Seismic Retrofitting of School Buildings of Cyprus

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SUMMARY:
The vulnerability of existing buildings to seismic forces and their retrofitting is an international problem. The majority of structures in seismic-prone areas worldwide are structures that have been designed either without the consideration of seismic forces, or with previous codes of practice specifying lower levels of seismic forces. In Cyprus, after the three earthquakes that occurred in 1995, 1996, and 1999, the Cyprus State, acting in a pioneering way internationally, has decided the seismic retrofitting of all school buildings, taking into account the sensitivity of the society towards these structures, which house the future generation of the society. In this paper the overall assessment methodology is presented, along with details of the over 10 year ongoing retrofitting program of the school buildings of Cyprus, with emphasis on the description of the program and the development of a wireless monitoring system.

Keywords: Seismic retrofitting, Schools, Monitoring, Existing structures

1. INTRODUCTION

Cyprus, being located on the boundary of two tectonic plates, the Eurasian and the African ones, has high seismicity. The boundary between the two plates is located in the sea on the south-west of Cyprus and is the source of a large number of earthquakes. Historical reports and archeological findings show that Cyprus was affected by strong earthquakes that in many occasions have destroyed its cities. Based on historical data there were 16 destructive earthquakes between 26 B.C. and 1900 A.C. Instrumental data have started being collected after 1896, when seismological stations started operating in neighboring counties. In the period from 1896 to 2004, more than 400 earthquakes, with their epicenters in Cyprus and the surrounding regions, were felt on the Island. From these, 14 caused damage, and some caused fatalities. The most destructive earthquakes in this period were those of 1941, 1953, 1995, 1996 και 1999. The study of the historical and recent earthquakes shows that there is an irregular seismic activity, with active seismic periods being followed by inactive ones. During the period from 1995 to 1999, an increase in the seismic activity was observed with strong earthquakes of magnitude ranging from 5.6 to 6.5 on the Richter scale being recorded.

Despite the recorded history of destructive earthquakes, the first seismic design measures in Cyprus were imposed after 1986 and the first seismic design code was introduced on a voluntary basis in 1992 and was made compulsory through a law in 1994. On January 1st 2012, all previous standards were withdrawn and were replaced by the Eurocodes, including Eurocode 8 for the design of seismic resistant structures. Therefore, the majority of structures have been designed without any seismic provisions, which increases their vulnerability to seismic loads. Schools, which are a subset of the building inventory, belong to a very sensitive category of buildings. The Cyprus State, acting in a pioneering way internationally, has decided the seismic retrofitting of all school buildings, taking into account the sensitivity of the society towards these structures, which house the future generation of the society. Any loss of life due to their seismic vulnerability will have unbearable consequences.

In this retrofitting program the schools have either been retrofitted, refurbished (and in most cases a combination of the two), or demolished. The structural systems of the existing schools in Cyprus are either reinforced concrete, load-bearing masonry, or a dual system. The total number of school buildings is 660. Of these, 26 were demolished and replaced by new ones at a cost of about 31 million Euros, 280 were retrofitted at a cost of 140 million Euros, 20 are now being retrofitted, 268 were considered as satisfactory and the rest are under evaluation. Therefore as of early 2012, about 90% of the school buildings of Cyprus are considered to be seismic resistant.

The school-building population has suffered various levels of damage from earthquakes that took place during their life-time. The physical damage due to time-effects and in many cases the lack of maintenance, deteriorated their load-bearing capacity. In addition, many schools were constructed before the introduction of seismic codes or designed with previous seismic codes and therefore they were not able to withstand the currently specified seismic loads. It was therefore recognized that many schools needed seismic retrofitting.

The effectiveness of this program is evaluated in an ongoing research project funded by the Cyprus Government and the European Regional Development Fund. This is done through a pilot application in which the cost-benefit method is used, adapted to local economic parameters, along with nonlinear structural analysis for the development of vulnerability curves, which will represent the condition of the structure both before and after strengthening, so as to make a first assessment of the school retrofitting project. In addition, an innovative wireless system of recording and analyzing signals is developed, which allows the in-situ recording of the dynamic characteristics of the structures in an effortless and affordable way, which will be the reference point for any future measurements. Finally, a life-cycle cost analysis methodology is developed that will allow the selection of the optimum level of future strengthening taking into account both technical as well as economic parameters, such as the up-to-date investment for the retrofitting of schools, the remaining life, as well as the maintenance cost of structural and non-structural elements (i.e. electrical and mechanical installations etc.).

