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JCI Guidelines for Assessment of Existing Concrete Structures

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ABSTRACT

From the view point of sustainability, continuous use of existing structures is quite important. Since methods for assessment of existing structures are different in many aspects from the design of new structures, the assessment requires various knowledge beyond the scope of design codes. Japan Concrete Institute (JCI) intended to establish technical rules for the assessment of existing concrete structures so that practicing engineers can apply specific methods for the assessment based not only on deteriorated conditions of the structure but on required structural performance. JCI guidelines for assessment of existing concrete structures will lead to limitation of construction intervention to a strict minimum and to a goal that is clearly in agreement with the principles of sustainable development. In this paper, the framework of the guidelines is outlined and some characteristic aspects are explained.

Keywords. Structural Assessment, Structural Performance, Existing Concrete Structure, Assessment Level, Investigation Grade

INTRODUCTION

Once concrete structures are completed, they start to be aging. Since built environment such as concrete structures of buildings, bridges, tunnels, dams and other infrastructures is a huge economic asset and growing larger every year, the assessment of built environment becomes more and more important and is now a major engineering task (ACI 2003). Although structural design codes have been developed for designing new structures, they are often not appropriate for the assessment of built environment because there are significant differences between design of new structures and assessment of existing structures. Various kinds of uncertainty exist in the design stage due to unknown factors contained in for example the prediction of load and resistance parameters of a new structure, unequal qualities of material and construction practices. Furthermore local environmental actions cause various types and degrees of damage such as cracking of concrete and corrosion of reinforcement which lead to deterioration of structural performance after a couple of decades. Evaluation of structural performance of members in a new structure is carried out according to equations in design codes assuming that there are neither cracks in concrete nor corrosion of reinforcement in the members. Then these assumptions fail in case of the assessment of existing concrete structures if they are damaged. At least, some modifications for the equations or other suitable equations need to be developed for assessment of existing structures.

Structural assessment of existing structures can be initiated when there is a change in loading (e.g. conversion of use of building, increase of traffic loads, etc.) or when there is a change in resistance of the structure because of structural deterioration or of accidental actions such as earthquakes. While a conservative design does not result in a significant increase in construction cost, a conservative assessment may result in unnecessary and costly inspections or interventions (Ruecker et al. 2006). Therefore, technical rules for the assessment of existing structures are obviously necessary. For this purpose, general requirements and procedures for the assessment of existing structures are provided in ISO 13822 (2001). This international standard does not specify any construction materials. Following this international standard, ISO/DIS 16311-2 (2012) has been drafted. This Standard (draft) provides the requirements for assessment of existing concrete structures, including a general framework for the assessment, a format for documentation of the condition assessment with assessed condition level and consequence level, and a format for documentation of the performance assessment with verified specific structural performance, while role of the International Standard is a model code for national code writers.

The JCI guidelines for assessment of existing concrete structures was developed in order to offer practicing engineers a methodological framework of the assessment that is composed of a stepwise procedure of beginning with simple methods and of going on to more sophisticated ones, if necessary. In this paper, the framework of the JCI guidelines and some characteristic aspects are explained.

SCOPE

The JCI guidelines for assessment of existing concrete structures describe general requirements and procedures for the structural assessment of existing concrete structures. In order to verify the structural performance, structural assessment can be initiated under the following circumstances, but not limited to when:

(a) an anticipated change in use or extension of design service life is planned;

(b) analyses of current structural reliability (e.g. for earthquakes, increased traffic actions) are required by authorities, insurance companies, owners, and so on;

(c) there has been a change in resistance because of structural deterioration due to time-depending process and actions (e.g. corrosion, fatigue) or structural damage caused by accidental actions.

The proposed guidelines present a methodological framework of the assessment of existing concrete structures, a stepwise procedure, and applicable methods developed for structural assessment. The guidelines are intended to explain the principles of structural assessment and to help practicing engineers finding suitable methods for the assessment objectives. They are also intended to make prominent the different levels of structural assessment, starting with simple but conservative methods and progressing to more refined but sophisticated methods. The guidelines can be applied to any kind of existing reinforced concrete structures such as buildings, industrial structures, bridges and other infrastructures.

