Committee Report: JCI- TC163A

Technical Committee on Crack Repair Evaluation in Concrete by Means of Non-Destructive Testing

Tomoki SHIOTANI, Takahiro NISHIDA, Keiyu KAWAAI, Hitoshi HAMASAKI, Takeshi WATANABE and Keiichi IMAMOTO

Abstract

The technical committee JCI-TC163A has been organized from FY2016 through FY2017. The target of research is to investigate the non-destructive testing (NDT) methods for evaluating repair of cracks in concrete. Focusing on the crack repair, repair methods for cracks in concrete are first surveyed. Then, the indices are referred to as to evaluate the repair results, and eventually addressed to effective NDT methods for repair evaluation. The issues facing the verification of repair results are examined by a questionnaire posed to managers and clients. The workflows of operation and maintenance are elucidated to confirm the repair results. Results show that the verification and confirmation of the repair results are in great demand for both owners and contractors of concrete structures. Thus, the indices necessary for verifying and achieving the required performance are identified. Concerning NDT methods, not only existing techniques but also brushing-up on the techniques are carried out to correlate with the indices for required performance and verification. As a result, a new workflow for the operation and maintenance of concrete structures is proposed for the evaluation of crack repair by means of NDT methods.

Keywords: Cracks, non-destructive testing (NDT), repair, required performance, repair results-based work flow

1. Introduction

Concerning optimal life-cycle scenarios for concrete structures in service, it is important to sustain the quality of structures during their service life, from the initial quality (both on the surface and in the interior) up to the service limits. As for performing preventive maintenance and subsequently constructing rational life cycle scenarios, the rational evaluation of internal concrete properties is of great significance to find out deterioration and damage in concrete as early as possible. This is because evaluation techniques that ensure reasonable repairs are inevitable for properly repairing the damage. At present, however, techniques for estimating internal deterioration and damage of concrete structures, in particular, from their surfaces are yet to be established.

Under the background, in the Japan Concrete Institute, “Technical Committee on Crack Repair Evaluation in Concrete by Means of Non-Destructive Testing” has been organized for two academic years from 2016 to 2017, chaired by Prof. Tomoki Shiotani, Kyoto University. The committee consists of four working groups (WG) and has carried out a series of lively discussions. Since it is not possible to discuss all types of deterioration and damage as well as the corresponding repair methods, the committee has focused on cracks nucleated in concrete. This is to be one key issue associated with concrete properties from exterior to interior, and known to readily decrease the safety in concrete structures at an early stage. Focusing on the cracks, working groups deal with various repair methods, the related indices and non-destructive testing (NDT) methods needed to verify repair results. Additionally, the issues facing the verification of repair results have been examined by a questionnaire posed to managers and contractors, and then surveyed the problems facing repairs and verifying their effects. Eventually, the committee has proposed one operation and maintenance workflow for generalizing the verification of repair results.

The committee members are listed in **Table 1**. As shown, it consists of the following four WGs.

WG1: Repair methods and evaluation items accounting for repair methods and objectives (Group leader: Prof. Keiyu Kawaai (Ehime University))

WG2: Evaluation methods for crack repair (Group leader: Prof. Hitoshi Hamasaki (Shibaura Institute of Technology))

WG3: Selection and classification of NDT methods (Group leader: Prof. Takeshi Watanabe (Tokushima University))

WG4: Evaluation workflow for construction, operation, and future vision of maintenance management system (Group leader: Prof. Keiichi Imamoto (Tokyo University of Science))

Furthermore, the technical committee has worked in active contact with the RILEM TC – 269 IAM: Damage Assessment in Consideration of Repair/ Retrofit- Recovery in Concrete and Masonry Structures by Means of Innovative NDT, chaired by Prof. Tomoki Shiotani, which is inaugurated in 2017[1).

Table 1: Committee structure

Chairman	Tomoki Shiotani (Kyoto University)
Secretaries	Takahiro Nishida (Kyoto University), Keiichi Imamoto (Tokyo University of Science), Takeshi Watanabe (The Unbniverisity of Tokushima), Tsukasa Mizutani (The Univerisity of Tokyo), Keiyu Kawaai (Ehime University), Hitoshi Hamasaki (Shibaura Institute of Technology)
[WG1: Crack repair methods and evaluation items accounting for repair methods and objectives]	
Group leader	Keiyu Kawaii (Ehime University)
Members	Kentaro Ono (Tokyo Metropolitan University), Toshiyuki Kanda (Chemical Construction Co., Ltd.), Mutsue Komuro (SG Engineering Corporation), Tetsuya Suzuki (Niigata University), Takahiro Nishida (Kyoto University), Tomoya Nishiwaki (Tohoku University)
[WG2: Evaluation methods for crack repair]	
Group leader	Hitoshi Hamasaki (Shibaura Institute of Technology)
Members	Nobuhiro Okude (TTC), Norihiko Ogura (CORE Institute of Technology Corp.), Tetsuya Suzuki (Niigata University), Takahiro Nishida (Kyoto University)
[WG3: Selection and classification of NDT methods]	
Group leader	Takeshi Watanabe (The University of Tokushima)
Members	Masayasu Otsu (Kyoto University), Kentaro Ono (Tokyo Metropolitan University), Norihiko Ogura (CORE Institute of Technology Corp.), Yoshikazu Kobayashi (Nihon University), Takahiro Nishida (Kyoto University), Hitoshi Hamasaki (Shibaura Institute of Technology), Tsukasa Mizutani (Tokyo University), Kazuo Watabe (Toshiba Corporation)
[WG4: Evaluation workflow for construction, operation, and future vision of maintenance management system]	
Group leader	Keiichi Imamoto (Tokyo University of Science)
Members	Nobuhiro Okude (TTC), Takahiro Nishida (Kyoto University), Naoki Masui (Masui Design Solutions), Kimitoshi Matsuyama (Nippon Koei Co., Ltd.), Yoshihiko Watanabe (West Japan Railway Company)
Cooperative members:	Dimitrious G. Aggelis, Eleni Tsangouri (Free University of Brussels), P.L. Pahlavan (Delft University of Technology), Stephan Pirskawetz (The Federal Institute for Materials Research and Testing, BAM)
Adviser	Masayasu Ohtsu (Kyoto University)