In this paper the overall assessment methodology is presented, along with details of the over 10 year ongoing retrofitting program of the school buildings of Cyprus, with emphasis on the description of the program and the development of the wireless monitoring system. In the first part of the paper, the guideline that was used to assess the safety of school buildings is presented. Then, the school inventory is described along with the details of the retrofitting parameters, such as methodologies used, cost etc. This is followed by the description of the wireless system that was developed and finally with an overall outline of the methodology to be used for the evaluation of the program.

2. GUIDELINE FOR THE ASSESSMENT OF THE SAFETY OF SCHOOL BUILDINGS

Following the decision for the retrofitting of the school buildings, which was a repercussion of the 1999 earthquakes of Turkey, Greece and Cyprus, a Technical Committee was formed to develop a guideline for the “Assessment of the Safety of School Buildings” (Chrysostomou et al. 2000). The Technical Committee consisted of two members of the Scientific and Technical Chamber of Cyprus and two members of the Technical Services of the Ministry of Education and Culture of Cyprus. At the time that this program started there were no retrofitting codes available either in Cyprus or abroad. There where though guidelines, such as FEMA 273 (ATC 1997), which outlined concepts and methodologies to be used for retrofitting. These concepts and methodologies formed the basis for the development of the guideline for the retrofitting of the school buildings, the main provisions of which are outlined below.

The methodology followed was to establish the existing condition of the structure, select a safety level against which the structure was checked and make a decision for retrofitting measures to be taken, considering at the same time economic and social factors. In case that retrofitting was needed, strengthening measures were taken until the safety level was satisfied.

The establishment of the existing condition of the structure included data about the soil properties, environmental conditions that may affect the structure, as well as the seismic zone in which it was located. In addition, it was required to collect all the available architectural and detailing drawings, including design calculations, the determination of the location and sizes of structural and nonstructural elements and identification of the structural system, possible changes that took place during the lifetime of the structures and finally, the technical characteristics of the building materials and condition of structural members with visual inspection and selective in-situ, as well as laboratory testing.

The safety level selected was that of "Life Safety". In this level, conforming buildings may suffer extensive damage both in structural and non-structural elements. They may need repairs in order to become operational and the repair may be economically infeasible. The thread to human life in buildings satisfying the requirements of this safety level is low.

This safety level was associated with ground accelerations based on the then specified accelerations (they have increased with the introduction of the Eurocodes, as of 1st January 2012) in the Cyprus Seismic Code (CCEAA 1994). Taking into consideration the definition of the seismic action in this code, ground acceleration levels were specified for a design life of 10, 20 and 50 years with a probability of exceedance of 10%. For buildings retrofitted in full according to the Cyprus Seismic Code, a Peak Ground Acceleration (PGA) on rock for 50 years was used, while for those that are expected to be replaced in 20 or 10 years, a PGA for 20 or 10 years were used, respectively. These estimates, which are expressed in the form of PGA (A_{max}) on rock and are defined for the seismic zones of the Cyprus Seismic Code, are shown in Table 2.1.

Table 2.1. Peak Ground Accelerations per Seismic Zone (CCEAA 1994)

Seismic Zone	Peak Ground Acceleration, A_{max} (g)		
	Design Life 50 years	Design Life 20 years	Design Life 10 years
1,2,3	0.075	0.075	0.075
4	0.100	0.075	0.075
5	0.150	0.100	0.075

