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Development of a Rapid Safety Inspection System for Damaged Buildings after Earthquake for Non-experts

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Abstract

After the Great East Japan Earthquake occurred in March 2011, Tokyo metropolitan government established an ordinance in 2013 to require the business operators to prevent the employee to return home at the same time and keep them in the office when the office building maintains its safety from aftershocks. The main aim of this ordinance is to prevent the blockage of rescue and fire-fighting activities by the traffic jam induced by the commuters heading their homes at the same time.

It has been said that probability of occurrence of Tokyo metropolitan earthquake within 30 years is about 70% in Tokyo metropolitan area. The damage of buildings by the earthquake is predicted to be more than several million. However, there are not enough building experts who are capable of confirming the building's structural safety after the earthquake. For the purpose of resolving the problem, we have developed the rapid safety inspection system of buildings for non-experts. The system supports building manager with no expertise on structural safety to judge the structural safety of a building just after earthquake occurrence. This system consists of the "judgment of the extent of damage with measurement", which is to measure the seismic intensity and the amount of story drift of a building with the measuring instruments, that is seismometer and simple story drift recorder KEGAKI, installed to a building, and the "judgment of the extent of damage by visual inspection", which is for the non-expert to check damages after the earthquake using the inspection list created by the experts in advance.

Rapid Safety Inspection, Measuring of building damage, KEGAKI system, Visual inspection, Non-experts

1. Background of the development

The Great East Japan Earthquake, which occurred in March 2011, caused serious damage to all over the eastern Japan covering from the Tohoku to the Kanto districts. In the Greater Tokyo Area, as many as 5,150,000 commuters lost their usual ways to commute due to the interruption of public transportation, and a large number of them tried going home from the center of Tokyo on foot or by car. Consequently, the roads were so congested that efficient deployment of ambulances and fire engines were obstructed (Fig 1).[1] In order to prevent the same situation from happening when a prospective earthquake occurs, the Tokyo Metropolitan Government put an ordinance into operation in 2013, which requires business operators to discourage their employees from going home simultaneously and to encourage them to stay in their offices.[2] However, only after the office buildings are found to be safe from aftershocks can the employees be allowed to stay. Even if the above-mentioned issue caused by employees who try going home simultaneously does not happen, a property owner or manager is obliged to secure the safety of those who in the building immediately after an earthquake occurs and to make a decision on whether to let them stay or to evacuate them out of the building.

In order to make the decision, it is imperative that the structural safety of the building should be examined immediately after an earthquake occurs, and, in order to conduct such examination, it is necessary for a technical expert in building structure to evaluate the extent of damage. On the other hand, it is estimated that multi-million buildings will be damaged and as many as 9,890,000 commuters will lost their ways to commute if a prospective Tokyo Inland Earthquake occurs,[3] and the current number of building experts is far too small to deal with all of the damaged buildings. While the Tohoku Earthquake damaged few buildings in Tokyo, a crowd of the commuters who lost their ways to commute caused the disruption. In preparation for a prospective Tokyo Inland Earthquake, it is essential to develop a system that enables a non-expert such as a property manager to rapidly evaluate the safety of a building.

In order to resolve these issues, we developed the Rapid Safety Inspection System, which enables a non-expert to rapidly evaluate the safety of a building.

