Information Systems for Repair Alternatives and Initial Cost Estimation of Damaged Building Structures

Can Balkaya*‡

*Department of Civil Engineering, Faculty of Engineering and Architecture, Nişantaşı University, Istanbul, Turkey.

(can.balkaya@nisantasi.edu.tr)

‡Corresponding Author; Can Balkaya, Department of Civil Engineering, Nişantaşı University, Istanbul, Turkey,

Tel: +90 212 210 1010, Fax: +90 212 210 1010, can.balkaya@nisantasi.edu.tr

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Abstract- The evaluation of existing structures for repair and strengthening results in the application of the most economical and effective repair techniques. The main focus is the existing buildings in seismic areas. The method of repair or strengthening depends on the damaged structural system, structural (life safety) issues, applicable seismic building code requirements, restrictions in available methods, and architectural and construction requirements. The consideration of new techniques, previous technical information on repair methods, experience of experts, and updated cost information are important in the evaluation. The most cost-effective schemes cannot be determined by choosing the most economical means to repair each component; an integrated approach is necessary. Also, recently the use of computers and networks to share the information are increasing. A knowledge-based information system has been developed for the integrated solutions. The level of damage is determined from the damage and structural information. In the evaluation, major damage conditions are grouped as ground damage, foundation damage and superstructure damage, and then these groups are divided into subgroups. Each repair method is represented by a specific format to determine the damage information index. The developed software is a self-modifying and learning system as a result of the data stored for common types of damaged buildings. The use of information systems results in rapid and effective initial cost estimation of repair methods.

Keywords Earthquake damage, Repair methods, Information systems, Building structures

1. Introduction

The main purposes in an earthquake damage evaluation are the correct determination of damage conditions and the level of repair, and the correct application of repair methodology and current techniques. The repair evaluation results in the application of the most economical and effective repair techniques considering life safety and structural issues according to code requirements. The damaged member can be repaired so that it provides service to the structure equivalent to that before the earthquake. However, this repair oversimplifies the minimum requirement for repairing most structural earthquake damage, since code changes and seismicity issues make this task much more complex. The structural engineer is responsible for the repair or retrofitting of the damaged building according to current codes and life safety requirements.

The evaluation and retrofitting of existing structures for seismic behaviour have recently focused on ASCE [1], and Japanese and Turkish research studies [2]. Current earthquake codes generally require higher earthquake forces than earlier ones. For this reason, there is a need for some additional codes to be applied for existing structures depending on their importance and functions of the structures such as residential buildings, hospitals, fire stations, schools, and historical buildings, etc. There are some guidelines for the seismic evaluation and seismic capacity, and retrofitting of existing buildings, ASCE [1], ATC-21 [3], Ohkubo [4]. Approaches for the evaluation of existing buildings that could be different than the code requirements to be applied for new constructed building structures have been discussed by Balkaya [5]. Approaches and research needs for the assessment of existing structures have been emphasized by Melhechers [6].

In addition to code issues, the most cost-effective repair schemes cannot be determined by choosing the most economical means to repair each component, but rather by applying an integrated approach to this evaluation. In the present study, a knowledge-based information system has been developed for the evaluation of earthquake damaged buildings. Major damage conditions are grouped as aesthetic, functional and structural damage, or a combination of these. The preferred checklist of applicable schemes for the repair evaluation is prepared in table form in a cost effective and level of strengthening order.

2. Evaluation of Damage Conditions

Damage conditions are divided into three main groups: ground damage, foundation damage, and superstructure damage. Then each group is divided into progressive subgroups as shown in Fig. 1. Each specific repair method is defined by using five group numbers (**D-GM-SL-MC-SMN**). From Fig. 2 these group numbers are for Damage (**D**) as G (Ground Damage), F (Foundation Damage), S (Super-structure Damage) or R (Removal and Replacement); General Method (**GM**); Specific Location (**SL**); Material Code (**MC**); and Specific Method Number (**SMN**). Damage conditions are considered for the evaluation of repair methods with their group numbers.

