Real-time Building Damage Estimation System based on Observed Building Response

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ABSTRACT :

It is important to maintain building functions following a large earthquake, and this requires a reasonable level of structural seismic capacity. Business continuity plans are generally drawn up for business continuity as much as possible and to scale down the influence of damage suffered in a large earthquake. It is therefore very important to instantaneously assess damage to many buildings and to determine their levels of usability. This is necessary to enable realistic changes to business continuity plans. To this end, a real-time damage estimation system for buildings has been newly developed. This system can quickly estimate building damage and send damage information by computer network to disaster headquarters or to other buildings. Damage information of all target buildings can then be displayed at disaster headquarters. This information can also be shared on a computer network. In this system, target buildings are classified into four ranks according their importance. Structural damage and damage to equipment and secondary systems are assessed in a way that is appropriate to the building's rank. This system has been applied to Kajima's buildings (Headquarters and branches) and is operational. Every time a small or medium-sized earthquake occurs, the accuracy of the evaluated responses and estimation of damage to each building has been improved, and it is thus hoped that the system will provide accurate results following a future large earthquake.

KEYWORDS: Building Damage Estimation, Building Responses, Real-time System

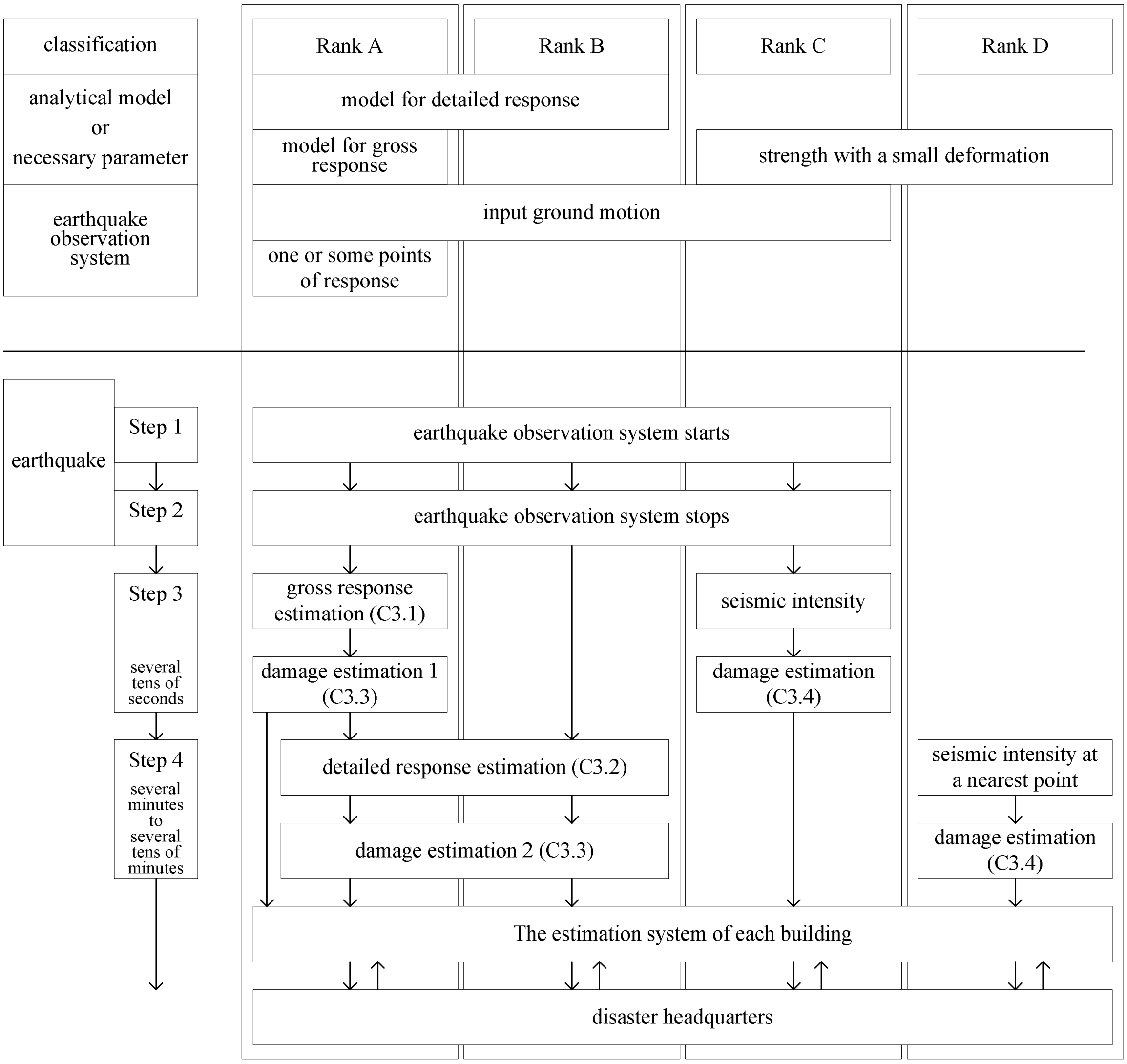
1. INTRODUCTION

This paper describes a building damage estimation system that provides useful information for headquarters to determine whether or not a building can be continuously used. This system can estimate not only structural damage but also damage to equipment and secondary building systems. Some data are available on structural seismic performance and actual damage in past earthquakes. However, few data are available on the seismic performance of equipment and secondary systems. Thus, shaking table tests were conducted to obtain useful data for estimating damage to secondary systems. This building damage estimation system estimates damage and sends damage information to disaster headquarters, who display damage information from all buildings. The same damage information is shared and displayed at all buildings. Target buildings are classified into four ranks on the basis of their level of importance, and building damage is estimated in different ways depending on rank. This system is applied to Kajima's buildings, including headquarters and main branches, and is now operational. This paper presents an overview of this system, a processing flow with time, an evaluation approach and results from an actual earthquake.

