June 15, 2010

Issue 3

MEMSCON Newsletter

Radio Frequency Identification Tags Linked to on Board Micro-Electro-Mechanical Systems in a Wireless, Remote and Intelligent Monitoring and Assessment System for the Maintenance of CONstructed Facilities

MEMSCON Facts:

- Contract No: 036887
- Project total cost: 4.632.430 €
  EC contribution: 3.814.816 €
- Project Start Date: 1/10/2008
  Duration: 36 Months
- Coordinator:

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Inside this issue:

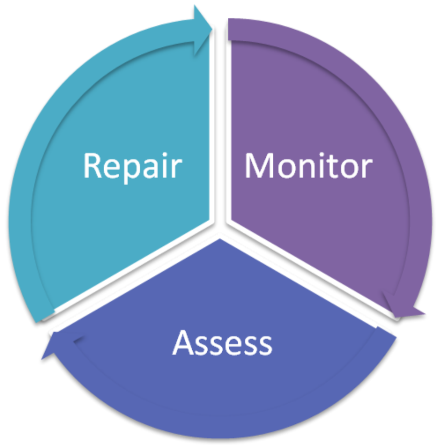
Editorial

Over the past decade earthquakes have been responsible for 60% of all deaths caused by natural disasters. One of the goals in project MEMSCON was to estimate structural damage in a monitored reinforced concrete (r.c.) building shortly after the seismic event, thus permitting the timely evacuation of unsafe buildings. The above estimate is used together with construction cost estimation principles to assess repair cost which is invaluable for quickly arranging for financing after an earthquake.

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 building. Another goal of MEMSCON was to estimate differential settlement between foundations as a function of time and the resulting physical damage at the global and structural component level for monitored r.c. buildings under operating loads. The above estimate establishes, timely, whether foundation movement is progressive and threatening to the building reducing dramatically the expense of remedial measures.

Still another goal of project MEMSCON was the development of MEMS-based accelerometers and strain sensors that would provide the required input for the above assessments.

The development of the hardware (accelerometers and strain sensors) has been described in the second issue of the Newsletter. This Newsletter focuses on the description of the software under development that, based on measurements of acceleration and strain, estimates seismic damage and damage due to differential settlements between foundations, select remedial measures and determine their cost. MEMSCON Newsletters are sent to all members of the MEMSCON Mailing List. If you are interested, you can register in this list (please find information in the contact section).



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Development of the Software

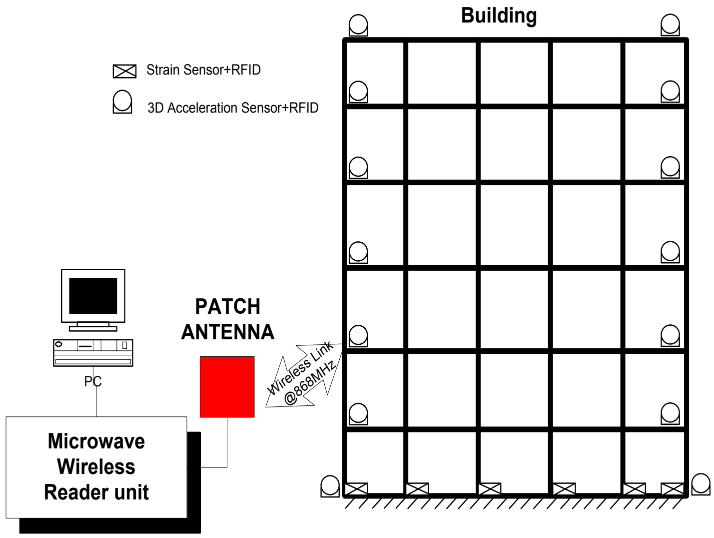

Figure 1. Placement of Sensors

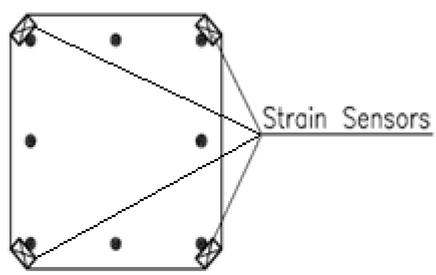

Figure 2. Strain Sensors at Bottom Cross- Sections of the Columns at the Ground Floor Level

Introduction

To provide the required input for structural assessment two three-dimensional accelerometers are placed on every floor and the building basement. Moreover, four strain sensors are placed at the bottom cross-sections of the columns at the ground floor level (see Fig. 1). They are attached at the reinforcing bars lying at the four corners of the above columns as shown in Fig. 2.