2. Crack repair methods and evaluation items (WG1)

2.1 Repair methods targeted for survey

The research activities of WG1: “Crack repair methods and evaluation items accounting for repair methods and objectives” are summarized. Clarifying the repair objectives and deterioration causes is the most important to select an appropriate repair method for cracks in concrete and concrete structures. This is because the presence of cracks definitely promotes penetration of the deterioration factors into concrete. It often presents a poor visual appeal and third-party influence badly. Even when repair methods were applied, there sometimes existed the cases where the repair objectives were not fully achieved, or the deterioration causes were not clearly identified. The facts have resulted in further deterioration than expected, which is referred to as re-deterioration. Consequently, the committee have targeted the survey on repair methods for cracks, keeping in mind the establishment of methods for the crack repairs through NDT results. Such crack repair methods currently available are summarized in **Figure 1**, as surface impregnation methods, surface covering methods, cross-section repair methods, grouting methods, filling methods, and crack covering methods. Prior to applying the repair methods, surface treatment is usually performed to remove fragile and damaged layers. As a result, the treatment often affects the subsequent repairs. Therefore, the committee takes into account the surface treatment methods. Based on these repair methods, the evaluation items and indices important to evaluating the objectives are investigated to establish their achievement levels to be estimated by NDT methods

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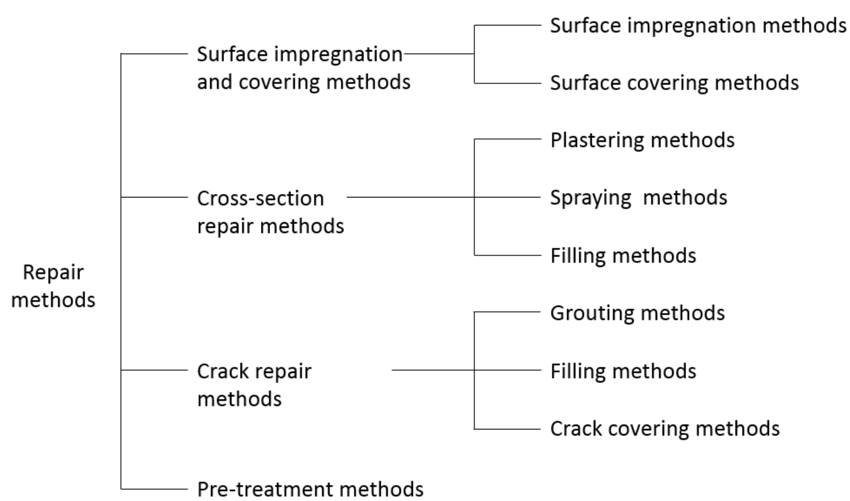

Fig. 1: Repair methods summarized.

2.2 Crack repair methods and evaluation items

As it is difficult to fully protect against cracks in concrete structures, crack repair for only minor damage is employed. The objectives of repairing concrete structures are: (1) restoration of cracks, delamination, and so forth; (2) inhibition or removal of further deterioration due to penetration of carbon dioxide, chloride ions, and hazardous chemicals; (3) inhibition of water penetration; and (4) restoration of stiffness and load-bearing capacities of structural members. The primary objectives of crack repair methods are to prevent the penetration of deterioration factors from cracks into concrete, to restore deformations due to cracks, and to fill cracks with adhesives.

Thus taking the purpose of crack repair into account, it can be classified into five issues as follows. "1. integrity," which is largely dependent upon "2. filling degree (depth)" of repaired materials and their adhesive properties at the interfaces, is also an important index for ensuring "3. resistance to deterioration factors". However, it is also plausible that deterioration could increase further due to residual materials, even when deterioration factors are partially removed by pretreatment. Consequently, "4. delamination prevention performance" and "5. resistance to advancing deterioration" are other important indices, in addition to durability of adhesives. Thus, the committee has selected such evaluation items, as safety, usability, third-party influence, visual appeal, and durability. Accounting for these mutual relevancies, it is possible to evaluate their connections and combinations. As one example, evaluation indices for repair results by the injection methods are derived. In addition, it is noted that the evaluation indices for the repair methods targeted may include those not currently measurable.

2.3 Derivation of evaluation indices in crack-injection methods

Repair evaluation items and indices for crack injection methods are summarized in **Table 2**. The purpose of crack injection methods is to restore the penetration resistance and the durability. The methods are applied to the deterioration period from the incubation to advanced stages. The resistance to penetration factors, filling degree, and anti-corrosion are indispensable items for evaluating repair results in concrete. In most cases of penetration factors, evaluation of the repair works against the deterioration is to be continuously made for a long period. Thus, from a long-term viewpoint, evaluation indices affecting the sustainability of repaired effects are to be considered. In contrast, the filling degree (depth) in cover concrete is an important index to be evaluated right after the repair. From the durability viewpoint, the repair objectives are associated with the anti-corrosion effect at rebar locations.

Further, when evaluating the restoration of substance-penetration resistance, it is desirable to be evaluated through NDT methods, by applying a long-term multiple monitoring before and after the repair at locations of the surface and the surface layer. At the present stage, it is not easy to estimate the evaluation indices by employing the individual NDT method. Accordingly in Section 4, we attempt the survey on inspection methods by employing NDT methods, which are particularly important for crack repairs in work, and report those methods for effective repair evaluation.