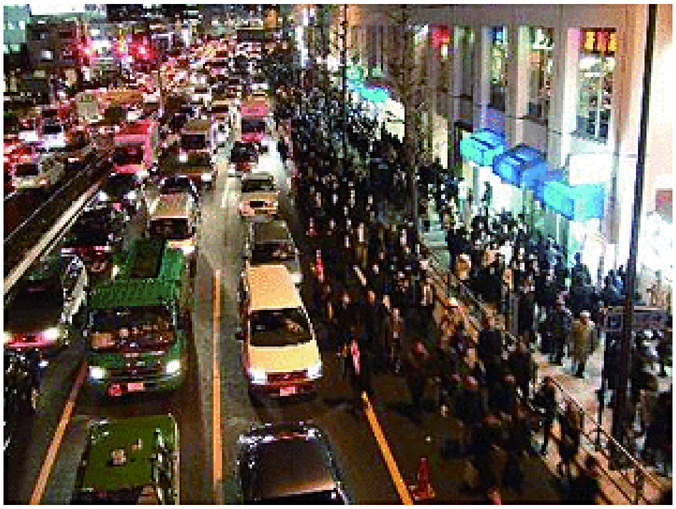

Fig 1- JR Shinagawa staion area in the evening on March 11, 2011

2. Structure of the system

2.1 Scope of application

Usually, a property manager etc. should inspect a building hit by an earthquake in accordance with the procedure shown in Fig 2. The system we developed should be applied to the section framed in red in Figure 2, which is for rapidly evaluating the safety of building structure (i.e. frames of a building such as columns, beams and shear walls) from aftershocks.

Even if the building structure is estimated to be safe, the decision on whether the building can be used after the earthquake should depend on comprehensive consideration of the damage to non-structural components and facilities of the building, condition of lifeline such as the electricity supply, the water supply and so on, and damage to the surroundings such as transportation or roads. This system is intended for helping a non-expert such as a property manager to rapidly evaluate the safety of a building within about one hour after an earthquake occurs, which corresponds to the first step of a series of judgments.

Evaluation of the safety of a building hit by an earthquake ought to be based on inspection by a technical expert in building structure (e.g. Postearthquake Quick Inspection of Damaged Buildings4)). Therefore, it is necessary to establish slightly more stringent criteria in order to produce a conservative judgment in this system, in which a temporary judgment has to be made before the inspection by a technical expert.