The accelerometers are only active during an earthquake. They report the history of accelerations during the seismic event. The strain sensors report strain measurements, under operating loads, in predetermined times, say, once every four months, or on demand.

Strain measurements provide input to software for the assessment of damage due to differential settlement between foundations.

Acceleration measurements provide input to software for the assessment of seismic damage.

The output of the above two software provides input to software for the selection of remedial measure and the determination of their cost.

An overview of the above software can be seen in Fig. 3.

These software are integrated in a Decision-Support-System (DSS) with an expert system and knowledge and data bases (DBs) - see Fig. 4.

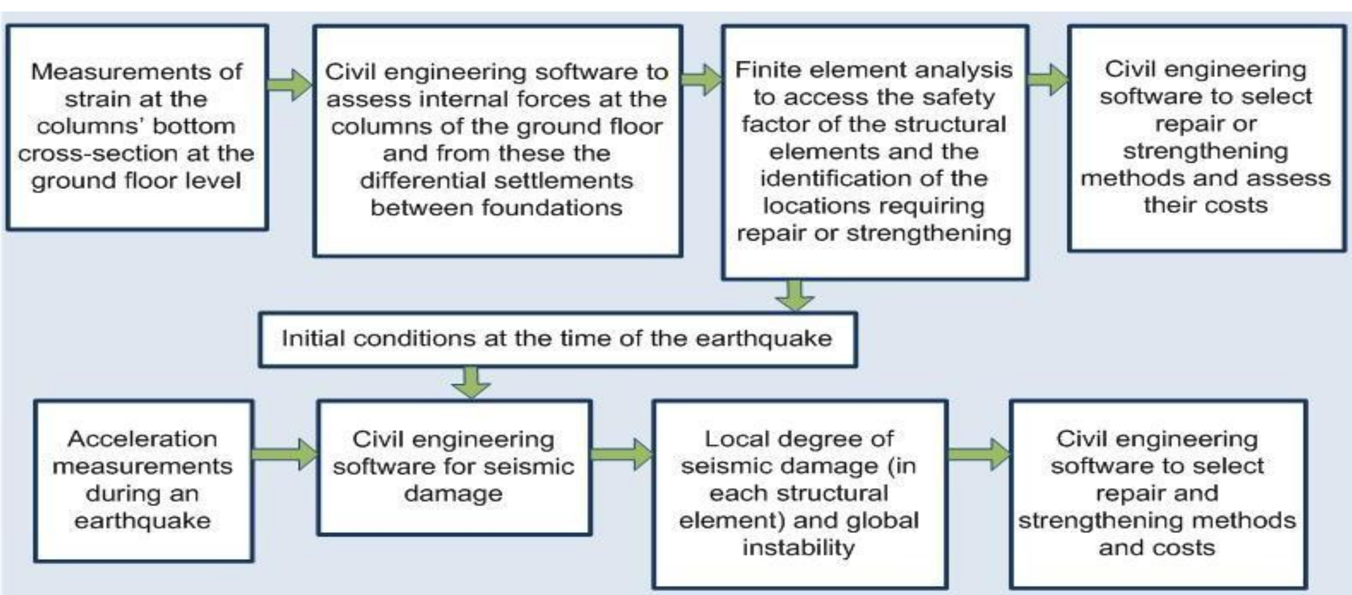

Figure 3. Overview of the software

Development of the Software

Software for the Assessment of the Damage Due to Differential Settlement between Foundations

The most frequent case of deviation from the assumptions accepted at the initial design under operating loads involves differential settlements between foundations exceeding those initially estimated and resulting in unacceptable values of internal forces and deformations at the members of the upper structure.

