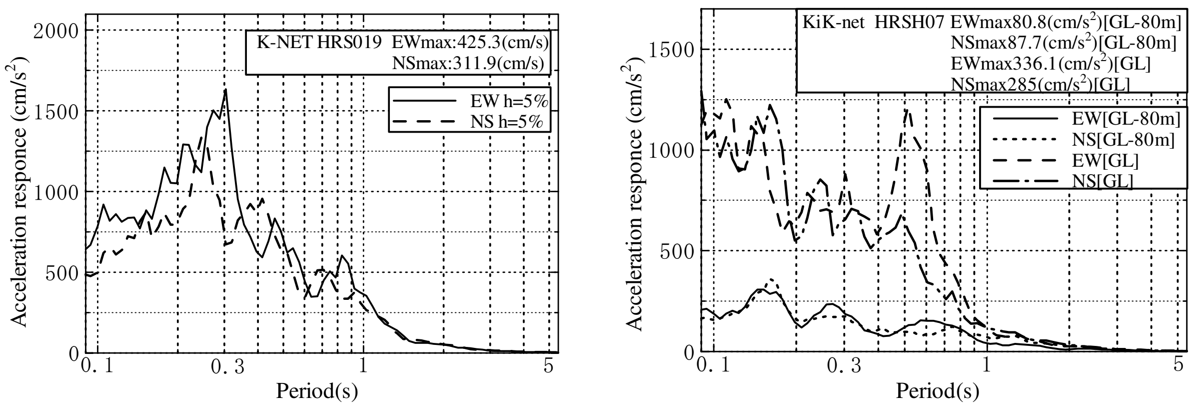
Seismic capacity evaluation has three levels depending on the complexity of calculation. I_{S1} is used for a preliminary classification and easiest to obtain, I_{S2} is used in seismic diagnosis for the most cases, especially for school buildings in Japan. I_{S3} is used for an actual retrofit work and is most costly and time consuming one to obtain necessary parameters. For previous damaging earthquakes, the I_{S2} index demonstrated to show a fair correlation between the seismic capacity of a building and its damage extent. The buildings whose I_{S2} values were equal or less than 0.3 were registered for severe and moderate damages, and the buildings which suffered from no or slight damages were estimated to have the value over 0.6. Therefore, the I_{S2} index has been recognized and recommended to use as a criterion for judging the seismic performance of buildings.

EVALUATION OF DAMAGED BUILDINGS IN KURE CITY

The Geiyo earthquake occurred at 15:28 (local time) on March 24, 2001 with magnitude 6.7 in the Japan Meteorological Agency (JMA) scale. The epicenter is located at 34.125N, 132.713E, in the southern part of Hiroshima Prefecture, with a focal depth of 51 km. The 2001 Geiyo earthquake and the 2000 Tottori-ken Seibu earthquake (M_{JMA} = 7.3) caused slight to moderate damages to structures. In the Geiyo event, the peak ground accelerations were registered as 425 cm/s^2 at Kyoshin Network (K-NET) Kure station

(HRS019) and 336 cm/s^2 at KiK-net Kure station (HRSH07) of the National Research Institute for Earth Science and Disaster Prevention (NIED). Figure 1 shows the acceleration response spectra of the earthquake ground motions at HRS019 and HRSH07. At HRS019 station, a dominant peak is seen in a short period range (0.25 to 0.3 seconds). At the sites having a similar soil condition as HRS019, the predominant ground motion is also considered to be in the range, between 0.25 to 0.3 seconds. At HRSH07, a downhole accelerometer at Gl –80m is deployed as well as a surface accelerometer. The downhole record can be regarded as the bedrock motion, and for the Geiyo earthquake, the short period contents around 0.15 s is dominant.

As can be seen in Figure 2, Kure City is located in the southwest part of Hiroshima Prefecture. This city has been developed in cliffy areas with high steep slopes. There are a total of fifty-four (54) public elementary and junior high schools in this region. Among them, the forty-nine (49) schools with one hundred twelve (112) buildings were constructed before 1981 and the seismic diagnosis was carried out for all these buildings before the Geiyo earthquake. The location of these schools is also plotted in Figure 2. Most of these school buildings are three or four-story. The number of buildings that were built before 1971 is the same as those constructed between 1971 to 1981.



