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A Proposal of Design System for Strengthening of Existing Concrete Structures by Performance-Based Design

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Summary

The paper presents the outline of the new design system for retrofitting of existing concrete structures on the basis of the performance-based design. Concrete structures, which are retrofitted with external cable, continuous fiber materials, steel plates, and concrete, are systematically verified if they have sufficient performance to satisfy required level with respect to all required performance items including structural safety and serviceability. Time-dependent performance deterioration of structures during service life is taken into account in the process of performance verification, so that durability and structural design are reasonably integrated.

1. Introduction

The Sub-Committee 307 under the Concrete Committee in the Japan Society of Civil Engineers has made the draft of the new design system for retrofitting of existing concrete structures in 1998[1][2]. The design system is on the basis of the concept of the performance-based design, which is accepted as the suitable design concept for general concrete structures in the next generation. The proposed design system consists of two parts: the basic frame and the retrofitting design manual. The former part contains the basic concept and common descriptions, while the latter does recommended equations to verify performances of structures retrofitted with external cable, continuous fiber materials, steel plates, and concrete. This paper focuses on outlining the former part, i.e. the basic frame of the proposed design system.

2. Performance of structures

Since the design system is based on the performance verification of structures, we preliminarily consider kinds of required performance of structures. Performance of structures are classified into following major categories.

- **Social and environmental friendliness**: ability to contribute to healthy social, economical, and cultural activities and to minimize harmful effects on surrounding social and natural environment.
- **Structural safety**: ability to avoid casualty due to structural failure and collapse.
- **Serviceability**: ability to make users of and people around the structures feel comfortable with the structures and to provide functions such as water tightness.
- **Constructability**: ability to assure safety and reliability during construction.
- **Easy Maintenance**: ability to make routine maintenance easy and to restore lessened performances in an economically and technically feasible way.
- **Easy demolition and recycling**: ability to make demolition and recycling easy.

Several performance items are contained in the above major categories as shown in Table 1. For each structure, a set of performance items is required quantitatively depending on kind, usage, and importance of the structure. In the proposed system, performance of structure is evaluated as a function of time, considering time-dependent deterioration due to loading and environmental attack. This is why durability of structures is not listed in the above categories. Durability can be implicitly considered by evaluating all other performance items along the time.

Table 1 Performance items

Categories	Items	
Social and environmental friendliness	Contribution to social, economical, and cultural activities	
	Harmful effect on surrounding social and natural environment	
Structural safety	Failure and collapse (normal action)	
	Failure and collapse (seismic action)	
	Stability	
Serviceability	Comfortable feeling	Comfortable ride / walk
		Anti-vibration
		Anti-noise
		Soundproof
		Heat-insulation
		Anti-odor / humidity
		Aesthetics
		Visual safety
	Functioning	Water-tightness
		Air-tightness
		Energy and substance insulation
Constructability	Safety	Danger to workers / surroundings
	Reliability	Quality of materials in the structure
Easy maintenance	Restorability	
	Easiness of routine inspection of the structure	
	Easiness of inspection of materials in the structure	
Easy demolition and recycling	Easy demolition	
	Easy disposal and recycling of materials	Easy disposal of materials
		Possibility of recycling of materials

