Condition-Based Maintenance Management

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Abstract

A methodology and the corresponding software implementation has been produced in this work in order to provide building managers with (a) an estimate of repair costs of instrumented reinforced concrete buildings shortly after the cessation of the earthquake motion which is invaluable for quickly arranging for financing and (b) a much needed quick estimate of the scope and cost of rehabilitation work for instrumented reinforced concrete buildings damaged due to differential settlement between foundations which is the most common reason for building damage.

The above repair estimates are based on an assessment of structural damage of the building elements. This assessment is based on sensor measurements of strain and acceleration in case of an earthquake or strain in case of differential settlement between foundations.

Moreover, the above repair estimates are part of an integrated package for the monitoring, structural condition assessment and maintenance/repair/rehabilitation/strengthening management of reinforced concrete buildings.

Keywords: repair building seismic damage, repair building settlement

1. Introduction

In case of an earthquake it can take several days for engineers to perform a rapid visual safety assessment and weeks before they complete a post-earthquake engineering analysis. During this time the owner and occupants are in a state of uncomfortable uncertainty about their safety. Moreover, immediately after an earthquake building stakeholders usually need an estimate of repair costs. To contract for and carry out a structural analysis and cost estimate of an earthquake-damaged building can require the stakeholders to wait weeks or months before reliable information is available. An automated assessment of the structural condition and a preliminary cost estimate for the required repairs could provide valuable information to owners, insurers, banks and public-relief entities to begin funding restoration efforts.

Under operating conditions the most common reason for changes in the internal forces during the building life-span is differential settlement between foundations on cohesive soils subjected to consolidation or due to deep excavations in the vicinity of the structure. It is important to establish whether foundation movement is progressive and threatening to the building, or a one-off occurrence which can be dealt with by limited repairs. When the movement is progressive and likely to result in serious damage to the building underpinning should be undertaken. Early detection of the settlement problem will result in a large decrease in the cost of remedial measures because problems are less expensive to fix when they are first developing, prior to significant physical deterioration. An automated assessment of the differential settlement between foundations as a function of time and the resulting damage to building components together with a quick estimate of the scope and cost of rehabilitation work is very much needed by building facility managers.

The goal of the EC funded project MEMSCON (1) is to provide a wireless network of MEMS-based strain and acceleration sensors for the monitoring of reinforced concrete (r.c.) buildings that will be integrated with software for decision-support on the planning of maintenance[1]. This software includes a Module on structural assessment that, based on input from strain and acceleration sensor measurements provides the degree of damage (Damage Index) of each structural element after an earthquake and, based on input from strain measurements, estimates the amount of differential settlement between foundations and the Safety Factor (SF) of each structural element in the monitored building. The above assessments of the structural condition of the building structural elements provide input to a Maintenance Management Module, described in this paper, that uses it to select a remedial measure and assess its cost.

2. Seismic Rehabilitation of Monitored Reinforced Concrete Buildings.

The building structural types considered are the r.c. moment frame and the shear wall types that account for the overwhelming majority of buildings in the earthquake prone European countries.

The optimum rehabilitation scheme for a seismically damaged building is a function of the specific building characteristics, including aesthetics and accessibility, exact damage of each component and rehabilitation objectives. Moreover, a complete rehabilitation scheme may consist of a combination of several techniques, e.g. insertion of a new lateral force-resisting component and enhancement of the seismic resistance of a damaged existing component.

It is not possible to provide generic guidance for optimum selection of a rehabilitation scheme for

1 The term maintenance in this work is taken to be synonymous with intervention that includes structural maintenance, repair, rehabilitation, retrofit and replacement and is used interchangeably with these words.

each building type: The 'optimum' rehabilitation scheme has to be derived by trial and error after the structural assessment of a number of structural modifications and is a lengthy process.

The goal of this work is to provide facility managers with a much needed quick estimate of the scope and costs of structural rehabilitation work. To accomplish this objective the building is considered to be a collection of discrete structural components. Based on measurements from the monitoring sensors dynamic analysis is used to estimate structural response and based on this a damage index for each one of the discrete structural components. Damage indices are connected to damage states for each structural component which – damage states – are defined in terms of repair efforts required to restore the component to its undamaged state (see Table 1).

