# FRAMEWORK FOR CATEGORIZATION OF REPAIR PRIORITY IN DETERIORATING REINFORCED CONCRETE STRUCTURES

*by*

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# CERTIFICATE

This is to certify that the thesis entitled "**Framework for Categorization of Repair Priority in Deteriorating Reinforced Concrete Structures",** being submitted by **Mr. Kamal Kant Jain** to the Indian Institute of Technology Delhi, India, for the award of the degree of "**DOCTOR OF PHILOSOPHY"** in Civil Engineering, is a record of original bonafide research work carried out by him under my guidance and supervision. To the best of my knowledge, the thesis has reached the requisite standard. The material contained in this thesis has not been submitted, in part or full to any other University or Institute for the award of any degree or diploma.


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# ABSTRACT

In deteriorating reinforced concrete (RC) structures, repair needs are typically evaluated on the basis of the structural condition. Accordingly, structural condition assessment facilitates decision making for appraisal of repair priority in deteriorating RC structures. But due to lack of measurability repair priority decisions are inherently qualitative. Moreover, these decisions are typically subjective to the perception, knowledge, and expertise of the professionals involved in structural condition assessment. Such qualitative and subjective decisions are prone to be inconsistent. Therefore, an attempt is made in this research work to develop a framework for consistent appraisal of repair priority in deteriorating RC structures. The research work is divided in two phases. In first phase, a comprehensive methodology is developed for appraisal of repair priority through visual inspection of deteriorating RC structures. In second phase, a framework is established for categorization of repair priority in deteriorating RC structures using condition assessment data.

Methodology for appraisal of repair priority through visual inspection is developed using fundamentals of visual inspection based condition assessment of deteriorating RC structures. From the extensive domain of the deteriorations in RC structures, only some of the frequently observed deterioration mechanisms are incorporated in this methodology. Incorporated deterioration mechanisms include: reinforcement corrosion, alkali aggregate reactions, freeze thaw attack, sulphate attack, acid attack / leaching, fatigue, shrinkage, and honeycombing (defect). These deterioration mechanisms and corresponding characteristic distress manifestations are used to prepare a comprehensive questionnaire. In the questionnaire, each distress manifestation is categorized into various states of varying severity and extent. These categorized distress manifestations represent condition of deteriorating RC elements, and hence are defined as condition descriptions. A repair priority based condition rating scale is

also defined in the questionnaire. Subsequently, questionnaire survey is pursued amongst experts from the field of concrete technology and construction engineering. Experts are asked to assign the most appropriate condition ratings for each of the condition descriptions based on their perception, knowledge, and expertise. Assigned condition ratings are retrieved from each individual expert's response to the questionnaire, and are combined to create a comprehensive knowledge base. Decisions based on this knowledge base represent the contribution of several experts, and hence the involved subjectivity is restrained.

However, data collected through visual inspection remains subjective to the inspection team's judgment. Subjectivity associated with the data collection is inherent to the visual inspection procedure and cannot be eliminated completely, but it can be significantly restrained by adopting consistent data collection procedure. Therefore, elaborate visual inspection guidelines are formulated. These inspection guidelines are based on the condition descriptions given in the questionnaire, and also incorporate the phenomenon of local and global occurrence of the deteriorations in structural elements. An identifying condition code is assigned to each of the condition descriptions in the inspection guidelines; these condition codes provide concise and systematic format for collection of visual inspection data.

The condition descriptions and condition ratings (based on the repair priority) are inherently qualitative, and are accordingly defined in relative but imprecise linguistic terms. Decisions derived using such information need to consider the involved fuzziness. Therefore, concepts of fuzzy set theory (FST) are used to model the decision making procedure. Correspondingly, membership functions (MFs) are required to characterize the involved fuzziness. Data collected through questionnaire survey (knowledge base) is used for generating relevant MFs.

A histogram based procedure is developed for consistent and systematic generation of various types of commonly used MFs, such as: multi-linear envelope MFs, linear (triangular / trapezoidal) MFs, and non-linear (Gaussian) MFs.

Membership functions (MFs) are obtained for each of the condition description in inspection guidelines, and hence for the corresponding condition codes. Henceforth, a computational model is established to integrate the decision making procedure. Established computational model takes element condition codes as input, and corresponding MFs are combined using rational aggregation rule to obtain the characteristic MF for the element. Element MF is defuzzified using area centroid method to obtain the element condition index. Element condition indices are then used to compute the structural condition index using weighted average method. Condition index values facilitate rational comparisons, and hence consistent inferences can be made for appraisal of repair priority through visual inspection. A software tool is developed to facilitate the implementation of the developed methodology.

In structural condition assessment of deteriorating RC structures, visual inspection is generally supplemented by relevant experimental investigations, and the data is obtained for various condition parameters. However, considerable lack of the guidelines / rules / formulations for appraisal of repair priority using condition assessment data leads to the decisions which are prone to inconsistency; therefore, possible development of the consistent decision making procedures is discussed. Correspondingly, a framework for consistent categorization of the repair priority in deteriorating RC elements is established. To explain the deterioration specific approach, carbonation induced reinforcement corrosion is used as the representative deterioration mechanism. Established framework emphasizes on the need of the repositories of condition assessment data, and demonstrates the development of predictive models through application of multiple discriminant analysis (MDA) technique. It is then discussed that, the linear classification functions obtained through application of MDA can facilitate consistent categorization of the element repair priority in deteriorating RC structures. Categorized element repair priorities can further be used to define a rational structural repair priority index using weighted average method. This index can then be used for comparative assessment of the structural repair priorities, and hence for structural repair prioritization.

Example cases are reported to demonstrate the applications of the research work. Appraisal of the repair priority using the developed framework facilitates systematic, rational and consistent comparisons, and hence can significantly assist the decision makers on policy making in the context of repair of deteriorating RC structures.

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