Table 2: Evaluation indices of crack injection method

Method	Repair	Period	Items	Indices	surface	layer	cover	time
Crack injection	Penetration resistance	From Incubation to acceleration stages	Resistance to penetration of factors	chloride ion	◎	○		long
				carbon dioxide	◎	○		long
				oxygen	◎	○		long
				water	◎	○		long
				water vapor	◎	○		long
				water vapor	◎	○		long
			Filling degree	Filling depth	◎	○		right after repair
	Durability	Acceleration stage	Anti-corrosion	corrosion			◎	long

◎:Primary target, ○:Secondary target

3. Evaluation methods for post-repair of cracks (WG2)

In WG2 group, "post-repair evaluation of cracks" is conducted. In particular, the current situation with respect to repair work for cracks and other damage is examined: whether the post-repair evaluation is actually being performed, or what type of evaluation is being done. In order to analyze the current situation, derive problems and study directions for the future, a questionnaire-based survey is made, surveying specifications (instructions) and technical guidelines.

As follows, the results of the questionnaire survey is stated. **Table 3** shows groups of respondents to the questionnaire survey. The number of questionnaire respondents was 104. As indicated, major respondents were from the civil engineering, and many of the responses came from contractors. The questionnaire was presented in the form of a web-site questionnaire, and the respondents were recruited through summons at annual meetings and from the committee associates. The respondents were mostly engineers with relatively high awareness, and many were from the Tohoku and Kanto Regions in Japan.

Questionnaire items are listed in **Table 4**. The answers were made with multiple choice and response. As for the necessity of evaluations after repair, most respondents think that it is necessary whether they were owners or contractors, and thus have answered that they want the evaluations based on appropriate methods. However, the post-repair evaluations burdens with the cost to be restricted. Approximately 70 to 80% respondents of both the ordering side (owners and designers) and contracting side (contractors or material developers) have answered that the owners are responsible for the cots. In the other case of the contracting side, it is replied that the cost should be covered by the both sides. In addition, the ordering side also indicates the possibility of bearing the post-repair evaluations in the future. So far, however, the post-repair evaluation has been implemented as additional survey responses of contractors as a part of quality control, without inspection costs burdened by owners.

Table 3: Groups for questionnaire respondents

Respondent groups	Respondent fields			Total
	civil engineering	construction	Other	
Owners	5	1	-	6
Designers	8	-	1	9
Contractors	53	14	-	67
Material makers	8	1	3	12
Other	9	-	1	10
Total	83	16	5	104

Table 4: Questionnaire items

Item	Details
Respondent attributes	Standpoint, field, involvement in repair work
Awareness survey	Necessity of evaluations, repairs methods requiring evaluation, cost burdens, responsibility for results, permissible structural damage
Fact-finding survey	Readiness of manuals and other elements, experience with evaluations
Additional survey	(Regarding implementation examples) target structures, purpose, repair method, maintenance method, implementation period, cost burdens, etc.

It is noted that some prudent engineers have an opinion that "the evaluations are not necessary to be done if the ordering side is not in demand, because required performance an evaluation standards are not clear", and that "it is difficult to determine the responsibility for the results evaluated." This implies that clarification of the required performance and evaluation standards are to be a future issue.

The repair methods available for the evaluation after repair are surveyed and results are summarized in **Fig. 2**. The majority in great demand is found to be cross-section repair methods, crack grouting methods, and surface impregnation methods. Regarding repair performance, the integrity with framework, filling performance of grouting material, and resistance to deterioration factors are of good request. The results clearly show that post-repair evaluation should be introduced. As for the permissible degree of structural damage, partially destructive testing (drilling and small-sized core sampling) methods are allowed up to approximately 80%, in the ordering side. When we consider ensuring measurable quantities, continued service, continuous evaluation, and so forth, it is realized that NDT methods impose little damage to structures and can be continuously evaluated at the desirable positions. The results conclude that the high need for post-repair evaluation and the merits of NDT evaluation are thoroughly understandable.

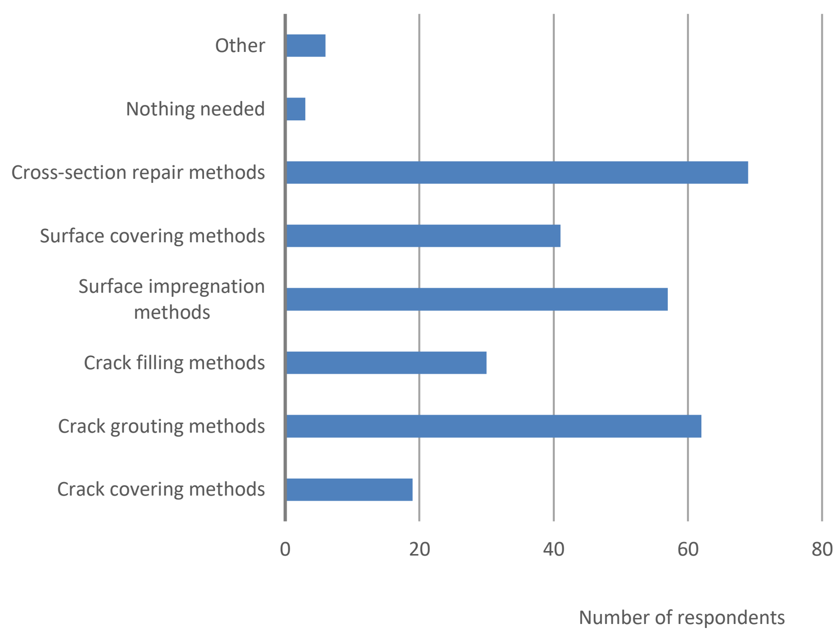

Fig. 2: Repair methods available for post-repair evaluation.

Examples of the post-repair evaluations are listed in **Table 5.** These are obtained from questionnaire respondents. Here, we focus on three methods of crack grouting, cross-section repair, and surface impregnation.

As for crack grouting (injection) methods, core sampling-based methods are set forth in the construction field (Repair work management guidelines, Ministry of Land, Infrastructure, Transport and Tourism (MLIT)). As a result, many respondents have replied the need for core sampling after crack repair. Elsewhere, a good concern to apply elastic waves, ultrasonics, and other NDT methods is also found. Prospective applications of elastic wave methods and the standardization of evaluation methods to the repair evaluation is to be referred to the survey reports by WG3.

