DEVELOPMENT OF A HYBRID EVALUATION METHOD FOR LONG-TERM STRUCTURAL SOUNDNESS OF NUCLEAR REACTOR BUILDINGS USING MONITORING AND DAMAGE IMAGING TECHNOLOGIES – NUCLEAR ENERGY SCIENCE & TECHNOLOGY AND HUMAN RESOURCE DEVELOPMENT PROJECT –

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ABSTRACT

This study develops assessment methods necessary to obtain a long-term structural integrity outlook for nuclear reactor buildings that suffered from the 2011 Great East Japan Earthquake disaster in which access to the site was extremely limited due to high radiation dose rates and contamination. The research is part of the “Nuclear Energy Science & Technology and Human Resource Development Projects” implemented by the Japan Atomic Energy Agency (JAEA) Collaborative Laboratories for Advanced Decommissioning Science (CLADS) in FY2021 to FY2023. This paper introduces an outline and overview of the project.

OUTLINE OF PROJECT

The project consists of four research topics as shown in Fig. 1.

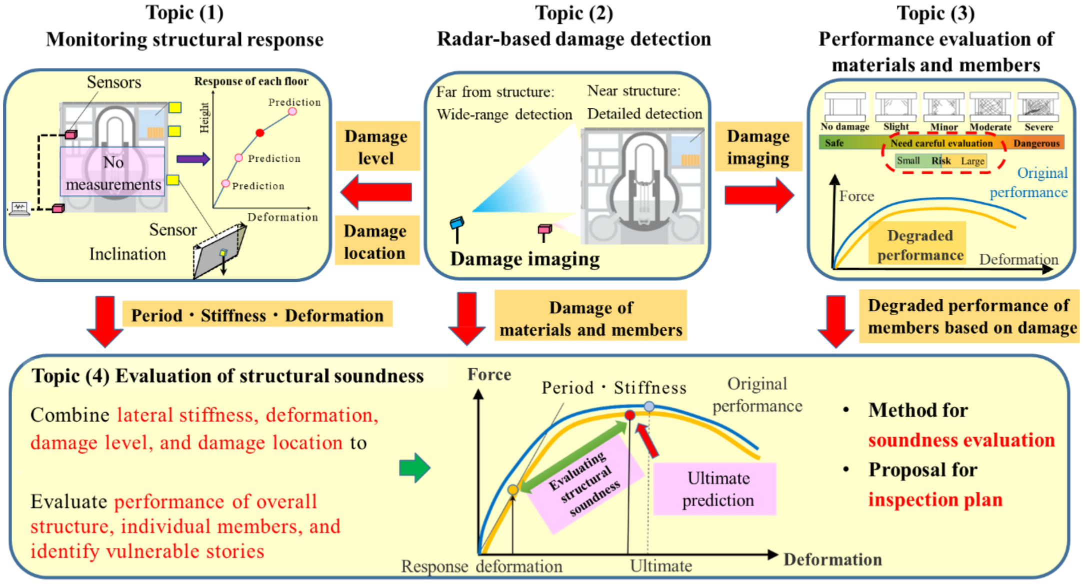


Figure 1. Outline of long-term structural integrity assessment

In the decommissioning work of Fukushima Daiichi Nuclear Power Station, the safety function (especially structural performance) of the nuclear reactor building is required to be maintained over a certain required level for an extended period of time before and after fuel debris retrieval. In this project, Tohoku University, Tokyo Institute of Technology, Shibaura Institute of Technology, Kisarazu National College of Technology, Nippon Institute of Technology, Osaka Metropolitan University, and JAEA collaborate to establish an appropriate maintenance management method for the reactor building. The four research topics are: (1) Development of building vibration properties/response evaluation method by monitoring external disturbances such as earthquakes, (2) Development of damage detection technology for concrete structures using electromagnetic waves, (3) Development of strength evaluation method for concrete materials and structural members based on damage detection information, and (4) Development of a performance evaluation method and proposal of a long-term maintenance plan.

TOPIC (1): MONITORING OF VIBRATION PROPERTIES AND RESPONSE EVALUATION

Prediction of Performance Curve and Dynamic Response Based on Observed Acceleration Records

The general procedure for evaluating damage and predicting response in future earthquakes is illustrated in Fig. 2. The procedure consists of four steps: (1) analytical performance curve (estimated lateral force-displacement relationship) of a target building structure is updated to match the observed response measured using accelerometers, (2) analytical damping factor (energy dissipation capacity) is updated to match observation, (3) damage level (structural soundness) is classified based on updated performance curve and damage criteria, and (4) future response and expected damage are predicted using high-intensity seismic inputs.

In step 1, the analytical performance curve is updated by constructing a curve which passes through observed response data including characteristics points (defined next) derived from monitoring records and smoothed using the Kalman Filtering method as shown in Fig. 3. Characteristics points are defined as points in a performance curve at which changes in structural vibration characteristics occur due to stiffness degradation caused by cracking, yielding, formation of flexural mechanism and failure. A sudden reduction is generally observed in instantaneous stiffness *K* around the four characteristics points represented by local maxima in the rate of change in instantaneous stiffness $\Delta K/\Delta S_d$. The performance curve is updated by amplifying the characteristics points in analytical curve to match those in the observed curve.