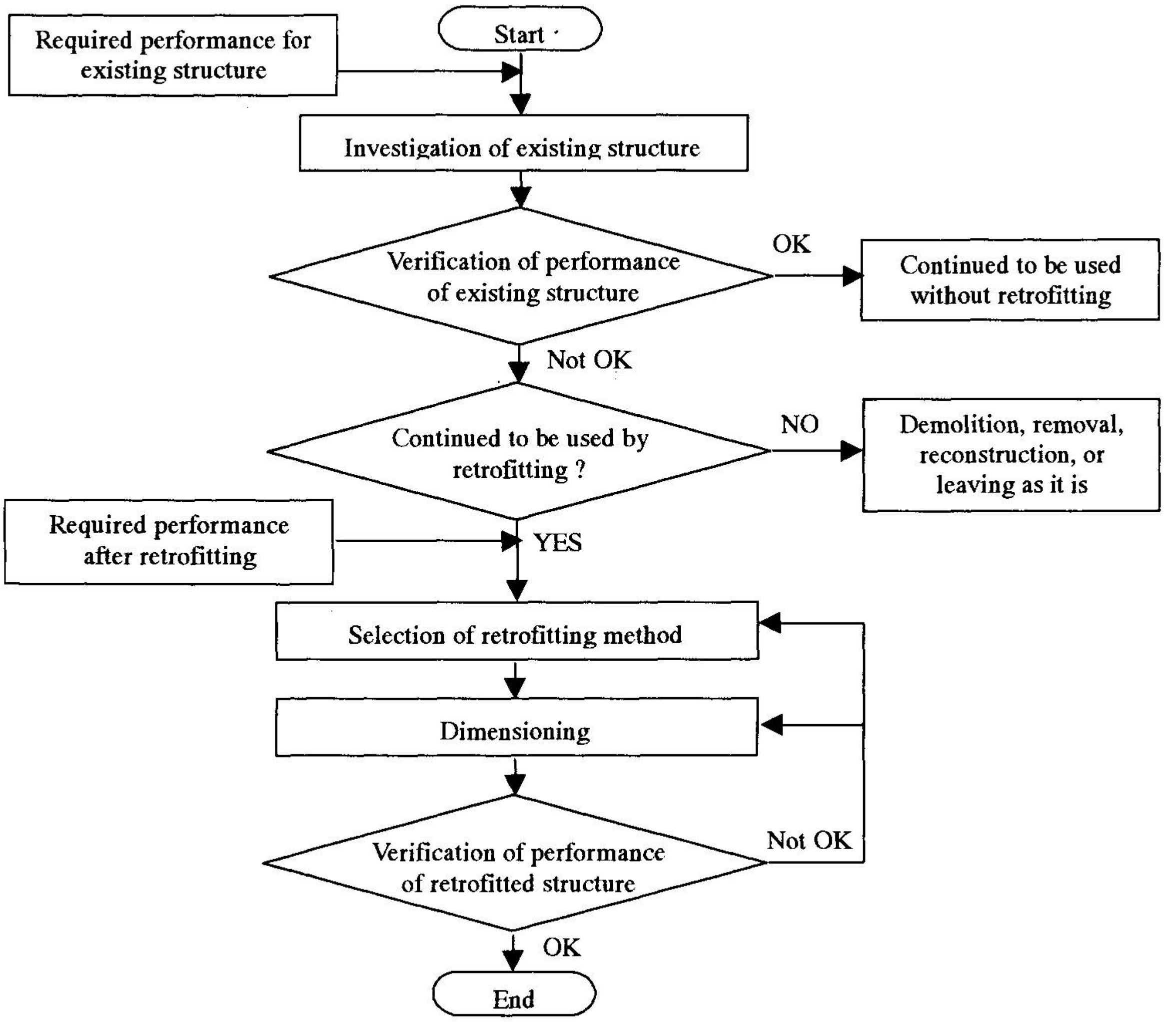

Fig.1 Flowchart of the proposed retrofitting design system

3. Outline of the proposed design system for retrofitting

The flowchart of the proposed retrofitting design system is shown in Fig.1. The system contains 1) investigation of the existing structure, 2) verification of performance of the existing structure, 3) selection of retrofitting method, and 4) verification of performance of the structure after being retrofitted. The objective existing structure is preliminarily investigated to obtain necessary information to evaluate its residual performances. Then, the residual performances of the structure at that moment are evaluated and verified if they satisfy the required level or not with respect to all required performance items. If it is found that the structure does not possess sufficient level of performance for some items and if the structure should be continuously used, then the retrofitting design proceeds according to the flowchart. An appropriate retrofitting method should be selected. Performances of the structure retrofitted by the selected method are evaluated and verified with required performances after retrofitting. In the performance verification of retrofitted structure, we have to confirm that the structure will keep sufficient level of performance to satisfy requirements at any time after retrofitting until the end of service life, considering time-dependent performance deterioration.