The design acceleration was specified using the design spectrum defined in the Cyprus Seismic code, which is described by the following two equations:

$$S_d = \frac{I \cdot A_{max} \cdot 2.5}{K} \quad \text{for } T \le T_1 \tag{2.1}$$

$$S_d = \frac{I \cdot A_{max} \cdot S \cdot 2.5}{K}\left(\frac{T}{T_1}\right) \quad \text{for } T > T_1 \tag{2.2}$$

where S_d is the design spectral acceleration, I is the importance factor, A_{max} is the peak ground acceleration defined in Table 2.1 for various design lives of the structures, S is the soil coefficient, K is the behaviour factor of the structural system, T is the fundamental period of the structure and T_1 is the corner period between the acceleration and the velocity regions of the design spectrum. It is specified in the technical guideline that the importance factor should be taken equal to 1.5, while the behaviour factor should be equal to 2.0 and 1.5 for infilled reinforced concrete frames and load-bearing masonry structures, respectively. The latter two values can be changed if adequate justification is presented.

The above apply to all types of structures while the acceptance criteria are specified for each of the two types of materials used for the construction of schools, namely, reinforced concrete and masonry.

For the reinforced concrete it is specified that the mean concrete cylinder strength should be larger than 10 MPa and that none of the specimens should have strength less than 8 MPa. The number of specimens is specified as one specimen per two classrooms with a minimum number of 6 specimens per floor, for each independent part of every wing, for every building or group of buildings. If the above limits are not satisfied then further specimens should be taken. Regarding reinforcement it is required that the diameter loss is restricted to 15% and that the yield strength should be no less than 220 MPa. In case that there is severe rusting it is required that the reinforcement is replaced. It is also required that the contribution of infill walls is taken into account with a conservative estimate of the compressive strength of hollow bricks bonded with mortar to be taken as 1.8 MPa and the corresponding shear strength to be 0.9 MPa. Chemical analyses are also required to establish the level of carbonation, as well as the presence of chlorites and/or sulphates.

Acceptance criteria are also specified for member forces and interstory drifts. The former are satisfied if checked against the provisions of the Cyprus Reinforced Concrete Code (CYS 159), now replaced by Eurocode 2, and the latter by checking against 2% for recoverable drifts, or 1% for unrecoverable ones. At least two load combinations are used shown below:

$$1.35G + 1.5Q \tag{2.3}$$

$$1.00G + 0.5Q + E(G + 0.5Q) \tag{2.4}$$

where G is the permanent load, Q is the live load specified equal to 3 kN/m^2 and E is the earthquake load.

Of utmost importance are the economic criteria that are specified, which state that if the cost of retrofitting exceeds one third of the replacement cost of the specific structure, then the decision for retrofitting is taken by a technical committee that consists of the designer, two governmental engineers, a representative of the Director General of the Ministry and a member of the School Board. The purpose of this committee is to decide whether to proceed with the retrofitting or decide for the school demolition and its replacement.

Both the equivalent-static and response spectrum methods are allowed to be used for the analysis of the structures. In both cases, infill walls should be modelled either with two equivalent diagonal bars, or surface finite elements. Nonlinear methods are also allowed to be used. Several methods are suggested to remove any deficiencies that increase the vulnerability of buildings such as removal of eccentricities, soft stories, short columns, disconnected stairwells, beam supported columns etc., or through the introduction of new structural elements, such as frames or structural walls. These measures can increase the stiffness as well as the strength of the structure, or both. The reduction of the mass, whenever possible, is also suggested, as well as local interventions on an element by element basis. Some suggested methodologies are the use of reinforced concrete (R/C) jackets, R/C walls or carbon fibres.

Similar provisions are given for load-bearing masonry structures. Due to the fact that the majority of these structures are single-story ones, special conditions are provided that whenever satisfied the structure is deemed to satisfy the acceptance criteria. These conditions are related to the length of solid walls per direction of the structure, the absence of cracks on the walls and the integrity and thickness of the load-bearing walls. Because of the difference of construction relative to the reinforced concrete ones, and the sensitive nature of such structures (which are considered as part of the cultural heritage), the methods suggested for retrofitting them are different than the ones described above for reinforced concrete structures. The use of injections and/or pre-stressing tendons, the construction of a ring beam, as well as the pointing of the joints, are the main methods proposed in the guideline. In addition, special care is taken for the introduction of diaphragmatic action, so as the seismic forces are shared by all the load-bearing walls.