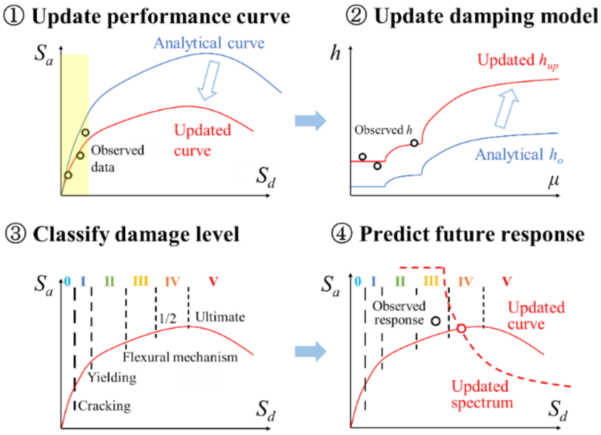


Figure 2. General flow of updating performance curve and response prediction

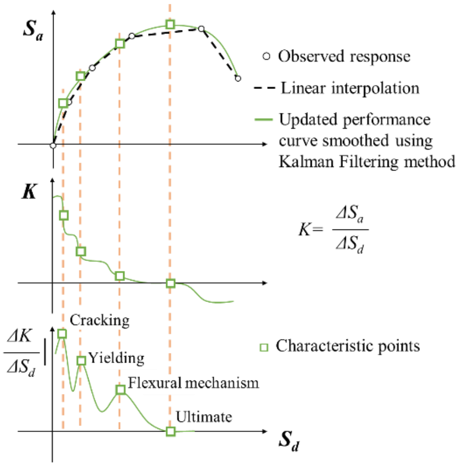


Figure 3. Characteristics points identification

In step 2, the analytical damping curve h_o is updated to match the observed damping factors in a procedure similar to that described in step 1. Observed damping factors are inferred from matching solutions produced using capacity spectrum method with measured response. The analytical damping curve is based on energy dissipation capacity as described by hysterical rules proposed by Takeda (1970) as shown in Fig. 4. Before cracking, analytical damping is amplified to the maximum value of observed damping occurring in uncracked response (Fig. 5). After cracking, analytical damping curve is amplified to match observed damping and smoothed using Kalman Filtering method producing updated damping model.

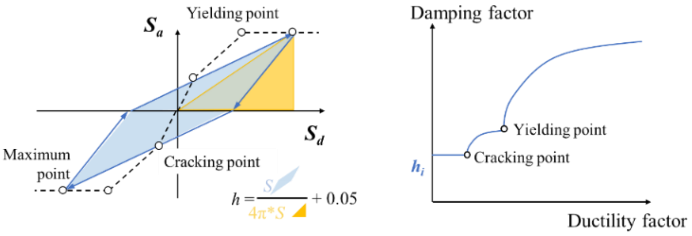


Figure 4. Hysteretic model proposed by Takeda (1970)

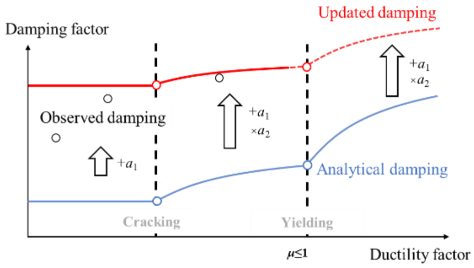


Figure 5. Updated damping curve

In step 3, the damage level of the structure is classified using six discrete regions of damage based on the identified characteristic points and performance curve (Fig. 6). Because the region between flexural mechanism and ultimate points spans large differences in deformation, the region is divided into two parts to distinguish between moderate and severe damage.

In step 4, the updated capacity curve, updated damping curve, and the damage classification method described in steps 1-3 are used to predict future response and damage level of the structure in high-intensity earthquake motions. In Fig. 7, the predicted response underestimates the observed response by approximately 20%, but the predicted damage level matches the observed damage level.

