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DAMAGE MECHANISM ASSESSMENT IN REHABILITATION OF DISTRESSED STRUCTURES

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ABSTRACT

A deficient structure can be defined as one which does not fulfil its intended function. This deficiency appears in the form of distress in its components. Various reasons which lead to the necessity of rehabilitation in any structure are described in this paper. Also described are various steps which are involved in a general rehabilitation programme. Most important of these steps consists of analysis of symptoms and diagnosis. To facilitate a quick identification, various known symptoms for all conventional construction materials are tabulated and the possible sources of trouble are indicated. The information for concrete structures is extracted from a publication by R.F. Warner [1]. A similar compilation for steel, wood and masonry is freshly prepared.

INTRODUCTION

The creation of a structure begins with the recognition of a need and the shape of the structure is essentially the conception of an idea to meet this need. The function of the structure is to faithfully fulfil this need throughout its life-time. Due to several (subsequently described) reasons, the performance of a structure may fall short of expectations. This is usually reflected in the form of distress in its components. The social, economic, technical or historical reasons may prohibit its demolition. In such a situation, the process of rehabilitation has to be initiated. Its broad and ultimate object is to restore and preserve the functional and structural integrity of the structure and its various components under the present and future extreme external actions.

This paper is concerned with different aspects of rehabilitation. A general rehabilitation programme is described. The symptom analysis and diagnosis of the possible sources of distress is made easy through a tabular presentation of symptoms and their possible causes. Such tables are presented for various construction materials such as concrete, steel, wood and masonry.

ORIGIN OF DISTRESS

The reasons for distress, alternatively, the need for rehabilitation arises due to different causes such as;

* The effect of any man-made or natural disaster.
* Deterioration of construction materials caused by the age of structure and adverse environmental conditions such as weathering, chemical action, abrasion, frost, wave action or fire.
* Design and construction errors.
* Use of sub-standard construction material.
* Change in use particularly in bridges.
* Improvement in knowledge and construction practices.

The last two aspects require some further explanation. It may become necessary to re-evaluate structural adequacy of a bridge in view of the changes in its use such as increased volume of traffic and heavier vehicular loads. The rehabilitation may become necessary eventhough there is no visual sign of any distress. Similarly, new discoveries may outdate or update the state of existing knowledge. The available knowledge as compiled in the building codes and standards has already been used in the past constructions. All new features that are discovered in the present research can only be included in the new constructions. The past and existing constructions fall outside its purview, eventhough the newly discovered knowledge may prove the then used design and construction practices to be unsafe. The past constructions are clearly going to need rehabilitation. In these two cases structural deficiency is the cause of rehabilitation.

OUTLINE OF A GENERAL REHABILITATION PROGRAMME

In the distressed or deficient structures, the damage to a structural component depends upon the severity of the damaging action. It may range from small cracks to a partial collapse. A general rehabilitation programme involves the following steps;

* Study of the existing and available documentation.
* Inspection to determine the extent of damage/deficiency.
* Calculation of the required strength.
* Estimation of the available/residual strength.
* Analysis of symptoms and diagnosis.
* Determination of a method for restoration of the desired strength.
* Imprementation of the rehabilitation measures.
* Testing to ensure restoration of strength.
* Preparation of documents for future reference.

The rehabilitation process of distressed structure is sensitive, time consuming as well as expensive. It must be carefully planned and systematically executed to ensure its full effectiveness. In the case of a deficient structure, the general rehabilitation programme involves the following steps;

* Study of the existing and available documentation.
* Structural analysis.
* Identification of deficient structural components.
* Structural strengthening and modifications.
* Implementation of the rehabilitation measures.
* Testing to ensure the effectiveness of above.
* Preparation of documents to be preserved for future use.

The above mentioned aspects are subsequently described. To ensure space, the discussion is limited to the rehabilitation of structures with visible distress or damage.

STUDY OF DOCUMENTS

The above mentioned general rehabilitation program begins with the study of documents related with the structural design, construction program and any past rehabilitation work that may have been done on the structure. In Indian conditions, there is generally a blackout of such information. The present task of rehabilitation shall become much simpler and lot more effective, if this kind of information is readily available. To ensure that this happens, the general rehabilitation program of the previous section ends with the preparation of documents regarding the current rehabilitation program and their preservation for any subsequent use.