Since the remaining service life of existing structures is generally shorter than the original design service life, probabilistic studies have been often carried out to allow for a lower performance level of the acceptable criteria than that of the current design codes and

standards (for example, JCSS 2001). In the JCI guidelines, however, the level of acceptable criteria is normally established in equivalence to that of the current design codes and standards. Former codes and standards that were valid at the time of construction of the existing structure are used only as informative documents.

PRINCIPLES OF STRUCTURAL ASSESSMENT

Objectives of Structural Assessment and Required Performance. Generally structural assessment is a process to evaluate how reliably the existing structure can fulfil the required performance for future use. Performance items targeted in the guidelines are as follows: safety, serviceability, adaptability for repair, and durability. Safety includes daily safety that is avoidance of risks due to daily actions such as spalling of cover concrete as well as structural reliability to carry current and future loads. Serviceability means capacity of a structure to perform the service functions for which it is designed and used. Serviceability limit states include unacceptable deformations and excessive vibrations. Adaptability for repair means easiness to recover damaged conditions of the structure. Durability is the capability of a structure to maintain the minimum performance under the influence of actual environmental degradation actions. In Table 1, examples of performance items, required performance, and verification criteria for the assessment are shown. When it is difficult to verify directly the structural performance, substitute performance may be assessed though the results are significantly conservative. Especially evaluation of the structural performance maintained in the future is usually not easy because of the uncertainty involved in the prediction of deterioration process. For such a time-dependent deterioration process, the substitution performance is often practically evaluated. For example, the remaining time for initiation of reinforcement corrosion or even for carbonation depth to reach the surface of reinforcements is regarded as the substitute performance for the durability.

Situations to require structural assessment are often caused by not only changes in use or increase of loads of existing structures but also design and construction errors including poor quality of building materials and workmanship. Such latter cases are not obvious just after completion of the new structure but are revealed after a couple of years. Furthermore any structure undergoes some degree of deterioration, though the rate of deterioration is dependent on the structure and the site specific.

Methodological Framework of Assessment. The principal framework and procedure of the JCI guidelines for assessment of existing concrete structures comply with ISO 13822 and include the following main parts as shown in Figure 1: objectives of assessment, scenario, preliminary assessment, detailed assessment, reporting results of assessment, and judgement and decision.

Specifying the assessment objectives and inquiring into the assessment scenario are essential prior to any inspections. Before starting the inspection activities, the objectives of the structural assessment of an existing concrete structure shall be specified in consultation with the client (i.e. the owner, the authority, insurance companies, etc.). Then scenario for the assessment shall be examined and documented, in which performance items and assessment level to be adopted as well as the grade for investigating the current condition of the structure and evaluation grade of performance maintained in the structure are specified so that the structural assessment can effectively proceed. Demands of the client, legal regulations, social conditions, benefits for the users, and economic efficiency need to be

Table 1. Items of performance, required performances and verification criteria

Items of performance	Required performance of resistance	Examples of verification criteria
Structural safety	Failure of members	Maximum stress of member
	Excessive deformation of members	Maximum deformation of member
	Structural failure	Maximum structural response
	Excessive deformation of structure	Maximum deformation response
Daily safety	Avoidance of risks due to daily actions	Permissible size and condition of exfoliation
Serviceability	Maintaining aesthetic aspect	Permissible width/length/density of cracks
	Maintaining comfortableness	Permissible deflection and deformation
	Maintaining water/air tight condition	Permissible values of water/ air tightness
		(Substitute performance): Permissible width/length/density of cracks
Adaptability for repair	Recovery of damaged condition without difficulties	Permissible expense and duration for repair
Durability	Deterioration due to corrosion of reinforcements	Permissible limit of deterioration of structural performance due to corrosion of reinforcements
		(Substitute performance): Permissible corrosion of reinforcements; Permissible carbonation depth & erosion of chloride ion
	Deterioration due to frost damage	Permissible limit of deterioration of structural performance due to frost damage
		(Substitute performance): Permissible depth/area of scaling; Permissible size of crack and spalling; Required performance for frost damage resistance
	Deterioration due to chemical erosion	Permissible limit of deterioration of structural performance due to chemical erosion
		(Substitute performance): Permissible depth and size of chemical erosion; Permissible rate of chemical erosion
	Deterioration due to alkali-silicate reactivity	Permissible limit of deterioration of structural performance due to alkali-silicate reactivity
		(Substitute performance): Permissible width and density of cracks; Permissible damage of reinforcements; Permissible expansion of concrete
	Deterioration due to shrinkage or thermal cracking	Permissible limit of deterioration of structural performance due to shrinkage and thermal cracking
		(Substitute performance): Permissible width/length/density of cracks