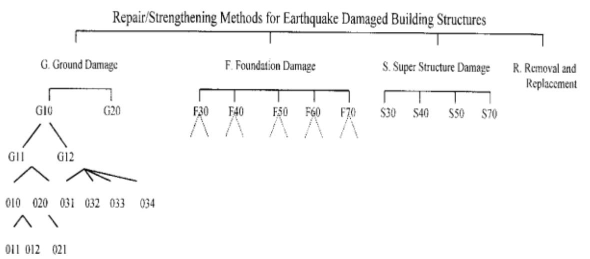


Fig. 1 Group numbering of repair methods

As an example, let S stand for the repair evaluation of superstructure damage. The general method expand number 40 is for the retrofitting method. Thus S40 is the retrofitting of the superstructure damage. If the superstructure damage is in the columns then using the specific location number 40 for column, the damage index becomes S40-40-…-…. For column strengthening by using reinforced concrete, the material code and specific method numbers are 20 and 210, respectively. Therefore, the damage index for a column strengthening method is S40-40-20-210. A typical screen for the developed system is shown in Fig. 2.

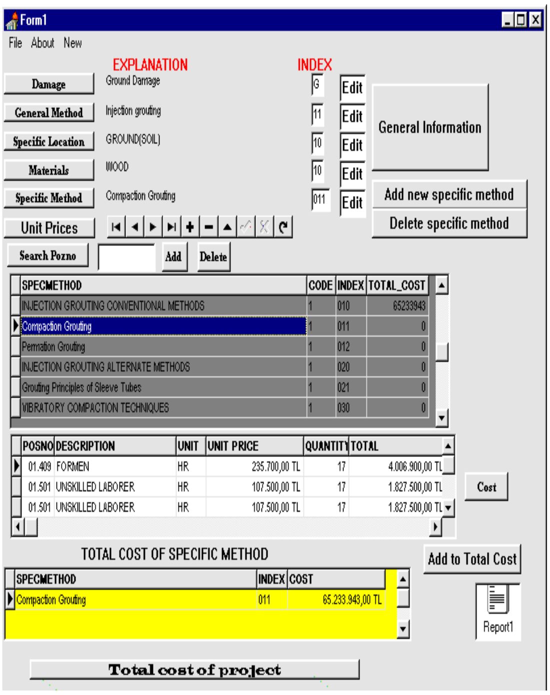


Fig. 2 Group numbering of repair methods

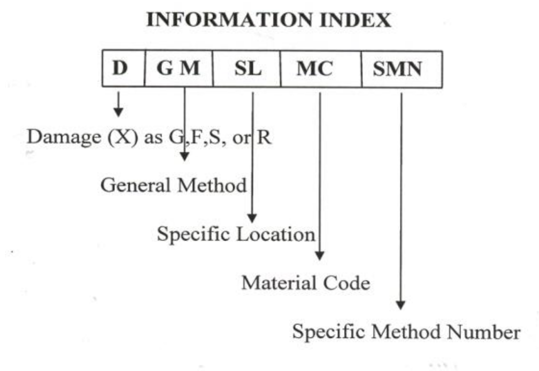


Fig. 3 Specification of repair methods

2.1 Determination of Level of Repair

The determination of the nature of the earthquake damage is important for damage evaluation. Thus for selecting repair methods, the condition assessment plays an important role in determining the distress level of a damaged building. Condition Assessment steps for the earthquake damage buildings are as follows:

Step 1. General Information about the Damaged Building: plan view, type of structural system, irregularities in plan and section, number of floors, type of floor system, foundation systems, construction joints with neighbouring buildings, type and quality of construction materials, wall indices (wall plan area on one floor to total floor area, etc.). An example of general information sheet used in the developed program about the investigated building is shown in Fig. 4.