It is difficult to find structural design and construction program of the historical monuments. This gap should be filled by the Archaeological Departments' documents and experience.

EXTENT OF DAMAGE

The term damage is essentially qualitative. In the early stages of a rehabilitation program, the object is to estimate magnitude of the problem through visual inspection. A record has to be prepared to show the following;

* Type of structure and its classification.

TABLE 1. DAMAGE CLASSIFICATION [2]

Damage State	Description
None to minor	No damage or minor non-structural damage
Light	Light structural and non-structural damage
Moderate	Moderate structural and widespread non-structural damage
Heavy	Heavy structural and non-structural damage
Severe to collapse	Severe damage or collapse

TABLE 2. NON-DESTRUCTIVE METHODS FOR CONCRETE STRUCTURES [3]

Property	Non-destructive test number*							
	1	2	3	4	5	6	7	8
Strength	●	●	●					
Adhesion to steel bars		●	●		●			
Hardness	●							
Stressed state		●	●			●		●
Ultimate strain		●	●			●		
Elastic properties		●	●			●		
Damping		●	●					
Conductivity								●
Density				●		●	●	●
Porousness		●		●		●	●	●
Moisture				●		●	●	●
Internal defects		●		●			●	●
Microcracks		●	●	●		●		●
Roughness						●		

* NOTES FOR TABLE 2
1 = Mechanical NDM. 2 = Acoustic NDM
3 = Oscillation NDM 4 = Radiography NDM
5 = Magnetic NDM 6 = Electrical NDM
7 = Radio wave NDM 8= Others

TABLE 3. SYMPTOMS OF DEFECTS AND DAMAGE IN CONCRETE STRUCTURES [1]

No.	Defect description	Possible cause(s)
1.0	ACTIVE CRACK	
1.1	Vertical cracks	Excessive moment
1.2	Inclined cracks	Excess shear or torsion
2.0	DORMANT CRACKS	
2.1	Vertical or inclined cracks	Temporary overload
2.2	Seperating cracks extending completely through member	Restrained shrinkage, Restrained thermal strain, Poor construction joint
2.3	Cracks at change in section	Local stress concentration
2.4	Cracks at change in shape	Lack of control joint
2.5	Isolated flexural crack in the region of low moment	Bar cut-off acting as crack starter
2.6	Dormant surface crack	Plastic setting, Poor curing, Loss of surface water, Windy condition at casting time
3.0	SCALING AND SPALLING OF CONCRETE	Excess compressive stress, Chemical attack, Substandard material
4.0	SWELLING OF CONCRETE	Alkali-aggregate reaction
5.0	DISCOLOURATION	Chemical attack, Fungus, Rusting of steel
6.0	SURFACE EROSION	Abrasion, Chemical attack, Poor or Permeable concrete
7.0	RUSTING OF STEEL	Insufficient concrete cover, Stray electrolytic currents
8.0	YIELDING OF STEEL	Overload
9.0	SNAPPING OF STEEL	Fatigue and brittle fracture, Substandard material
10.0	EXCESSIVE DEFLECTION	Overload, Foundation movement, Incorrectly placed reinforcement, Inadequate reinforcement

* Construction material
* Type of damaging action
* Importance of the structure
* Frequency and probability of occurrence of damaging action
* Present condition

The importance of the structure includes the financial loss and magnitude of threat to human lives. It may be possible to quantify damage by using the classification proposed by Schodek [2] which is partially reproduced in Table 1. Further extension of this work appears possible. More research in this direction is presently underway.

CALCULATION OF REQUIRED STRENGTH

Any structure transfers the dead and live load acting on it to the foundations with which it is attached. This transfer takes place through a mechanism - direct load transfer, beam action, slab action etc. If this mechanism continues to operate even under the disaster loading, the structure is likely to survive the disaster without complete collapse. The calculation of required strength involves identification of this mechanism.

