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HEURISTIC APPROACH IN STRUCTURAL STRENGTH EVALUATION AND RETROFITTING OF EXISTING BUILDINGS IN SEISMIC AREAS

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Abstract. *The migration of the population, to developed areas, lead to birth of overcrowded areas with claim for residences, financial, administrative, cultural and industrial facilities. The density augmentation of the population required sophisticated solutions from the authorities to ensure adequate environmental state suited for the 21th century. Due to the huge demand of the facilities significant number of buildings must be strengthened and modified to be suitable to the new demands. This change claims increase of surfaces and storey addition. This trend leads to the hazard of the new urban agglomerations versus natural causes as flood, fire and earthquake.*

The present paper is devoted to structures which were built before the implementation of any code or obsolete ones for the seismic design. Strengthening and retrofitting of existent buildings is a major interest of the actual engineering effort to provide the suitable structures to the new demands and to be stable under seismic loads. Each seismic event is accompanied by damages that better design and execution would have prevented. In general, severe earthquakes are followed by intense research of the causes which damaged structures. In some cases the code is changed due to the short comes which were observed.

This means that each experiment including earthquakes is followed by a learning process that provides new solutions, use of new materials and new design strategies. This process must be a heuristic process according the abilities of evaluation and implementation.

1 INTRODUCTION

One of the ways to solve problems is to use a heuristic process**.** The idea to solve problems is not a new one but it was promoted by G. Polya [1] as a method of teaching mathematics at Princeton University. There is thorough link between heuristics and artificial intelligence. The former involves human involvement at each step of the solving process. Heuristics developed in various fields of activities. Jakob Nielsen [2] developed a series of guidelines to be followed during the task solving. There are a lot of domains which are prone to this process. The aim of our work is to use heuristics for the field of civil engineering with stress upon the seismic design and retrofitting of structures.

Significant example is provided by the effort to strengthen buildings (churches) before L'Aquila earthquake. In [3] Lagomarsino presents the damages of the historical buildings as consequence of the L'Aquila earthquake with detailed description of the damages of a series of buildings. Among the buildings which were damaged there were two churches that went under a strengthening process by modern techniques, such as substitution of the original timber roof with stiff r.c. slabs. Unfortunately this is not the single example where application of the codes may provoke unwanted accidents of the strengthened buildings.

Usability guidelines, or heuristics involve the existence of the problems evaluated by a certain number of evaluators to get the best solution. There are certain guidelines promoted by different experts in heuristics. For exemplification the Nielsen's 10 principles will be used. These principles are the following:

1. Match the Real World
2. Consistency and Standards
3. Help and Documentation
4. User Control and Freedom
5. Visibility and System Status
6. Flexibility and Efficiency
7. Error Prevention
8. Recognition, Not Recall
9. Error Reporting, Diagnosis, and Recovery
10. Aesthetic and Minimalist Design

During the evaluation session, the evaluator goes through the solution several times and inspects it by comparing the list of the usability principles.

In the case of seismic design civil engineers learnt to design earthquake resistant structures in time. At the actual stage typical code deals with the environmental conditions, the structure per se, the solution to be adapted to achieve the structure and the solution to retrofit an existent structure.

We get continuous updating about the seismic risk the area of interest is prone to. We get information about the faults that might become active in a certain area. Sometimes a fault reveals itself and in that case it may be too late as the seismic event already occurred such as in Haiti in 2010, in Japan 2011 etc.

The prognosis of the seismic intensity affecting a certain region must be estimated as precisely as possible. The spectral acceleration has to be indicated in the region we do design for. Erroneous assumption of this information leads to severe damages and even failure like in 1977 during the Romanian (Vrancea) earthquake where the code was built upon an acceleration spectrum which suited the Californian earthquakes with period of 0.4sec instead of 0.8-1.2 sec as it occurred during this specific earthquake. As a consequence tall buildings went under resonance during the seismic event.

The structural characteristics must be indicated according the destination and the importance of the structure to be designed or retrofitted. The destination of the designed building is in thorough link with the importance of the building. A building which has to provide housing and services immediate after the seismic event occurred is categorized as important. Such buildings must resist the seismic load without significant damages in spite the fact that the earthquake may be severe. The ability to dissipate the energy induced into the building is provided by the ductility level to which the building was designed.