3. COLLECTION OF DATA FOR THE RETROFITTING OF THE SCHOOLS IN CYPRUS

In order to assess the effectiveness of the program, a data collection was performed, in order to obtain the details of the building inventory and the methods that were used for the retrofitting of schools. This was a very laborious task since to obtain these data one had to look into the records kept in paper form by the Ministry of Education and Culture. It was impossible to check every single folder; therefore the data presented here cover the majority of the schools for the period up to the end of April 2011.

Since vulnerability and cost/benefit analysis will be used for the assessment, a number of parameters were defined and collected during this operation, which will facilitate the assessment. These are: 1) the number of buildings each school consists off, since they may consist of different structural systems and may have different ages, 2) the year of construction, including the starting and finishing date of the construction, which is related to the design code used and consequently the design accelerations, 3) the structural system of each school, 4) the height of each building, 5) the type of intervention, which may include seismic retrofitting, strengthening, or refurbishment (such as changing of tiles, painting, upgrading of electrical and mechanical installations, etc.), or even expansions to cover new needs of the school, 6) method of intervention based on the guideline presented in the previous section, which includes jackets, structural walls, carbon-fibres, steel elements, or mixed methods for RC buildings, and construction of ring beams, replacement of masonry elements, strengthening or replacement of roofs for masonry structures, 7) the acceleration that was specified for the design/retrofitting of the structures, 8) the service life that was used as described in Table 2.1, 9) the remaining life of the structure, 10) the material properties of the structure before any intervention, 11) the results of chemical analyses, if any, 12) the retrofitting cost that covers only the cost of the intervention on the structural system, which in this case it was very difficult to be identified since it was mixed with the cost of other simultaneous interventions in the school building, and 13) the replacement cost, which is defined as the cost for building a new school.

3.1. Analysis of the Data

As of early 2012, 280 schools have been retrofitted with 20 being in the process of being retrofitted, while another 26 were demolished and replaced. As it was mentioned before, it was not possible to have access to all the folders kept by the Ministry of Education and Culture, therefore, the data presented below refer to the recorded data for 117 schools all over Cyprus. Even for these schools, the 13 parameters mentioned above were not always possible to be recorded, since they were missing from the records, therefore some of the graphs presented below correspond to a subset of these schools. For each graph the sample size is indicated for easy reference.

As it is shown in Fig. 3.1., 68% of the school buildings in Cyprus are made of reinforced concrete, 22% is a dual system consisting of reinforced concrete and masonry, and 10% are made of masonry.

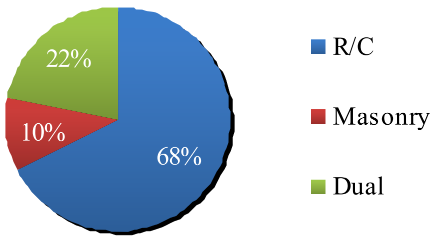

Figure 3.1. Structural system of school buildings (sample: 105 schools)

Of these, 73% were built before 1986, 12% between 1986 and 1992, and 15% after 1992 (Fig. 3.2.). The significance of these dates is that before 1986 all structures in Cyprus, including schools, were designed for gravity loads only, without any provisions for earthquake loads. In 1986, the first guidelines for seismic design were introduced followed by the introduction of the 1st Cyprus Seismic Code in 1992, which was made compulsory in 1994. It is therefore clear that only 15% of the schools were designed for seismic loads, while another 12% were designed using the guidelines. This made the need for upgrading the schools for seismic loading imperative.

For 50% of the buildings, upgrading, strengthening and maintenance operations were undertaken (Fig. 3.3.) while for only 8% it was required, in addition to the above, to make expansion of the school and upgrading of the electrical and mechanical installations.