Given the size of each member and the loads acting on it as input, it is straight forward to compute the load carrying capacity of each member as well as the strength that is required for a safe operation of the load transfer mechanism under

TABLE 4. SYMPTOMS OF DEFECTS AND DAMAGE IN STEEL STRUCTURES

No.	Defect description	Possible cause(s)
1.0	EXCESSIVE VERTICAL DEFLECTION	Overload, Undercapacity member, Foundation movement, Incorrect joint connections, Exclusion of inelastic effects
2.0	TWISTING OF MEMBER	Overload, Eccentricity of Loading (twisting), Incorrect joing connection, Initial deformation of member
3.0	EXCESSIVE LATERAL DEFORMATION	Excess unsupported free length, Exclusion of inelastic effects in design, Initial deformation of member
4.0	LOCAL BUCKLING OF FLANGES	Overload, Excess moment, Excess unsupported free length
5.0	RUST FORMATION AND SCALING	Exposure to moisture, Leakage from above
6.0	CHIPPING OF PAINT	Induction of plastic deformation, Leakage from above, Exposure to moisture, Substandard material

disaster loading.

In the design of non-structural members, its connection with the structural members may fail through punching, yielding or shearing. The non-structural member may get loaded due to distress in the structural members with which it is connected. The failure of non-structural members is of serious concern under disaster loadings such as earthquakes.

ESTIMATION OF RESIDUAL STRENGTH

This step is the most complex as well as vital. It not only affects the subsequent rehabilitation programme but also is crucial in the success of the actual rehabilitation measures. It is imperative that a non-destructive method of testing is employed in this step. Sabnis and Millstein [3] have given a complete list of non-destructive testing methods for concrete structures and its utility (Table 2). This table must be updated to include any new development and experience with their use.

It appears possible to develop a numerical non-destructive method for the analysis of distressed structures. More work in this direction is in progress.

ANALYSIS OF SYMPTOMS AND DIAGNOSIS

It is now required to put together the information of the previous steps and to pin-point the exact cause(s) which led to the present form of distress. This exercise must take into account the material of construction of the structural component under distress.

The distress in concrete structures can appear in a large number of ways. There are an equally large number of causes of these forms of distress. Warner [1] has given an exhaustive list of these defects and possible causes (Table 3). With the help of this information, it is reasonably easy and accurate to fix the possible

TABLE 5. SYMPTOM OF DEFECTS AND DAMAGE IN WOOD STRUCTURES

No.	Defect description	Possible cause(s)
1.0	SAGGING WITH CRACKS	Overload, Excess moment
2.0	SAGGING WITHOUT CRACKS	Inelastic deformation (creep)
3.0	TWISTING OF MEMBER	Overload, Eccentricity of loading (twisting), Insufficient bonding with upper deck, slenderness, Initial deformations
4.0	DELAMINATION	Moisture, Overload, Incorrect grain orientation, Unseasoned/underseasoned wood
5.0	MOIST PATCHES AND DISCOLOURATION	Moisture, Chemical attack, Leakage, Insufficient damp proofing
6.0	FUNGUS GROWTH	Moisture, Leakage, Insufficient damp proofing
7.0	SMALL HOLES ON SURFACE	Termite attack, Moisture, Leakage
8.0	RANDOM SURFACE CRACKS	Unseasoned/Underseasoned Wood, Overload

cause(s) leading to a particular form of distress.

A similar form of symptom-and-causes charts for structural steel, wood and masonry as construction material are prepared and these appear in Tables 4, 5 and 6 respectively.

Based on the information given in Table 3, Warner [1] prepared a diagnosis chart also. This chart is updated to include the information presented in Tables 4-6. The updated diagnostic chart appears in Table 7.

METHODS TO RESTORE THE REQUIRED STRENGTH

Suitable guidelines for these are available in the published literature [4-7]. The remedial measures, obviously, will depend upon the material of construction. In the case of steel or wood constructions, various measures such as the following are easily possible:

* Replacement of the distressed member.
* Strengthening of the member by welding in the case of steel and by nailing in the case of wood.
* Cutting of the distressed portion and replacement

In the case of masonry or concrete construction, such measures are not possible, therefore, more eleborate arrangements are required. It is not surprising that a large bulk of published material deals with the techniques of rehabilitation of reinforced concrete members and on the materials to be used in the rehabilitation. The rehabilitation methods have also been diversified depending upon the type of member - column, beam, slab or footing.