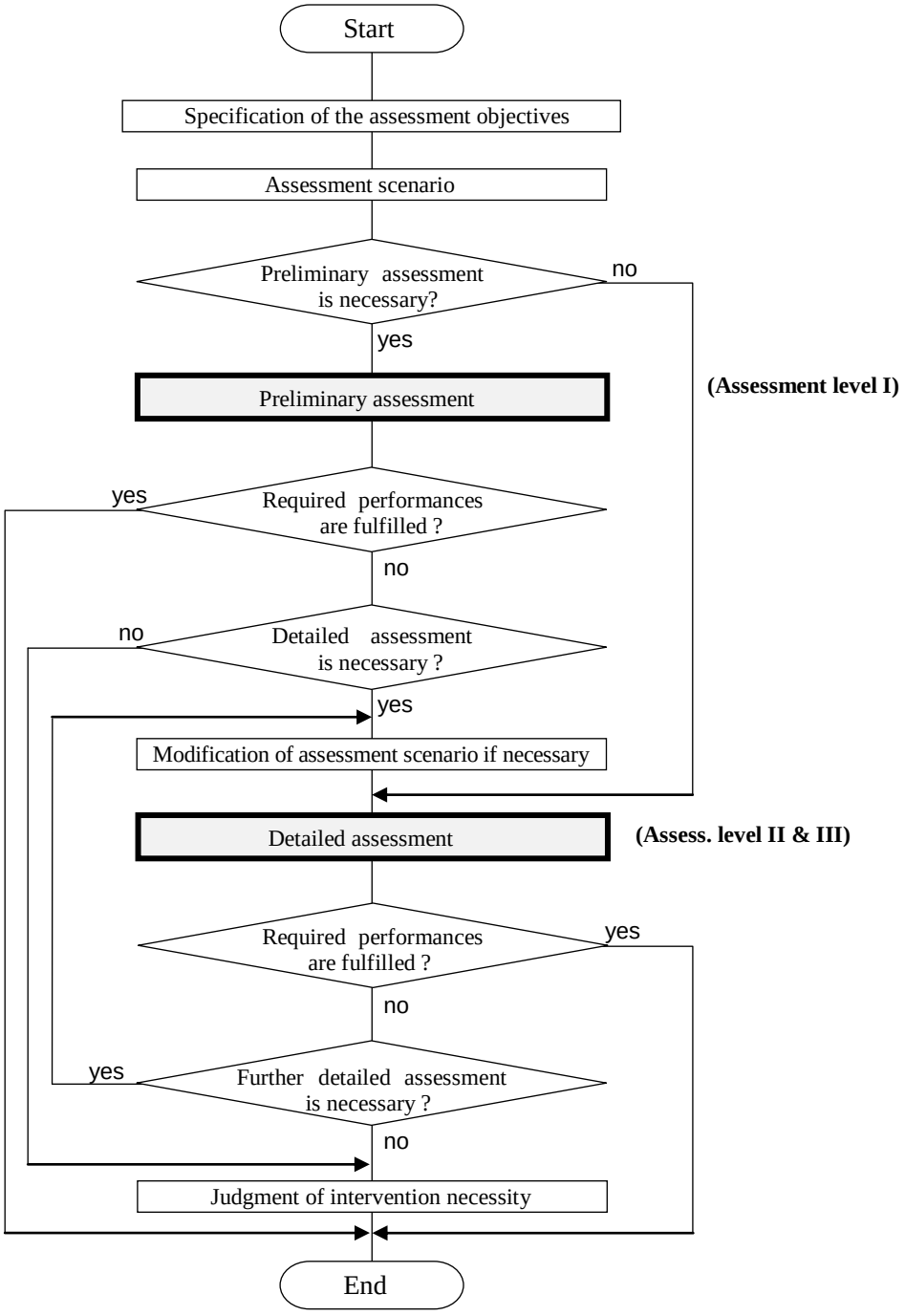

Figure 1. General flowchart for assessment of existing concrete structures

taken into consideration, too.

As shown in Figure 1, assessment procedures vary in the sophistication and usually it is recommended to start the assessment with the preliminary assessment. If it is not verified by the preliminary assessment that the performance maintained in the structure exceeds the required performance, a detailed assessment shall be generally proposed. In the detailed assessment, more sophisticated works are carried out than the preliminary assessment. For example, a more detailed study of previous documents, more detailed inspections and material testing as well as structural analysis and verification are carried out for achieving correct judgement. In the JCI guidelines, the detailed assessment is classified into two levels dependent on the sophistication of the method to evaluate the performance maintained in the structure (e.g. load-carrying capacity of the structure). If it is not verified even by the detailed assessment that the maintained performance does exceed the required performance, further detailed assessment will be done even on the same level with some modifications of models or on the higher level.

Outline of the Preliminary Assessment. The aim of the preliminary assessment is to provide information of the current condition of the structure, to clarify the seriousness of the deterioration, and to judge whether the required performance is sufficiently provided in the structure or a detailed assessment is necessary. The preliminary assessment is composed of the following three components: study of documents and visual inspection, establishing the verification criteria based on general knowledge and previous experience, and preliminary verification by comparing the collected data and the verification criteria (Figure 2). Possible immediate actions should be reported to the client if necessary.

