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Review Paper

Procedural sequence in the repair of buildings

Noel P. Mailvaganam and Tony Alexander

This review paper presents the guidelines for a step-by-step execution of any repair project. These procedures could make the execution of repair projects systematic, which will serve better to achieve the desired objective.

The sequence of activities involved in the repair of buildings progresses from the identification of a problem, through the selection of a consultant, specification of repair materials and procedures, drawing up of contractual documents, and finally, to the execution of the repair work. The principal participants in a repair programme are the owner and the consultant who undertake both separate and joint tasks in the resolution of the technical and financial issues at each step. The procedure shown in *Table* 1 provides a methodology to identify repair needs and establish a repair strategy[1,2].

Depending on the complexity of the problem and the owner's level of experience and technical competence, a consultant may or may not be involved. In the latter case, the owner would then have to perform all the repair tasks including assessment of the technical needs of the repair, preparation of appropriate specifications and administration of the contract. In most cases however, a consultant is retained to design the technical requirements of the repairs and to act as the interpreter of specifications for the repair as well as administrator of the contract between the owner and the contractor. The owner, being the best judge to assess the financial implications of the various strategies for repair, has to evaluate answers to the questions "what, how, when and why" pertaining to the repair and decide on the most suitable course of action.

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Step-by-step procedure for repair

Eight steps have been detailed here which present both technical and non-technical aspects that must be considered in the formulation of a repair strategy for reinforced concrete structures.