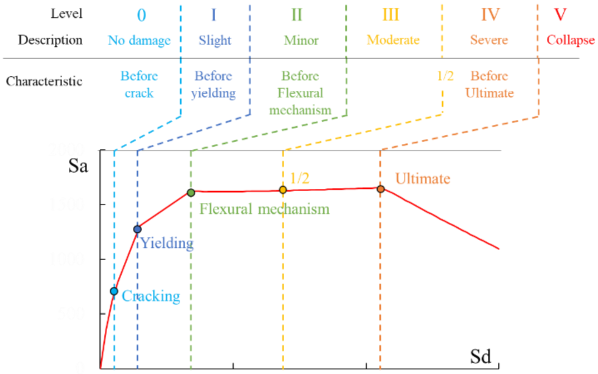


Figure 6. Damage classification

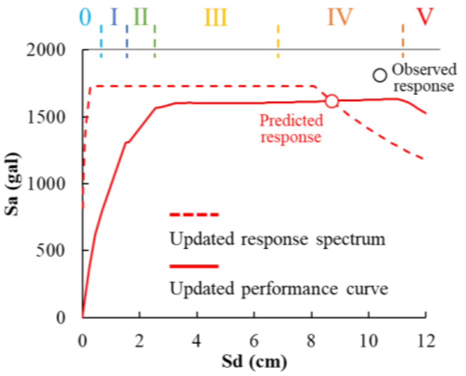
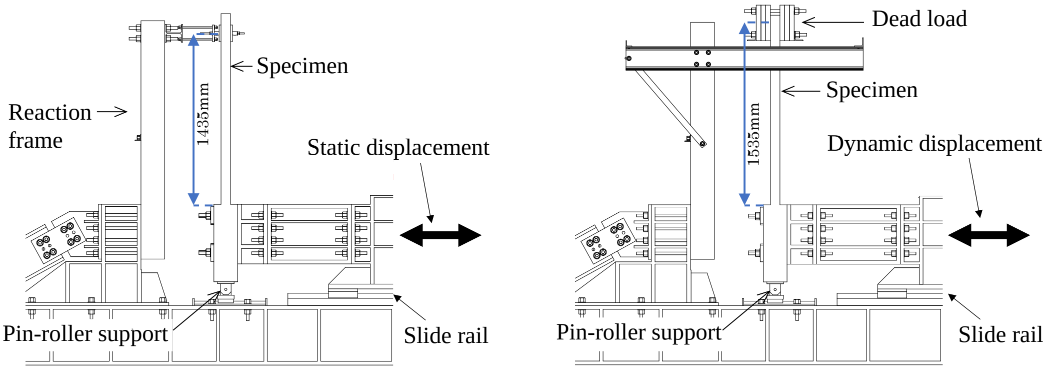


Figure 7. Prediction of future response and damage level

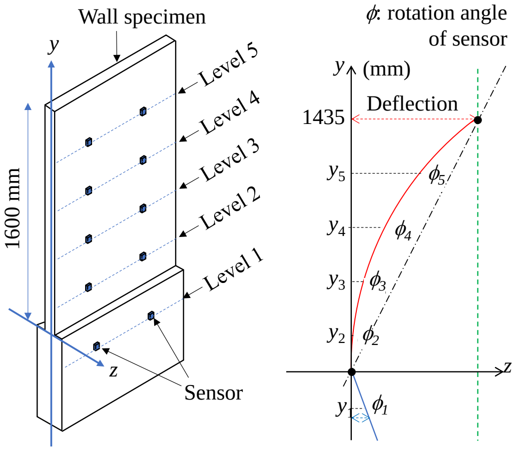
Observation and Evaluation of Long-term Deformation

In order to monitor the long-term structural integrity of members in buildings, a measuring system using accelerometers and gyro sensors is developed based on loading tests of reinforced concrete specimens. Fig. 8 shows loading setup of static and dynamic tests. The sensor units, in which both the accelerometer and gyro sensor are installed, were pasted on the wall specimen as shown in Fig. 9a. As shown in Fig. 9b, the deflection (displacement) of the wall head is calculated by identifying the rotation angle of the sensor with a gradient of deflection curve. The accelerometers were used as inclinometers in the static test, and the rotation angle was obtained by integrating an angular velocity measured by the gyro sensor in the dynamic test. The estimated deflections were compared with observed values and the results of the measuring system show good accuracy as shown in Fig. 9c and 9d. For long-term monitoring, sensors can be installed on those members expected to deteriorate and be damaged by earthquakes.



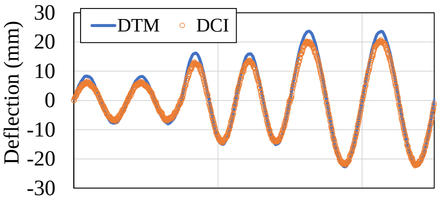
(a) Static test (b) Shaking test

Figure 8. Loading setup

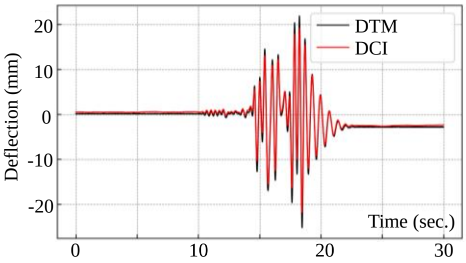


(a) Position of MEMS sensor

(b) Curve identification with rotation angle of sensor



(c) Time history of static loading test



(d) Result of shaking test

Figure 9. Comparison between displacement transducer measurement (DTM) and deflection curve identification by sensors (DCI)

TOPIC (2): DAMAGE DETECTON TECHNOLOGY USING ELECTROMAGNETIC WAVES

Development of Imaging Technology by Terahertz (THz) Wave

Inspection methods using electromagnetic waves and optical systems, such as radar-based rebar inspection, have also already established and are used regularly in the field to estimate damage in structures. On the other hand, for areas that are difficult to access, such as the controlled areas of nuclear power plants, measurements must be evaluated using non-contact and remote non-destructive testing methods but these methods have not yet been fully developed. For example, it is difficult to obtain information about cracks in the interior of concrete buildings and the corrosion condition of steel reinforcement bars by visual inspection or optical images. The testing method to obtain such information in a non-destructive manner has not yet been established. Therefore, terahertz (THz) waves, which have the property of penetrating concrete, are used to investigate the fundamentals of developing a noncontact, non-destructive inspection method for reinforced concrete buildings.