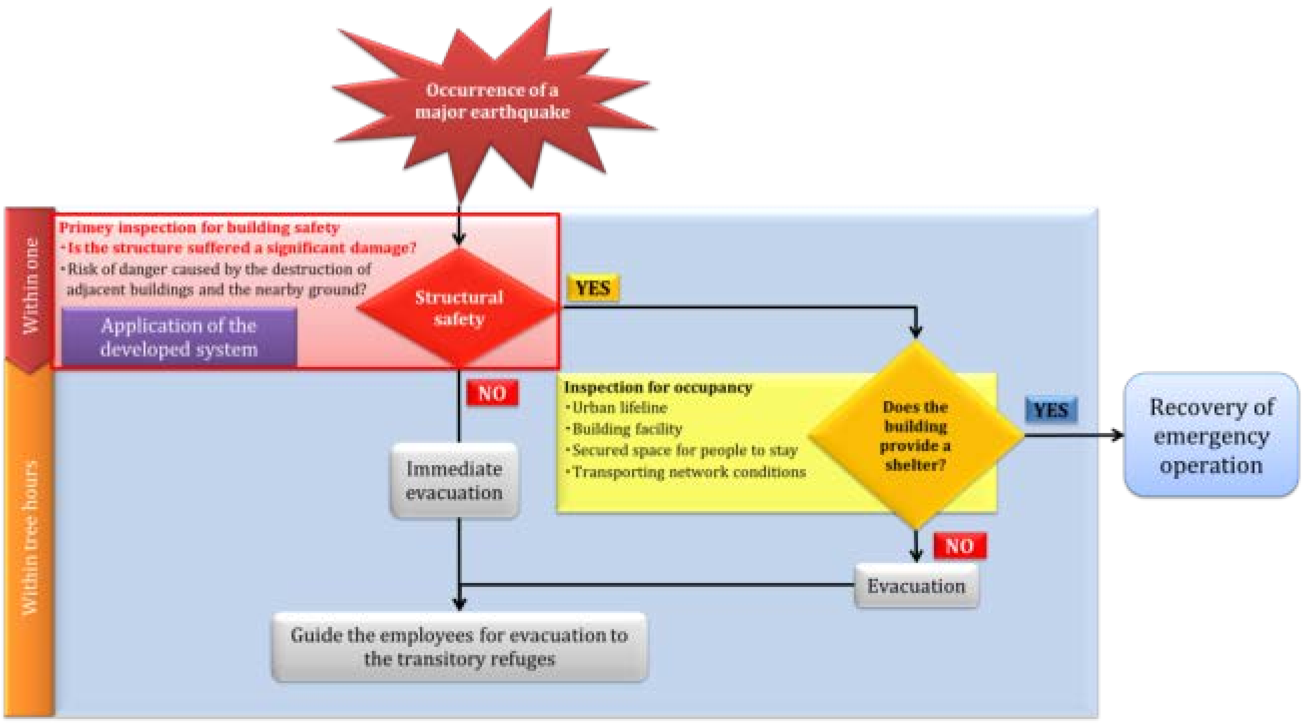

Fig 2 -Safety Inspection of buildings after a major earthquake

2.2 Characteristics of the system

The proposed system is characterised by the fact that the safety of a building is determined on the basis of two judgments as shown in Fig 3: one is a "judgment of the extent of damage with measurement" by way of measuring instruments installed in the building, and the other is a "judgment of the extent of damage with a quick inspection checklist" by way of visual inspection of damage to each elements of the building.

A safety evaluation system for a high-rise building has been already put into practice, and is introduced into many buildings. [5] It is a system where more than one seismometer is installed in a building and the maximum story drift of the building is estimated on the basis of the observed values. However, in the case of a low- or mid-rise building, it is difficult to make an accurate estimate of story drift on the basis of an observed value with a seismometer, and it is expensive to install more than one seismometer in a building. Therefore, safety evaluation system for a low- or mid-rise building has not been developed very much. In the system we developed, in order to include low- or mid-rise buildings in the scope of its application, we adopted the method of using measurement of story drift with KEGAKI system, which will be mentioned later, and visual inspection of damage.