Such settlements are mainly due to:

- Geotechnical parameters of the foundation soil more adverse than those initially estimated
- Deep excavation in the vicinity of the structure
- Dewatering of the underlying soil layers causing settlement due to soil consolidation

To calculate the resulting internal forces at critical cross-sections of the structural members measurements of strains are needed at four points in each cross-section. Then, from the constitutive laws of the structural materials and on the assumption of linear distribution of strains over the area of the cross-section, one can estimate the stresses and their resultants, the internal forces.

For the above one needs on the average 6 strain sensors per structural element. The implication is that for an average 6 storey building one needs approximately 2000 strain sensors.

In this work the required number of strain sensors has been dramatically reduced. Thus, strain sensors are only needed at the bottom cross-section of the columns at the ground floor level. The implication of this is that for an average 6 storey building only about 60 (as opposed to 2000) sensors are needed. This is possible because, instead of aiming at a direct assessment of the internal forces in each member, some critical global parameters of the overall stress condition are being sought. Then, under operating conditions, the internal forces in each structural member as well as their structural adequacy and the differential settlement between foundations are being assessed through a commercially available finite element programme that accepts as input the measured values of the above critical parameters. In more detail the above are executed in the following steps:

- From the strain measurements the axial forces and the bending moments in two principal directions at the bottom cross sections of the columns at the ground floor are calculated.
- The variations of these forces with respect to those developed at the initial state after the finishing of the structure are calculated.
- The differential displacements between the foundations of the columns are calculated from the compatibility condition with the above variations in internal forces.
- The total structure, represented by a finite element space model, is analyzed for the actual applied loads and the estimated differential settlements, by using a non linear structural analysis computer programme. The output is the values of internal forces and displacements for the totality of the structural members.
- The values of the safety factors of the critical cross sections for the estimated values of internal forces with respect to their available ultimate strength are calculated and compared to their permissible values, in order to estimate their structural adequacy.

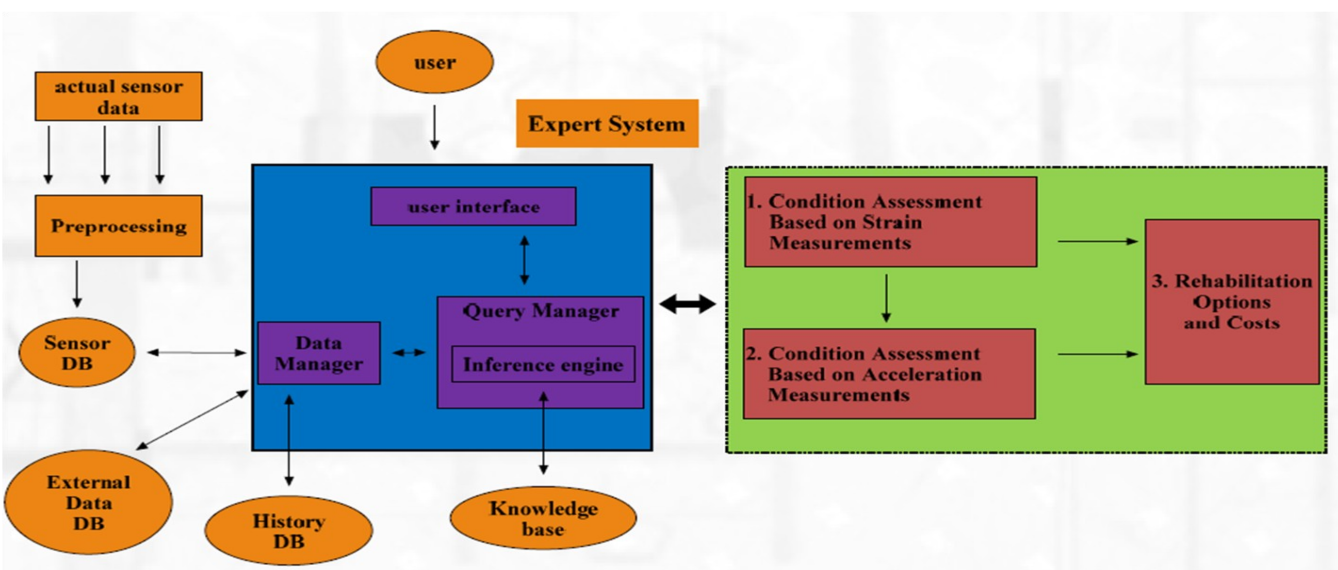

Figure 4. General Architecture of the Software in the DSS.

