Residual Structural Performance Evaluations of Piers Using Artificial Intelligence

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Introduction

In Japan, the construction of numerous social infrastructure facilities during the postwar period of rapid economic growth has resulted in many structures being in service for over 50 years, highlighting the importance of proper maintenance and management. As of March 2020, approximately 21% of public port facilities were more than 50 years old, a figure projected to rise to approximately 43% by March 2030 and 66% by March 2040. Additionally, as of March 31, 2019, 10,178 of 58,839 public port facilities required emergency measures [1], and numerous port facilities owned by private companies, such as those in the steel, cement, and nonferrous metals sectors, faced similar maintenance challenges.

Figure 1. Port pier deteriorated due to reinforcing steel bar corrosion

Although the Port and Harbor Act has been revised to make inspections of port facilities mandatory, in many cases, particularly in the private sector, breakdown-type maintenance has been practiced, meaning measures are taken only after a facility failure occurs (Figure 1). The Ministry of Land, Infrastructure, Transport and Tourism estimates that, by shifting from breakdown-type maintenance to preventive maintenance, the annual cost of maintenance, management, and updating of social infrastructure facilities under its jurisdiction would decrease by approximately 50% in FY 2048, and by approximately 30% over the 30-year period from FY 2019 to FY 2048 [1]. A similar trend is expected for private port facilities, as cost reductions through preventive maintenance are anticipated to promote maintenance, repair, and reinforcement work. However, as the deterioration and performance degradation estimates from maintenance surveys only represent the facility conditions at a certain point in time, and given that there has been no technology available to provide managers with a reasonable index to determine the usability of the facility or when repairs and reinforcement should be performed, facility managers often rely on their own judgment (Figure 2).

To address this challenge, we have developed a technology that allows the service life of structures to be estimated according to the evaluated residual bearing capacity based on the survey results for harbor piers. This development aims to provide facility managers with the necessary information to facilitate decision-making processes.

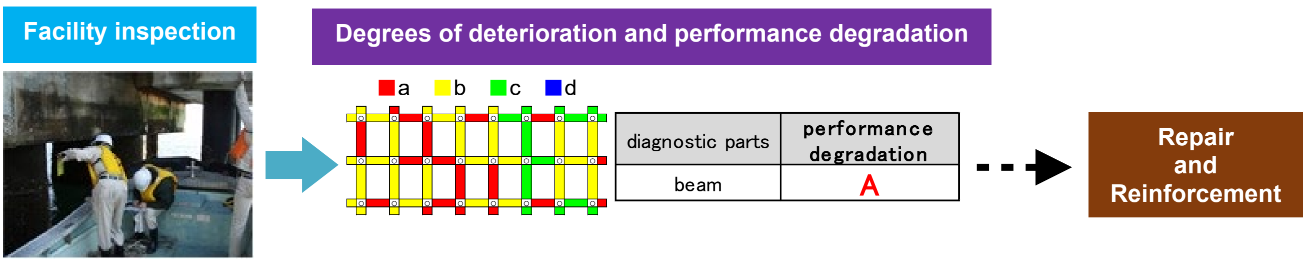

Figure 2. Survey and diagnosis process used in current maintenance and management

Technology overview

Figure 3 illustrates the conventional process for evaluating the residual capacity of a pier structure. In this process, to evaluate the residual strength, it is necessary to measure the degree of corrosion in the reinforcing steel bars of beams; this measurement involves removing the concrete on the underside of the beams to expose the reinforcing steel bars and perform several measurements (generally using calipers) to estimate the degree of corrosion. Following the corrosion level estimation of the reinforcing steel bars for each beam, FE analyses for each beam are performed to estimate the properties of an equivalent frame model. The equivalent frame model of each beam member is required to conduct a structural analysis of the entire pier system. The residual capacity can be estimated by modeling the entire pier system using an equivalent frame model and conducting seismic response analyses. However, when a significant number of beams have corroded steel bars, the amount of concrete that must be removed, and the number of locations that require attention, become enormous, making this approach impractical. In addition, when performing FE analyses, it is best to use an approach that considers not only the reduction of the bar diameter but also the expansion pressure generated as the reinforcing bar corrodes. These factors make it challenging to evaluate the residual strength using the conventional method previously described.