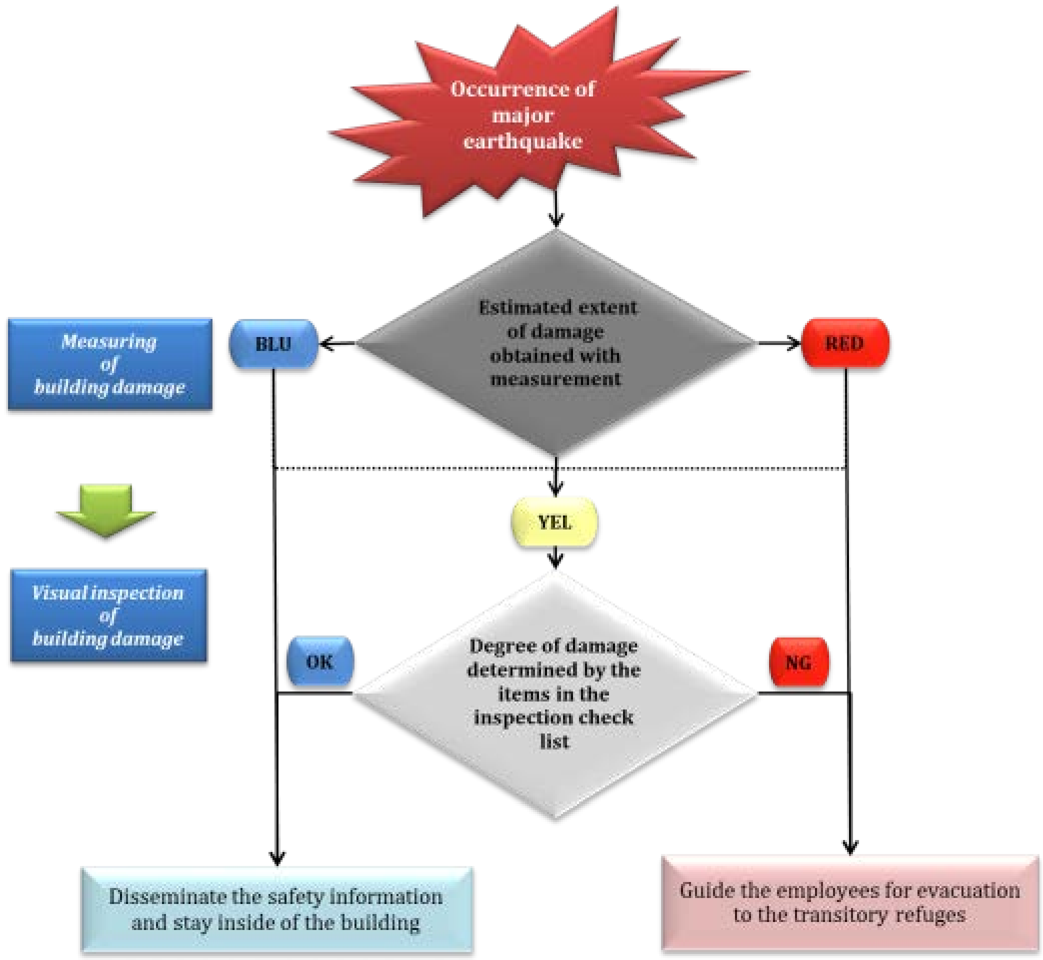

Fig 3- Flow of Rapid Safety Inspection System

2.3 Judgment of the extent of damage with measurement

Judgment of the extent of damage with measurement is based on two results of measurement: one is strength of input seismic motion to a building, which is measured with a seismometer, and the other is story displacemant, which is measured with a story drift recorder KEGAKI. Usually the seismometer (Fig 5) is installed on the floor of the first floor, and the story drift recorder KEGAKI is installed on the floor that is supposed to have the largest story drift (Fig 4).

A story drift recorde Kegaki is an instrument that traces the story drift of a floor on which it is installed, on the acrylic board as a horizontal two-demensional orbit. [7] The mechanism of a story drift recorder KEGAKI and an example of its measurement are shown in Fig 6 and 7 respectively.

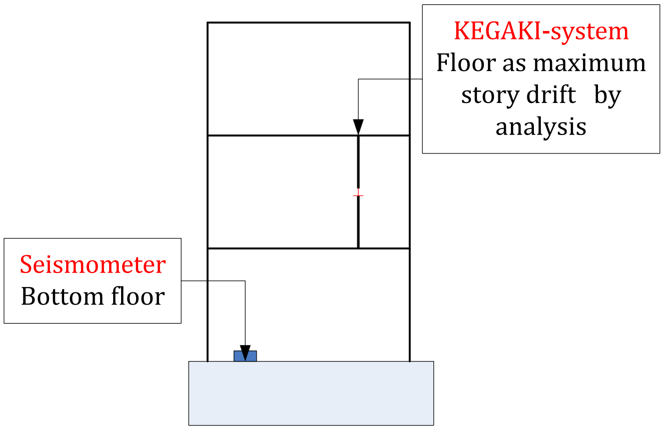

Fig 4 Locations of measuring instruments

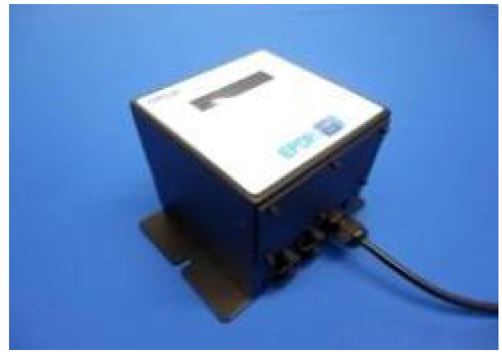

Fig 5 EPDP-CUBE 311[5] (Earthquake Perception Damage Prediction)