Development of the Software

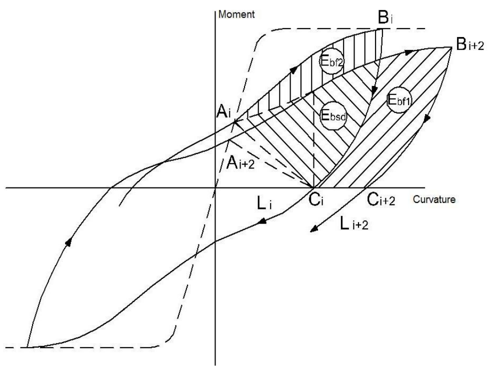

Figure 5. Hysteresis Loop Pattern and the Various Modes of energy

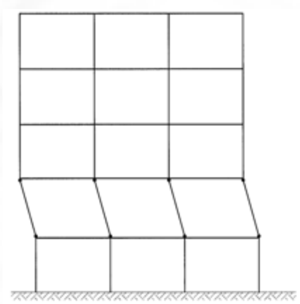

Figure 6. Global Failure Condition

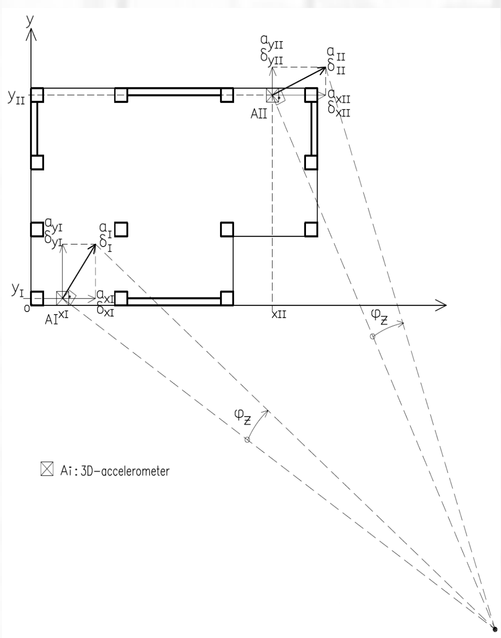

Figure 7. Measured Accelerations and Translations at AI, AII as Functions of Time a=a(t)

Software for the Assessment of Seismic Damage

According to current codes the seismic design of buildings has to satisfy the following requirements:

- Dissipate a large amount of seismic energy in the form of heat to the environment. For this, it is acceptable for a number of structural members to exhaust their flexural strength and develop large elasto-plastic deformations in the form of plastic hinges at their critical cross-sections. Prerequisite for this is that ductile flexural behavior will be insured at the plastic hinges while brittle fracture due to shear forces or torsional moments will be avoided.
- Prohibit global failure of the structure. Such failure ensues when a kinematic storey mechanism is formed after the formation of plastic hinges at the end cross-sections of the columns in his storey.
- Plastic hinges are damages. They have to have a low degree of damage for two reasons: First, to be easily repaired after the earthquake and second, to have a reserve capacity for further elastoplastic deformation to resist aftershocks which usually follow the main strong seismic shock.

A monitoring system should permit:

- Localisation of the damaged structural members
- Estimation of the local degree of damage at the damaged cross sections
- Estimation of the global instability (total failure of the structure)

The above are necessary for decisions on the continuous use of the structure after the earthquake shock.

A recording system permitting the direct measurement of strains at the critical cross-sections requires a large number of strain sensors equal to the number suggested in the previous section of this Newsletter (approximately 2000 strain sensors for a typical 6 storey building). Moreover, these strain sensors should be able to report at seismic frequencies (about 50 measurements per second). Such a system is prohibitively expensive. The system selected in this work involves the installation of a small number of three-dimensional accelerometers, two per storey of the building, in combination with a commercially available finite element programme for structural analyses. The estimation of the local and global condition of the structure after an earthquake is based on the results of the above analyses.