2. CLASSIFICATION OF TARGET BUILDINGS AND PROCESSING FLOW

This newly developed system can estimate damage to many intended buildings and display the results at disaster headquarters simultaneously. At the same time, the estimated results of all buildings can be checked at each building. In other words, all the information on building damage can be shared with all concerned. For the damage estimation at each building, this system can determine structural damage states (no damage, minor, moderate and major) and damage to secondary systems such as ceilings, the exterior walls and the partitions. Table 1 shows the processing flow for each building rank.

Table 1. Processing flow for each rank



Notation: (C*.*) is a described chapter No.

2.1. Classification of target buildings

We divided all the target buildings into four ranks on the basis of importance, because it is not realistic to observe the vibration data of all buildings. Thus, the system is applied in four different ways.

Rank A (Importance level 1)

The most important buildings are classified into rank A. Their earthquake observation systems have more than two accelerometers: one for monitoring the input ground motion on the basement or ground floor and the others for monitoring building responses. They have two types of analytical models. With the model for estimating general responses, we can obtain the story drift angles and the floor response accelerations. With the earthquake response analysis model, we can obtain the detailed responses of beams and columns and the responses of building parts.

Rank B (Importance level 2)

The next most important buildings are classified into rank B. Their earthquake observation systems have one accelerometer, which is for monitoring the input ground motion. These buildings have only an earthquake response analysis model. With this model, we can obtain the detailed responses of beams and columns and the responses of building parts.

Rank C (Importance level 3)
The next most important buildings are classified into rank C. Their earthquake observation systems have one accelerometer, which is for monitoring the input ground motion. We can calculate the Japanese seismic intensity from the observed acceleration, and we can roughly estimate building damage from the obtained seismic intensity and building strength.
Rank D (Importance level 4)
A large number of other buildings are classified into rank D. They have no observation system, and they obtain the Japanese seismic intensity from a neighboring observation point. We can roughly estimate building damage from the obtained neighboring seismic intensity and the building strength.