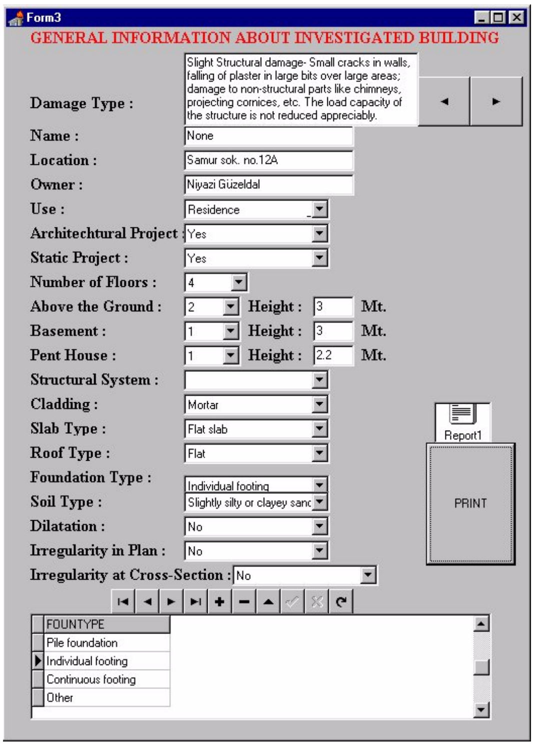


Fig. 4 General information about the investigated building

Step 2. General Damage Categorization: Damage conditions are categorized as structural and nonstructural. Structural damage state ranges from cracking to collapse of structural members. However, nonstructural damage is a result of deflections or cracking of secondary elements such as brick walls. Damage ranking is done according to the level of damage depending on the structural function, location, crack size and type of cracks.

Damage ratings of buildings are calculated considering all structural and nonstructural members such as columns, beams, shearwalls, floor systems, footings and non-structural members. Using the damage rating information in the databases, final ratings are evaluated as no damage, or slightly, moderate or heavily damaged buildings. This information is used to determine the level of repair/strengthening for selecting repair methods.

Building codes or repair guidelines may affect the level of repair. A damaged structure may require strengthening above its pre-earthquake condition due to these additional requirements. The strengthening of existing buildings using current codes is another issue, especially if they were designed according to earlier codes. The knowledge-based program can be used by considering the level of repair/ retrofitting obtained from damage ranking and wall indices without performing any structural safety evaluation. However, the final repair or retrofitting of the structural system depends on structural analyses and design, and must satisfy the current building/earthquake code requirements. Currently, FEMA 274 [7], ASCE [1], UBC [8] (for new constructed building structures), and Turkish Earthquake Codes [9] are considered in the seismic design.

3. Seismic Performance Evaluation

Seismic performance of the investigated buildings for illustration purposes can also be estimated based on the previous investigated data according to wall indices before performing structural safety evaluation. Total area of the walls in the construction area of the plan in both x and y directions separately as wall indices can be obtained by using 'Shiga's Graph' in Fig.5 taken from the Progress Report on Damage Investigation after 1999 Kocaeli Earthquake conducted by Architectural Institute of Japan [2]. Wall indices are the sum of horizontal sectional area of columns (Ac) and the shear walls (Aw) in the first floor. The weight of the building (W) was calculated from sizes of beams, columns, slab, and arrangement of partition walls. If the data were not available, it was assumed that to be 8 kN/m^2 with non-structural elements.

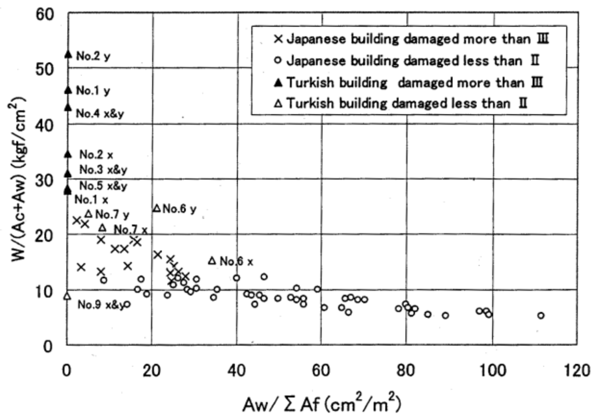


Fig. 5 Shiga's Graph

The marks plotted with 'x' or 'o' in the figure express the Japanese buildings suffered heavy damage or slight damage in 1972 Miyagiken-oki Earthquake respectively. Similarly, 'Δ' and 'Δ' express the Turkish buildings heavy or slight damage in 1999 Kocaeli Earthquake respectively. Buildings plotted in the upper left zone of this graph are judged to have relatively low seismic performance.

The seismic evaluation of 160 branch buildings either belonging to or rented by a commercial bank in Turkey was investigated by Middle East Technical University (METU) after 1999 Turkish Earthquakes. The seismic performance of buildings were initially assumed from the wall indices in both x and y directions. Different than the moderately damaged buildings, in this research, wall indices are calculated for the nondamaged existing building structures as for x-direction: (Shearwalls in x-direction + 0.50 x Column Area in x-direction + 0.10 x Brick Walls Area in x-direction)/Total Building Floor Area. Wall index in y-direction is calculated similarly. In addition to these indices, structural analyses were performed according to Turkish Earthquake Code [9] as an aid to judging the structural capacity.