The assessment of **local stability** conditions involves the detection of the cross-sections where plastic hinges are formed and the estimation of the corresponding damage degree. The calculation procedure involves the following steps:

- The accelerometers provide input on accelerations as a function of time in every floor during the earthquake. Double numerical integration of these functions yields the corresponding absolute horizontal translations as a function of time
- The above translations for each moment in time (and there are 50 such moments per second during an earthquake) are inputted as imposed displacements in a sequence of non-linear analyses on the finite element space model of the structure (already constructed for the condition assessment based on settlements) by using a com-

Development of the Software

mercially available structural analysis programme. From these analyses one can derive the maximum values of the internal forces and curvatures at the critical cross-sections of the structure.

- In the cross-sections where the maximum bending moments equal the yield bending moment or where the maximum curvature exceeds the yield curvature, the damage degree is calculated as follows: From the successive imposed displacements and the corresponding structural analyses described above the bending moment-curvature diagrams for the above cross-sections are developed. These diagrams representing the development of the pair of values for bending moment-curvature during the successive cycles of the seismic oscillation, constitute the hysteresis loop pattern (Fig. 5). The various areas inside the loops represent the different modes of energy (dissipated, restoring, released, elastic and complimentary). These, in the form of a modified Parc and Ang Damage Criterion, are used to determine the damage degree for the damaged cross-sections in terms of energy quantities.

Global instability (total failure) of the structure ensues when both end cross-sections of the totality of the columns in a storey develop plastic hinges and a storey kinematic mechanism is formed (Fig. 6).

The safety factor against global instability defines the degree of storey mechanism formation for each storey in the building. It is estimated as follows:

- Because of the diaphragmatic behavior of the storey slabs the relative horizontal translations between successive storey slabs at any moment is considered to be a total relative storey rotation around a vertical axis passing through an instantaneous pole of rotation.

- From the relative translations of the two accelerometers on the floor one can estimate the coordinates of the instantaneous pole of rotation (Fig. 7).

- Then the distance of any point of the slab from the pole of rotation is calculated, the relative horizontal translation between the end cross-sections of each column is derived and so is the resultant moment with respect to the instantaneous pole of rotation for each column and the whole floor (the latter moment being the sum of the moments at the columns).

- The factor of safety against global failure is the ratio of the floor moment at yield curvature to this resultant floor moment.

Software for the Selection of remedial Measures and the Estimation of their Costs

This software accepts input from the software on damage due to differential settlements on the magnitude of differential settlements as a function of time. Thus, it can be established, timely, whether foundation movement is stabilising or is progressive and threatening to the building reducing dramatically the expense of remedial measures.

Input from the above software additionally includes the safety factors for all structural members. Based on these methods for strengthening or repairs are selected and their cost estimated.

"The assessment of **local stability** conditions involves the detection of the cross-sections where plastic hinges are formed and the estimation of the corresponding damage degree."

Damage Ratio	Damage State	Possible Repair Technique	Probability of Usage
D<0.2	Light	Epoxy Injection	High
		FRP Jacketing	Low
0.2 < D < 0.4	Moderate	RC Jacketing	Average
		FRP Jacketing	Average
		Steel Jacketing	Below Average
0.4 < D < 0.6	Severe	Replacement	Above average
		RC Jacketing	Average
D > 0.6	Collapse	Replacement	High
		RC Jacketing	Below Average

Table 1. Common Repair Techniques for Various Damage States

Development of the Software

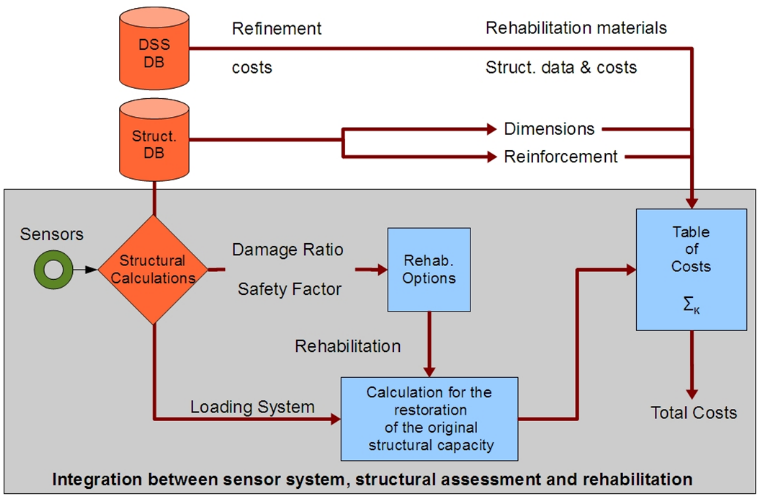

Figure 8. Procedural Flow Chart

In the case of an earthquake, this software accepts input from the software on seismic damage on the structural elements that have been damaged and their degree of damage. Based on the latter degree it presents common repair methods to bring the element to its pre-earthquake state (see Table 1 for repair techniques for light, moderate and severe damage).