2.2. Processing flow

This newly developed system operates according to this processing flow. We developed different flows depending on categorized building Ranks. The concrete operations for each Rank are conducted along following steps.
Rank A
Step 1: Immediately after an earthquake occurs
The observation system senses the tremor at the basement floor or ground floor, and starts recording the acceleration of the basement floor (input) and of the upper floor (response). It continues to record until the vibration of the input ground motions and the building responses become small.
Step 2: After an earthquake
The observation system gathers the observed acceleration data and sends them to the workspace of the calculator.
Step 3: Several tens of seconds after an earthquake
The calculator enters the observed input ground motion and the building responses recorded at one or more floors into the analytical model to obtain the building's general response. The calculator then estimates all the story drift angles and the accelerations of all floors (see 3.1). Next, building damage is estimated instantly from the story drift angles and the floor accelerations (see 3.3). The estimated damage information is sent to disaster headquarters.
Step 4: Several minutes to several tens of minutes after an earthquake
At the same time as the Step 3 process, the calculator enters the observed input ground motion into the analytical model to obtain the detailed responses of beams and columns (see 3.2). More detailed building damage is estimated immediately from the ductility ratios of the beams and columns, and from the cumulative plastic deformation ratio etc. in addition to the story drift angles and the floor accelerations, which are estimated from the analytical model to obtain the building's general response (see 3.3). The estimated damage information is renewed and sent to disaster headquarters.
Rank B
Step 1: Immediately after an earthquake occurs
The observation system senses the quake at the basement floor or ground floor, and starts recording the acceleration of the basement floor (input). It continues to record until the vibration of the input ground motion becomes small.
Step 2: After an earthquake
The observation system gathers the observed acceleration data and sends them to the workspace of the calculator.
Step 4: Several minutes to several tens of minutes after an earthquake
The calculator enters the observed input ground motion into the analytical model to obtain the general response of the building and the detailed responses of beams and columns. Building damage is estimated immediately from the story drift angles, the floor accelerations, the ductility ratio of the beams and columns, the cumulative plastic deformation ratio, etc. The estimated damage information is sent to disaster headquarters.
Rank C
Step 1: Immediately after an earthquake occurs
The observation system senses the quake at the basement floor or ground floor, and starts recording the acceleration of the basement floor (input). The observation system continues to record until the vibration of the

input ground motion becomes small.
Step 2: After an earthquake
The observation system gathers the observed acceleration data and sends them to the workspace of the calculator.
Step 3: Several tens of seconds after an earthquake
The calculator computes the Japanese seismic intensity from the observed acceleration at the building and estimates the damage from the calculated Japanese seismic intensity and the building's strength (see 3.4). The estimated damage information is sent to disaster headquarters.

Rank D

Step 4: Several minutes to several tens of minutes after an earthquake
The calculator obtains the Japanese seismic intensity from the nearest point of the intended building from the Japan Meteorological Agency. It then estimates the damage from the obtained Japanese seismic intensity and the building's strength (see 3.4). The estimated damage information is sent to disaster headquarters.

Headquarters

The disaster headquarters collects and displays damage information on all the target buildings and can therefore comprehend the damage to each building several tens of seconds after the earthquake stops. For Rank A, the more detailed damage information is added within several tens of minutes. Additionally, the damage information comprehended at the disaster headquarters can be displayed at every building.