To address these challenges, we initially developed a technique to evaluate the residual strength by using the deterioration levels “a” to “d,” obtained from general periodic inspections (Figure 4) [2]. In order to evaluate the residual strength based on the degree of deterioration, it is necessary to estimate the parameters of equivalent frame models of the beams corresponding to each degree of deterioration. Structural experiments were performed to establish a relationship between each degree of deterioration and the strength capacity of the corresponding beam members. By subjecting the lower reinforcing bars of the experimental beams to electrolytic corrosion, specimens that represent each degree of deterioration were fabricated. The corrosion condition of the reinforcing bars was assessed using test pieces to ensure that the specimens corroded as designed. The structural experiments revealed that the failure modes varied depending on the degree of deterioration, and differences in the strength capacity of

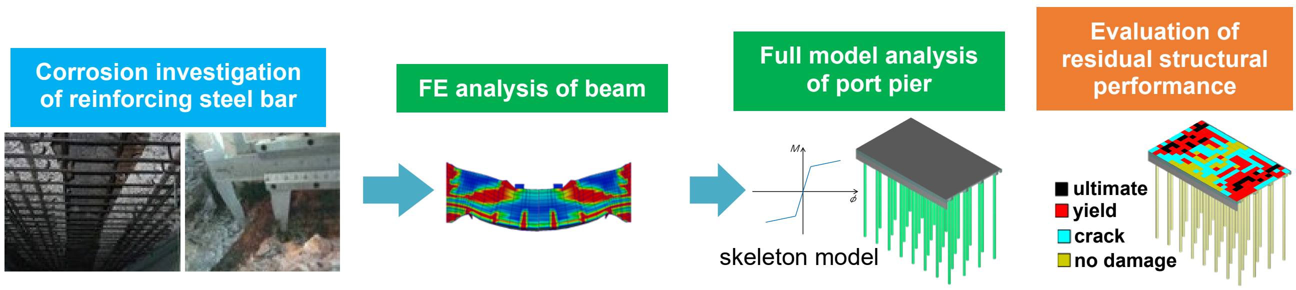

Figure 3. Conventional process for evaluating the residual structural performance of a pier

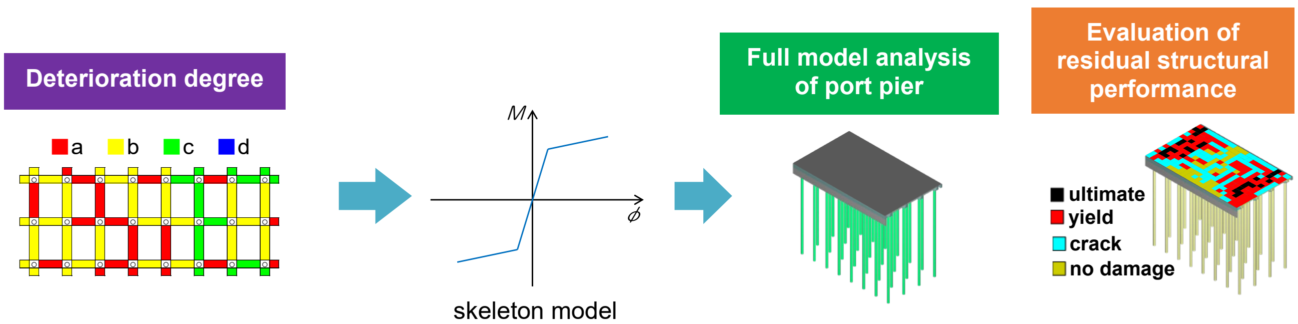

Figure 4. Method for evaluating the residual structural performance of a pier based on the degree of deterioration results