The flow chart of the procedure followed in this software can be seen in Fig. 8.

The user selects one of the suggested repair methods for each damaged element and then the model estimates the cost to repair each element and sum it up to get the total direct structural repair cost.

The Integrated DSS

All of the above software was integrated in a DSS for proactive rehabilitation and rehabilitation following seismic damage.

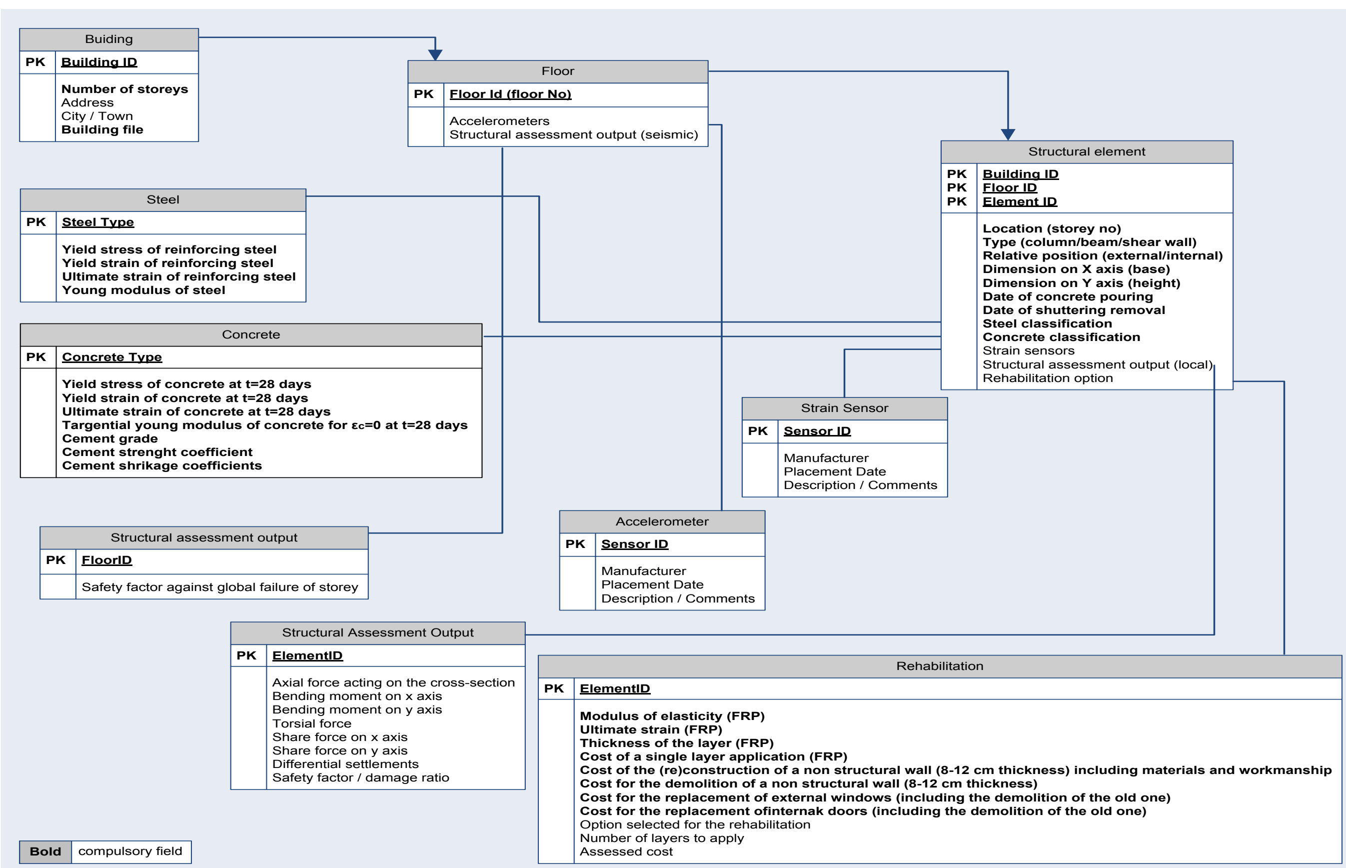

Figure 9. The Database Diagram

Development of the Software

This DSS also includes an expert system with a friendly user interface and knowledge and data DBs (see Fig. 4).

An overview of the database diagram can be seen in Fig. 9.

A graphical user interface provides the graphical environment with which the end-user can retrieve current and historical data from the DBs while also provides real-time alerts and warnings in case of unsafe situations and allows the end-user to examine different scenarios for hypothetical situations.