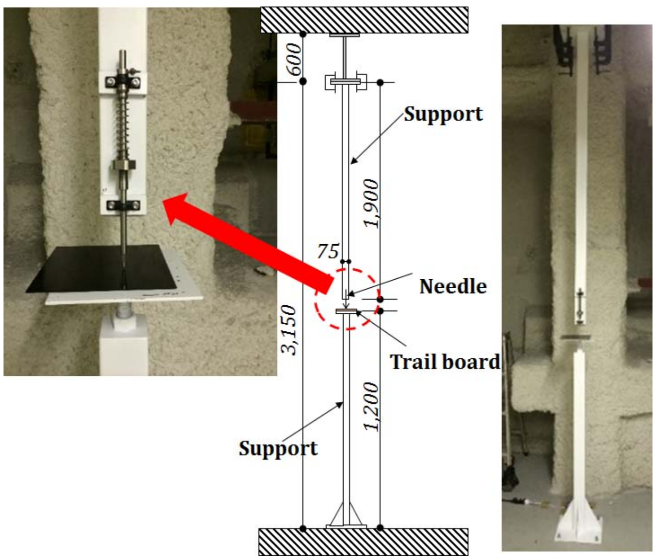

Fig 6 KEGAKI system for measuring story drift

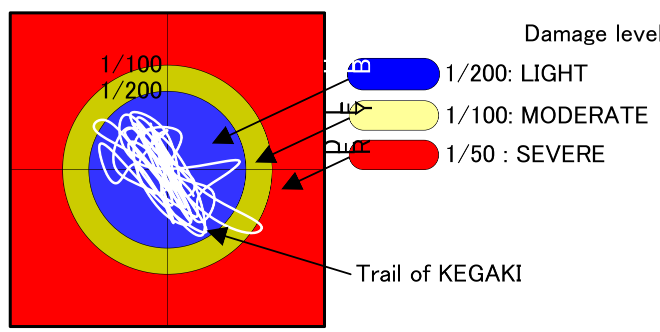

Fig 7 Tracing of story drift recorded by KEGAKI System (image)

2.4Judgment of the extent of damage with a quick inspection checklist

We developed the quick inspection checklist that enables a non-expert without technical knowledge of building structure, such as a property manager etc., to visually inspect damage to a building and to evaluate the extent of damage. A non-expert cannot distinguish structurally important elements of a building. Therefore, the rapid inspection checklist consists of the damage inspection sheet (Fig 8), in which the damage level of the elements specified in advance by experts are entered, and the judgment sheet of building safety (Fig 9), in which the extent of damage to the building is evaluated with the sum of the damage level of each element.

For judgment of damage level with the damage inspection sheet, referential pictures such as shown in Figure 108) should be prepared in advance, and the damage level of each element is evaluated on a 5-grade scale (from I to V).