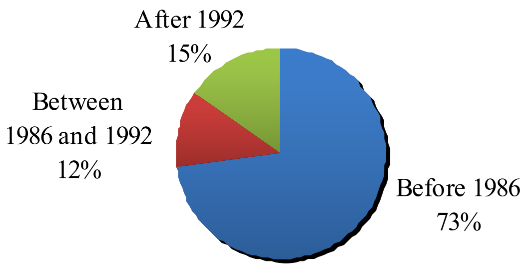

Figure 3.2. Period of construction of school buildings (sample: 111 schools)

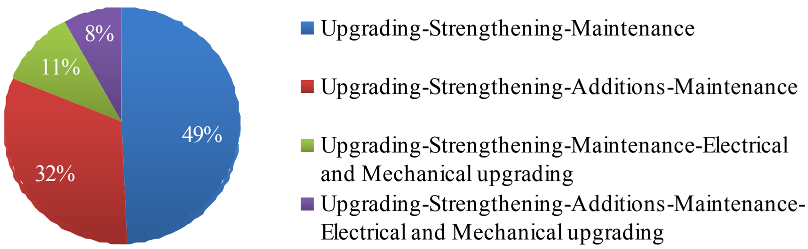

Figure 3.3. Type of intervention in school buildings (sample: 111 schools)

Another very important parameter that had to be decided was the selection of the design life (Table 2.1), which had an effect on the acceleration for which the schools were going to be designed for. As it is shown in Fig. 3.4, 79% of the schools were designed for a 20 year remaining life, 19% for a period of 50 years while only 2% for a period of 10 years. Hence, based on this graph, the majority of the school buildings will need to be re-assessed in about 10 to 20 years from now.

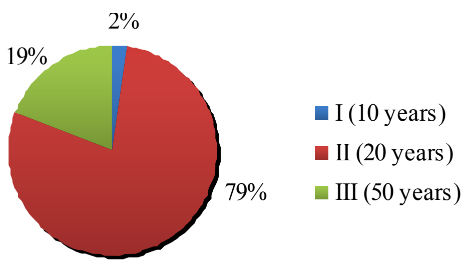

Figure 3.4. Service-life of school buildings (sample: 47 schools)

The strengthening cost of school buildings is shown in Fig. 3.5. Although special care was taken to include only the strengthening cost excluding maintenance or other costs, these numbers may include some of these costs. It can be observed from Fig. 3.5 that the strengthening cost for 14% of the schools was either between 75.000 – 125.000 Euros or between 475.000 – 525.000 Euros. The mean value of the strengthening cost was 483.667 Euros. To get an idea of the level of the additional costs, it is noted that the Contract Value (total cost of construction) varied from 75.992 Euros to 2.120.711 Euros.

The replacement cost is shown in Fig. 3.6 in which it is indicated that 65% of the schools have a replacement value of up to 500.000 Euros, with another 22% in the bracket of 500.000 and 1.000.000 Euros. This is a very important value, which was used to make the decision for strengthening or not as explained earlier.