Ductility abilities may be achieved through certain strategies indicated by the design recommendations of the code. Examples of increased ductility abilities belong to design strategies and control implementation.

For structures achieved from reinforced concrete special care must be placed upon achievement the concrete confination by means of closer stirrups or by applying FRP textiles by gluing procedures.

Steel structures must be carefully welded or ensembled by means of special screws to ensure the ductility abilities of the structure.

Other materials used to achieve structures are ceramics, glass, wood, aluminum, fiberglass profiles, plastics etc.

Each material must be used according the codes which have been developed based upon tests and careful analysis according the recommendations provided by the available codes.

A great step ahead was achieved in the field of structural control of structures prone to dynamic loads like wind, earthquake, blasts, etc.

Among controlled buildings the base isolated solutions have been implemented and applied for actual structures. Base isolation is not a new idea. In China it was used from ancient times as the upper structure of a building was placed on a layer of sand which, permitted its movement during earthquake excitations due to inertial forces. A range of new solutions was developed to ensure the base isolation of structures in what concerns the gap between the upper structure and its foundation. Among the best known solution it is worth to mention the use of rolls, Teflon layers, rubber cushions with and without led core, inverse pendulum, etc. Partly the codes refer to these solutions. To use them one must understand the physics behind the solution and to be able to perform the analysis which provides the solution.

On the other hand, controlled solutions may be achieved by means of devices that dissipate the energy induced into the structure and avoid the structural elements to be loaded over their strength abilities. Some of these solutions are the tuned mass dampers (TMD), the liquid tuned mass dampers, the viscous dampers, the friction dampers etc. In spite of the fact that these devices have been implemented and proved their efficiency in the case of severe earthquakes there are few code provision for their design and application.

There is still o lot of work to implement all the above specifications into reliable codes to be used for an entire range of loads which may occur due to an earthquake. We have to learn how to use the experimental data and the analysis allowable in the FEM routines. We must learn to use the results provided by such programs in order to apply them into the design process. Since the abilities of computer memories augmented to very large scales giga, terra, peta (soon) the interpretation of the results will be the main intricacy to be solved by the software users. It means that the designer must understand the data to be input into the computer and to be able to use the results in the designing process. The heuristics developed for the achievement of seismic resistant structures must be kept clear and available to the great mass of the designers whose task will be to achieve structures able to stand seismic loads. A short exemplification will clarify the principles to be used for achieving true, clear and easy use of codes and analysis results.

2 THE ENVIRONMENTAL CHARACTERISTICS

The code must provide for each area the environmental characteristics which will lead to the estimation of the loads acting upon the designed structure. The code must give the assumed peak ground acceleration which is due to occur in a specific area. Amplification phenomena have to be taken into account if there is any possibility to take place. It means that micro-zonation must be done in order to avoid unsatisfactory structural behavior of the designed or of the retrofitted structure.

The soil characteristics, at the building site have to be chosen according the existent conditions. The values to be taken into account for the determination of the seismic coefficients have to be chosen and explained thoroughly. According the intensity at the situ and the soil characteristics the acceleration spectrum is built.

The structural characteristics have to be taken into account. The importance of the building must be established carefully. Buildings are ranged according their importance, the highest coefficient is chosen for the most important building. The designer must decide the ductility of the building according the ability of energy absorption as product between force multiplied by the sway that does not damage the building

3 THE STRUCTURAL CHARACTERISTICS

The structural characteristics have to be taken into account. The importance of the building must be established carefully. Buildings are ranged according their importance, the highest coefficient is chosen for the most important building. The designer must decide the ductility of the building according the ability of energy absorption as product between the force multiplied by the sway that does not damage the building.

The response period of the structure is determined according the code provisions or by careful analysis by computer software. Usually it is compulsory to compute the fundamental period of oscillation of the structure for the static equivalent method but structural dissymmetry claims the modal method of analysis to be used.

The seismic analysis is achieved following the static analysis made by the limit state approach.

3.1 Results

The results must be carefully treated as the combination of the loads taken into account as dead, live, earthquake such as according the code provision to get the greatest load possible.