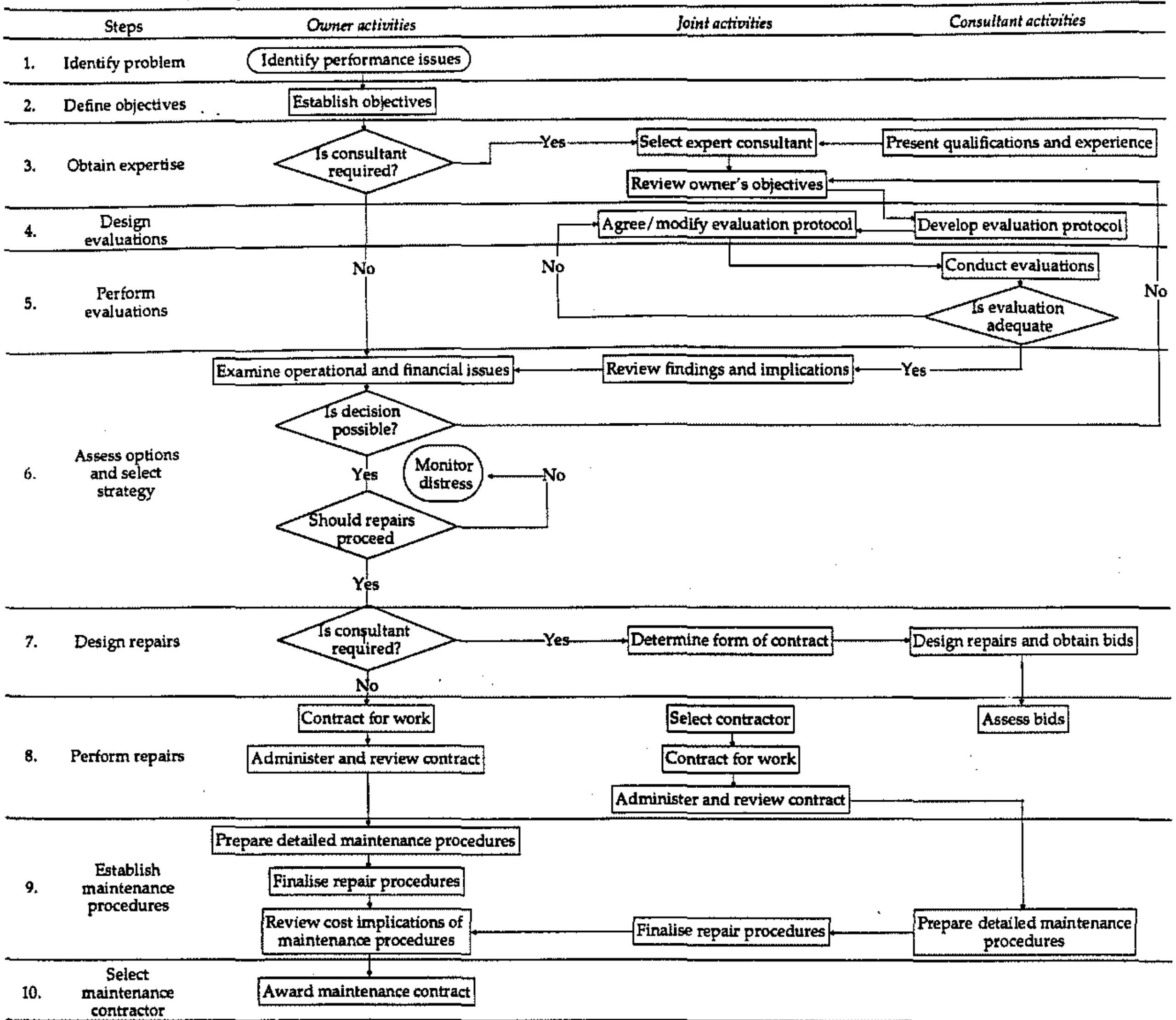
Identify the problem

Before proceeding with any remedial effort, it is imperative that the cause, effect, and degree of influence that the identified problems have on the present and long term serviceability and integrity of the structure are established. Once the causes are known, mechanisms of the problem can be determined. Rational decisions can then be made concerning a suitable remedial action plan, selection of materials, preparation of drawings and specifications. Proper evaluation of the problem and understanding the cause, therefore, is crucial and is often the deciding factor between success and failure of a repair.

Visual inspection will identify many problems. For example, colour variation, poor surface finish, segregated layers, laitence bands, cracking, honeycombing or bad construction joints in concrete are all symptoms of deficiencies in the design, materials, or construction practices. Most of the observed symptoms result from the simultaneous action of a number of these factors, *Table* 2[2]. While identification of the visible symptoms of distress helps to quickly focus on some common concrete problems, it often requires a detailed investigation by a non-destructive testing specialist to determine the cause of deterioration.

Symptoms of a deficiency must be differentiated from the actual cause of a deficiency, and it is critical that causes and not symptoms be addressed. For example, cracking is a symptom of distress that may have a variety of causes. Selection of the correct repair technique depends upon knowing whether the cracks are active/passive and whether the cracking is due

Table 1 Flowchart giving a methodology to identify repair needs and establish a repair strategy



to causes such as repeated thermal cycling, accidental overloading, drying shrinkage, inadequate design or construction, etc.

Define objectives

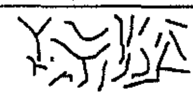
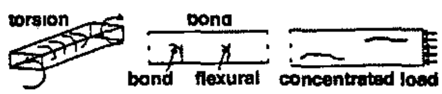
A decision to repair or replace a structure involves issues such as service life cycle analyses. The life cycle of a structure is often determined on financial rather than technical considerations. Economic life assessment requires analysis of various data such as the initial investment, costs for administration, energy, repair, inspection, cleaning, etc[4]. The technical factors may include assessment of environmental condition, nature of loading, service conditions, safety, and structural changes (including additions and alterations).

Soon after the problem has been identified, the owner must establish the objectives of the repair as well as any constraints that would affect its implementation. The objectives and constraints usually include aesthetics, funding, limitations on the amount of repair that can be performed at one time, the life expectancy of the repair, and the maintenance that the owner intends to do once the repairs have been completed.

Obtain the necessary expertise

Having elected to proceed with the repair work, the owner must decide whether an expert consultant is required to assist in the development of repair strategies or the coordination of the repairs. The selection of the expert should be based on relevant experience with similar evaluation work, and financial capabilities.

Table 2 : Characteristics and causes of cracks

Cause	*Time of formation*	*Manifestation*		*Remarks*
Plastic settlement (slump cracking)	First few hours after casting	Cracks along lines of reinforcement Cracks at changes in shape of section		Cracks can be large (> 1 mm)
Plastic shrinkage	First few hours after casting	'map' cracking or long cracks on surface of slabs cast in drying conditions		Cracks can be large (2-4 mm not uncommon)
Early thermal cracks	Not till after several months or years from construction	Large cracks at construction joints in wall. Other cracks depending on nature of restraints		Can be controlled by reinforcement (< 0.4 mm) by limiting pore sizes or control of temperature
Shrinkage	Not till after several months or years from construction	Similar bending or tension cracks	see below	Usually small if reinforcement present (< 0.4 mm)
Corrosion	Not till after several months or years from construction	Cracking along lines of bars, developing into spalling		Initially small (0.2 mm), increasing with time; rust staining may be visible in wet condition
Alkali-aggregate reactions	Not till after several months or years from construction	Occurs in wet conditions frequently as 'map' cracking. Only occurs with certain types of aggregate		Cracks can be large (> 1 mm)
Loading in service	Depends on usage of structure			Generally small (< 0.4 mm) if design for strength is satisfactory. Large cracks are generally an indication of misunderstanding of the response of the structure at the design stage
Restraint	Depends on external influences, settlement, etc.			Usually small (< 0.4 mm) if sufficient reinforcement present
Creep deformation	First 5-10 years	1. Shortening in the height of a concrete framed building 2. Deflection of slabs at mid-span 3. Crack development in the slab or beam soffit at mid-span and in the slab or beam top surface over supports		