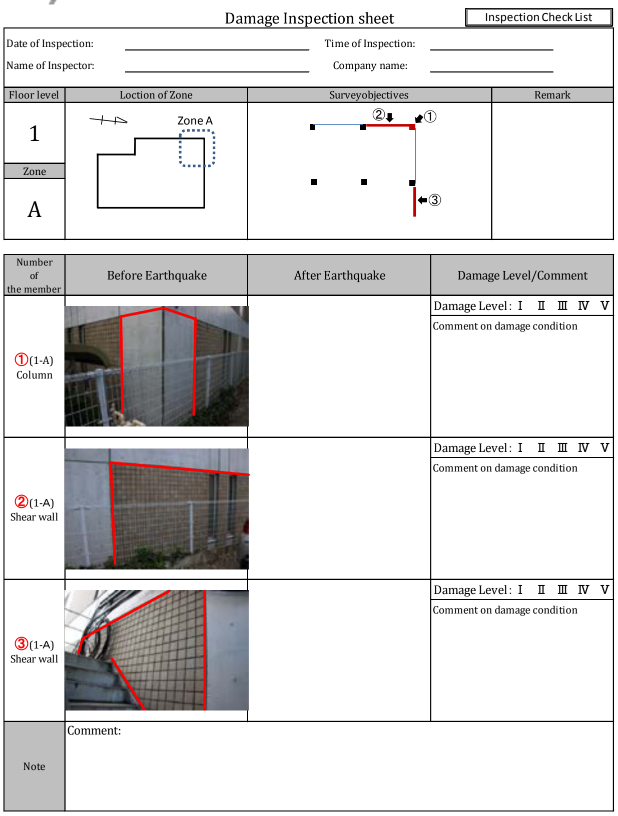

Fig 8 Damage inspection sheet

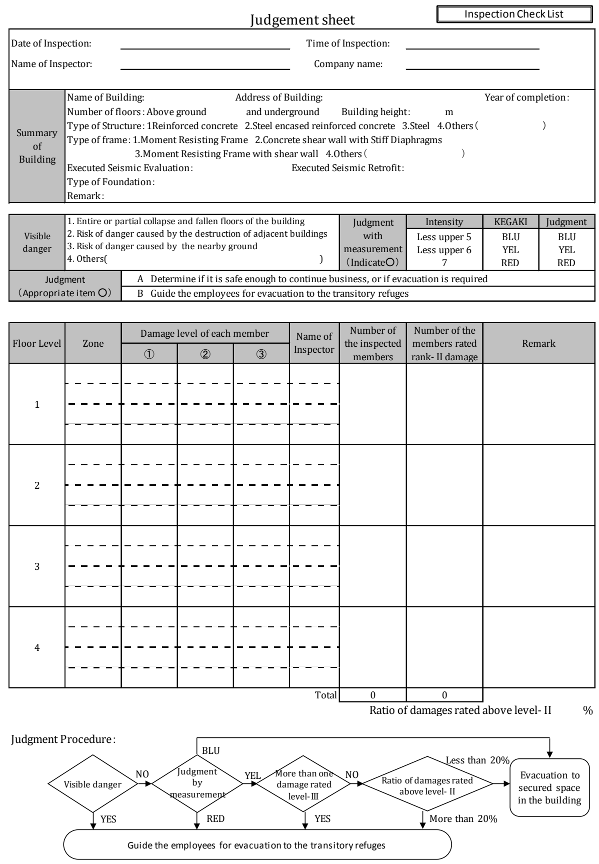

Fig 9 Judgment sheet of building safety

	Damage Level I	Damage Level II	Damage Level III	Damage Level IV	Damage Level V
Column					
	Slight cracks (0.2mm or less wide)	Clearly visible cracks (0.2-1mm wide), but no spalled concrete observed	Relatively large cracks (1-2mm wide) spalled concrete observed, but no exposed re-bars	Many large cracks (2mm or wider) and significant amount of spalled concrete observed. Re-bars are exposed but not deformed	Significant amount of re-bars are exposed, deformed, buckled, or raptured. Concrete inside of the columns are collapsed and causing them the vertical deformation

Fig 10 Illustrated damage level (for reinforced concrete column)

3. Examination before introduction of the system

3.1 Examination of building structure

Before the introduction of this system, a technical expert in building structure should inspect the structure of a building, and the results of it should be reflected in the quick inspection checklist. In addition, locations of measuring instruments in the building and a threshold of safety judgment should be established.

Regarding inspection of building structure, the expert should grasp the characteristics of the building such as location and finish of main structural components through the review of drawings for the building, and conduct push-over analysis and seismic response analysis of a prospective earthquake. Then, the expert should examine which element can be easily damaged and which part can have fatal effects if damaged, and the findings should be reflected in the quick inspection checklist. Furthermore, on the basis of story displacement response and torsional response of the building, the expert should identify which floor or which element may have larger story drift and decide the location of a story drift recorder KEGAKI with the threshold as amount of story drift.