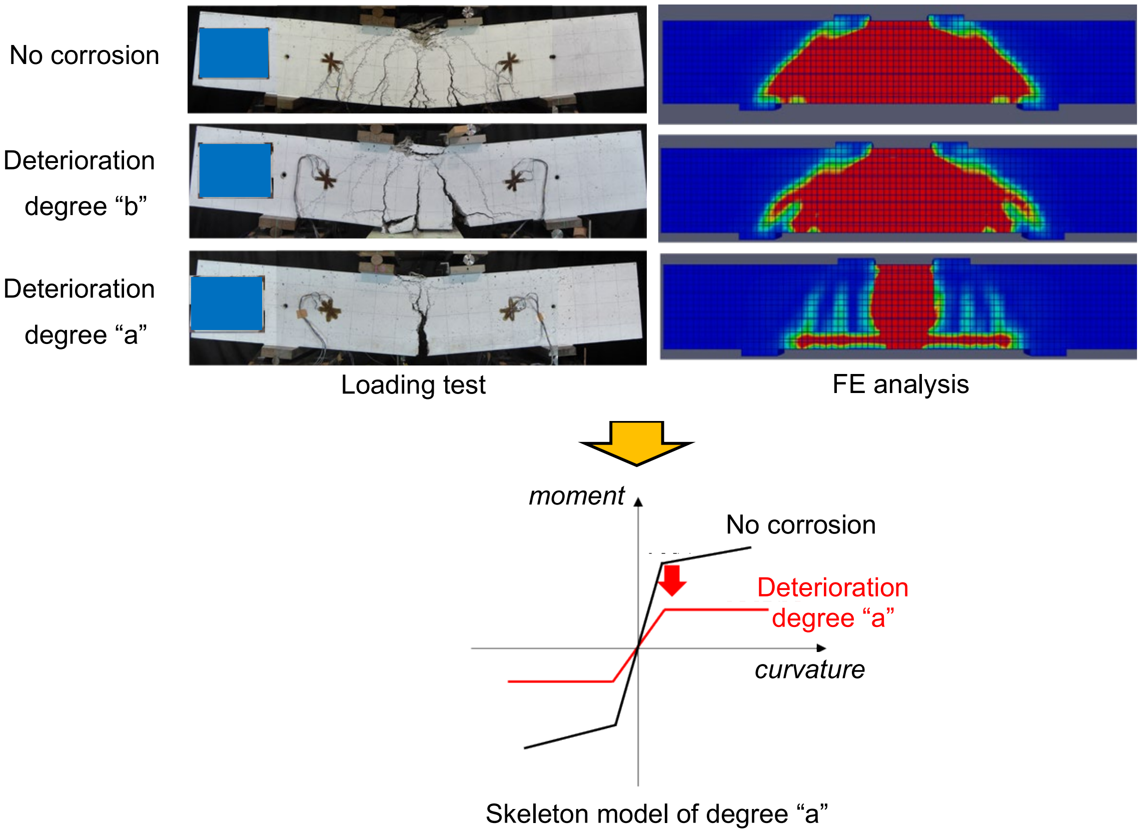

Figure 5. Relationship between the degree of deterioration and the flexural capacity of beams, and a Skeleton model

the specimens were also found. FE analyses was also performed, demonstrating the numerical reproducibility of the experiments (Figure 5). In this structural experiment, the rebar was forced to corrode via electrolytic corrosion, which is different from the rebar being corroded by exposure to natural environments. This means the impact of dimensional effects could not be eliminated. Therefore, we took advantage of the opportunity to remove portions of the aged pier beams as part of the pier updating work, conducting loading tests and clarifing the relationship between the corroded beams and bearing capacity in the natural environment. The impact of the size effect was also discussed by comparing the structural performance of the specimen with that of the actual beam and the actual dimensions of the specimen. To address the concerns that remained following the structural experiments on reduced fabricated specimens, additional loading tests were performed using an actual deteriorated beam (removed as part of pier updating work); these experimental results allowed us to further clarify the relationship between the beams corroded under natural exposure and their strength capacity; also, the impact of the scale differences was evaluated by comparing the structural performance of the reduced specimen with that of the actual beam.