4. Basic concept of verification of performance

To practice performance verification, both performance of structures and requirement should be expressed quantitatively. Hence, each performance item listed in Table 1 should be represented by a corresponding physical variable which can be evaluated through available computational methods. This variable is called performance index in this study[3]. For instance, in order to verify structural safety, we conventionally quantify performance of structure in terms of axial force capacity, flexural capacity, shear capacity, and etc. If a highly reliable finite element program were available, structural safety could be verified by the computed structural behavior under the given loading action without any consideration of axial force capacity and etc. Consequently, performance index for each performance item depends on employed computational method. Table 2 shows examples of performance indices for some performance items, which are mainly related to mechanical characteristics of structures. Figure 2 shows the basic flowchart for verification of performance using performance index.

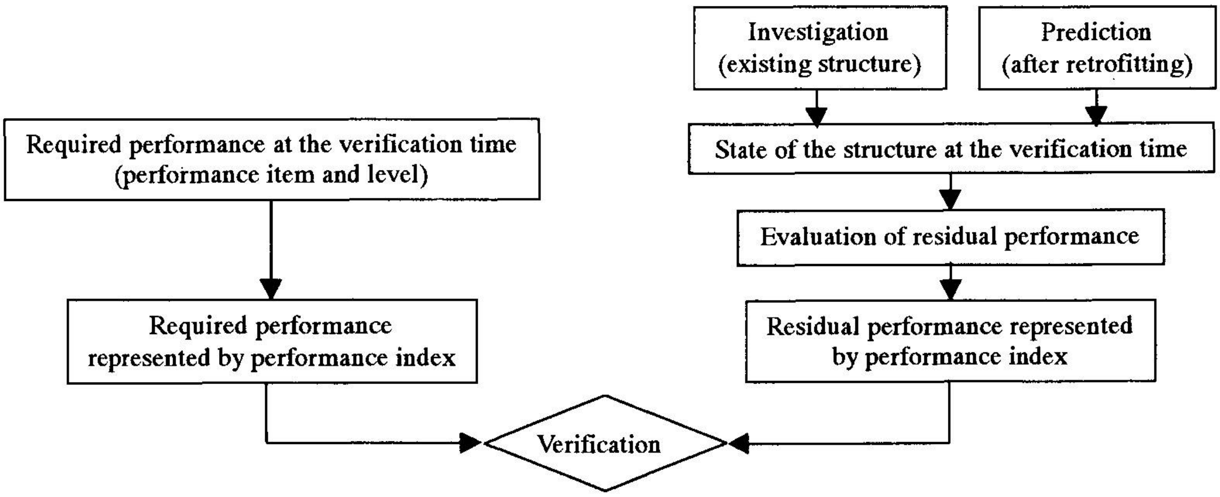

Fig.2 Verification of performance using performance index

Table 2 Performance indices

Categories	Items	Indices (by simple method)	Indices (by precise method)
Structural safety	Failure and collapse (normal action)	Axial force capacity, Flexural capacity, Shear force capacity, Torsional moment capacity, Fatigue strength, and Ultimate deformation	FEM analysis
	Failure and collapse (seismic action)		
	Stability	Overturning moment	
Serviceability	Comfortable ride / walk	Deflection, Step, Stiffness, Gap, Flatness and type of pavement	Acceleration transferred to passenger / walker
	Anti-vibration	Type of pavement, Stiffness, and Mass	Vibration level
	Anti-noise		Noise level
	Soundproof	Type of soundproof wall	
	Aesthetics	Crack width, Crack density, and Size and density of stain	
	Visual safety	Deflection, Crack width, and Crack density	
Easy maintenance	Restorability	Remaining deformation, Remaining crack width, and Damage in materials	FEM analysis

5. Verification of performance along the time

Retrofitted structures should have sufficient level of performance for all required performance items at any time after retrofitting until the end of their service lives. To confirm this, we should carry out performance verification along the time axis, considering time-dependent performance change due to loading and environmental actions. Figure 3 schematically shows the concept of performance verification of structure after retrofitting.