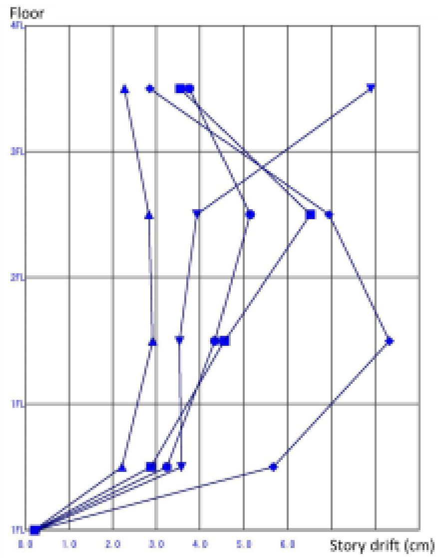

Fig 11 -Results of seismic response analysis (Example)

3.2 Preparation of a quick inspection checklist

A quick inspection checklist should be prepared in order to enable accurate and efficient judgment of the damage to building structure with visual inspection immediately after an earthquake occurs (Fig 8). The expert in charge of the examination of building structure should conduct an on-the-suit investigation to select the elements to be inspected, and take pictures of the parts as reference. It is important to limit the number of elements to be inspected, considering it is non-experts that will use the checklist for quick inspection immediately after an earthquake occurs.

3.3Determine where to install a story drift recorder KEGAKI and its threshold

The location of a story drift recorder KEGAKI should be determined on the basis of the vibration characteristic of a building found through the above-mentioned examination of building structure as well as comprehensive consideration of the ease of installment and maintenance of the recorder.

Two concentric circles should be drawn on the trail board as thresholds of story displacemant. Based on the results of seismic response analysis of the building, each radius of the concentric circles should be established to create three areas in a way such as shown below (Refer to Fig 7).

BLU:	Story drift is light, and damage is less than light
YEL:	Story drift is moderate, and damage is light or more than light, but less than severe
RED:	Story drift is severe, and damage is severe or more than severe

4. How to implement the system

4.1 Implementation at normal condition

4.1.1 Establishing roles and responsibilities to implement the system

In order to secure proper implementation of the system at the time of earthquake, it is necessary to establish roles and responsibilities to implement it before an earthquake occurs. Specifically, who are in charge of the following should be decided in advance as well as who are backup when the persons in charge are absent.

- Commander : A person who supervises the implementation of the system and makes the final decision about the safety.
- Measurer : A person who checks results of measurement with a story drift recorder KEGAKI and a seismometer.
- Damage inspector : A person who checks the damage level with the quick inspection checklist
- Notifier/Guide : A person who notifies all persons in the building of the result of rapid inspection and, as necessary, guides them in order to secure safety.

4.1.2 Drill for implementation

In order for the above-mentioned roles and responsibilities to function properly when an earthquake occurs, it is necessary for the persons in charge to join a drill for the implementation periodically. In addition, it is also effective to conduct a drill to implement the system, which is intended for an earthquake with high seismic intensity, at the time of an earthquake with low seismic intensity that cannot cause any damage.

4.2 Implementation at the time of earthquake

4.2.1 Condition to start the system

It is necessary to decide in advance at which level of seismic intensity the system should be started. For example, the following can be a condition to start the system.

[Example] The system should be started if one of the following happens.

- Seismic intensity registers more than lower 5 on the scale of the Japan Meteorological Agency at the nearest observation point.

- Shaking becomes strong enough to cause a feeling of imminent danger, and the commander decides to start the system.

4.2.2 Criteria for safety judgment

The flow of safety judgment through this system is shown in Fig 12. The judgment is made through the following 4 steps.

1) First, whether or not it is an obviously dangerous situation such as "the building is clearly leaned" or "there is a fire in the building." If this is the case, all persons in the building should be instructed to immediately evacuate out of it [End of judgment].
2) (If there is no obvious danger) the measurer checks measurement of the story drift recorder KEGAKI and the seismometer, and reports it to the commander. The commander decides which category, red, yellow or blue, it belongs to in the predetermined judgment matrix (Table 1). If it is red, all persons in the building should be instructed to evacuate out of it [End of judgment]. If it is blue, all persons in the building should be instructed to stay in it[End of judgment].

Table1 -Judgment with measurement

Range of KEGAKI (Story drift angle) / Measured intensity	LIGHT (less than 1/300)	MODERATE (above 1/300 - less 1/150)	SEVERE (above 1/150)
Lower 5 or less	BLU	YEL	RED
Upper5 – Upper6	YEL	YEL	RED
7	RED	RED	RED

※ For the detail of KEGAKI, see Figure 8.