Capacity spectrum of existing structures are considered [10], with different level of safety [7]. 3-D effects and collapse mechanism are studied in the structural configuration considering existing damaged structural elements and material properties. The main purpose is to see the possible collapse mechanisms to satisfy the minimum code requirement for the life safety.

4. Knowledge Based Information Systems

Information systems are not limited to the accumulation of new methods. This also involves relating something new to what we already know. Domain knowledge is obtained partly from conventional sources; that is textbooks, research papers, reference manuals on repair alternatives [11] and field experience from previous earthquakes. Knowledge based information systems is probably the most time-consuming activity in the evaluation of damaged buildings with an integrated approach.

Knowledge based information has been used to find the appropriate integrated solutions, or minimum solutions satisfying the constraints. The constraints in the evaluation of repair alternatives are the available funds, the minimum level of repair, restrictions in the method, building code requirements, availability of materials and skilled labour, construction requirements and construction time. Integrated solutions are necessary for effective solution methods.

As an example, evaluation of the treatment methods for soils under foundations (G10) is given in Table 1. Similarly, improvement methods and their evaluations for embankment and slope stability (G20) are shown in Table 2. Improvement methods are considered such as in-place soil strengthening, geometric changes and replacement of soil, retaining reinforcement, drainage improvements, and in-place compaction.

Table 1. Evaluation of treatment methods for foundation

	Treatment Methods
	Injection Grouting Techniques
	— Conventional Methods
G11-10-00-011	— — Compaction grouting
G11-10-00-012	— — Permeation grouting
	— Alternate Methods
G11-10-00-020	— — Grouting principles of sleeve pipes
	Vibratory Compaction Techniques
G12-10-00-031	— Dynamic compaction
G12-10-00-032	— Deep dynamic compaction/ or dynamic consolidation
G12-10-00-033	— Vibro compaction
G12-10-00-034	— Vibro displacement

Cost Increasing; Level of Strengthening

Table 2. Evaluation of improvement methods for embankment and slope stability

	Improvement Methods for Embankment and Slope Stability
	In-place Soil Strengthening Procedures
G21-10-00-041	— Chemical grouting
G21-10-00-042	— Intrusion grouting
	Geometric Changes and Replacement of Soil Shapes
	— Geometric changes
G22-10-00-051	— — Flattening slope
G22-10-00-052	— — Removing some of the soil
G22-10-00-053	— — Construction berm/butress at the toe of the slide
	— Compacting soil with/without additives
G22-10-00-061	— — Lime/cement
G22-10-00-062	— — Geosynthetics
G22-10-00-063	— — Superlight materials
	Retaining Reinforcement for Embankments of Slopes
	— In-ground column and wall techniques
G23-10-00-071	— — Jet grouting columns and panels
G23-10-00-072	— — Mixed in-place lime/cement columns
G23-10-00-073	— — Soil doweling
G23-10-00-074	— — Driven in-piles
	— In-place reinforcement procedures
G23-10-00-081	— — Soil nailing
G23-10-00-082	— — Ground anchoring
G23-10-00-083	— — Rock bolting
	— Retaining walls for embankment and slope stability
	— — Cantilever-type walls
G23-21-00-091	— — — Tie-back wall
G23-21-00-092	— — — Soldier beams
G23-22-00-090	— — Gravity walls
G24-10-00-095	Drainage Improvements
G25-10-00-096	In-place Compaction

Cost Increasing; Level of Strengthening

The computer software has been written for the evaluation of earthquake damaged building structures. The flowchart in Fig. 6 shows the main steps. In this flowchart, the first step is the determination of the structural and damage information in the field. The level of repair is to be estimated by using damage ranking information, and structural information. Note that all this information are obtained in the field work. By using knowledge based information system databases the level of seismic performance has also been estimated. The next step is to select the repair/retrofitting method by using the built-in database of the program according to the level of repair and cost information. The program lists the repair methods in a cost effective-way with their relative level of strengthening. The computer software also evaluates the cost of the repair method by interacting with current cost databases in the evaluation of repair methods. Structural analyses have been performed externally in the final preparation of design calculation and projects. The last step is to select the most appropriate and economical repair methods among the integrated paths.