The analysis may be performed linearly or according non-linear approaches. Since new methodologies have been proposed such as the performance analysis through the pushover behavior of the structure superposed to the acceleration spectrum exciting the structure the capacity vs. demand is promoted. The structure is judged according the difference between its capacity, illustrated by the pushover ability and the demand visualized by the acceleration spectrum normalized to force. Great attention must be paid when this method is used to take into account the entire range of loads which act upon the building.

4 RETROFITTING OF EXISTENT STRUCTURES

4.1 Generalities

Existent structures must be maintained and in majority of cases must be strengthened to resist the prognosis of the loads which might affect them during their service life. The design of these buildings took into account mainly the loads of gravity which act vertically. The horizontal loads and the loads which affect dynamically these buildings were not been taken into account. It means that this kind of loads might affect this building in a very severe manner.

The categories of buildings which have to be strengthened refer to residential, public and industrial ones. Among these buildings there are some which are considered "Historic Monuments" and their architecture is characteristic to the town and this value must be protected to keep the historical heritage of the area. The aspect of these buildings must be preserved and the strengthening has to be achieved without any change that will affect the architecture externally or internally. The main solutions which are recommended refer to use same kind of materials which have used initially or to strengthen elements by injection of efficient gluing products (epoxy, or other). Steel profiles, FRP textiles must be avoided mainly due to aesthetic reasons. The range or the mass distribution of this kind of buildings must be maintained in spite of any advantage that some change may ensure.

Building which are not considered "Historic Monuments" may be completed by annexes which are added horizontally or vertically, by supplementary areas or stories. This solution is considered in Israel a win win situation since the entrepreneur achieves the work with money he obtains from selling the supplementary flats he builds. It means that the investment is covered by the money obtained by selling the added residences.

4.2 Rehabilitation requirements

According most of the codes, dealing with the rehabilitation of existing buildings a series of requirements have been established to be successful in the ensuring the features of the buildings to resist seismic effects. The design and execution of the retrofitting is the result of a lengthy learning process - a heuristic approach with a range of requirements to achieve a resistant, efficient and esthetic structure.

The main requirements refer to:

- Rehabilitation methods
- Analysis procedures
- Rehabilitation procedures
- General design requirements
- Foundation and geologic hazards
- Acceptance criteria

Each stage of the documentation must follow the principles of heuristics for achieving the task of clarity and efficiency (see table No. 1)

Principles	
1. Match the real world	The necessity to execute the retrofitting should be clearly explained and motivated
2. Consistency and standards	The physical phenomena which may occur and their link to the actual codes
3. Help and documentation	Clear documentation and motivation must be emphasized
4. User control @ Freedom	The multiple choices which were made by the designer should be presented and motivated
5. Visibility and system status	The stages of the retrofitting should be thoroughly defined
6. Flexibility and efficiency	Documentation should be elaborated for frequent use of certain solutions
7. Error prevention	Error prevention must be ensured
8. Recognition not recall	All information should be available
9. Error reports. Diagnosis and recovery	Error that occurred must be described
10. Aesthetic and minimalist design	The design should be simple and straight

Table 1: The principles of the heuristic approach for structural retrofitting

The application of the upper principles must achieve a very straight design and a project which enables the authorities to get a very clear image about the stage of the work and to avoid faults which can lead to damages or to undesired structural behavior.

5 RETROFITTING BY TAMA 38

TAMA 38 is the methodology which was developed and accepted in Israel to achieve the retrofitting and strengthening of structures built before 1980 according codes, almost neglecting the horizontal dynamic effects. Since majority of the population live in such buildings the risk of collapse of these buildings is high leading to economic and human life loss in case of an earthquake. The development of new approaches and production of new efficient materials together with the economic needs lead to special strengthening solutions. This approach is feasible in areas were the need of hosing is high. The TAMA 38 is not implementable in areas where there is no housing need. In these areas the retrofitting must be supported by money from taxes and seldom will consist from adding any structural annexes. The strengthening solutions will be simpler and more efficient.

5.1 Environmental conditions

The strengthening process will take into account the seismic intensity of the area the structure is placed. The expected seismic intensity is provided by the code and it may be refined by the use of the micro-zoning maps. Besides the seismic intensity the designer must be aware about the geological characteristics of the area which can provide information about the amplifications that may occur during seismic excitations in a certain area.