THz waves are difficult to generate and detect and have therefore been called an “unexplored electromagnetic field”. However, with the development of high-frequency devices and laser equipment, THz waves are now being researched and developed worldwide. The energy of THz waves is comparable to room temperature, making them safe for the human body and highly permeable to non-polar materials such as concrete. On the other hand, they are highly absorbent of polar substances such as water. To illustrate the results of scanning surfaces with THz waves, the reflected transmission THz spectra and 2.8 THz images for corrosion products on the surface of galvanized steel sheets covered with impermeable material are shown in Fig. 10. An absorption peak due to zinc chloride is detected around 2.8 THz, and the absorption around 2 THz is an absorption attributed to hydrates of zinc chloride. The application of interference rejection algorithms is effective for imaging measurements at a single frequency, and the image produced by 2.8 THz matches well with the close-up photo of corrosion on pipe in Fig. 10.

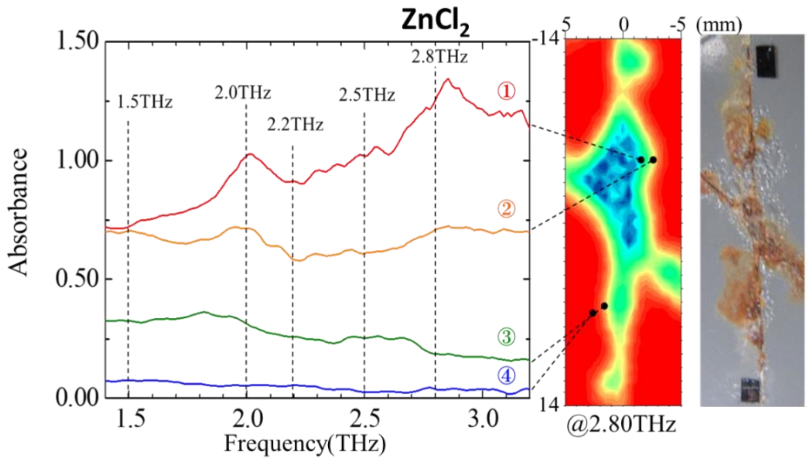


Figure 10. THz spectra and 2.8 THz imaging for corrosion steel plate

Development of Imaging Technology by Sub-terahertz (sub-THz) Wave

Remote diagnosis of RC buildings focuses on even lower frequencies of gigahertz waves (~0.1 THz). The characteristics of these electromagnetic waves are linearity like light and material permeability like radio waves. Sub-terahertz (sub-THz) waves, which are similar to radio waves, have a high ability to penetrate materials. Sub-THz waves can therefore be expected to be used to assess the internal structural integrity of RC buildings as well as the surface. Cracks as concrete damage can be evaluated from the reflection and transmission of sub-THz waves with respect to the crack width and crack direction. Sub-THz waves are particularly transparent to concrete because of the higher proportion of coarse aggregate that is mixed into the concrete. If cracks are present in the concrete, since both transmission and reflection are affected by the scattering of sub-THz waves, the reflection of sub-THz waves at the concrete-air interface can give an indication of the internal condition. In addition, water distributed in the cracks inside the concrete structure can be detected with high sensitivity as a sensitizing element because the absorption by water as a polar liquid is large. Fig. 11 shows the transmission image of water penetrating into the cracks of concrete. A TUNNETT diode (200 GHz) was used as the light source.

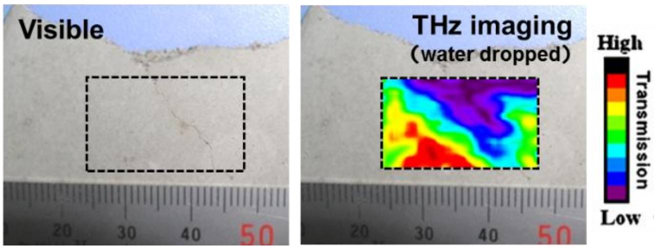


Figure 11. 200 GHz imaging of water penetrating into cracks in concrete

TOPIC (3): DAMAGE EVALUATION BASED ON DAMAGE DETECTION INFORMATION

Damage to Performance of Concrete

As mentioned above, THz and sub-THz terahertz waves have the potential to be applicable as nondestructive testing of RC buildings. For example, as shown in Fig. 11, cracks in concrete can be visualized. This section introduces nondestructive testing trials for concrete materials subjected to different levels of damage with degradation of mechanical properties.