3. METHODS FOR EVALUATING BUILDING RESPONSE AND DAMAGE

3.1. Story response estimation with an analytical model for gross response

This section describes a method for estimating story drift angles and floor accelerations immediately after an earthquake stops.
As discussed above, this method is applied to Rank A buildings. It uses the observed records which are the input ground motion and one or more accelerations of the upper floors. When calculating the story drift angles, the observed accelerations are integrated to the absolute displacement, and the relative displacements are obtained by subtracting the input ground displacement from the response displacements. If the number of observed points at the upper floors is m and the number of stories of the building is n, j-order modal time history is calculated by multiplying the observed relative displacement vector by the inverse of the mode matrix.

$$\{q_j\} = [\phi_j]^{-1}\{x_j\}$$

$\{x_j\}$: observed relative displacement vector, $m \times 1$

$\{\phi_j\}$: mode matrix, $\mathrm{m} \times \mathrm{m}$

$\{q_j\}$: j - th modal time history ($j = 1$ to m)

m : number of observed components

The modal time histories of 1 to m orders are estimated, so the relative displacement vector corresponding to all the degrees of freedom are estimated by multiplying the mode matrix of $n \times m$ by modal time histories of 1 to m orders.

$$\{x\} = [\phi]\{q_j\}$$

$\{x\}$: relative displacement vector , $n \times 1$

$\{\phi\}$: mode matrix, $n \times m$

n : the number of stories (vibrational degrees of freedom)

The story drift angles are computed using the relative displacement vector. The absolute accelerations are calculated in the same way by first computing the relative acceleration vector.

3.2. Detailed response estimation by earthquake response analysis

The detailed responses are computed by an earthquake response analysis. This method can estimate the detailed building responses, which could not be obtained from the model for estimating the gross response. This method is used for Rank A and B buildings, which are comparatively important buildings, so basically the three-dimensional analytical model is adopted and modeled for each constructed element. However, if the characteristic of the building vibration is well shown, we can use a simple model, for example, one based on the push-over analysis. The input ground motion at the basement or ground floor is entered into the developed model and the earthquake response analysis is conducted. The percentage of yielding members, the maximum ductility ratio, the maximum cumulative plastic deformation ratio and the story residual drift angle are thus estimated.

3.3. Structural damage estimation by building response

Using the two methods described above, we can obtain various types of estimated building response. We can thus estimate the damage as shown below.

Step 1. Define the standard values ${}_iX_u$ of various response types.

Step 2. Set the weighting factors ${}_i\beta$ of various response types.

Step 3. Calculate the ratios ${}_iX_r/{}_iX_u$ of the response values to the standard values.

Step 4. Compute the building damage *D* from this equation $D=\sum_i {}_i\beta \cdot {}_iX_r/{}_iX_u$.

Step 5. Select one of the minor, moderate, or major damage corresponding to damage *D*.

Table 2 shows an example of the standard values ${}_iX_u$ and the weighting factors ${}_i\beta$.

Table 2. Example set of standard values ${}_iX_u$, weighting factors ${}_i\beta$ and classification with *D*

(a) Standard values ${}_iX_u$, Weighting factors ${}_i\beta$

type	${}_iX_u$	${}_i\beta$
Maximum story drift angle	1/50	0.3
Percentage of yield members	1.0	0.1
Maximum ductility ratio	8.0	0.3
Maximum story residual drift angle	1/100	0.3