Outline of the Detailed Assessment. The aim of the detailed assessment is to carry out a quantitative assessment of the structure and the procedure of the detailed assessment is shown in Figure 3. In principle, the detailed assessment is composed of the following three components: detailed inspection, estimation of values of material properties and actions relevant to the structural analysis, determination of structural properties, and verification. Besides these three components, prediction of material properties in the future has to be carried out if the future performance of the structure is required to be assessed.

Assessment Levels. In the JCI guidelines, three assessment levels are defined dependent on the sophistication. Assessment **Level I** is the simplest procedure but it is conservative and offers only a rough assessment result. Assessment Level I is applied for the preliminary assessment. On the other hand, the detailed assessment is classified into two levels dependent on the sophistication of the method to evaluate the performance maintained in the structure. On the **Level II**, the maintained performance is evaluated according to equations

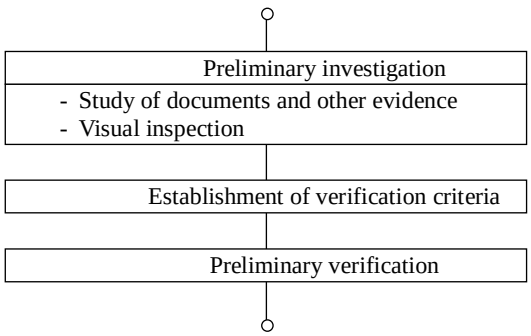

Figure 2. Flowchart of preliminary assessment (assessment level I)

given in the current design codes and standards but modified if necessary. For example, when reinforcements are corroded, the section area of the reinforcement needs to be reduced as much as the most critical location. On the **Level III**, the maintained performance is evaluated by an advanced numerical analysis such as nonlinear finite element analysis in which local information of damaged concrete and corroded reinforcements can be reflected directly on the numerical model.