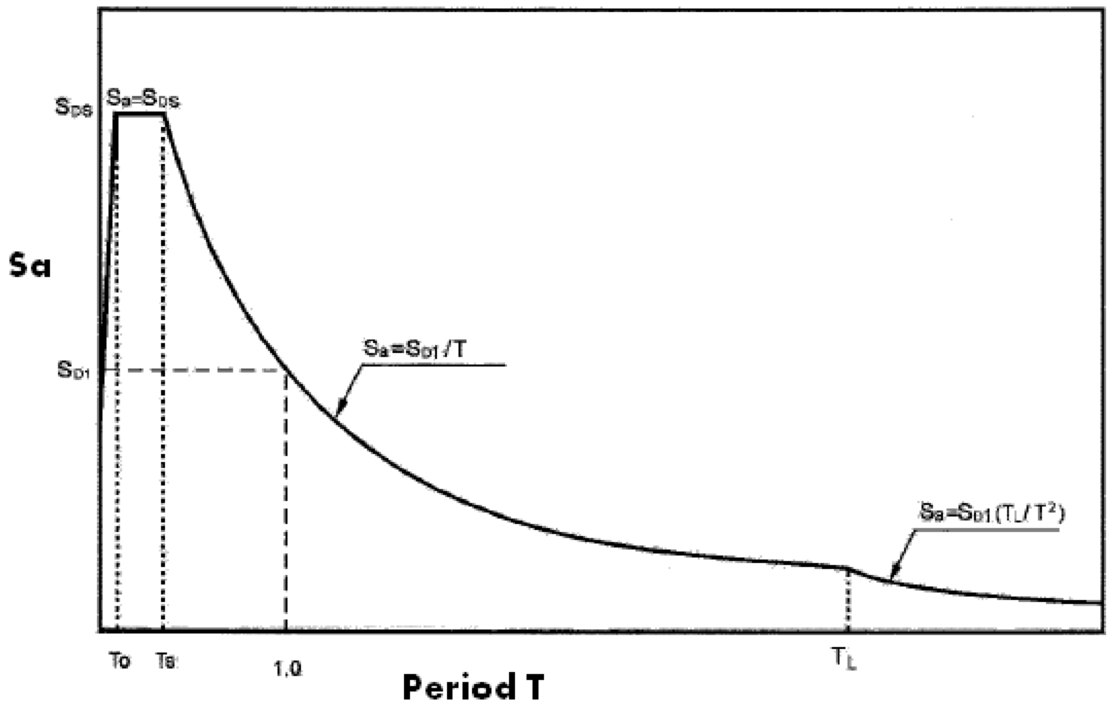

Fig. 1 The Spectral Acceleration Response

5.2 The structural characteristics

The main characteristic of an existent structure is its period of oscillation. Since majority of the retrofitted structures have less than 10 storey the main energy is introduced into the structure by means the first mode of oscillation through the fundamental period of vibration. This value can be approximately established only due to limited knowledge of the materials and both the initial design and the modification done along the structures' life. Destructive phenomena as concrete carbonation and steel corrosion change this characteristic either.

According recent research and studies the importance of ductile structural behavior was emphasized and design strategies changed accordingly. In case of reinforced concrete due to closer stirrups concrete behaves as a confined entity with increased stress – strain abilities. But in case of existent buildings we cannot take into account abilities of ductility (see fig. 1).

For existent buildings we cannot take into account any information about the used material (Fig. 2) we can assume and check the structural behavior by using micro-tremors. Since many of these buildings suffered severe loads and modification during their life time the model we use must be thoroughly tuned according the actual structural state.

5.3 The structural retrofitting

According the recently developed approach – the structural performance analysis – the structural capacity and the demand due to the load have to be compared. The capacity is established through the pushover approach while the demand is defined by changing the acceleration spectrum of the area into a spectral force – displacement diagram. The intersection between the capacity and the demand curves defines the performance point and provides information about the structural stability. This procedure can be applied by means of the finite element method. One of the routines which may be applied for this analysis is SAP2000 developed at Berkeley California.