(a) HRS019 station (b) HRSH07 station

Figure 1. Acceleration response spectra with 5% damping ratio for the earthquake ground motions at (a) HRS019 and (b) HRSH07 stations

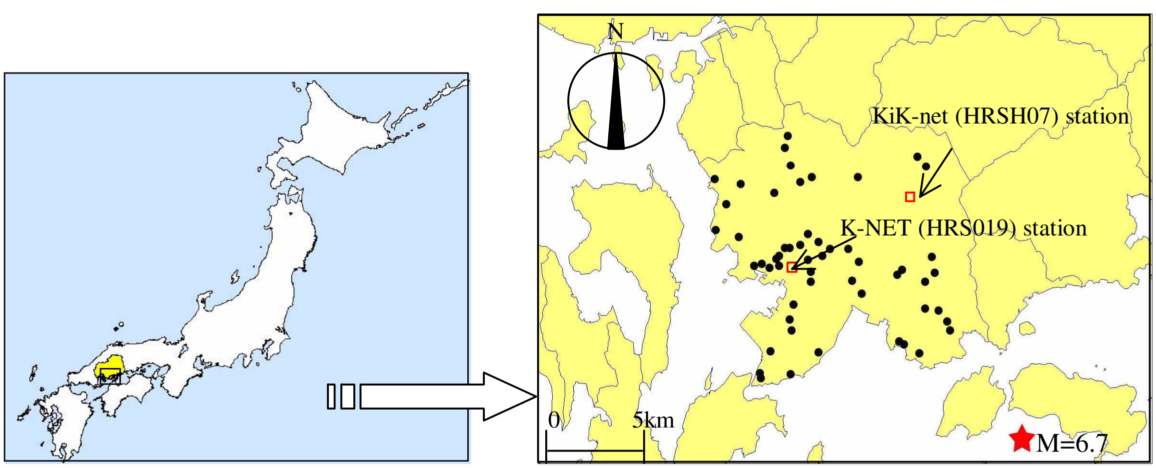


Figure 2. Location of the schools and earthquake observation stations (K-NET and KiK-net) in Kure City

Immediately after the Geiyo earthquake, many researchers conducted building damage surveys. However, only the damages of severely damaged buildings were reported and thus, it is difficult to know the damage levels for all the school buildings in Kure City. Therefore, the present authors first established a unified damage classification for the Geiyo earthquake in our field survey conducted between May 28 to 31, 2002. In the field survey, building damage was investigated by visual inspection and hearing to the principals of the schools. Microtremor observations were also carried out for all the school sites to characterize the site condition.

As the result of the field survey, the structural damage patterns of the buildings were classified into the cracks on columns and shear-walls, the damages to non-structural walls, and the separations of expansion structural-joints. It should be noted when columns have damage, the associated deformation becomes large, and hence shear-walls and/or non-structural walls also suffered from damage in the most cases. We also found that most of the three-story school buildings suffered from severe damages on their structural members.

RELATIONSHIP BETWEEN SEISMIC PEFORMANCE AND DAMEGE EXTENT

Many researchers have pointed out that the second seismic index (I_{S2}) correlates well with the damage level [2-4]. Figure 3 shows the distribution I_{S2} values for the school buildings in Kure City. Although about 20% of the buildings have the I_{S2} value of 0.6 or more, there are many buildings with low seismic performance. Figure 4 shows the relationship between the damage level in the Geiyo earthquake and the year of construction of the buildings. Some buildings constructed before 1971 suffered from damages on columns and shear-walls, but no building constructed on and after 1971 suffered from damages on columns and shear-walls; only they had damages to non-structural walls and expansion joints.

Figure 5 shows the relationship between the concrete strength and year of construction. In seismic capacity evaluation, the smaller value of the specified design concrete strength and the strength by core compression tests is used as “the concrete strength”. As for the core strength, an average compressive strength of concrete from two or more cores should be extracted from each floor of an individual building. In this study, the concrete core strength is used is “the concrete strength”. The solid line in Figure 5 shows the specified design strength. It is considered that the expected damage level decreases with increasing the concrete strength. In is observed that the structural members tend to suffer from serious damage when their concrete strengths become smaller than 18 N/mm^2.