In order to obtain the different levels of degradation of the mechanical properties of the concrete, rapid freezing and thawing cycles using liquid nitrogen were applied to the concrete specimens. As a result, gradual damages can be introduced up to a severely damaged state, as shown in Fig. 12. The sub-THz waves, from 30 GHz to 50 GHz by continuously changing the frequency every 0.02 GHz, were applied to the specimens with different damage levels. Fig. 13 shows an example of results measured as reflected waves from the specimen. Here, the vertical axis indicates the rate of change of Young's modulus, and the horizontal axis indicates the sub-THz reflectance. This figure shows the possibility of measuring changes in mechanical properties as changes in sub-THz reflectance. This is thought to be measured as a change in mechanical properties due to cracks caused by freeze-thaw cycles. However, the relationship between changes in mechanical properties and sub-THz reflectance is not uniform. This is thought to be an effect of sub-THz wave interference.

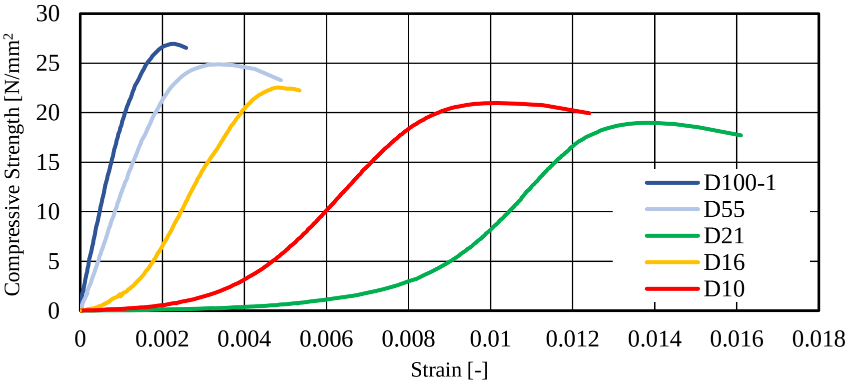


Figure 12. Stress-strain relationship with different level of damage

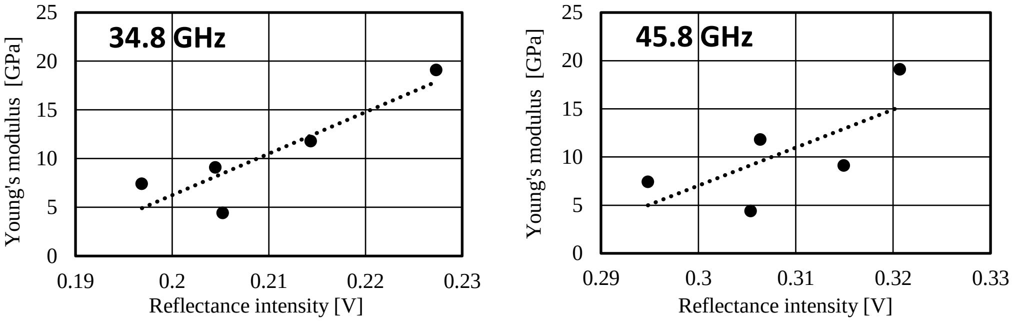


Figure 13. Variation of Young’s modulus with reflectance intensity

Effect of Rebar Corrosion on Bond-Slip Characteristics

In order to consider the mechanical properties of RC structures, it is necessary to focus not only on the concrete material but also on the mechanical properties of the rebar and the bond properties between the rebar and concrete. In addition to the above-mentioned measurements targeting changes in the mechanical properties of concrete materials, we attempted to measure changes in the bond properties of rebar and concrete, particularly sub-THz wave reflectance. Here, concrete specimen with rebar and slits that can simulate different crack widths and lengths was fabricated, as shown in Fig. 14. These specimens can simulate changes in bond properties.

Figure 14. Test specimen with crack for imaging

Examples of the experimental results are shown in Fig. 15. Here, the results are shown for each simulated crack (slit) length, with bond slip on the horizontal axis and bond stress on the vertical axis. These graphs show that bond strength decreases and the bond-slip increases as the crack length increases. Fig. 16 shows examples of measured reflectance distributions of specimens with different bond properties. In a specimen without a crack, sub-THz waves did not reflect at the concrete surface but were reflected at the rebar with the penetration into the concrete cover. Thus, the measured reflectance shows high values. In the cases of simulated crack presence, the reflectance decreases significantly for small crack widths. On the other hand, when the crack width is relatively large, the measured reflectance shows an intermediate between these two values. These results suggest that the rebar and concrete bond properties may also be measured as sub-THz reflectance.