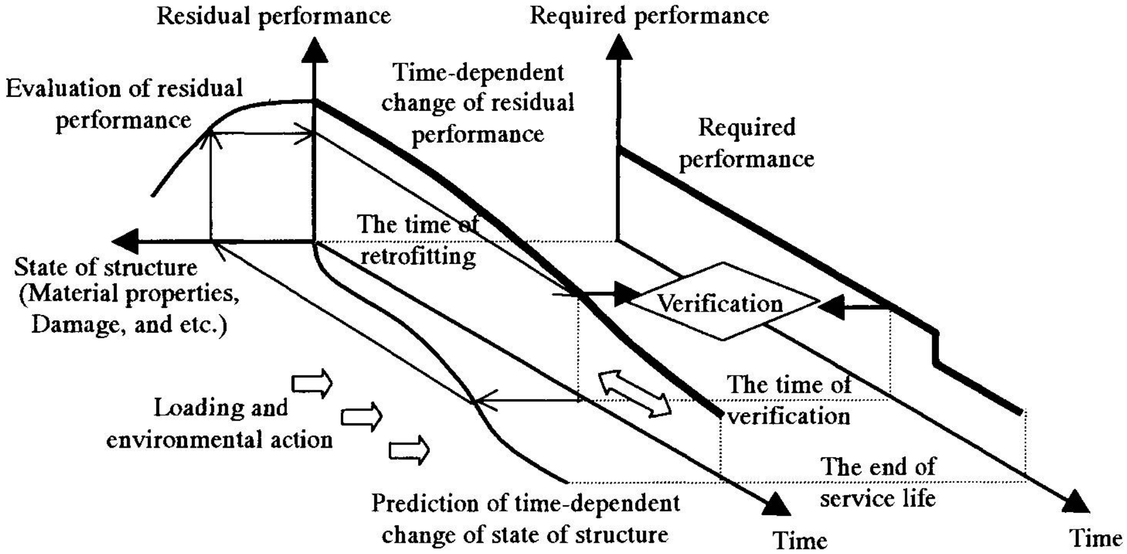

Fig.3 Verification of performance along the time

To attain the scheme shown in Fig.3, we need two essential technologies, which are 1) prediction of time-dependent change of state of structure and 2) evaluation of residual performance of structure at each time. The latter was discussed in the chapter 4. As for the former problem, we have to predict time-dependent change of state of structure, which includes material properties within structure, accumulated damage, concrete crack, corrosion of reinforcing bars, and remaining deformation, under given loading and environmental conditions. At the current stage of technology, however, we have not yet developed universal computational method that can precisely simulate every possible time-dependent change in concrete structures based on physical and chemical models. We should, therefore, estimate it by means of available simplified methods. At the simplest level of assumptions, deterioration of materials within structures may be accounted by material safety factors which are appropriately determined considering material types, structural types, construction conditions, and loading and environmental conditions. Proper detailing, such as minimum concrete cover, may further simplify the process to consider the time-dependent change in material properties. For example, if a thick concrete cover is provided, the corrosion of steel reinforcement may not be considered at all. Nevertheless, the proposal shown in Fig.3 would realize the integration of durability and structural design in the most rational way. The authors, therefore, insist that further study should be focussed on development of reliable prediction method for time-dependent change of structures to complete the proposed design system.

6. Conclusion

The outline of the design system for retrofitting of existing concrete structures which has following characteristics was presented in this paper:

1) The concept of the performance-based design is adopted.
2) Progress in concrete technology, such as development of precise simulation method, will be flexibly employed without any change of the framework of the design system.
3) Durability and structural design are rationally integrated taking time-dependent performance change into account in the process of performance verification.

Though not discussed in this paper, the JSCE Sub-Committee 307 has also proposed the recommended equations for evaluation of performance indices of structures retrofitted by major retrofitting methods, namely external cable method, wrapping or jacketing method using continuous fiber materials or steel plates, and concrete wrapping method. Major areas requiring more study to complete this design system are:

- Improvement of recommended equations for evaluation of performance indices,
- Development of universal prediction method for time-dependent change of structure due to loading and environmental attack.

Acknowledgment

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