Table 1
Proposed Relation Between Damage Ratio, Safety Factors, Damage States and Repair Techniques.

Damage Ratio	Safety Factor	Damage State	Possible Repair Techniques	Probability of Usage (2)
D<0.2	1.3	Light	Epoxy injection FRP jacketing	High Low
0.2<D<0.4	1.0	Moderate	RC jacketing FRP jacketing Steel Jacketing	Average Average Below Average
0.4<D<0.6	0.8	Severe	Replaceme nt RC jacketing	Above Average Average
D>0.6	0.5	Collapse	Replaceme nt RC jacketing	High Below Average

Rehabilitation techniques are connected to the various damage states and their costs are estimated. Finally, the cost of the repair of each and every one of the damaged building components is summed up to calculate the total direct rehabilitation cost.

Many techniques are being continuously developed and used for the rehabilitation of earthquake damaged buildings. This work provides a selected compilation of common component-level rehabilitation techniques that are practical and effective. Included are the addition of concrete, steel or fiber -reinforced polymer (FRP) jackets in confining r.c. columns and beams, epoxy resin injections for slightly damaged components and replacement of severely damaged components.

There is no universally accepted standards for choosing repair methods for damaged r.c. components. Even if the damage state is clear, as can be seen in Table 1, there is more than one rehabilitation technique that can be used. The choice depends not only on the damage itself but on a number of parameters such as availability of materials, equipment, personnel, company expertise etc. To help the user select a repair technique the probability of usage of each one of the identified appropriate techniques for the various damage states based on the literature is reported in Table 1.

Rehabilitation costs include direct costs for structural and non-structural damage and indirect costs to the community. The scope of this research is limited to direct structural rehabilitation costs including the necessary cost to remove and reset non-structural elements in order to repair damaged structural elements. Beck et al. (2) have shown that non-structural damage contributes the majority of costs at low levels of shaking while at moderate to strong shaking (which is the main focus of this work) structural damage dominates, contributing 75% to 85% of total rehabilitation cost.

The structural components considered in MEMSCON are columns, beams, shear walls and slabs when there are no beams. A formal taxonomy of components has been employed to provide unambiguous reference to component types and their damage states, repair methods and costs (see Fig. 1).

An example of the Module results can be seen in Fig.2. This example involves a damaged column located at the building façade necessitating use of scaffolding. This column will be repaired through use of a layer of FRP. To apply this layer a door and a window needs to be replaced and some square meters of non-structural walls have to be demolished and reconstructed. The total cost of the repair is 4290€ (see Fig. 2)

The 'restore components' method suggested herein even though might not provide the optimum rehabilitation scheme, it will provide a much needed quick estimate for approximate rehabilitation costs.

3. Proactive Maintenance under Operating Conditions.

It is not possible to measure the absolute value of settlements through strain sensors. However, it is possible to estimate the support reactions at the columns' bottom cross-section on the foundations, at which locations the strain sensors are only placed in the instrumented r.c. building. The changes in values of the support reactions that are estimated in sequential periodic measurements compared to the values measured in the initial condition of the building constitute the input for a finite element analysis. The sum of the measured axial forces on the columns equals the sum of the active vertical loads on the structure. The vertical loads that are applied on the members in the model are equal to the initial design loads multiplied by the ratio of the total active loads to the total initial design loads. Then the analysis is performed to derive stresses and moments that are compared to limit values in order to determine the SF of structural members and the amount of differential settlement between foundations. The above analysis at the time of periodic measurements of strain will establish, timely, whether foundation movement is progressive and threatening to the building reducing dramatically the expense of remedial measures.

The SFs determined above are connected to damage states for each structural component which – damage states – are defined in terms of repair efforts required to restore the component to its undamaged state (see Table 1). Rehabilitation techniques are connected to the various damage states and their costs are estimated. Finally, the cost of the repair of each and every one of the damaged building components is summed up to calculate the total direct rehabilitation cost.