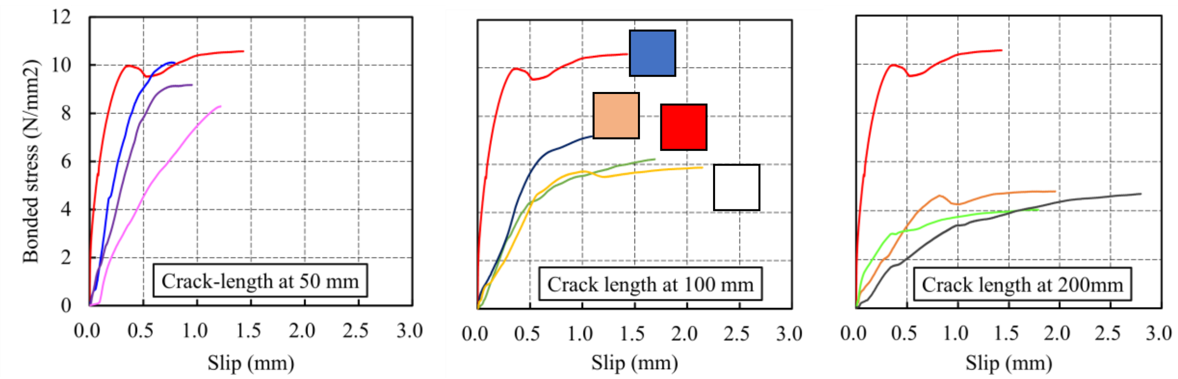
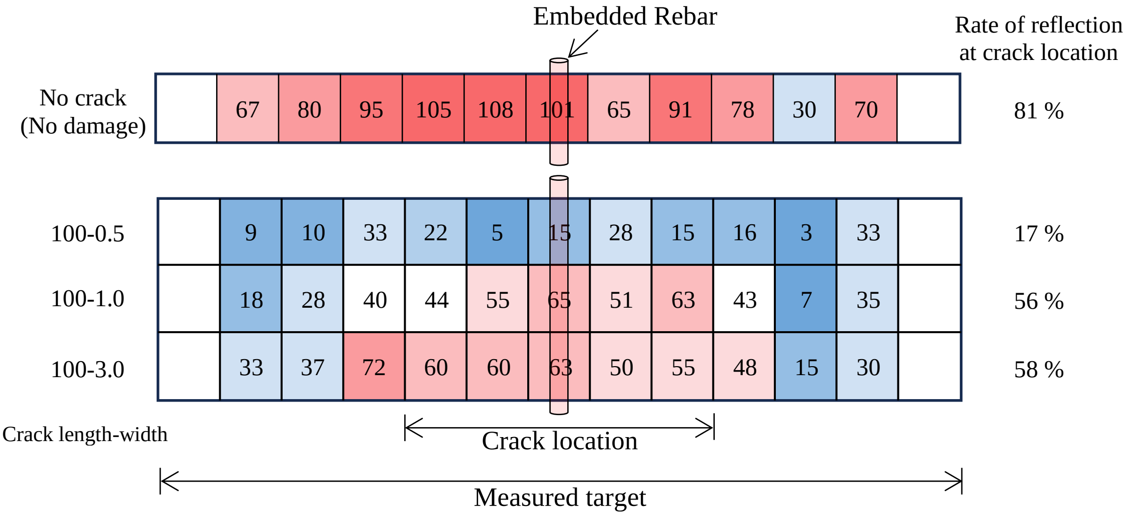


Figure 15. Bond-slip relationship with different crack length



Crack length-width														Rate of reflection at crack location
No crack (No damage)		67	80	95	105	108	101	65	91	78	30	70		81 %
100-0.5		9	10	33	22	5	15	28	15	16	3	33		17 %
100-1.0		18	28	40	44	55	65	51	63	43	7	35		56 %
100-3.0		33	37	72	60	60	63	50	55	48	15	30		58 %

Figure 16. Examples of measured reflectance ratio

Seismic Performance Evaluation of Shear Walls Based on Deteriorated Material Properties

As per the above-mentioned experimental results, the change (degradation) of the mechanical properties of concrete and rebar bonding can be measured as sub-THz wave reflectance. Here, we perform FEM analyses in which the changes in these mechanical properties are given as constitutive laws. The stress-strain curve of concrete shown in Fig. 12 is used as a constitutive law for the analyses. As shown in Fig. 17 as examples, the analysis assumes that these changes in mechanical properties occur as different patterns in the earthquake-resistant wall. The obtained results can be organized for the database so that the changes in mechanical properties can be simply evaluated based on each pattern and damage level, as shown in Fig. 18.