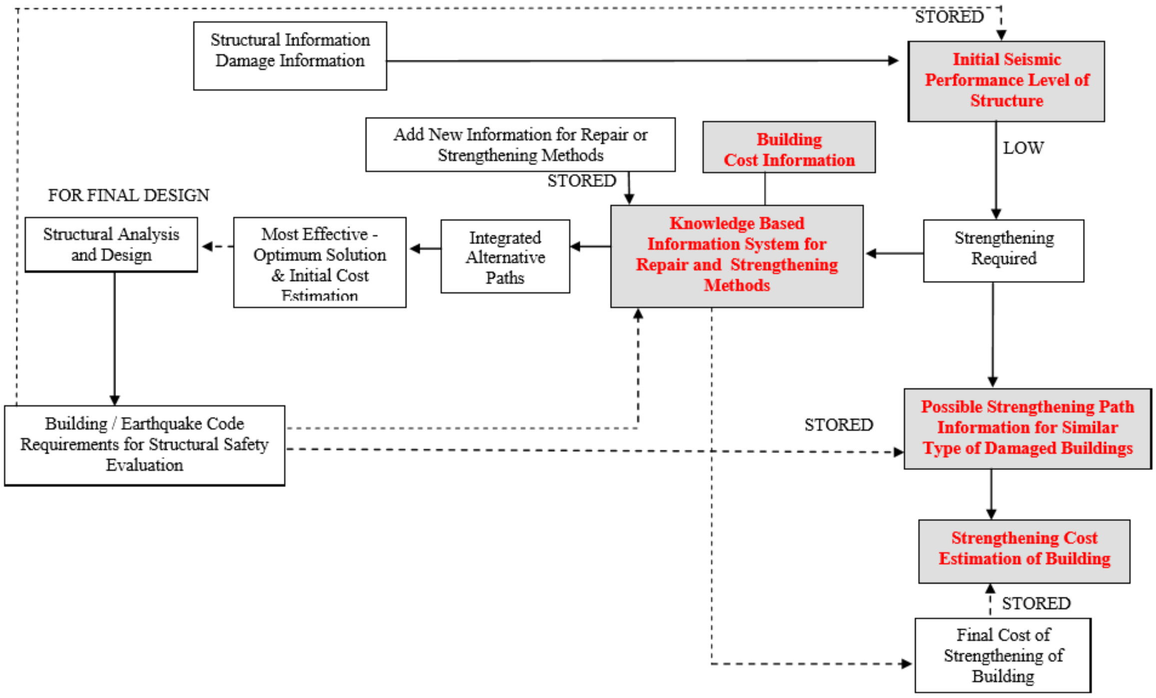


Fig. 6 Evaluation of earthquake damaged building structures

5. Integrated Approach

In the integrated approach, the selection of the most appropriate repair methodology depends on economics and minimum code requirements. An effective solution is obtained considering the optimum solution between the level of strengthening and economy satisfying at least the minimum code requirements or required level of risk considering life safety. However, there will be some problems related to construction techniques and construction equipment, existing architectural constraints, environmental effects, and existing foundation systems. Because of these problems, a particular repair method has not been considered in the integrated path solutions.

5.1 Cost Estimation

Accurate estimate of cost requires the availability of reliable cost and performance data. Considering existing and new construction methods and materials, cost estimation becomes difficult when considering different possibilities. In addition, labour and material costs keep changing. Thus, cost data is collected and organized into a format that makes the cost information instantly accessible through computers. On the other hand, the available old cost information of a repair method has to be taken the basis for a new rapid estimate by considering inflation rates. In this study, Means Building Construction Cost Data [12], and the Turkish Ministry of Public Works Unit prices [13] are used as cost databases. The software gives the total repair costs of building according to available integrated paths by using the latest unit prices. Detail cost estimation has been evaluated by entering quantity, labour, equipment, etc. Once the analysts establish detailed description of the repair method to be undertaken, then for new cases, the repair cost of that method has been determined only changing some quantities rather than working on the task of the method.