Using the experimental results introduced above, it became possible to evaluate the residual capacity of the beams based on the degree of deterioration. However, estimating the residual capacity of the entire pier structure would require a case-by-case structural analysis of the pier system, which poses challenges in terms of cost and time. In addition, to estimate the service life of a structure, it is necessary to evaluate not only the residual capacity at the time of inspection but also estimate the residual capacity multiple years after the inspection.

To further enhance the capabilities of our technology and tackle the challenges described in the previous paragraph, we have developed a technique to evaluate the residual capacity without relying on case-by-case structural analysis, utilizing artificial intelligence (AI) (Figure 6). This AI was trained using approximately 2,000 combinations of structural analysis conditions and structural analysis results as training data (Figure 7). This training data was generated to include a set of explanatory and objective variables.

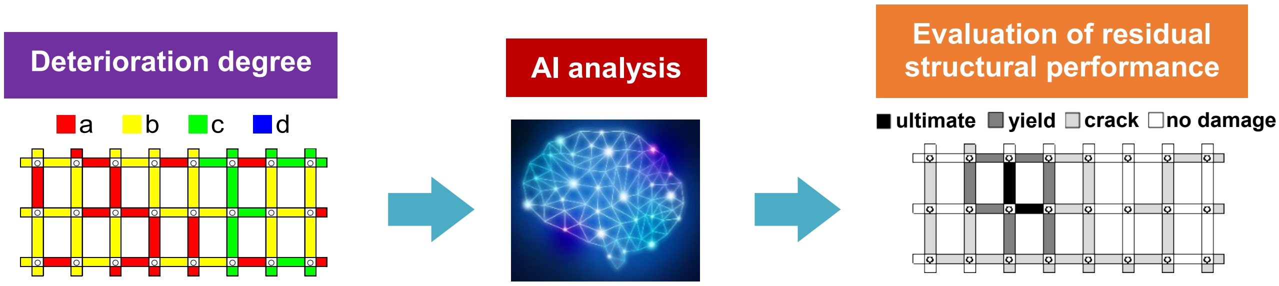

Figure 6. AI-based method for evaluating residual structural performance