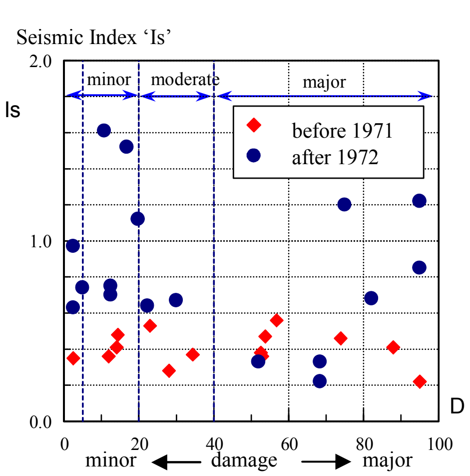
(b) Damage classification

Damage Evaluation	*D*
Minor	0<D<0.25
Moderate	0.25<D<0.50
Major	0.50<D

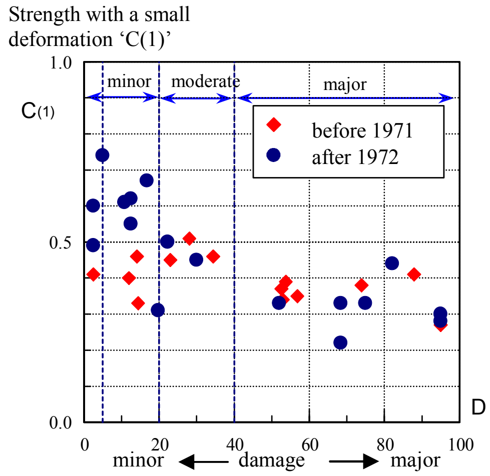
For damage estimation with gross response, we only have the result of maximum story drift angle. Thus, the summation of the weighting factors ${}_i\beta$ used in the damage estimation is set to 1. Next, after detailed building responses are obtained, the weighting factors ${}_i\beta$ are reset to the values of Table 2. The damage estimation then becomes operative once again, so the system updates the result of the damage estimation.

3.4. Quick structural damage estimation based on damage investigation in past earthquake

A simple method is developed for quickly and easily estimating structural damage. The structural damage is estimated only from the Japanese seismic intensity at the point of the target building and the structural performance of the building. In Japan, it is commonly said that structural damage has a strong relationship with 'Is (Seismic index of structure)'. In the Hyogo-ken Nanbu earthquake, the seismic capacity was evaluated and the actual damage was estimated for reinforced concrete school buildings in the area in which the Japanese seismic intensity was over 6. We rechecked the relationship between several structural parameters and the examined damage, and we found more correlation between structural damage and the building strength 'C(1)' than 'Is'. 'C(1)' is the strength when buildings are deformed small, and the deformation is about 0.4% in reinforced concrete buildings. This relationship is shown in Fig 1. In the left figure, some severe damage data are seen although they have a large 'Is' value. In the right figure, we can see a downward tendency. A quick damage estimation table is derived from Fig 1(b). The developed estimation table is used to estimate structural damage to buildings classified into ranks C and D.



(a) Seismic index 'Is'

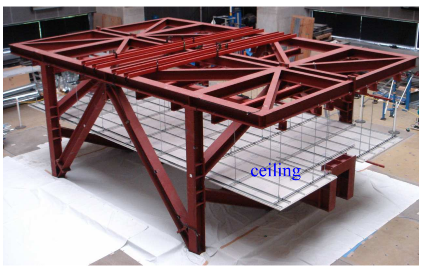


(b) Building strength with a small deformation 'C(1)'

Fig 1. Relationship between structural performance and damage

4. SHAKING TABLE TEST AND SIMULATION TOOLS FOR DAMAGE ESTIMATION OF EQUIPMENTS AND SECONDARY SYSTEMS

Even if a building avoids major structural damage in a large earthquake, equipment or secondary systems such as ceilings and walls may suffer considerable damage, which may well interfere with business continuity. Evaluation of this kind of damage is just as important as structural damage estimation. Therefore, because few data are available on their seismic capacity, we conducted shaking table tests on ceilings, ceiling-hung equipment, lighting and pipes connecting items of equipment. The test specimen is shown in Fig 2. As a result, we obtained useful information and developed tools to simulate their behavior.