The emphasis in the following case study is how to estimate the total repair/retrofitting cost of similar types of damaged building structures by using stored path information. In this case study, 92 reinforced concrete buildings moderately damaged after the 27 June 1998 Adana-Ceyhan Earthquake with different number of floor levels and total construction area ranging from 500 m^2 to 7000 m^2 were studied. These buildings are mostly in earthquake region I (highest earthquake hazard region) in Turkey, and retrofitting projects were prepared by METU. In the retrofitting of the buildings, the retrofitting methods are similar such as column jacketing by using steel, infilled shearwalls inside the reinforced concrete frame, and epoxy injection. Depending on the damage level of the building infilled shearwalls were replaced, amounting to 1-1.5 % of the building basement floor area. Total repair costs corresponding to the selected final integrated path are shown in Fig. 7. Depend on structural type, percentage of infilled wall area, type and level of strengthening, earthquake region, repair cost could be estimated the data stored by using the correlation as shown in Fig. 7. This cost only includes the structural retrofitting cost calculated from structural retrofitting projects. The cost of architectural repair after structural retrofitting and taxes are not included.

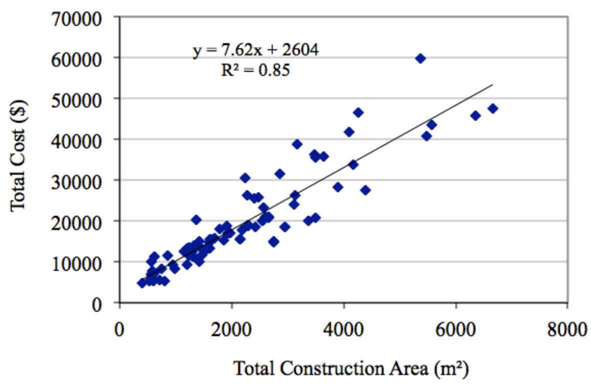


Fig. 7 Repair cost estimation for moderately damaged R/C buildings

5.2 Structural Safety Evaluation

The main objectives for the safety evaluation are to prevent a total collapse of the building or some of its parts, and minimize the danger to life safety as well as avoid financial losses. Structural analyses can be performed before and/or after as a part of the repair alternative evaluation depending on the engineering recommendation for initial rapid cost estimation. The structural configuration, structural type, and the damage level of the building, existing soil and material properties are parameters in the rapid structural safety evaluation. In the final decision, the selected alternatives have been rated to satisfy code requirements. Therefore, structural analyses are performed by using SAP90 [14] finite element analysis program. If the building is designed according to former design codes, the level of damage is determined by first analysing the existing building with current code requirements, and considering seismic performance, capacity spectrum and collapse mechanisms for live safety. Seismic performance, structural capacity, allowable stress levels, drift limitations, and other code requirements have been checked. If retrofitting is necessary, then the retrofitted building is reanalysed by using SAP90 or any general purpose structural analysis program.

There are many repair methods for strengthening the existing structural system. If the damage ratings of the building were moderate or heavily damaged, general structural system strengthening can be preferred rather than repair of the many individual load carrying members (reducing their force levels). For structural system strengthening, shear walls may be added as infilled walls inside the RC frame or the outside of the building connected with existing frames, new frames, steel braces, and member strengthening as column jacketing, beam strengthening, or a combination of these approaches [7]. If the strengthening cost of heavy damaged building is approximately 40-50% greater than the total cost of building considering the service life, the demolition and reconstruction of the building may be preferred.

The main purpose of the following case study is to illustrate how to estimate the seismic performance of existing building structures. 160 branch buildings of a commercial bank are investigated for the earthquake safety evaluation and preparation of strengthening projects (if necessary) by METU. The 86% of the investigated buildings are the reinforced concrete structures. The structural systems of these are 54% of R/C frame types and 32 % of the R/C frame-shearwall types. Building distributions according to seismic areas are shown in Fig. 8. Note that the earthquake region I is the highest seismic region in Turkey. Wall indices are calculated by using the formula in Seismic Performance Evaluation Part for nondamaged existing buildings in seismic areas. Wall indices in both x any y directions are shown in Fig.9 for the investigated 160 buildings. Structural analyses were also performed for the structural capacity and the Turkish Earthquake Code requirements [9].