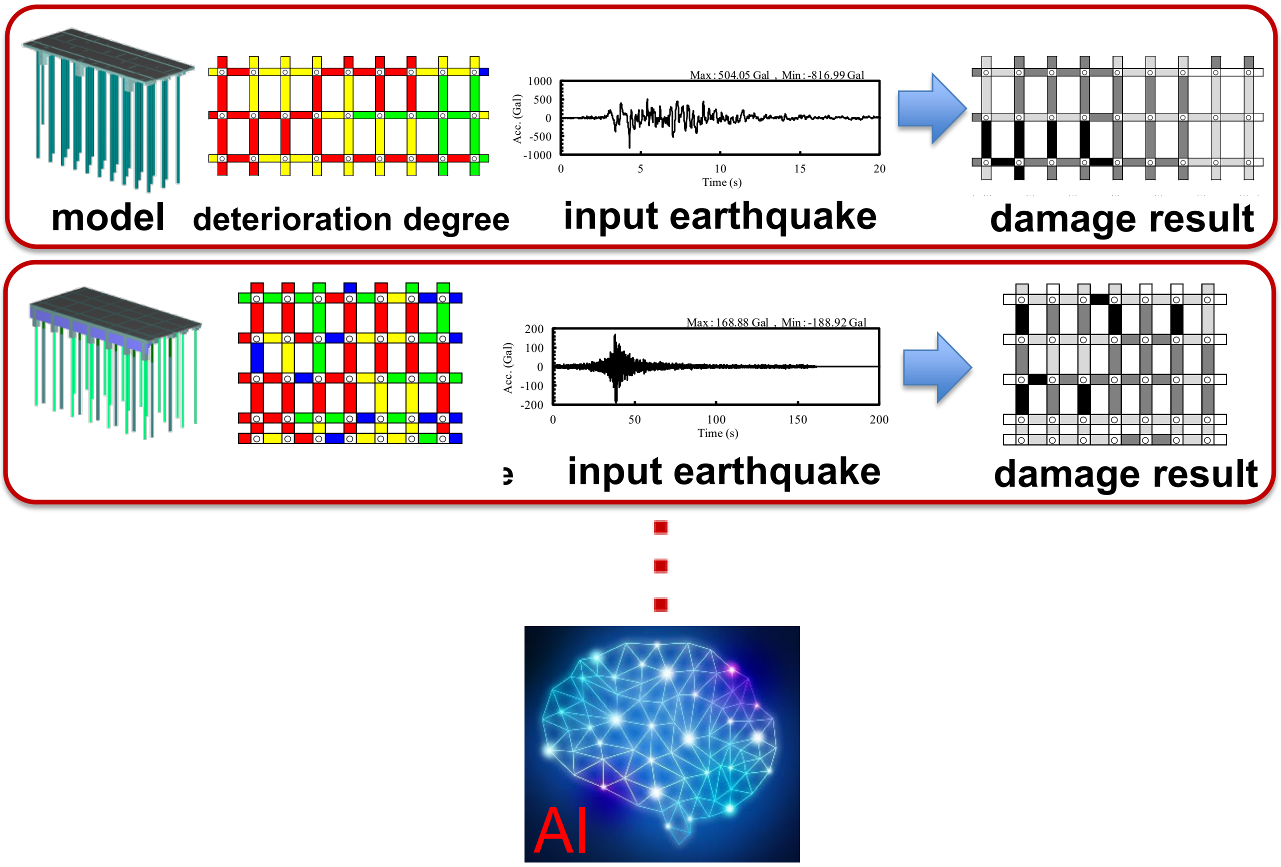

Figure 7. Training and building an AI model

Technology applications: Accuracy estimation and effectiveness

Figure 8 shows the prediction results of the residual strength capacity of deteriorated Piers A and B. The residual strength capacity was evaluated using the AI model as well as structural analysis. The percentage of correct predictions is shown based on a comparison between the two. The results demonstrate that the developed technology can predict the residual capacity with high accuracy. In the piers in the study, the prediction of the beam locations that lead to ultimate damage beams were also successful. Figure 9 shows the results of the evaluation of the residual capacity for a total of 400 cases, including the two cases mentioned above, and the validation of the prediction accuracy. In general, more than 80% of the beams can be predicted correctly, with a median validation result value as high as 88%.

The AI-based evaluation technique makes it possible to immediately identify the specific beam members that would be damaged by seismic forces and the extent of the damage. Some of the time and economic benefits of this