Table 5: Examples of post-repair evaluations

Repair methods	Non-destructive testing methods	Destructive testing methods
Crack injection and grouting	• Visual • Crack depth measurement by ultrasonic methods • Gas detection methods • Elastic wave tomography	• Visual after core sampling • UV irradiation after core sampling • Adhesion test • Post-diagonal perforation endoscopic crack observation
Cross-sectional repair methods	• Hammering test • Polarization -resistance measurement	• Bond strength (adhesive force) test
Surface impregnation methods	• Water repellency test • PWRI Discrimination methods for permeable concrete protective material(draft) • PWRI Gas permeability test • Polarization resistance (corrosion rate)	• Water absorption prevention layer verification after core sampling • Post-core sampling chemical analysis

Concerning cross-section repair (restoration) methods, both integrity with framework and the results of corrosion inhibition are to be verified for work quality and repair results. In the case of surface impregnation methods, electrochemical evaluation by NDT is normally applied to estimate the corrosion inhibition effects. Essentially, the state of impregnation is subject to verification, which can be made by NDT methods as well as core sampling. One method is proposed by the Public Works Research Institute (PWRI) [2]. The impregnation rate at the concrete surface is measured using an electrostatic or resistance-type impregnation rate meter at the concrete surface after work.

As a summary, this working group has investigated the introduction of NDT methods in the post-repair evaluation. Based on the survey of questionnaire and analysis of the results, it is confirmed that both owners and contractors realize the great need for the post-repair evaluation, but clarification of the required performance and evaluation standards remains a future prospect. As for the need to introduce NDT methods, three methods of crack grouting, cross-section repair, and surface impregnation are focused. It is concluded that the standardization of evaluation methods and collection of specific examples is necessary for evaluating the filling state of grouting material.

4. Selection and classification of NDT method (WG3)

There exist definitely high expectations for evaluating repair and retrofit results through inspections by means of NDT methods. In WG3 group, issues facing the evaluation of repair results and evaluation indices applicable to the repair methods are stated, and some applications verified repair results by NDT methods in existing structures are reviewed.

4.1 Issues for repair and retrofit (re-strengthening)

In the case of a concrete structures, NDT methods are available for inspecting concrete for implementing maintenance of the structure in service. The methods currently applied are visual examination, hammering, and measuring cover depths and rebar arrangements by means of NDT. Thus, the causes of cracks and deterioration in the concrete are evaluated. Recently, new techniques for visualizing interior conditions of concrete and on-site monitoring are under development to put them into use. Since repairs and retrofit are basically applied to existing structures, the evaluation is definitely in demand before and after the repair. A target of the WG is to evaluate such repair results by NDT methods.

According to the JCI "Practical Guidelines for Investigation, Repair and Strengthening of Cracked Concrete Structures -2013-," standard examinations are prescribed on the cause of cracks, the evaluation of them, the need for repairs and retrofit, and the procedure for repair and re-strengthening. These guidelines include Sections "6.7 Inspections" and "6.8 Recording and monitoring procedures for repair and re-strengthening".

When NDT methods are applied to the structure in service, inspection and examination shall be done. As shown at the top of **Fig. 3**, in the conventional diagnosis, facing issues are summarized as the past case. In contrast, at the bottom, diagnosis of a post-repair structure is illustrated. Particular issues for applications of NDT methods are summarized.

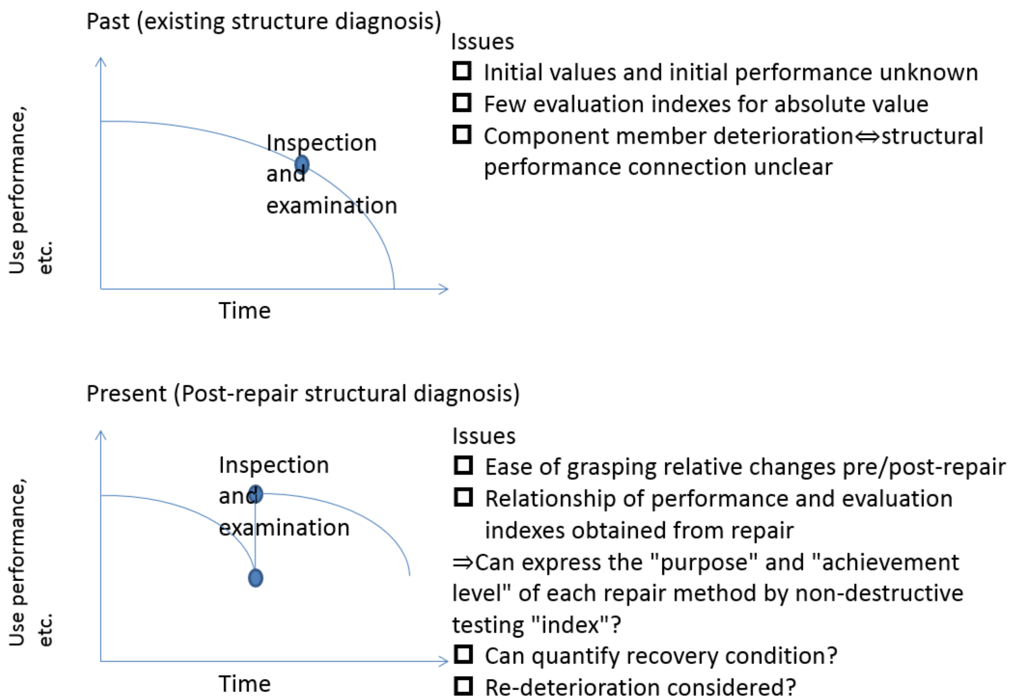

Fig. 3: Evaluation image of existing structure before and after repair.