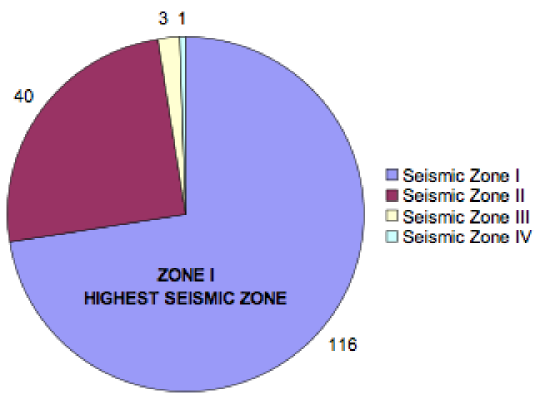


Fig. 8 Investigated building distribution in seismic regions

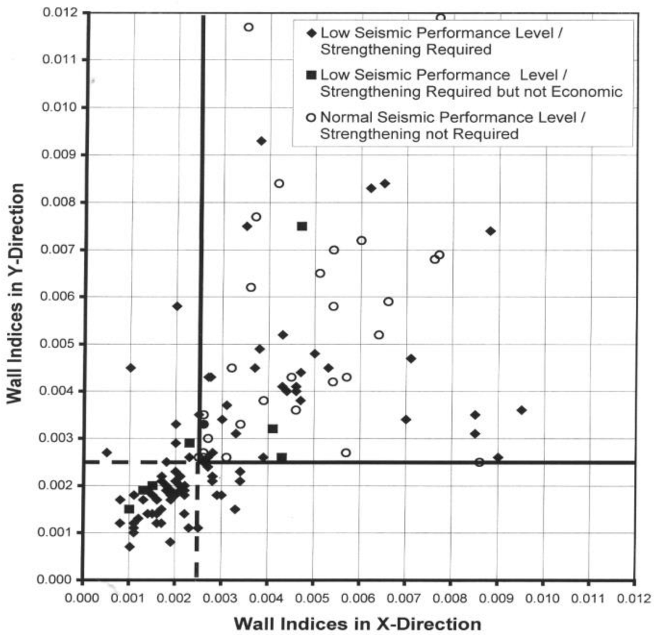


Fig. 9 Wall indices for seismic performance of investigated buildings

As a result of this research, it is observed that when the wall indices in x or y directions are less than 0.0025 the seismic performance of the building can be assumed as low seismic performance level and that building needs a strengthening. If the wall index in only one direction is less than 0.0025 means that the strengthening will be mostly in that direction due to low seismic performance in the corresponding earthquake loading direction.

5.3 Selecting the Most Cost Effective Path

One of the investigated buildings has been presented to show the integrated approach in the evaluation. The superstructure has been taken from Wasti and Sucuoğlu [15] moderately damaged reinforced concrete buildings after the 1 October 1995 Dinar earthquake. In the field, structural and seismic condition assessments were done by a team from METU. The building is a four-story reinforced concrete building, and has no irregularity in plan and elevation. Roof and slabs are flat plates. The damage was observed mainly at the ground level. There is no permanent deformation or partial collapse in the building. There is slight structural damage in the structural system above the ground level. SAP90 [14] and Turkish Earthquake Code [9] were used in the structural analysis and design of retrofitted buildings.

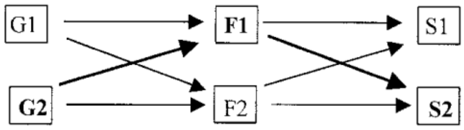
The damaged building has been analysed [16] in three stages: ground damage, foundation damage and superstructure damage. For each repair group, two alternative repair methods are studied and compared for the evaluation. Cost estimates for repair methods are calculated according to Ministry of Public Work Unit Prices [13]. The integrated paths and their evaluation are shown in Table 3. The total cost estimation for each path is converted to USD.

Note that the permeation grouting is found to be more expensive than compaction grouting because it is done more slowly in Table 3. In the knowledge-based information system described in Table 1 it is also indicated that permeation grouting is an expensive procedure. Thus by using knowledge based system there is no need to calculate this path. However it is only considered as an alternative to illustrate the procedure.