Methods of Data Acquisition. The main difference of assessment from design is that various uncertainties involved in the design can be significantly reduced by site specific data acquired from the real existing structure. In general within one applied assessment procedure, the sophistication of the individual components should be about the same grade. For the detailed assessment, higher grades of investigation for the inspection and data acquisition method shall be applied than those for the preliminary assessment.

There is a wide range of data acquisition methods with varying cost and accuracy. Choice of the method is highly dependent on the assessment objective and on the assessment level. While simple methods are applied in a lower assessment level, more sophisticated methods of higher accuracy need to be applied for a higher assessment level to reduce the uncertainties of data. Since any additional damages caused by testing on the structure should be avoided, non-destructive testing methods are preferable whenever it is possible. Besides the data which describe the current condition of the structure, maintenance reports and data of periodic measurement can be sometimes useful for predicting future performance as information about time dependent process such as deterioration.

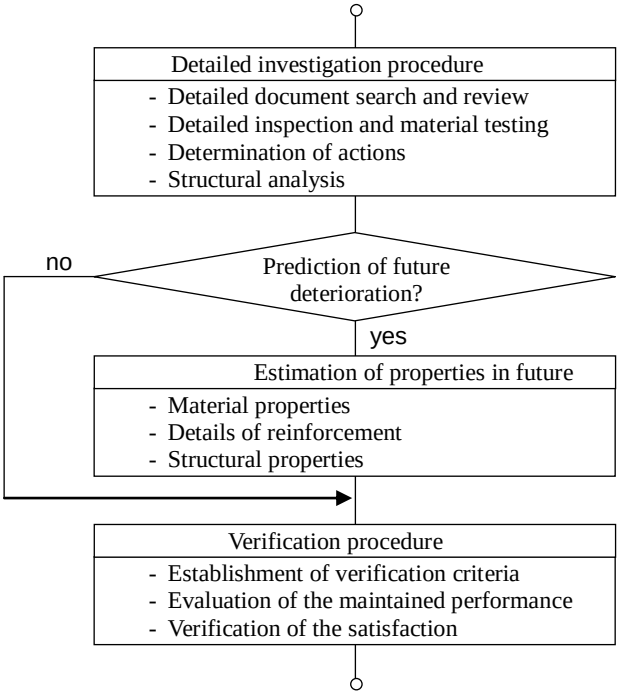

Figure 3. Flowchart of detailed assessment (assessment levels II & III)

Study of Documents. Study of documents of design and construction process as well as maintenance reports is generally the first step for collecting data of the structure for the assessment. Especially for the preliminary assessment, material properties and structural properties and dimension can be obtained from drawings and other design specifications. Loads can be usually determined from current design codes and environmental actions can be obtained from inspection reports.

Investigation Grade. For structural assessment, collection and evaluation of data to investigate current conditions of the structure through inspection, study of documents, material testing and others are necessary. Investigation of material properties, structural details, and loads and actions is carried out based on one of the following three grades of methods dependent on the accuracy of obtained data. (1) **Grade I**: study of design documents and specification, and preliminary inspection such as visual observation; (2) **Grade II**: further document search, detailed inspection and material testing; direct measurement from the structure (small number of samples), and indirect measurement from the structure (large number of samples); (3) **Grade III**: detailed inspection and material testing; direct measurement from the structure (large number of samples). While investigation Grade I can be applicable for the preliminary assessment, investigation Grades II or III need to be applied for the detailed assessment of either assessment Level II or Level III. Especially for the assessment Level III, sufficient number of data with high accuracy is required in order to reflect the real conditions of the structure on the numerical analysis.

Determination Grade of Material Properties. For evaluating the performance maintained in the structure or establishing the verification criteria, determination of material properties relevant to the analysis of current condition of the structure is necessary. There are three grades in methods to determine the values of the properties dependent on the accuracy of the obtained results as follows. (1) **Grade I**: design values, specific ones and results of visual inspection are adopted as they are; (2) **Grade II**: simple mean values and/or some modified values reflecting the influence of the scatter of data directly obtained from the structure though the number of samples is limited. Generally accepted information on the variability of values of structural properties or statistical evaluation of a large number of data indirectly obtained from the structure are also applied if possible; (3) **Grade III**: Difference among members and variability of data inspected from the structure are taken into account to determine the material properties.