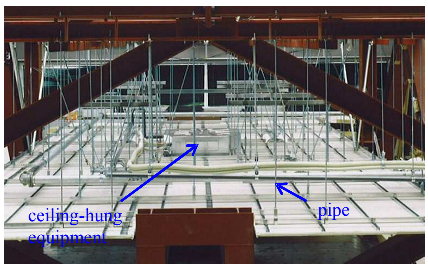
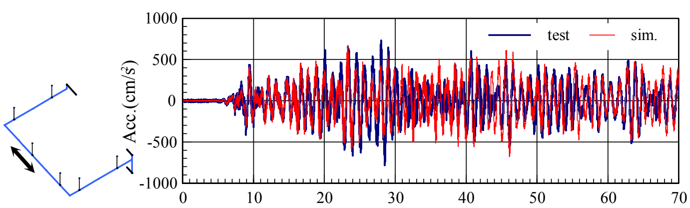
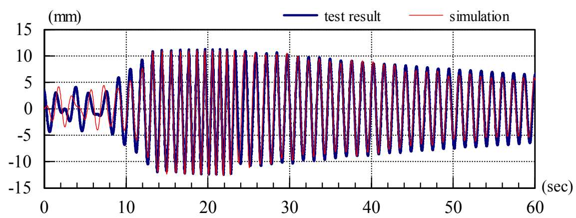


Fig 2. Shaking table test specimen



(a) Acceleration of pipes by random excitation



(b) Displacement of ceiling by sweep excitation

Fig 3. Comparison of test results and simulation

For rank A and rank B buildings, for which we have observed or calculated building accelerations, test results from the shaking table test and the simulation tools allow damage estimation of pipes and ceilings from the prediction of seismic behavior. For rank C and D buildings, the damage evaluation flow using the Japanese seismic intensity and building size was developed from the quick damage estimation table for equipment and secondary systems.

5. EXAMPLE

An example is shown here where the developed system was operating during an earthquake, which occurred on July 19, 2008. Its epicenter was off Fukushima Prefecture and its magnitude Mj was 6.6. It was rather small and did not cause building damage, but many acceleration records at target buildings were observed over a wide area and the developed real-time system ran. Fig 3 shows the initial view displayed at disaster headquarters. The headquarters and branches across the Kanto area are plotted as rectangular areas and the estimated damage to each building is written in those rectangular areas. The epicenter is plotted as a red X. The earthquake information, for example, magnitude is also written in Fig.3. Fig 4 shows the image displayed on the calculator of building A, and at the same time, this image can be seen at disaster headquarters. The estimated structural damage and secondary system damage are also displayed. The secondary systems estimated at building A are the exterior wall, partitions and ceilings. The estimation of whether or not the structure and the secondary systems of building A can be continuously used is shown in Fig 4. This is based on the structural damage and the secondary system damage. The information shown in Figs 3 and 4 is provided to disaster headquarters to build or modify a business continuity plan after an earthquake.