The case where crack-filling (injection) methods are selected for crack repair is considered. In order to verify whether the crack is filled or closed, visual observation is available. However, it is generally not possible to obtain such information in the depth direction, as the depth of a surface crack and that of the repair material injected. Since it is limited to assess the result only from the surface, the use of NDT methods is desired to obtain information inside concrete quantitatively. Obtaining the velocity distribution of elastic waves two- or three-dimensionally, quantitative comparison between before and after repair can be made, including the depth direction. Once the repair material is thoroughly grouted and has hardened, the propagation velocity generally becomes larger compared to that before the repair. However, the propagation of elastic waves before and after the repair does not always have a one-to-one relationship. Therefore, it is sometimes difficult to explicitly connect the results with physical improvement of concrete.

Concerning the needs to be considered, it is to be clarified which performance and how much performance is expected to be recovered after the repair. As shown in **Fig. 3**, the vertical axis of the graph indicates "Use performance, etc." It could imply physical properties including strength and durability to be improved by the repair or re-strengthening (retrofit). In order to apply NDT methods to evaluation of the repair, specific property of concrete is to be considered. Therefore, one example of elastic-wave velocity is discussed below.

4.2 Verification in a real structure

As an example, **Fig. 4** shows a column member cut from a real structure. Three-dimensional velocity distributions before and after epoxy-resin grouting are analyzed by applying a three-dimensional elastic wave tomography technique. Thus, the injected state is evaluated. According to the left graph of **Fig. 4**, several low-velocity regions are clearly observed before grouting, while the increase in the elastic-wave velocities is found in the whole region after grouting as shown in the right. The results show that the internal cracks are reasonably filled with grouted material. It implies that the elastic-wave tomography is applicable to evaluate the filled state of internal cracks visually and quantitatively that could not be verified by the surface observation.

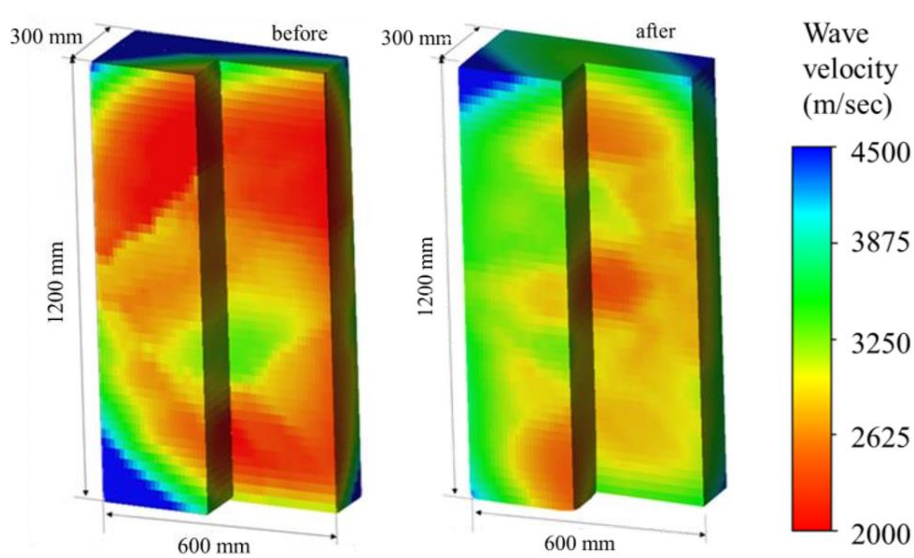

Fig. 4: Three-dimensional elastic-wave velocity distribution before and after grouting[3).]

5. Construction of maintenance management system (WG4)

In the group of WG4, the results of other WGs are comprehensively analyzed in order to construct the maintenance system. As a result, achievements of the committee are categorized into three issues: (1) - (3) below. Then, the basic systems for operation and maintenance are constructed and proposed as the issue (4).

(1) Operation and maintenance systems for road bridges

(2) Operation and maintenance of concrete railway structures currently implemented in JR West

(3) Proposed relations between repair and NDT methods in the deterioration processes

(4) Basic systems for operation and maintenance in consideration of repair evaluation

5.1 Operation and maintenance systems for road bridges

In Japan, the operation and maintenance of road bridges follow the regular bridge inspection guideline of the Ministry of Land, Infrastructure, Transport and Tourism (MILT) established by the National Highway and Risk Management Division (June, 2014). The guideline has specified a close visual examination for inspection, and such NDT methods are applicable, if necessary, as palpation and hammering. Elsewhere, a post-repair inspection is explicitly mentioned in the repair work manual for concrete structures by the Public Works Research Institute (PWRI) (August, 2016). Here, as shown in **Fig. 5**, the design work for repair and post-repair testing and inspection are clearly prescribed. In addition, it is considered that a post-repair inspection is to be considered, because faster deterioration than expected, referred to as re-deterioration is often observed within one year after repairs. Due to changes in environmental conditions (air temperature, humidity), a periodic post-repair inspection is recommended to be planned approximately one year after any repair work.

In the U. S., the Federal Highway Administration (FHWA) started the “Pontis” bridge management system in the 1990s, wich was supported with that of the California Division, and incorporated with asset management techniques. Pontis serves as a framework for management techniques, mainly for preventive maintenance. Here, NDT methods are recommended as effective means for ascertaining the state of concrete in bridge structures. The National Bridge Inspection Standards (NBIS) (2004) set forth regular inspections to be conducted within two years, based on the issue that the FHWA handles the pre- and post-repair inspections. The code includes not only visual examination, but also NDT methods in regular and detailed inspections of "Fracture Critical Members." Currently, NDT methods tend to be specified in the "bridge inspection manuals" enacted by highway authorities in each state.