Establishment Grade of Verification Criteria. For establishing the verification criteria based on the required performance, one of the following three grades is applied. (1) **Grade I**: Based on general knowledge and previous experience, the verification criteria are established as critical conditions corresponding to the performance-based limit states of the structure. The verification criteria can be also drawn by a numerical analysis in advance in which typical damaged conditions are related to the performance-based limit states; (2) **Grade II**: The verification criteria are established on the basis of critical values of the structural response to the design loads or on critical values given in the current codes; (3) **Grade III**: The verification criteria are established on the basis of investigation and analyses on indexes directly related to the required performance. For detailed assessment on Level III, the verification criteria are established in the Grade III, or at least in the Grade II.

Evaluation Grade of Maintained Performance. Performance maintained in the existing structure is evaluated by means of one of the following methods which are directly corresponding to the assessment levels. (1) **Grade I** corresponding to Level I: Based on the comparison of data acquired in preliminary investigation and widely accepted experience

Table 2. Assessment levels and corresponding grades for investigation, determination of material properties, establishment of verification criteria and evaluation of maintained performance

Assessment level	Grade			
	Investigation	Determination of material properties	Establishment of verification criteria	Evaluation of maintained performance
I	1,(2)	1	1*	1
II	(1),2,3	(1),2,3	2,3	2
III	2,3	2,3	(2),3	3

"*" In addition to critical conditions based on general knowledge and previous experience, a numerical analysis can relate damaged conditions to the performance-based limit states of the structure in advance.

that relates to the required performance; (2) **Grade II** corresponding to Level II: The performance maintained in the structure is evaluated according to equations given in design codes and standards, though those equations are relevantly modified if the structure is deteriorated; (3) **Grade III** corresponding to Level III: By means of an advanced numerical analysis, the maintained performance is evaluated in such a way that current conditions observed in the structure are reflected directly on the numerical model.

In Table 2, possible combinations of assessment levels and corresponding grades for investigation, determination of relevant values of material properties, establishment of verification criteria, and evaluation of maintained performance are shown.

PRELIMINARY ASSESSMENT

Study of Documents and Visual Inspection. Study of design and construction documents and other evidences is the important first step. Then visual inspection of the structure needs to be carried out to get the information of the current condition of the structure. It is also required to examine whether the degree of deterioration recorded in the previous report has increased or not. The visual inspection includes a general registration of damage observed in the structure such as cracks, spalling, deformation, rust spots, etc. These results should be documented.

Definition of Verification Criteria. On the basis of previous studies as well as general knowledge and experience, the verification criteria corresponding to the objectives are established in the Grade I. In previous studies, relations between deteriorated conditions and the degraded performance of the structure have been deeply investigated in Japan (JSCE 2008, JCI 2009). For establishing the verification criteria relevant to the objective, such data-base can be applied. The verification criteria can be also drawn by a numerical analysis in advance in which typical damaged conditions are related to performance-based limit states of the structure. In an annex to the JCI guidelines, several figures of a bridge damaged by alkali-silicate reaction are shown as an example which can relate typical damaged conditions to the performance-based critical states of the structure.

Preliminary Verification. Based on the results of the preliminary investigation, the performance maintained in the structure is evaluated by the comparison between the obtained results and verification criteria above established. Thus it is verified semi-

quantitatively whether the current condition of the structure is acceptable or not. Detailed assessment is recommended if necessary after considering the importance of the structure, its remaining service life, deterioration rate of the condition, and so on.

DETAILED ASSESSMENT.

Detailed Documentary Search and Review. Since updated knowledge about the present state of the structure is required for the detailed assessment, more comprehensive search and review of documents than those of the preliminary assessment are carried out.