Table 3. Integrated paths and their evaluation

G. Ground Damage Repair	**Damage 25%**	**Relative Level of Strengthening**	**Cost**
G1. Permation Grouting		1.2	2110 $
G2. Compaction Grouting		1.0	782 $
F. Foundation Damage Repair	**50%**		
F1. Sister Wall		1.0	3365 $
F2. Replacement of Wall		1.2	6557 $
S. Superstructure Damage Repair	**25%**		
S1. Column Strengthening by Steel Casing		1.1	500 $
S2. Column Strengthening by Reinf. Concrete		1.0	304 $

PATHS:



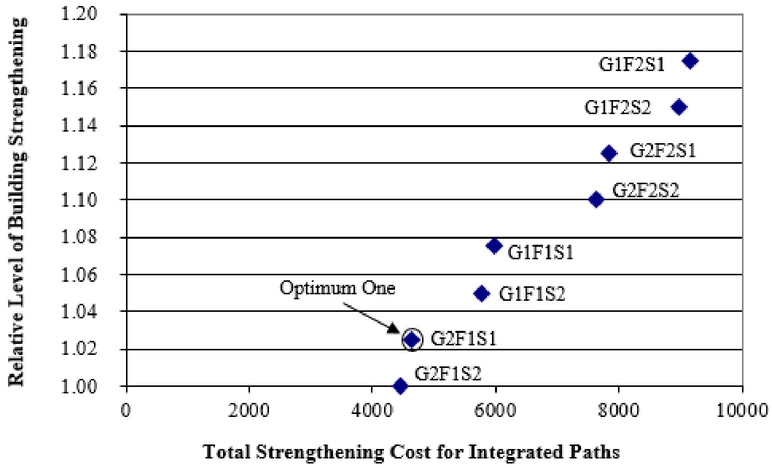


Fig. 10 Integrated path evaluation – cost versus strengthening level

Integrated suitable paths among alternative methods are selected to find the total cost estimation of the damaged building. There are two alternatives for each ground damage (G1, G2), foundation damage (F1, F2) and superstructure damage (S1, S2). Therefore the available integrated paths are: G1 F1 S1, G1 F2 S1, G2 F1 S1, G2 F2 S2, G1 F1 S2, G2 F1 S2, G1 F2 S1, G2 F2 S1. The final path shown as bold (G2 F1 S2) is selected from Table 3 among the repair methods considering structural safety evaluation, level of strengthening, construction requirements, and economy.

Among the integrated paths approximately 100 percent difference between the lowest and the highest cost of the building repair has been occurred. The level of strengthening by using that specific method is also ranked according to the damaged conditions of the investigated building. In this case study, because of heavy damage in the ground and foundation, the damage ranks are assumed for ground, foundation and superstructure as 25%, 50%, and 25% respectively. For each method the relative level of strengthening is indicated in Fig. 10. Then the level of strengthening for the building is defined as the multiplication of main group damage percentages by selected the level of strengthening. As an example the path G1 F1 S1 is corresponding to a relative level of strengthening of 0.25x1.2+0.50x1.0+0.25x1.1=1.075. Although the final selected path G2 F1 S2 is corresponding to the level of strengthening, 1.0, it means that integrated path also satisfies the minimum code requirements. The final path information corresponding to (G2 F1 S2) has been stored with damage repair information index as: G11-10-00-011, F40-31-00-206, S40-40-20-211 to be used for the similar types of damaged buildings.

6. Conclusion

There are many different approaches for the evaluation of repair methods for earthquake damaged buildings. Costs, codes, and repair techniques vary with time and place. To find the most economical and effective repair or strengthening method with current cost estimates, a knowledge-based information system has been developed using conventional information for building structures.

It is a challenging task to provide information systems for large numbers of damaged buildings that need to be rehabilitated after earthquakes before accruing of new earthquakes as well as to minimize time for evaluation of repair alternatives. Thus, knowledge-based information systems provide a powerful and most useful tool in selecting cost-effective methods for repair and strengthening of building in seismic areas.

The program is self-modifying for new repair methods, and is a part of a learning system and behaves as an expert system as a result of the data stored for common types of damaged buildings. The repair cost and seismic performance of the building for the level of repair can be estimated by using stored information. Developed information system program interacts with the current cost databases The most cost-effective alternative has been obtained by using integrated approaches. Knowledge based systems are found very effective in the application of integrated approaches.

Acknowledgement

Computer applications for the present study were conducted by Süleyman Ilıkkan, a former graduate student at the Middle East Technical University.

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