The owner and the consultant must come to a mutual agreement and understanding of the objectives and constraints, including the financial, operational and technical considerations that not only affect the methodology of the repairs to be performed but also the level of effort and investigation techniques that the consultant will use to assess the repair needs.

Design the evaluation protocol

Evaluation of the distress in a structure is to obtain information on the extent of deterioration, and to establish the cause and significance of such deterioration. Based on the agreed objectives, the consultant should develop an evaluation protocol. The nature and purpose of the various tests and analyses should be reviewed and agreed upon by the owner before the consultant begins the evaluation. Evaluations can be performed in stages, making it possible to minimise the cost of the evaluation by eliminating some of the tests that become unnecessary as information is gathered. On the other hand, during the course of the evaluation the consultant may determine that additional information is required beyond what can be obtained by using the agreed protocol. The additional investigation requirements should then be presented to the owner and agreed upon as before.

Perform evaluation

The prime objective is to identify the possible causes of any visible distress and to establish the structural integrity, and satisfactory performance of the structure. Often this requires an indepth investigation which can be categorised into five tasks[5] —

- collation of information
- establishment of in-service conditions
- field visit
- detailed survey
- evaluation of data.

(i) **Collation of information :** The first task involves the collation of all existing information on the

Table 3 : Decision matrix for selection of deck rehabilitation method

Criterion	*Concrete overlay*	*Waterproofing membrane and paving*	*Cathodic protection*	*Rationale*
Delamination and spalls exceeding 10 percent of the deck area		No	No	Where extensive patching is required, it becomes more economical and more durable to construct a new concrete overlay.
Corrosion potential more negative than -0.35V over more than 20 percent of the deck area Moderate on heavy scaling exceeding 10 percent of the deck area		No	No	Patch repairs and waterproofing rarely reduce corrosion activity and may accelerate it. The amount of patching becomes too expensive and consequently uneconomical.
Active cracks in deck slab	No	No		Cracks active under live load or temperature change are reflected in a concrete overlay
Remaining life of structure less than 10 years	No		No	Additional cost of a concrete overlay or cathodic protection is not justified.
Concrete not properly air-entrained			No	Application of a bituminous surfacing (without waterproofing) may accelerate deterioration of the concrete.
Complex deck geometry; skew exceeding 45°, curvature exceeding 10°, or changing superelevation	No			Concrete finishing machines (especially those used for low slump concrete) have difficulty accommodating complex geometry.
Limited load capacity of structure		No	No	Bituminous overlay is a nonstructural component. Concrete overlay can be especially useful where the span to thickness ratio of the deck exceeds 15*.
Electrical power unavailable			No	Power is required for rectifier (unless mains, solar, wind, or battery power can be provided economically)
Epoxy injection repairs previously performed and will not be removed			No	Epoxy insulates the underlying reinforcement from cathodic protection

* Capacity after rehabilitation must be verified. Additional strengthening may be necessary
* See OHBDC section 7.

structure. Once all the pertinent data is collected, a detailed review is carried out and a check list is prepared. The check list should include all data which is required for an indepth evaluation.

(ii) **Establishment of in-service conditions** : This task ascertains the extent to which the intended function of the structural components matches the in-service conditions. Once a preliminary assessment of the design function of the structural components of the building is made, the following items should be identified[6,7,8,9] :

- areas of high stress
- areas exposed to freezing and thawing, temperature and humidity fluctuations, dry or wet environment etc.
- existing service conditions, that is, heavily loaded areas subjected to vibration, abrasion, exposure to chemical spillage and elevated temperatures or temperature variations and variation in wind loads.

(iii) **Field visit** : The first two tasks give a preliminary overview of the condition of the building being investigated. During the site visit, specific and detailed notes should be made, preferably on pre-planned sketches and tables. The following is a list of the activities to be completed during the site visit[5,8,10] :

- observe visual condition
- note condition of the areas of high stress
- make photographic records
- note condition of areas exposed to the elements
- identify areas of concern
- identify cracks and locations of spalled and deteriorated concrete
- carry out limited measurements, for example, crack width and length, extent of spalling or delamination etc.