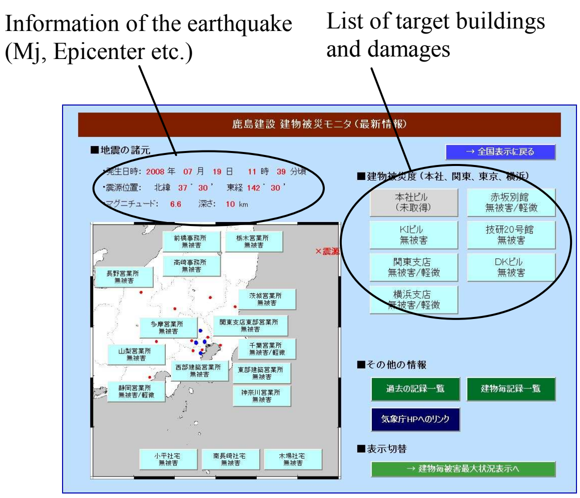


Fig 3. Initial view at disaster headquarters

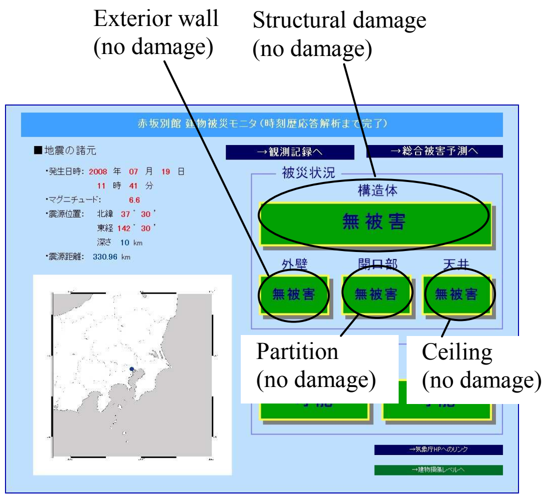
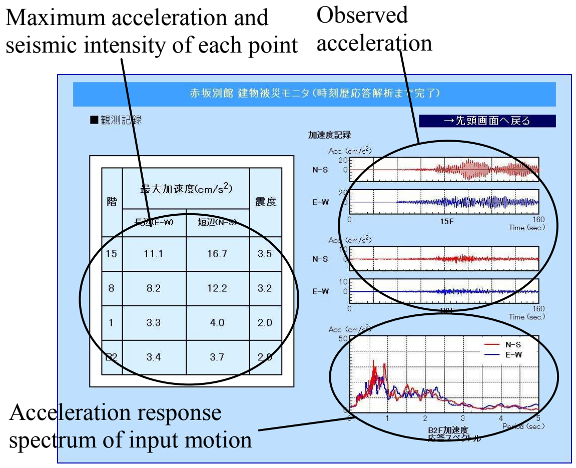


Fig 4. Main image of building A

From here, figures for managers of each building and structural engineers are shown. Those figures are used to assist them to understand the parts where there was large damage or to be checked first in building A. Fig 5 shows the observed accelerations at building A. The structural damage in Fig 4 and so on is based on these vibration records. In building A, there were three accelerometers on the upper (15^{th}, 8^{th} and 1^{st}) floors in addition to the basement floor. The left table of Fig 5 shows the maximum accelerations and the Japanese seismic intensity of each observed floor. The Japanese seismic intensity is very useful for explaining the amplitude of vibration imparted to people in the building. Fig 6 shows an example of a building response. Here, the distribution of maximum story drift angle is shown. This response is evaluated from the gross response estimation. Every time an earthquake occurs, the model for gross response estimation and earthquake response analysis is updated in order to improve the accuracy of simulation of building behavior. This advanced operation is conducted by structural engineers. In the same way, the damage estimation methods for the structure and secondary system can be renewed if new knowledge is acquired. As a result, this system can adopt the most accurate estimation from the response and damage at the time.



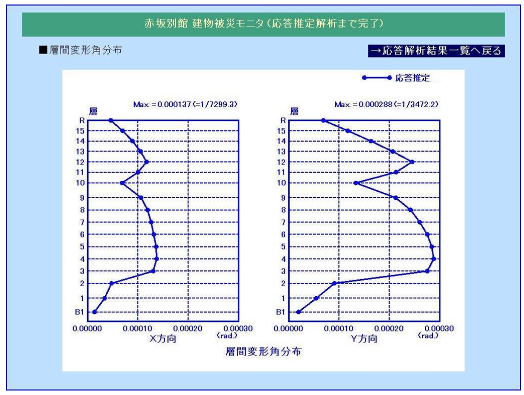


Fig 5. Observed acceleration at building A　　Fig 6. Estimated maximum story drift angle

6. CONCLUSION

This paper has described a newly developed real-time damage estimation system available for a business continuity plan. This system can quickly estimate building damage and send damage information via a computer network to disaster headquarters or to other buildings, and damage information of all the target buildings are displayed at disaster headquarters. At the same time, the damage information of all the buildings can be shared via a computer network. With this system, the target buildings are classified according to building importance. Structural damage and damage to equipment and secondary systems are estimated appropriately for each building. This system has been applied to Kajima's buildings (Headquarters and branches) and has been operational. Every time a small or middle class earthquakes occurs, the accuracy of the evaluated response and estimated damage to each building has been improved, and it is hoped that this system provide accurate results in a future large earthquake.

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