IMPLEMENTATION OF THE REHABILITATION MEASURES

This step effectively determines success of the rehabilitation process and future of the rehabilitated structure. Therefore, the suggested guidelines for the rehabilitation as well as in the use of materials to be used in rehabilitation must be religiously

TABLE 6. SYMPTOMS OF DEFECTS AND DAMAGE IN MASONRY CONSTRUCTION

No.	Defect description	Possible cause(s)
1.0	DIAGONAL CRACKS	Differential settlement, Lateral ground movement
2.0	CRACKS AT OPENING CORNERS	Overload, Oversized openings, Insufficient spacing of openings
3.0	DAMP PATCHES ON SURFACE	Insufficient damp proofing, Moisture, Leakage
4.0	CHIPPING OF PLASTER	Poor mix, Application of dry surface, Windy condition at the time of application, Substandard material
5.0	CRACKING AT WALL TO WALL JOINT	Lateral ground movement, Differential settlement, Poor mix, Faulty construction
6.0	EFFLORESCENCE	Poor brick quality, Moisture, Leakage, Insufficient damp proofing, Chemical attack
7.0	CRACKS IN PLASTER	Frost action, Lack of curing, Confined shrinkage, Thermal effect
8.0	SURFACE EROSION	Abrasion, Wave action, Chemical attack
9.0	DISCOLOURATION	Chemical attack, Cyclic wetting and drying

followed.

TESTING TO ENSURE REHABILITATION

A very popular cause of distress in the structure is poor workmanship. If it can exist in the actual construction, there is no reason why it can not appear in the rehabilitation program as well. To prevent rehabilitation of a recently rehabilitated structure, some testing is essential to ensure a satisfactory rehabilitation. No guidelines are offered for it in this paper, however, it is recommended that no rehabilitation programme must be certified as satisfactory unless it has been demonstrated through testing. A Monitoring and Enforcing Agency (MENA) may be established for this purpose [8].

The existing by-laws and codes of practice on reinforced concrete, steel, masonry and wood construction must be modified to become specific in dealing with the cases of poor quality construction materials, unsafe construction practices and distressed structures as well as structural components. This shall also require an explicit inclusion of human error factor in the structural design procedures to minimize distress in the structures [9]. All such informations may be collected at one place and released for use in the form of a code of practice.

CONCLUDING REMARKS

Various sources of distress in steel, concrete, wood and masonry structures are described in this paper. The consequent rehabilitation programme is given in general terms. Several tables are presented for a quick identification of the source of distress. More such information may be collected and it may be compiled in the form of a code of practice to be made available to the designers and builders.

TABLE 7. DIAGNOSTIC CHART (extension of chart by Warner [1])

GENERAL CAUSE	SPECIFIC CAUSES	EXCESS DEFLEC-TION		CONCRETE Construction								MASONRY Construction									WOOD Construction								STEEL Construction				
		Short-term	Perma-nent	Active cracks	Dormant cracks	Spalling	Swelling	Discolouration	Surface erosion	Rusting of steel	Yielding of steel	Diagonal cracks	Crack at openings	Damp patches	Chipping of plaster	Crack at wall joint	Salt-deposit	Cracking of plaster	Surface erosion	Discolouration	Sagging and cracks	Sagging only	Twisting	Delamination	Discolouration	Fungus growth	Small holes	Random cracks	Twisting	Lateral deflection	Local buckling	Rusting scaling	Paint chipping
MATERIAL TECHNO-LOGY	Contaminated water (salt water, oils)					●		●	●	●					●				●	●													
	Contaminants in concrete (saw dust)							●	●	●					●				●	●													
	Inappropriate admixtures (low F_c^*)					●				●																							
	Expansive aggregates					●	●																										
	Alkali-aggregate reaction			●		●	●																										
	Poor surface finishing					●			●	●									●														
	Permeable concrete or mortar					●		●	●	●				●			●		●	●													
	Low temperature during pour or plaster					●			●						●				●														
ENVIRON-MENTAL EFFECTS	Carbonic acid (dairies, breweries)								●						●				●						●							●	
	Hydrogen sulphide (sewers)								●						●				●						●							●	●
	Sulphate attack						●		●						●				●						●							●	
	Flue gases							●	●										●	●					●							●	●
	Wave action, water flow, cavitation								●										●						●	●						●	
	Cycles of freezing and thawing					●			●						●				●					●									
	Cyclic wetting and drying						●		●					●			●		●	●				●	●	●						●	
	Cyclic changes in temperature			●	●													●						●									●
	Electrolytic attack			●		●				●																							
	Exposure to moist environment					●	●			●				●								●		●		●						●	●
FOUNDA-TION PROBLEMS	Settlement		●																														
	Differential settlement		●	●	●	●					●	●	●			●					●		●						●				
	Lateral ground movement			●	●	●					●	●	●			●					●		●						●	●	●		
	Heaving		●	●	●	●					●	●	●			●					●		●						●	●	●		
	Frost					●			●	●					●				●														