3) (If it is yellow) the damage inspector inspects the damage with the rapid inspection checklist, and reports it to the commander. The commander makes a judgment in accordance with the judgment sheet of building safety (Fig 10). In the case of this building, if it has 2 or more elements whose damage level is classified as III or larger, all persons in the building should be instructed to immediately evacuate out of it [End of judgment].

4) (If it has 1 or no part whose damage level is classified as III or larger) if the number of parts whose damage level is classified as II or larger accounts for 20% or more of all the parts inspected, all persons in the building should be instructed to immediately evacuate out of it [End of judgment]. If the number of parts whose damage level is classified II or larger accounts for less than 20%, all persons in the building should be instructed to stay in it (End of judgment).

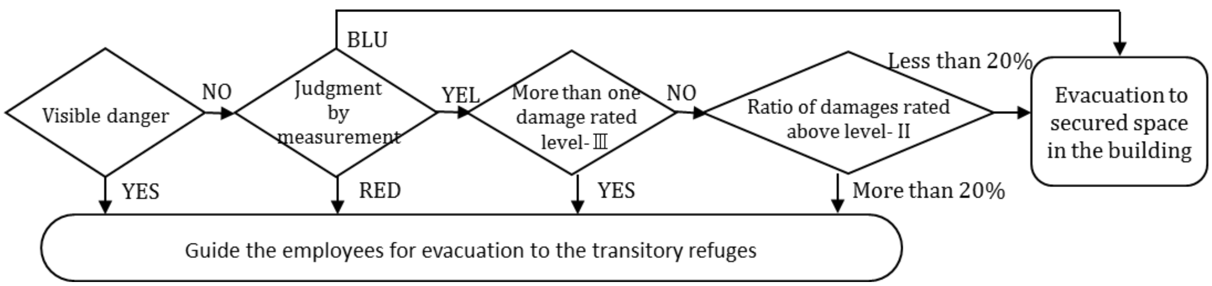

Fig 12- Flow of judgment

(3) Guiding persons in building

When guiding persons in the building according to the quick safety evaluation with this system, it is necessary to pay attention to the following in order to secure their safety.

-If instructing them to evacuate out of the building, it should be in accordance with an evacuation plan that is prepared in advance in order not to cause disruption.

-In particular, the time, weather condition, and damage around the building should be considered, too.

-If instructing them to stay in the building, the damage to non-structural components of the building should be also monitored, and they should be guided to a safe place in order to avoid a secondary disaster.

5. A case to which the system was introduced

This system was introduced to a four-story office building constructed with reinforced concrete structure in Saitama prefecture, and now is in operation (Fig 13). Also introduced to a two-story steel-framed building in Shizuoka prefecture.

Fig 13 -A mid-rise building to which this system was introduced

6. Conclusion

We developed a system that helps a non-expert without specialized knowledge of building structure, such as a property manager etc., to rapidly inspect damage to a building and to evaluate the safety of the building immediately after an earthquake occurs. The characteristics of the system are as follows.

1. We adopted the method of using measurement of story displacemant with a story drift recorder KEGAKI and visual inspection of damage, in order to include low- or mid-rise buildings, whose amount of story drift is difficult to measure with a seismometer, in the scope of the system.
2. It is necessary for a technical expert to examine the structure of a building and conduct an on-the-suit investigation before this system is introduced. In this way, the system enables a non-expert without specialized knowledge of building structure to evaluate the extent of damage swiftly and effortlessly on the basis of the results of measurement and damage inspection.
3. Only one story drift recorder KEGAKI and one seismometer are necessary as measuring instruments. Therefore, the introduction cost is relatively low.

7. Acknowledgements

Professor Masamitsu Miyamura in Kogakuin University (then), who developed the story drift recorder KEGAKI, helped us to apply it to this system. We would like to express our sincere gratitude for his support.

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