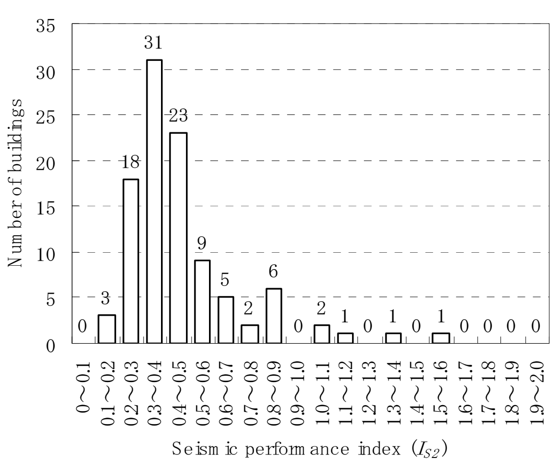


Figure 3. Distribution of I_{S2} value for the school buildings in Kure City

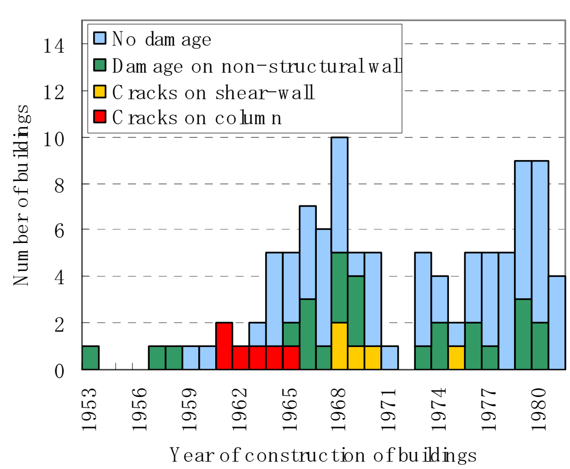


Figure 4. Relationship between the year of construction of the buildings and number of buildings in each damage class

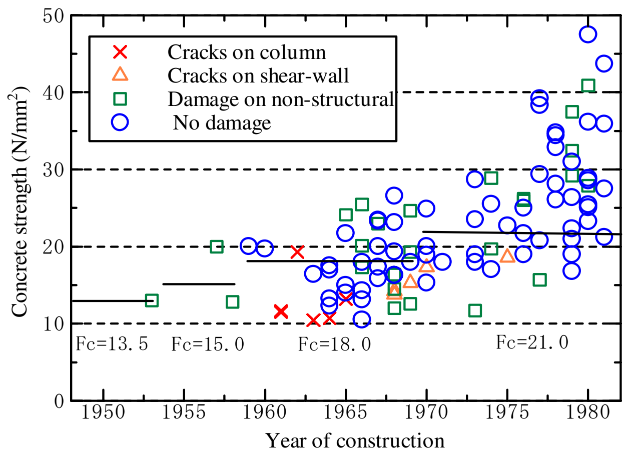


Figure 5. Relationship between the year of construction and concrete strength

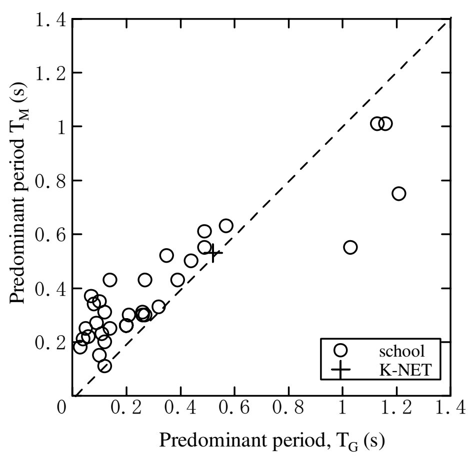


Figure 6. Relationship between the predominant periods, T_G, from SPT-N values and predominant period, T_M , from microtremor observations