As in the case of seismic damage this work provides a selected compilation of common repair techniques that are practical and effective and can be seen in Table 1.

A procedural flow chart of the Rehabilitation Module can be seen in Fig.3. Structural calculations provide the S.F. (or damage Index in case of seismic damage) of each structural component. This determines the rehabilitation options that are available. The user selects one of these options and the programme calculates the specifics (e.g. thickness of the FRP layer, reinforcement, etc.). Then construction cost estimation methods are used to determine the repair cost for the specific location and size of the damaged component. (see Fig. 3)

The component level rehabilitation approach can provide a more cost-effective strategy than structure-level rehabilitation because only the damaged components are repaired to bring the structure to its pre-damaged state or to a higher state when new codes demand higher standards.

4. Validation

In the next few months the software on Maintenance Management described herein as well as the whole integrated package for monitoring, structural assessment and support on maintenance planning will be field tested in a r.c. building in Athens, Greece.

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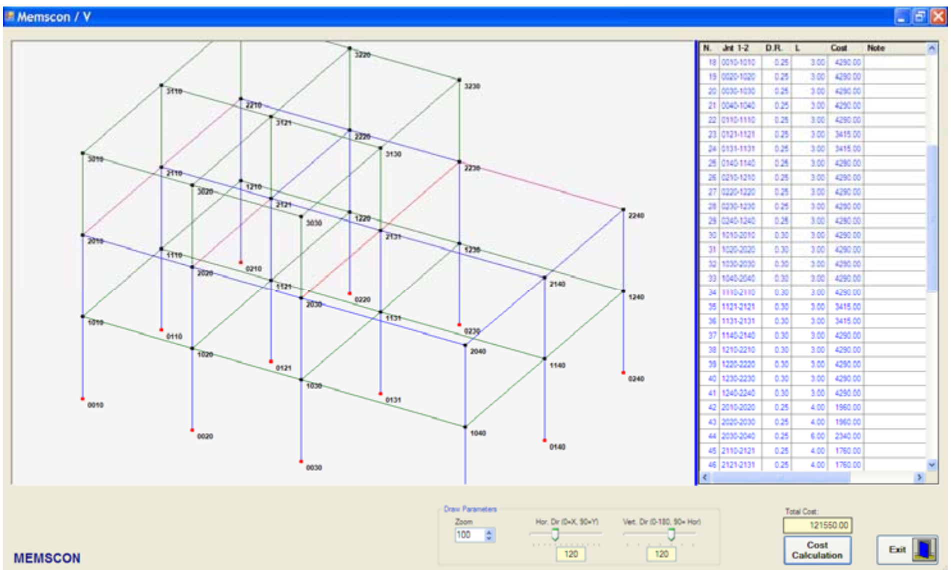

Fig. 1 The Structural Elements of a Building under Study with their Damage Rates and Cost of Repair