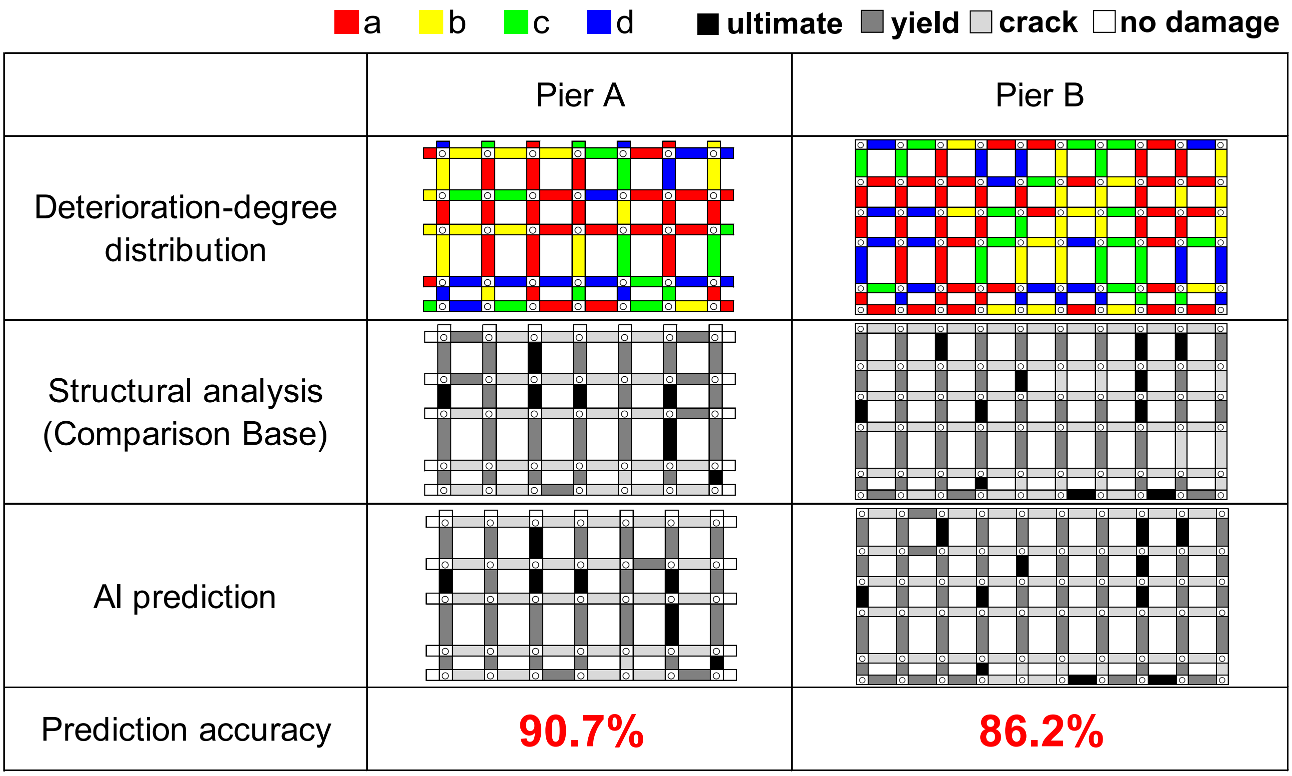

Figure 8. Verification of AI model accuracy

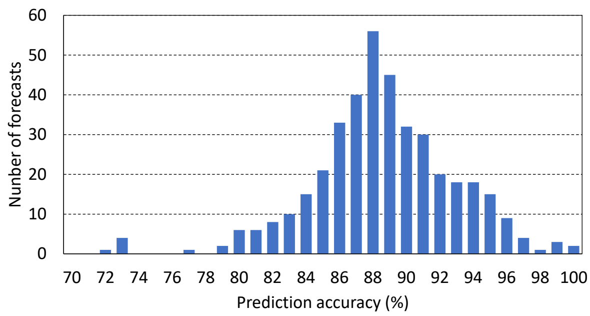

Figure 9. Results of the residual structural performance evaluation for a total of 400 cases

technology are the elimination of the need for removing concrete, FE analyses, and structural analyses of entire pier systems, as mentioned earlier. As an illustrative example, for a pier measuring 3,000 m^2, it would take approximately two to three months to remove concrete, two months to conduct FE analyses, and one and a half months to conduct a structural analysis of the entire pier, totaling five and a half to six and a half months. By utilizing this technology, general periodic inspections and deterioration assessments can be completed in approximately one half to one month, and the residual capacity assessment via AI takes approximately 0.1 months, resulting in a total of 0.6 to 1.1 months for a residual capacity assessment. Therefore, the time required to calculate the residual capacity has been reduced by up to 91%.