Detailed Inspection and Material Testing. For collecting the detailed information of the present conditions of the structure, detailed inspection and material testing are carried out. Before starting the inspection, it is required to draw up an inspection plan in which inspection items corresponding to the objective, available methods, time schedule and necessary preparation matters are described. Compressive strength and Young's modulus of concrete are often evaluated from concrete cores directly taken from the structures. Besides these items, other material properties such as carbonation depth, chloride penetration depth, expansion due to alkali-silicate reaction and so on are measured from cores. Detailed observation of corroded state of reinforcement and cracking of concrete is a key issue in detailed inspection. It is recommended to estimate details of reinforcement and cover depth by means of suitable non-destructive test methods. In the JCI guidelines, a list of available test methods and a table to show possible combinations of the inspection items and required information for evaluating the performance maintained in the structure are shown.

Determination of Actions. For evaluating structural safety and serviceability, loads and mechanical actions are necessary information. Besides these mechanical actions, data of environmental actions need to be collected for simulating the time-dependent deterioration process of materials, because such simulation is essential for predicting the structural performance in the future. In principle, loads and mechanical actions are determined according to standards and current design codes. When the objective of the assessment is for a change in use or renovation of the structure, changes of loads and actions should be carefully taken into account.

Evaluation of Maintained Performance. Based on the information obtained from study of documents and detailed inspection above mentioned, structural performance maintained in the structure is evaluated. In the JCI guidelines, two different grades of means to evaluate the performance are shown for the detailed assessment though characteristics and applicable limits of the means need to be carefully taken into account. One (i.e. Grade II) corresponding to assessment Level II is to apply the same equations as those used in designing new structures though material properties are based on the detailed inspection results and the influence of deterioration of the structure is reflected on the values of variables used in the equations. The other (i.e. Grade III) corresponding to assessment Level III is to apply an advanced numerical analysis method such as nonlinear finite element analysis in which the current condition of the structure observed in the detailed inspection is reflected directly on the numerical model.

When a means of Grade III is applied, it is required to describe the following items concerning the evaluation means as clearly as possible in the report: method of the structural analysis; name of the computing system or program; modelling of the structure; constitutive models for materials including damaged or cracked concrete, corroded reinforcement, bond

properties between concrete and reinforcement, and influence of the corrosion on the bond properties; modelling of damaged components; prediction methods for future performance; verification criteria based on the required performance.

Evaluation of Future Performance. For evaluating the structural performance in the future, it is necessary to simulate the time-dependent process of the deterioration of the structure. In the JCI guidelines, theoretical models and numerical methods are introduced for predicting the deterioration process which will give data of variables necessary for evaluating the future performance of the structure.

While durability is the capability of a structure to maintain the required performance under the influence of actual environmental degradation actions, it can be possible to evaluate the durability by comparing the structural performance at present and one in the future for the remaining service life.

Verification of Structural Performance. For verifying that the performance maintained in the structure meets or exceeds the established verification criteria, the following equation should be confirmed either for assessment Level II or Level III.

$$PI_{pos} > PI_{req} \tag{1}$$

where PI_{pos} : performance maintained in the structure at present or in the future.

PI_{req} : verification criteria established from the required performance.

For example, in case of structural safety, the maintained performance should exceed the verification criteria that is the required load-carrying capacity. On the other hand, in case of structural serviceability, the maintained performance should be examined whether a sufficient resistance against an excessive deformation of members is provided in the structure or not. If the verification criterion is established by the permissible deformation for that purpose, the maximum response of the deformation of members obtained by structural analysis should be smaller than the verification criteria.

Judgment and Recommendation. At the end of the procedure of the assessment, the responsible engineer reports judgment and recommendation about the obtained results such as one of the followings:

(a) The structure has maintained the sufficient performance. No further actions such as further detailed assessment or intervention is necessary.

(b) Further detailed assessment needs to be done and/or some monitoring is necessary.

(c) Some interventions are necessary because the structure has insufficient performance.

CONCLUDING REMARKS

The assessment of existing structures is getting more and more important due to the social and economic reasons while generally accepted guidelines for practicing engineers to assess existing concrete structures are still limited. The JCI guidelines are expected to be widely applied to practices and they will be improved in the future on the basis of accumulated feedbacks from the application experience.

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