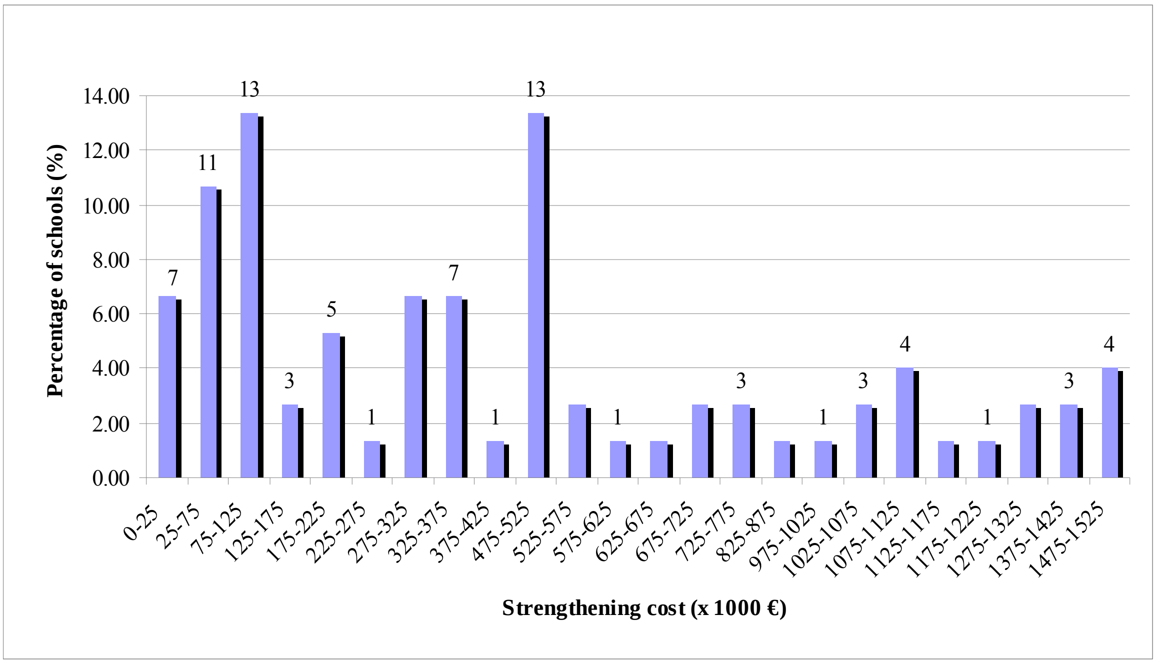

Figure 3.5. Strengthening cost of school buildings (sample: 75 schools)

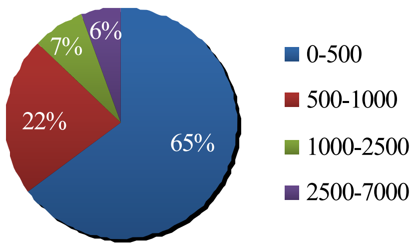

Figure 3.6. Percentage of schools per replacement cost bracket (x1000 €) (sample: 109 schools)

The next five graphs present data regarding the methods of strengthening used. When R/C jacketing was used as a strengthening method (Fig. 3.7), it was mainly applied to columns (79%) and to a lesser extent to other structural members. When structural walls were used as a method of retrofitting (Fig. 3.8.), in the majority of the cases new ones were constructed (80%), while in 16% of the cases existing columns were converted into walls. In only 4% of the cases external infill walls were partially replaced by R/C walls.

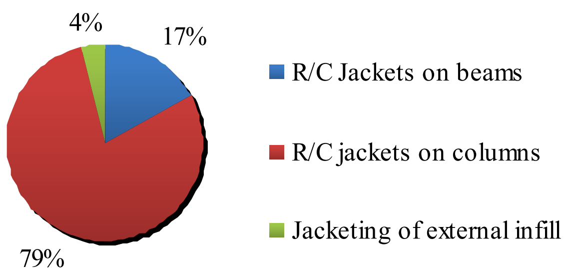

Figure 3.7. Retrofitting with R/C jackets (sample: 53 schools)

For 11 schools in the sample there was a need for retrofitting the foundation (Fig. 3.9). In 37% of the cases a new foundation was required, while strengthening with additional reinforcement or with R/C jackets was required for 27% of the cases, respectively. For 9% of the cases the foundation was not according to the original drawings and it had to be altered so as to meet the design.

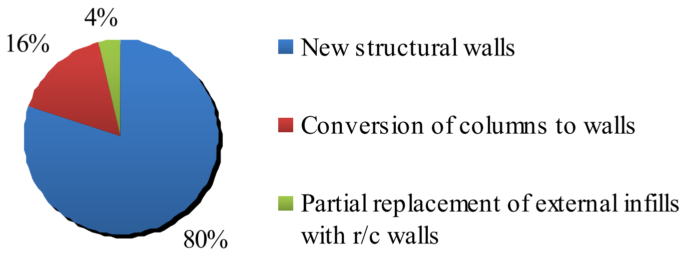

Figure 3.8. Retrofitting with R/C structural walls (sample: 25 schools)