Fig. 10 shows a picture of the building as seen by the user. The various colours of the structural elements correspond to the various damage states (red for severe, yellow for moderate and green for light damage).

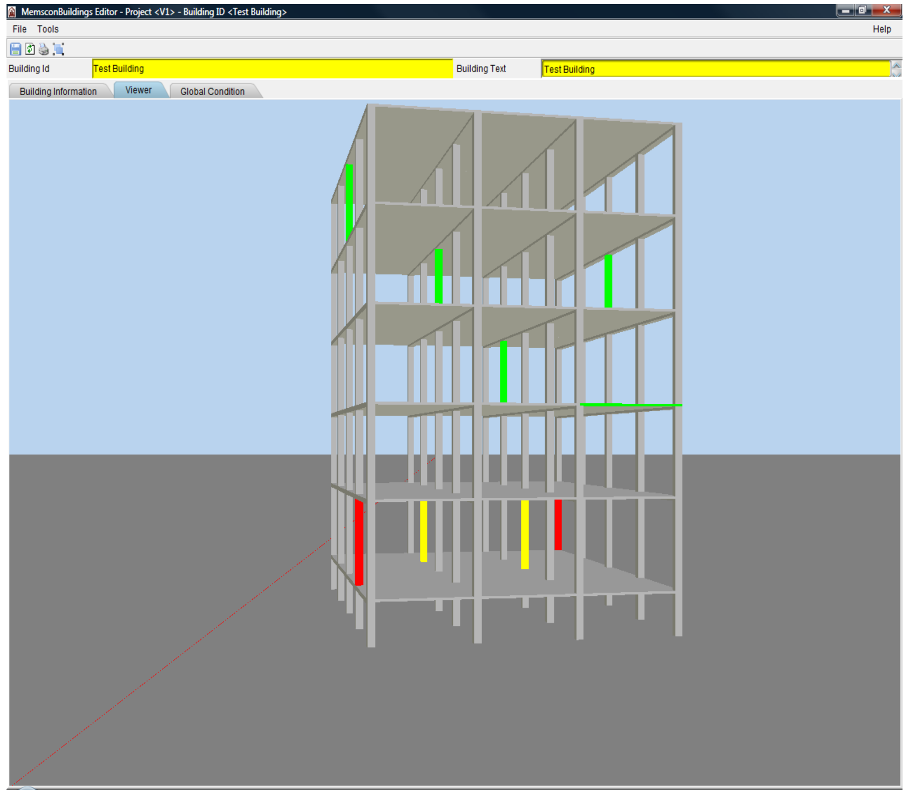

Figure 10. Picture of the building as seen by the user.

Workshop on Structural Monitoring and Assessment of Civil Engineering Structures

As part of a contractual obligation MEMSCON partners are organizing a workshop on Structural Monitoring and Assessment of civil Engineering Structures.

This workshop will take place on October 7, 2010 in Bucharest, Romania.

Local Organizer SITEX 45 SRL

Contact person, Dr Dumitru Ulieru (dumitru_ulieru@yahoo.com.hk, sitex45@gmail.com)

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Radio Frequency Identification Tags Linked to on Board Micro-Electro Mechanical Systems in a Wireless, Remote and Intelligent Monitoring and Assessment System for the Maintenance of CONstructed Facilities

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