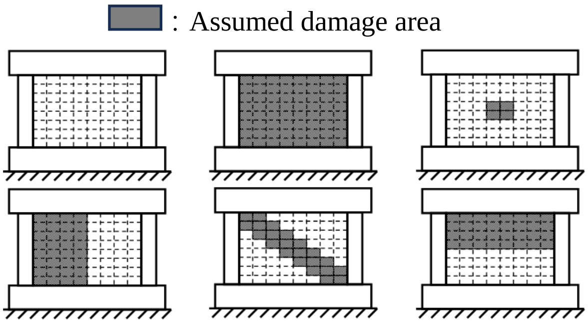


Figure 17. Examples of FEM Analytical Model

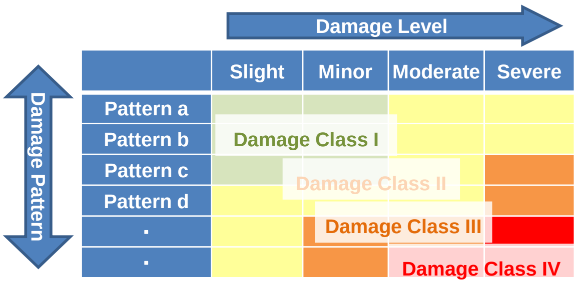


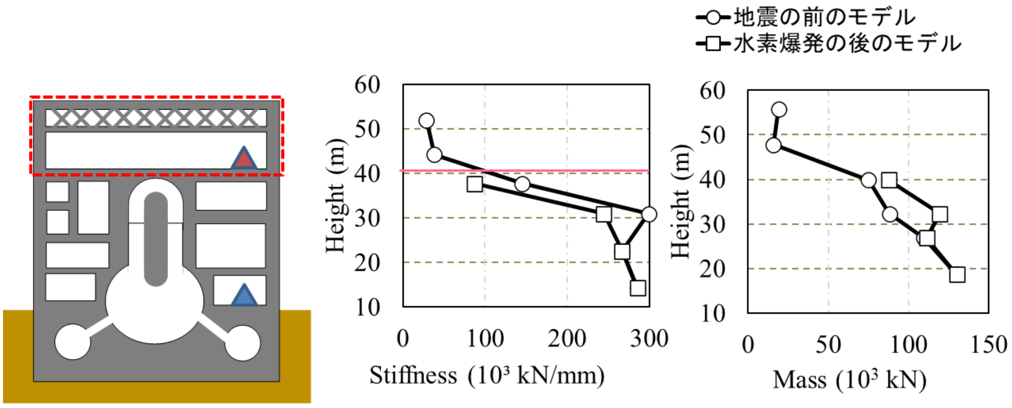
Figure 18. Damage classification based on pattern

TOPIC (4): PERFORMANCE EVALUATION METHOD AND PROPOSAL OF A LONG-TERM MAINTENANCE

Structural Soundness Estimation of Reactor Buildings

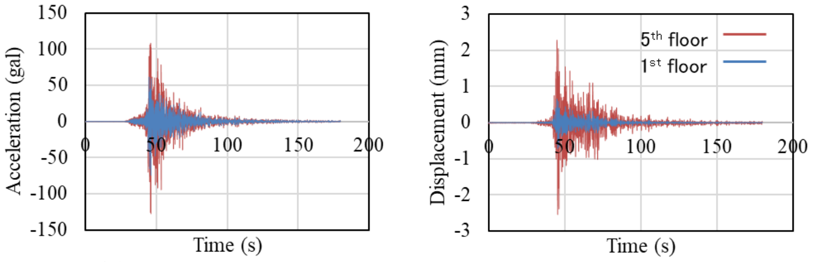
The developed evaluation method was applied to a reactor building in Fukushima Daiichi Nuclear Power Plant (1F). Elevation of the structure is illustrated in Fig. 19 and the shear stiffness and mass distribution are plotted against height with values based on report by TEPCO (2012). Accelerometers were installed in the building on floors 1 and 5 after the 2011 East Japan Earthquake disaster. Several acceleration records during minor and moderate earthquakes were observed as shown in Fig. 20. Displacement response is obtained by double integration of acceleration records.

Performance curve of analytical model was updated by the method described in Topic (1) using observed records as shown in Fig. 21. Relationship of damage levels and displacement was identified by the method described in Topic (2) and (3).



(a) Elevation of structure (b) Stiffness distribution (c) Mass distribution

Figure 19. Structural characteristics of target reactor building in Fukushima Daiichi



(a) Acceleration records (b) Displacement

Figure 20. Observed acceleration record and evaluated displacement of Fukushima EQ (March, 2021)

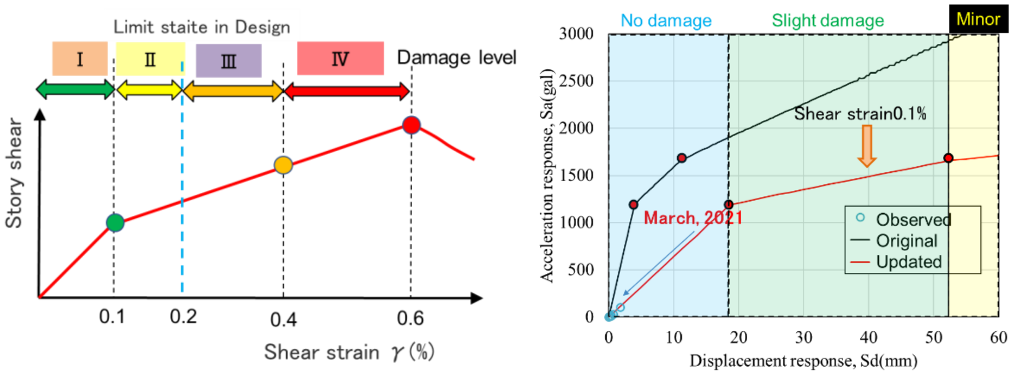


Figure 21. Structural soundness estimation example of reactor building

To safely complete the decommissioning of an accident-damaged nuclear power plant which requires decades, it is essential to monitor the condition of the reactor building at appropriate intervals throughout the entire decommissioning duration. Based on the results of these periodic checks, corrective measures such as repairs should be implemented as needed to maintain structural integrity and ensure safety. To achieve this, it is crucial to develop an appropriate long-term maintenance plan for the reactor building and execute an appropriate maintenance program. The long-term maintenance plan consists of three elements: maintenance target areas, maintenance tasks, and timing of maintenance implementation. The envisioned image and ideal form of the long-term maintenance plan are discussed below.