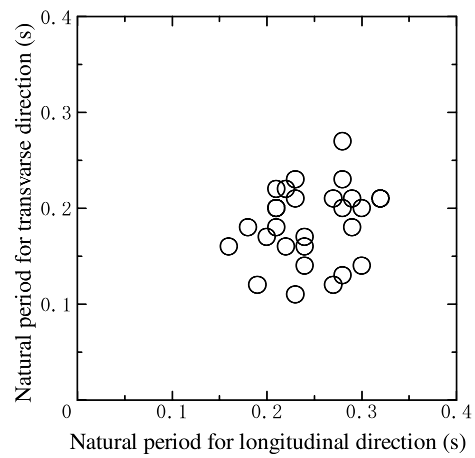


Figure 7. Natural periods of buildings to the two directions

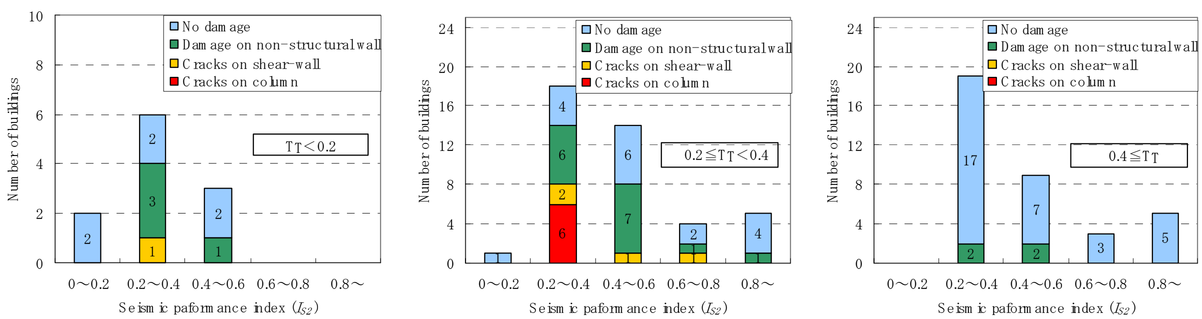
It is necessary to use the actual concrete strength in order to evaluate proper earthquake performance. However, in the absence of such strength values, the specified design strength is usually used in seismic capacity evaluation

Since an input earthquake motion changes with the site characteristics, Figure 6 shows the predominant periods T_M of the sites obtained from the microtremor observations. At each location, the standard penetration test (SPT) N-values are available and the predominant period of the site, T_G, can be estimated from the N values [5]. However, it is pointed out that the estimation of the S-wave velocity from SPT N-vales used in the reference [6] is not so good. On the other hand, the H/V ratio of microtremor represents the predominant period of the site by many studies [7-8]. Figure 6 shows the relationship between T_G and T_M. In the figure, T_G is seen to be under-estimated in the range for 0.5 s or less, and T_G is over-estimated in the period larger than 1 s.

Figure 7 shows the natural periods of school buildings to two directions. The natural periods were also measured by microtremor. The school buildings in Kure City are mostly three or four story, and their natural periods are between 0.12 s to 0.23 s in the transverse direction and between 0.2 s to 0.3 s in the longitudinal direction. The natural period for the transverse direction is short compared with that for the longitudinal direction because many walls are placed in the transverse direction.

Based on the predominant period of the sites estimated from microtremor, we classified the school buildings into three groups and the relationship between the I_{S2} and actual damage in the Geiyo earthquake is investigated as shown in Figure 8. The school buildings on the site in which T_M is between 0.2 s to 0.4 s are seen to suffer from heavy damage. Even for the school buildings whose I_{S2} is high, the shear-walls and the non-structural walls suffered from some damages. On the other hand, for the sites whose T_M are less than 0.2 s or larger than 0.4 s, almost no damage was observed even the I_{S2} was low. Thus, the damage level of buildings is dependent of the site chracteristics, which affects the amplification of earthquake ground motion. In case of analyzing the relationship between the seismic capacity of a structure and its actual damage, it is necessary to consider the site response characteristics, typically represented by the predominant period.

We discuss hereafter only on the buildings with the predominant period between 0.2 s to 0.4 s. Figure 9 shows the relationship between the predominant period of the ground where a building is located and the natural period of the building. According to the figure, the buildings whose the natural period and the predominant period of the site are close suffer from severe damage.



(a) Less than 0.2 s (b) Between 0.2 s to 0.4 s (c) Larger than 0.4 s

Figure 8. Relationship between the I_{S2} value and number of buildings in each damage class the sites where T_M is less than 0.2 s, between 0.2 s to 0.4 s and larger than 0.4 s

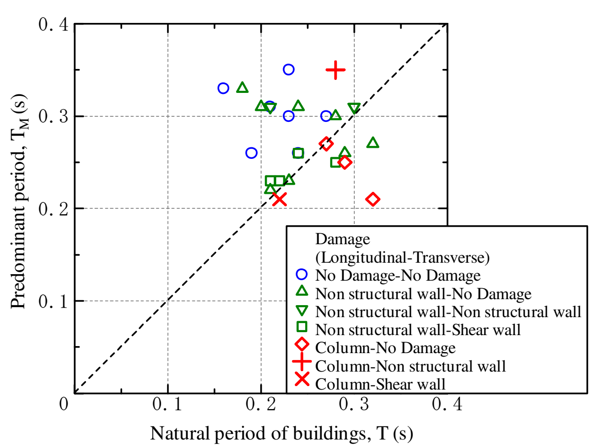


Figure 9. Relationship between the natural period of buildings and predominant period of ground for each damage class