continued

CONSTRUCTION ERRORS	Formwork problems (lack of strength and bracing, premature removal)		●		●	●																											
	Poor concrete/mortar (excess water, wrong mix, batching error)	●	●	●		●			●						●				●														
	Inadequate curing (low strength, high shrinkage and creep)		●	●		●									●			●															
	Excessive vibration				●				●																								
	Oversize pours				●	●																											
	Overload during construction		●		●	●					●																		●	●	●		
	Poor construction joints				●	●				●				●																			
	Inadequate damp proofing					●		●	●	●				●	●				●						●		●	●				●	●
	Application on dry surface														●			●															
	Use of unseasoned/underseasoned wood																				●	●	●	●									
DESIGN ERRORS	Loads/moments under estimated	●	●	●	●						●		●								●		●						●	●	●		
	Strengths over estimated	●	●	●	●						●		●								●		●						●	●	●		
	Stiffness over estimated	●	●	●	●						●		●								●		●						●	●	●		
	Omission of control joints			●	●																												
	Exclusion of inelastic effects (plasticity and creep)		●	●	●						●																		●	●	●		
	Inappropriate method of analysis	●	●	●	●						●	●	●					●			●		●						●	●	●		
	Excessive eccentricity of loading		●	●	●						●	●	●					●					●						●	●	●		
DETAILING ERRORS	Incorrect drawings	●	●	●	●						●										●		●						●	●	●		
	Steel congestion				●	●				●																							
	Sharp changes in member dimensions			●	●	●																											
	Bar termination and overlapping			●	●																												
	Inadequate cover				●	●				●					●			●															
	Anchorage problem			●	●	●																											
	Incorrect orientation of grains																						●										
	Oversized/too close wall openings												●																				
	Insufficient joint details			●								●										●	●						●	●	●		
	Excessive unsupported free length																													●	●		
BUILDING TECHNOLOGY	Temperature effects (in cold storage)			●														●															
	Cladding connections				●																												
	Inadequate drainage							●	●					●			●							●	●							●	●
	Inappropriate wearing surface (for fork lift trucks etc.)								●										●														
UNEXPECTED ERRORS	Earthquakes		●	●	●	●					●	●	●			●					●		●						●	●	●		
	Gas explosion and bomb blast		●	●	●	●					●	●	●								●		●						●	●	●		
	Collision		●	●	●	●					●	●	●								●		●						●	●	●		
	Collapse of adjacent building		●	●	●	●					●	●	●								●		●						●	●	●		
	Shock loads		●	●	●	●					●	●	●			●					●		●						●	●	●		
	Termite attack																										●						
HUMAN ERRORS	Poor workmanship				●	●			●	●				●	●			●						●				●	●				
	Use of sub-standard materials	●	●	●	●	●	●	●	●	●	●			●	●		●	●	●	●		●		●	●			●				●	●
	Lack of supervision and quality control	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Communication gaps	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

concluded

The information made available in this paper may serve as a starting point for this purpose.

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