Unlike routine maintenance activities, maintenance activities for an accident-damaged nuclear power plant are extremely restricted due to high radiation levels and severe contamination, making accessibility to maintenance targets extremely limited. Therefore, a strategically focused approach is more strongly required than in the case of normal reactor decommissioning to minimize the number of maintenance target areas, essential for appropriately understanding the integrity of the maintenance targets. By narrowing down the maintenance target areas, it is possible to reduce the amount of required maintenance resources (maintenance implementation organization/personnel × required time, necessary equipment and materials, etc.). This is particularly important in the maintenance for accident-damaged plants where restrictions such as radiation exposure are stringent. The results of this study suggest that introducing the concept of damage risk importance (structural strength margin × environmental factors) and selecting maintenance target areas based on this concept is effective and efficient.

For the narrowed-down maintenance target areas, it is crucial to adopt an effective and efficient approach to perform maintenance tasks (such as inspections, monitoring, and corrective measures like repairs), essential for appropriately understanding the integrity of the maintenance targets. Usually, the optimal method is selected from existing methods that can be applied. However, if such methods are not sufficiently developed, there is a need for research and development. In this study, as mentioned earlier, we are working on the development of monitoring methods using acceleration sensors/gyro sensors and non-destructive inspection methods using terahertz waves, etc.

Regarding the timing of maintenance implementation, it is typically determined by predicting the progression of aging, conducting inspections when a certain level of degradation is anticipated, and setting the implementation time of next inspection. Similarly, corrective action timing is determined to address repairs before functional failure is predicted. In such cases, it is common to conservatively evaluate the progression of aging to ensure that degradation does not exceed predictions. However, overly conservative assessments can lead to excessively early scheduling of the next inspection or corrective action, resulting in the unnecessary consumption of resources. Therefore, in this study, we are working to establish an aging prediction method based on realistically forecasting or measuring the conditions of various parts of the reactor building and its surrounding environment. This approach aims to strike a balance between conservatism and resource efficiency. To summarize, Fig. 22 illustrates the conceptual image of the long-term maintenance plan for the damaged reactor building.

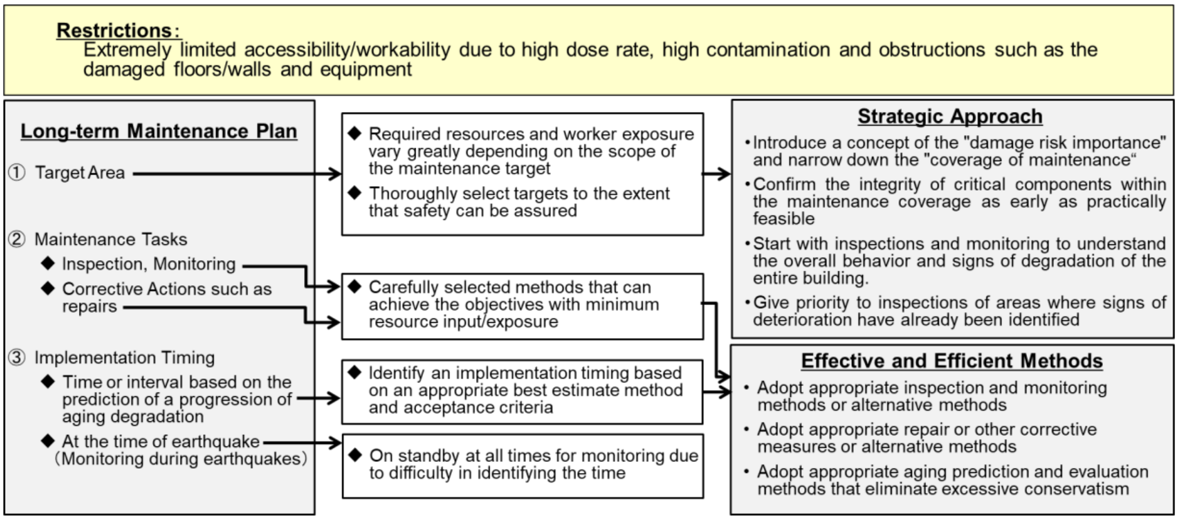


Figure 22. Conceptual image of long-term maintenance plan

CONCLUSION

A long-term evaluation method targeted to monitor nuclear power plants is proposed and evidence supporting its effectiveness in detecting damage suggests its reliability. A maintenance plan designed to check the integrity of the building periodically is essential to minimize risk.

ACKNOWLEDGEMENT

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