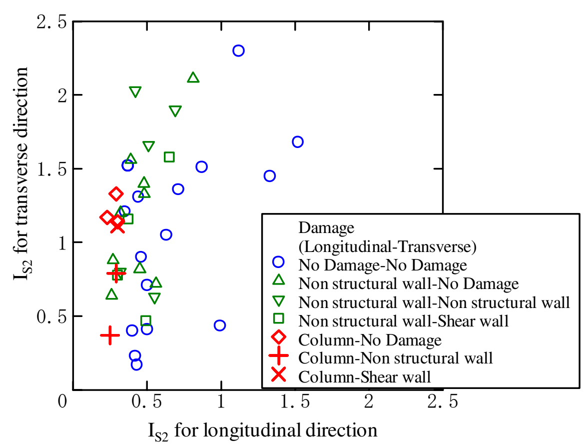


Figure 10. Building damage data plotted on I_{S2} values for two directions

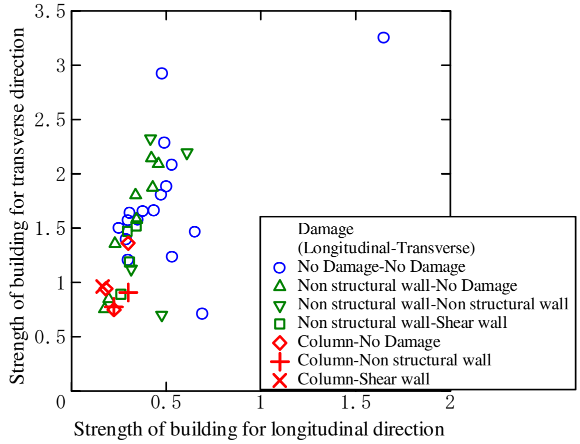


Figure 11 Building damage data plotted on strength of building, C_{CW}, for two directions

Figure 10 shows the relationship between I_{S2} for each direction and its damage level. It can be seen that in the longitudinal direction, buildings whose natural period are less than 0.3 s have structural damage at least to some extent. On the other hand, in the transverse direction, the relationship between the I_{S2} and damage level is not so clear. In seismic capacity evaluation, the seismic performance for the two directions is considered separately.

For buildings that have many walls like schools, it is thought that a building whose I_{S2} value to the transverse direction with many walls is hard to be damaged. However, it turned out that several buildings were damaged to the transverse direction under the influence of the low seismic capacity to the longitudinal direction. In case the seismic performance of a building is evaluated, it is necessary to evaluate the seismic capacity of the both directions.
Considering the fact that seismic diagnosis does not become so popular, grasping earthquake resistance from the sectional area of walls and columns is investigated. The strength of a building is calculated from its concrete strength, and the wall and column area index. The wall and column area index, ${}_0C_{CW}$, is calculated by

$$C_{CW0} = \frac{\sum 2.5A_W + \sum 0.7A_C}{ZWA_i} \tag{3}$$

where A_W and A_C are the sum of wall sectional areas and total column sectional areas for each floor in each direction, respectively. Z represents the regional coefficient of the ground motion intensity in a corresponding seismicity zone, W is the building weight summed upper than a reference floor, and A_i shows a distribution of the story shear force of the building to the vertical direction. The ultimate shear stresses of the wall and column are 2.5N/mm^2 and 0.7N/mm^2, respectively.

Figure 11 shows the strength of buildings for each direction and the damage level. The strength of a building, C_{CW}, is computed by the multiplication of ${}_0C_{CW}$ and concrete strength. From this figure it can be seen that the damage level of school buildings becomes small as the building strength, C_{CW} increases. For the building damage observed in the Geiyo earthquake, the C_{CW} correlates well with the damage pattern.

CONCLUSION

In this study, we investigated the damages of school buildings in Kure City, Japan by the 2001 Geiyo earthquake and analyzed the relationship between the seismic capacity and theist actual damage level. In a field survey, we carried out visual damage inspection and microtremor observation. In the analysis of the relationship between the seismic capacity and damage, the site condition should be considered properly otherwise the relationship is not so clear.

The seismic index data for over one hundred school buildings in Kure City were studied and, we found that their seismic index are generally low, about 80% of them have the I_{S2} value less than 0.6.

On the earthquake motion level which Kure city experienced, the structural members generally sustained no or slight damages. However, the building with low concrete strength experienced cracks on the column while the building of high concrete strength had almost no damage. The concrete strength is found to have significant effects on structural damage. It is necessary to assess an actual concrete strength in order to evaluate the proper earthquake performance of a structure.

The damage level of a building changes with the site characteristics where the building is located. Good correlation between the seismic index (I_S) of structure and the damage grade is observed when the sites were classified by their predominant period.

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