Such a preliminary assessment provides the requisite information upon which a decision to conduct a more detailed investigation can be based. The areas of most concern should be identified and the requirements of a more detailed survey established.

(iv) **Detailed survey** : A detailed survey should include non-destructive tests, a core-sampling or brick removal programme, dimensional measurements of structural components, mapping of

cracks, installation of instruments to monitor movements of cracks or movement of the targeted structural components etc. A list of all tests required to be done, and their relevant details including respective advantages and limitations should be drawn up at this stage[5,7,12].

(v) Evaluation of data : Establishing the problem, the probable causes and factors influencing the deterioration requires careful study and analysis of the information gathered in the investigation stage. This usually involves proposing a hypothesis and testing the resultant scenario against the observed facts. Two or three such hypotheses and scenarios may be looked at and tested for their veracity against the available facts. Examination of the available facts often reveals the need for further investigation to resolve unanswered questions[5,7,13,14,15].

Select a repair strategy

Based on the evaluation, alternative methods of repair in keeping with the owner's objective could be considered. The completed technical assessment and the suggested repair strategy should be reviewed jointly by the consultant and owner. The owner must then ascertain the impact that repairs will have on on-going operations, the future use of the property, and determine the most appropriate alternatives of financing the repairs.

Owners should assign high priority to the repair of structural defects to assure a safe and serviceable condition. When repair costs are high, restoration work can be staged over several years which makes prioritising the work essential. Contingency funding, for latent areas of deterioration which were not noted in the investigation, is important. Should the repair prove unnecessary at the time of the investigation, the progress of the deterioration in the structure should be monitored for any changes that would signal the need for another evaluation or remedial action.

Design the repairs

Based on the technical and economic considerations, the service life of a structure can be established and a decision to repair or replace it can be taken. Once a decision is made to carry out repairs, an activity matrix which includes names of structural elements, type of degradation, type of repair, method of repair, and recommended repair material should be developed. An example of a decision matrix is shown in *Table* 3. The *Table* deals with practical considerations in selecting a rehabilitation method exclusive of costs. The matrix is constructed in a way that it leads, by elimination, to the selection of the rehabilitation scheme which has the least disadvantages. The criteria in the table are not rigid because of the complexities of the decision making process, but the figures are a useful starting point which could be applicable to most structures[7,16].

The selected method of repair should achieve one or more of the following objectives[5,17]:

- prevent the ingress of corrosion promoting materials such as moisture, chlorides and carbon dioxide
- reinstate the structural integrity of the element by restoring or increasing its strength and stiffness
- improve durability
- improve the appearance of the concrete surface.

If the repairs are simple enough for the owner to be able to develop the specification and contract documentation for the needed repairs and administration of the repair contract, the assistance of the consultant may not be required. Often however, a consultant is retained to develop the technical design of the repairs, including the selection of repair materials, the description of the techniques to be used to implement the repairs, and the locations where the various repairs are to be performed. The owner and consultant together should agree on the form of contract that would best suit the proposed repairs.

Perform the repairs

Depending upon the specific condition of the deteriorated structure, the options for the repair included are : crack injection, patch and waterproof, concrete overlays (including normal slump concrete, low slump concrete and latex modified concrete) and cathodic protection[5,13,17].

Once the specifications and contract documents have been prepared, the owner or the consultant invites bids from contractors to do the specified repairs. Contractors should necessarily be prequalified, that is, only contractors having experience with repair work of a similar scope and type should provide bids. The owner and consultant should jointly review the bids and select a contractor. The selected form of contract can then be formalised by the owner and contractor after which the repairs begin.

Two types of contract that are commonly used are the Stipulated Price (SP) contract and the Unit Price (UP) contract. The SP contract bases payment on a lump sum value for the repair work, which may seem attractive to owners. It demands however, that the scope and extent of the repair work be very well detailed in the technical specifications and drawings for the repairs. This is not always possible for the repair of existing structures that usually have hidden conditions. The UP contract bases pay on the actual amount of repair work done to rehabilitate the structure which allows the total cost of the work to be adjusted to accommodate hidden conditions. This type of contract demands more on-site review of the work by the consultants to assess the extent and cost of the work needed.

The consultants should frequently review the repair work in process for general conformance with their design in order to resolve the technical issues that arise during the repair process and verify the quality of the repair work as it is being performed.

Conclu~~sion~~ding remarks.

While the methodology of repairs that is adopted will vary from case to case, the broad guidelines presented in this paper are applicable for any repair project. These could form the basis for systematic execution of all such jobs.

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