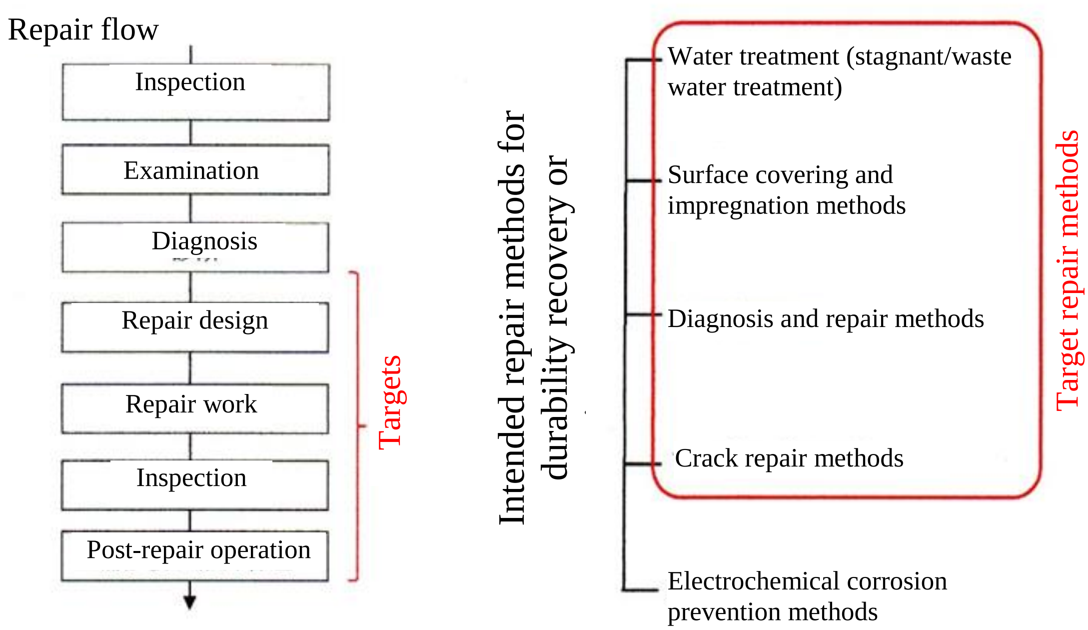

Fig. 5: Scope of target manuals

5.2 Operation and maintenance of concrete railway structures currently implemented in JR West

The Japan Railway Company (JR) West has established the system of "concrete repair work managing engineer" for operation and maintenance. Presently, it stipulates completion inspection items per method; for example, in cross-section repair methods, chipping depth, rebar cleanliness, cross-section repair (rebar back filling, adhesion testing), and other items are inspected. Further, techniques to non-destructively evaluate microcell corrosion and substance penetration are in progress, as well as techniques to predict advancing rebar corrosion, and to evaluate changes in substance penetration over time.

5.3 Proposed relations between repair and NDT methods in the deterioration processes

The working group has examined deterioration processes, and countermeasures in relation with NDT methods. As one example, **Table 6** shows the case of salt damage. The examinations in the deterioration process in the fatigue of slab fatigue, repair for all deterioration processes, and examination to verify reinforcement effects are illustrated in **Fig. 6**.

Table 6: Repair and NDT methods for salt damage

Methods		Effects	Evaluation items for verification
Surface treatment	coating	Decrease in chloride-ion penetration and corrosion rate	・Adhesive strengths of coating materials ・Chloride concentration in concrete
	impregnated		・Impregnated depth ・Chloride concentration in concrete
Cross-sectional restoration		Removal of chloride ions and anti-corrosion	・Adhesive strengths of repaired materials ・Chloride concentration ・Half-cell potentials and polarization resistances
Cathodic protection		Anti-corrosion	・Deterioration of anode materials ・Electric power supply ・Half-cell potentials and depolarization amount
Desalination		Removal of chloride ions and anti-corrosion	・Chloride concentration during power ・Distribution of chloride concentration in process ・Half-cell potential and polarization resistances

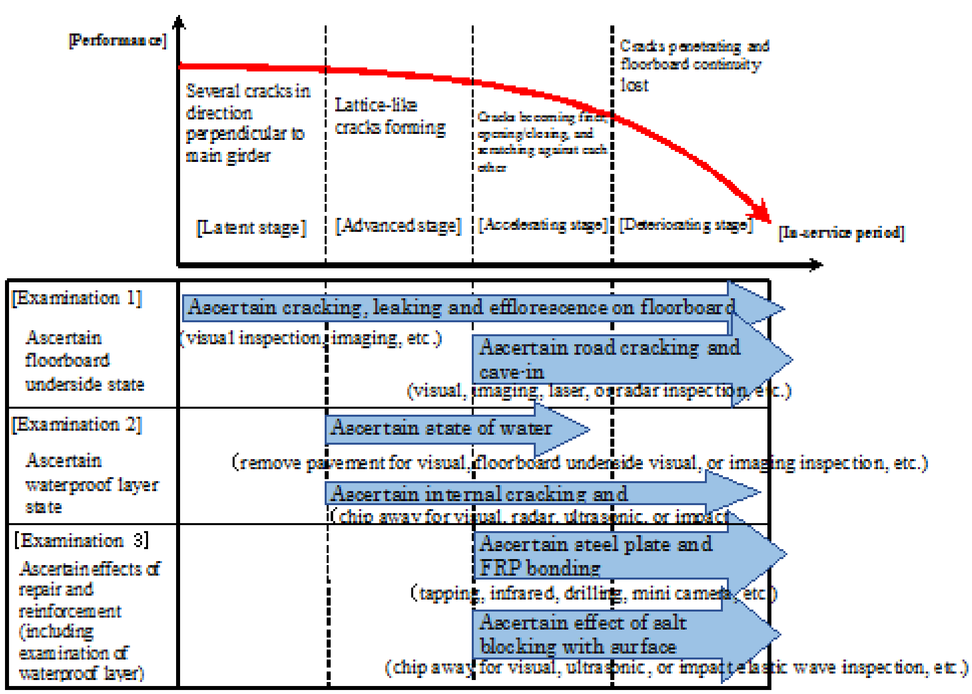

Fig. 6: Image of deterioration process in the fatigue of slab.

The figure clarifies the necessity for selecting suitable examination methods in the deterioration of concrete slabs according to the process involved, which ascertains the deterioration process of target structures, and verifies the effects of countermeasures.