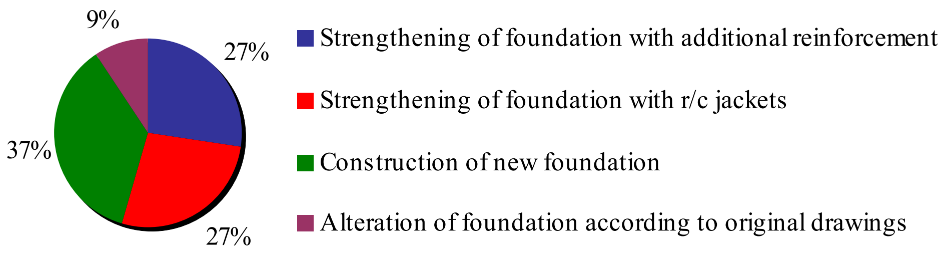

Figure 3.9. Retrofitting of foundations (sample: 11 schools)

The methods used for the retrofitting of columns are shown in Fig. 3.10. In 74% of the cases columns were strengthened using R/C jacket, while in 14% of the cases FRPs were used. In the rest of the cases either the shear or the column reinforcement was increased. For the case of beams (Fig. 3.11) in 31% of the cases R/C jackets were used, while in 50% of the cases FRPs were used, either in the form of wraps (7%) or in the form of strips (14%) with the rest 29% not identified specifically.

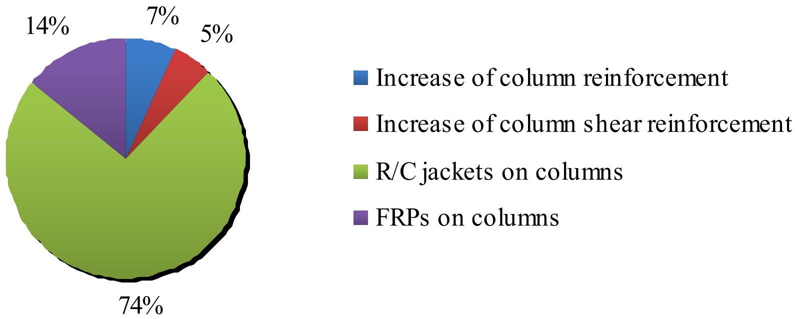

Figure 3.10. Method for retrofitting columns (sample: 57 schools)

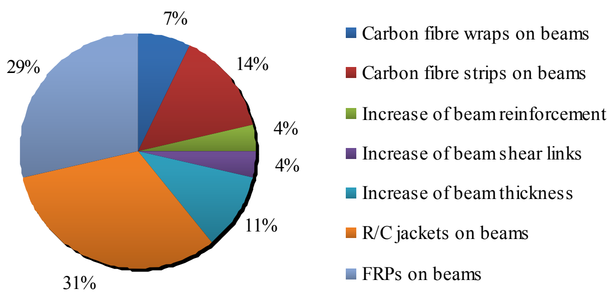

Figure 3.11. Method for retrofitting beams (sample: 20 schools)

4. DESCRIPTION OF THE WIRELESS SYSTEM DEVELOPED

An innovative wireless system of recording and analyzing signals has been developed within this research project that will allow the in-situ recording of the dynamic characteristics of the structures in an effortless and affordable way, which will be the reference point for any future measurements. Any changes in their period of vibration compared to this benchmark will signify the need for a detailed investigation for locating the sources of any possible problem.

The whole system developed by the partner of the project SignalGeneriX consists of two independent subsystems (Fig. 4.1): the first one on the left of the figure is the personal computer on which the developed graphical unit interface (GUI) is running, and the second one is the wireless sensors system, which consists of the data-processing unit, the data-acquisition unit and the selected accelerometer (or other) sensors. The received data are stored in a database which is located in the data-processing unit. The communication between the two subsystems is achieved through Wi-Fi that provides adequate bandwidth for efficient data transfer.