Moreover, by combining this technology with a probability model for deterioration, such as a Markov chain model, it becomes possible to determine the change in residual capacity over time, allowing for a specific period to be established during which the pier can remain in service. Figure 10 shows an example of a residual capacity evaluation for present and future conditions. As depicted in the figure, the evaluation of the residual capacity shows that there is only either “no damage” or “crack damage” at the current level of deterioration, suggesting that immediate repairs are not necessary. However, when the residual capacity was evaluated based on the predicted deterioration over the next 10 years using a Markov chain model, beams with damage beyond the yield point were found. Utilizing these results, repair work can be planned within a specific timeframe, such as 10 years, allowing for timely action. By determining when immediate repairs are required and which beams will be affected, measures such as partial repairs can be effectively implemented.

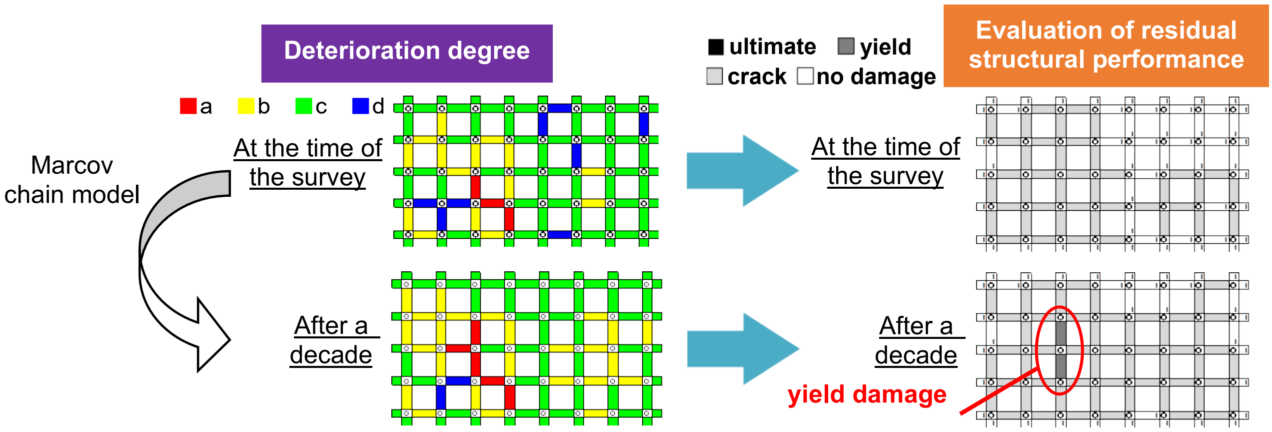

Figure 10. Example of a future prediction of residual structural performance

Conclusion

This technology has been developed to provide key assistance to facility managers, providing answers to frequent questions related to the usability of the piers such as: "I understand the results of the inspection survey, but how long can this pier be used?" “Will it be damaged in a seismic event?” and so on.

Our motivation for developing this technology stems from the recognition that facility managers require an indicator that effectively assists them in making informed decisions related to the repair and reinforcement of pier structures. We believe that by understanding the specific hazards associated with a deteriorating pier, facility managers will be able to proactively engage in maintenance and management, thereby shifting to preventive maintenance and management practices. Our aspiration is that the use of this technology will promote rational and systematic maintenance management.

References

[1] Ministry of Land, Infrastructure, Transport and Tourism (2020). White Paper on Land and Transportation, pp. 142–146.

[2] Uno, K. and Iwanami M. (2018). Evaluation method of residual structural performance based on the judgement result of deterioration degrees and its application to corroded pier, Journal of the Japan Society of Civil Engineers B3, Vol. 74, No. 2, pp. I_55–I_60.