5.4 Basic systems for operation and maintenance in consideration of repair evaluation

Based upon above examination and research, the working group has classified the maintenance management into type I (standard) to type III (high importance). As an example, a proposed operation and maintenance workflow is illustrated in **Fig. 7** to **Fig. 9** for management type III. Following the regulated inspections with 5 year period in **Fig. 7**, occasional repair work and inspection lead to opportunities to promote the repair evaluation process. In the repair evaluation process, the "repair evaluation workflow" always results from repair work. In the case, inspection techniques could include NDT methods, which are reasonably selected and implemented based upon the type of work and required performance. In addition, when unsatisfactory performance arises, the workflow returns to the re-repair plan.

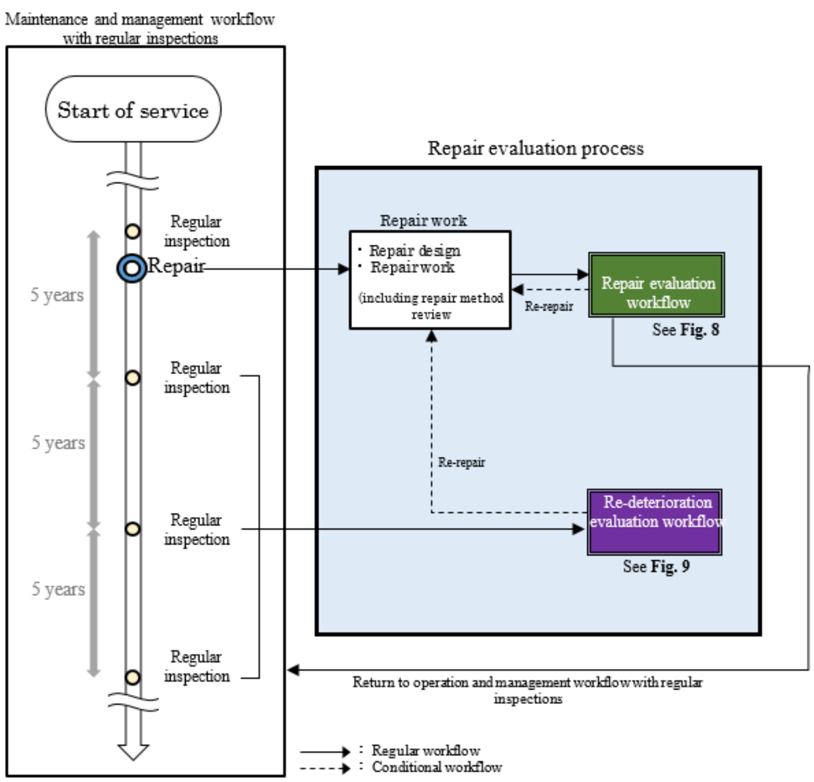

Fig. 7: Basic system.

As shown in **Fig. 8**, even in the case that no problems appear, re-inspection is to be provided one year later. In other words, only when there are no problems, in the results of an inspection performed immediately after repair, or in the results of a follow-up inspection one year later, the repair evaluation process is referred to as complete, and the workflow returns to the regular inspection workflow.

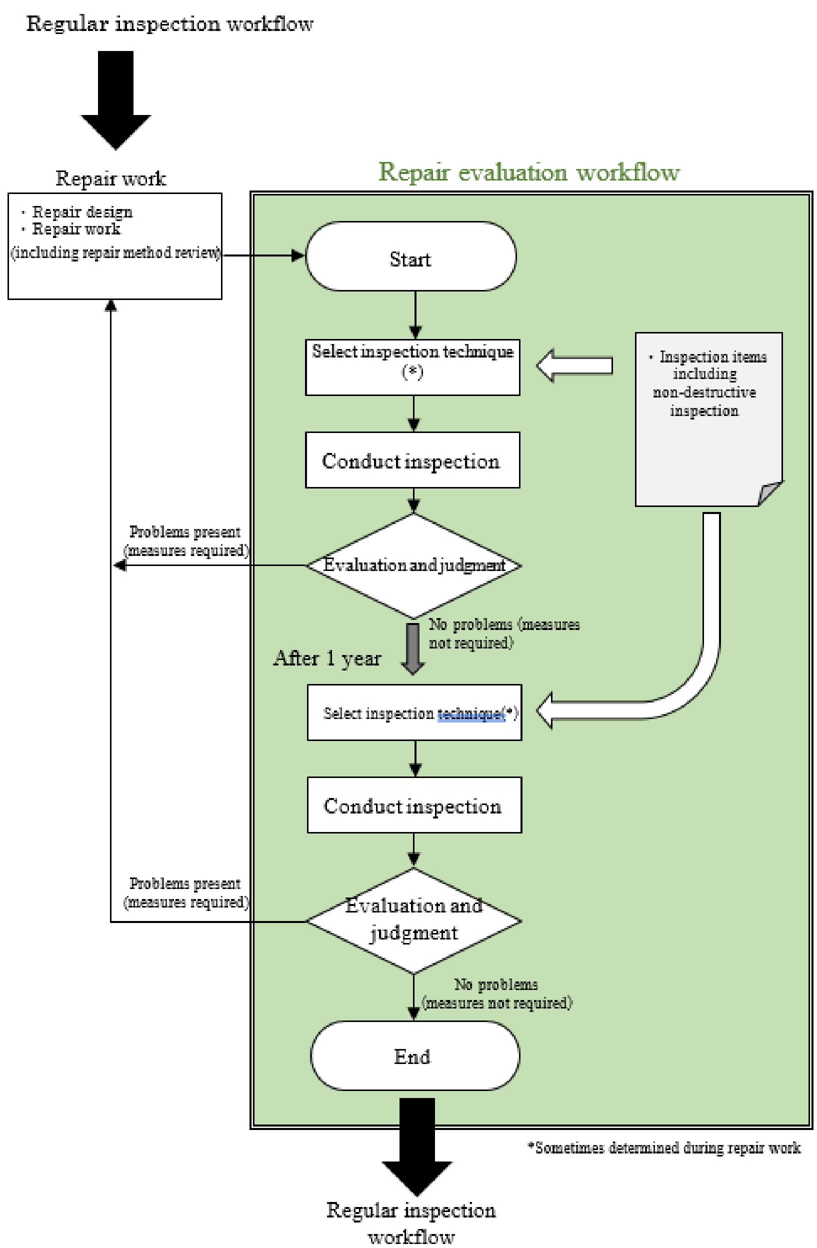

Fig. 8: Repair evaluation workflow.