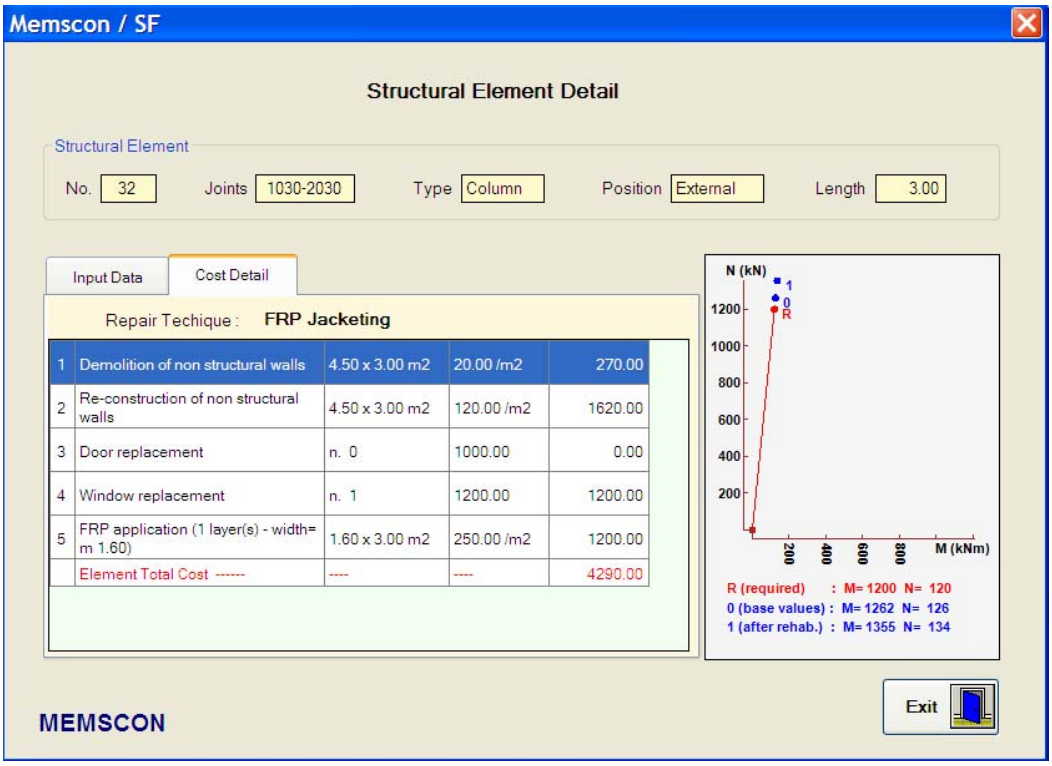

Fig.2 Example of the Results of the Rehabilitation Module

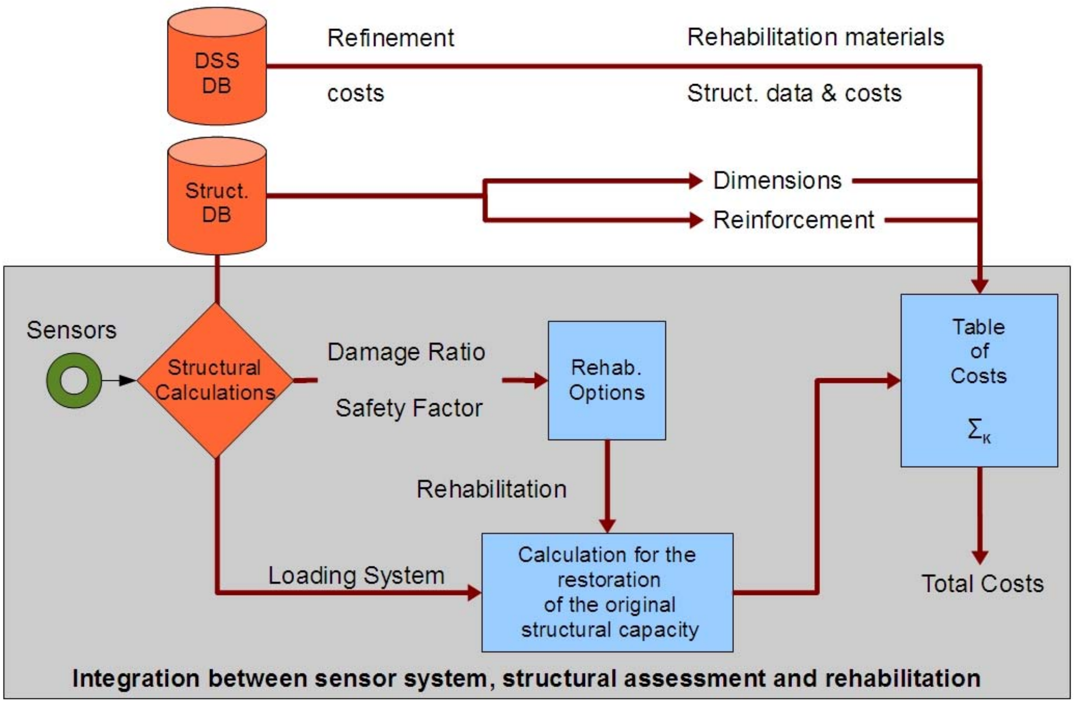

Fig.3 Procedural Flow Chart of the Rehabilitation Module