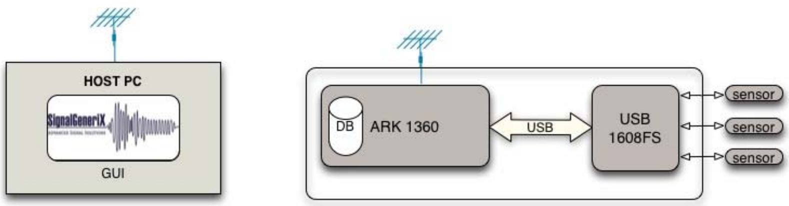

Figure 4.1. Wireless system

The main innovation of this wireless system compared to similar systems lies in the fact that it can be used for recording and wirelessly transmitting signals from ambient vibrations. This requires a series of specific characteristics that are very demanding for such a system. The minimum requirements for both the sensors and the data acquisition unit have been defined by the research team taking also into account the need to have a scalable system that could integrate any kind of different sensors for future extended investigations. For the accelerometer sensor the minimum requirements specified were: sensitivity 500 mV/g, range ±2g, bandwidth DC – 100 Hz, noise 10 mg rms, and supply current to be less than 50 mA. An accelerometer was used that meets all these minimum requirements and has a range of ±4g and a supply current of 3 mA. For the data acquisition unit the minimum requirements were: 8 single-ended channels, 3 differential channels, input ranges of ±2.5, ±5, ±10 V, sampling frequency per channel 50 samples per second and resolution 16 bits. The data acquisition unit used meets all the above specification and it has 4 differential channels, additional input ranges of ±0.625 and ±1.5 V, and a sampling frequency of 50,000 samples per second.

The system is now undergoing testing and will soon be used for the recording of data on the schools selected for the pilot application, so as to establish the dynamic characteristics of the structures. The system can be extended in the future to record parameters such as carbonation and oxidation (when the accuracy and reliability of such sensors is improved) that will allow the application of corrective measure before the effects of these parameters become visible. It is the wish of the Technical Services of the Ministry of Education and culture to install such systems on as many schools as possible, so as to have the capability of remotely monitoring the structural behaviour of their structures and be able to take corrective measures in due time.

5. OVERALL METHODOLOGY FOR THE EVALUATION OF THE SCHOOL RETROFITTING PROGRAM

It has been decided that the methodology for the assessment of the strengthening project of the school buildings be based on the benefit-cost analysis, since it allows the quantitative assessment of the strengthening methods applied to the building. For the application of this method vulnerability curves are needed for the development of which a hybrid approach will be used (Kappos et al., 1988 and

2006) that combines the available empirical data of seismic damage with nonlinear analyses of appropriate models. Furthermore, the definition of the seismic hazard of the area under study and a series of economic data concerning mainly the cost of buildings (construction and strengthening) is required (Fig. 5.1). To this end, the collection of data described in section 3 will be invaluable. The vulnerability curves, that consider both the condition before and after the strengthening, taking into account the possibility of alteration of the structural system due to the strengthening measures taken (e.g. from frame to frame-wall system), will be developed in a pilot study for a standard reinforced concrete and a corresponding load-bearing masonry school building. Finally the benefit-cost ratios will be calculated and in this way the effectiveness of the retrofitting, which is based on real cost, will be assessed.

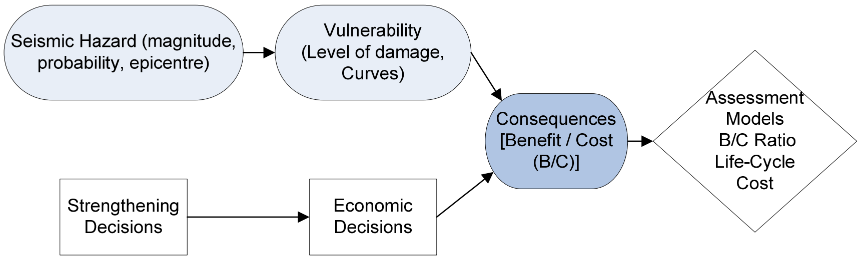

Figure 5.1. General outline of the benefit/cost analysis

In order to make possible the future strengthening of school buildings, the life-cycle analysis method will be developed, which facilitates the selection of the optimum level of future strengthening. Apart from the economic data that will be obtained from the cost/benefit analysis described above, it will be required to obtain the operational and maintenance costs, which will be provided by the Technical Services of the Ministry of Education and Culture of Cyprus. It is underlined that this analysis is superior to the standard benefit-cost analysis, in that it allows the estimation, not only of the optimum level of strengthening, but also the optimum time interval for the strengthening. For the determination of the optimum level of strengthening the development of different vulnerability curves for each type of retrofitted structure is required.

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