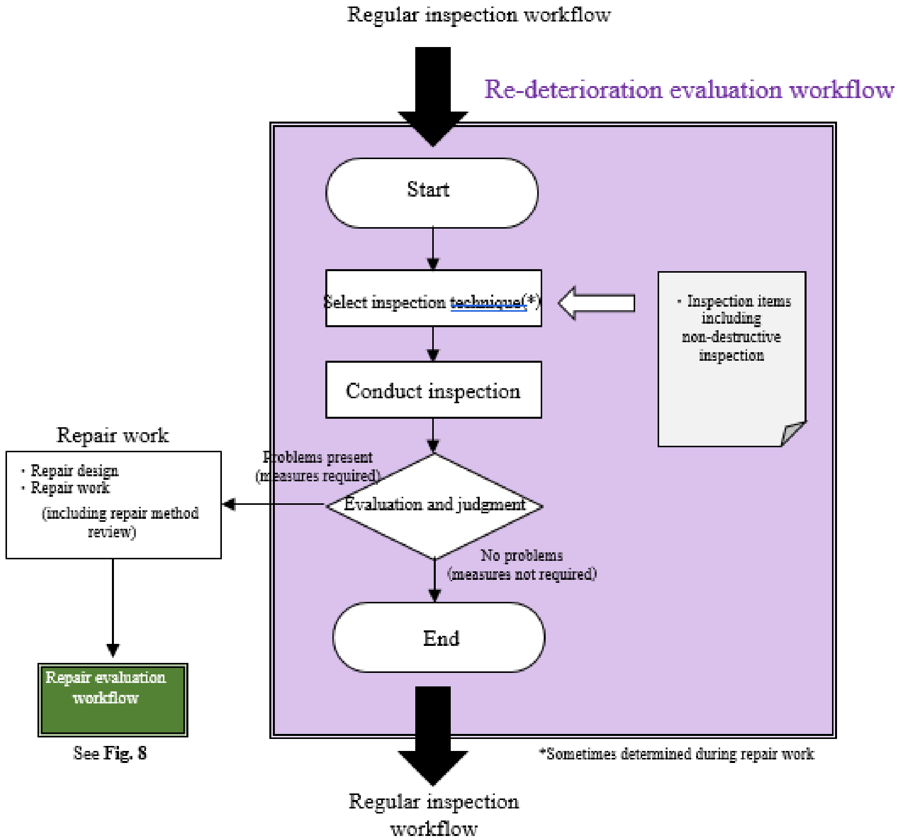

Fig. 9: Re-deterioration evaluation workflow.

The reason for re-inspection one year later stem results from consideration of the effect of seasonal fluctuations, and the fact that re-deterioration often occurs within one year of repair. Thus, "re-deterioration evaluation workflow" is proposed as shown in **Fig. 9**. The issue follows "Repair measure work manuals for concrete structures: August 2016, Public Works Research Institute." The repair evaluation process is normally triggered by the regular inspection, which definitely reflects a history of repair in the structure during regular inspections. If there exists a record of repair during regular inspection, the process proceeds to the "re-deterioration evaluation workflow." In a similar manner to the "repair evaluation workflow," in **Fig. 8**, the proper inspection techniques are selected and implemented, and then the repair work is evaluated and assessed. In the case that there are no problems based upon the results of evaluation and assessment in the "re-deterioration evaluation workflow," the workflow returns to the regular inspection workflow. The process mentioned is the case of management type III, which is targeted toward structures of high importance and members or work with many experiences of re-deterioration.

Management type I is referred to as the standard type, in which the repair evaluation process is implemented only for repair work after the structure is in service. Thus, operation and maintenance are conducted, following the regular inspection workflow, once after completing the repair process. Management type II is situated in between management types I and III. For example, when there exist doubts about re-deterioration during regular inspection, in addition to management type I, the workflow shifts to the repair evaluation process.

Essentially, it would be desirable that management type III shall be applied to all structures. However, efficient and effective operation and maintenance is to be carried out amid budget constraints. Consequently, it is important to properly ascertain the condition and importance of structures, and then select the proper management type.

6. Conclusion

The technical committee T163A has been working on the establishment of methods for evaluating repair of cracks in concrete using NDT methods. The following achievements are stated:

1) Such issues for crack repair evaluation are selected and evaluated as “integrity”, “filling degree (depth)”, “resistance to deterioration factors”, “delamination prevention performance”, and “resistance to advancing deterioration”.

2) The introduction of NDT methods in the post-repair evaluation is proposed and studied. Based on the survey of questionnaire and analysis of the results, it is confirmed that both owners and contractors realize the great need for the post-repair evaluation. To implement the post-repair evaluation, clarifying the required performance (indices) for verification is definitely a prerequisite. To this end, corresponding NDT methods shall be improved and proposed as to be applicable to determine and evaluate the indices.

3) Based on the repair methods, the evaluation items and indices important to evaluating the objectives are investigated to establish their achievement levels to be estimated by NDT methods. To this end, issues facing the evaluation of repair results and evaluation indices applicable to the repair methods are stated, and examples of verifying repair results by NDT methods in existing structures are reviewed.

4) We have proposed the operation and maintenance workflow with three management types. In the proposed workflow, repair work is always followed by “repair evaluation workflow,” and thus

inspection techniques are selected and implemented. In the case, NDT methods are available, based upon type of work and required performance. Concerning the management types, it is noted that the workflow returns to the re-repair plan, when issues such as unsatisfied required performance occur. And only when there are no problems, in the results of an inspection performed immediately after repair, or in the results of a follow-up inspection one year later, the repair evaluation process is referred to as complete, and the workflow returns to the regular inspection workflow.

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