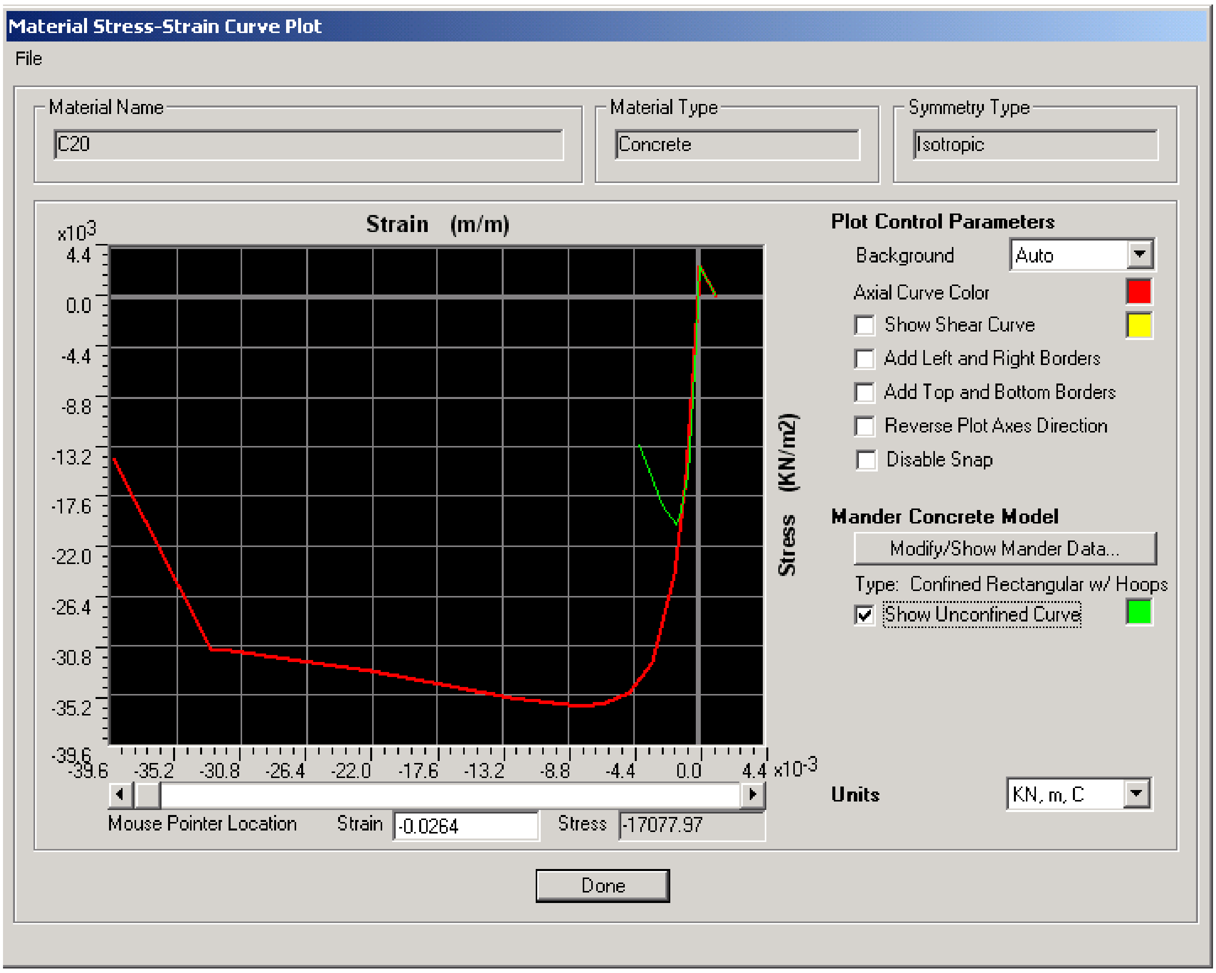

Fig. 2- Comparison between unconfined (green) and confined (red) behavior

5.4 Retrofitting Case

A specific case will be treated to exemplify the strengthening of a residential building. The building presented in Fig. 3 is a typical building built before 1980. It was designed as a framed five storey structure without proper rigidity against horizontal loads. The frame was made of reinforced concrete without any confination at the zones prone to turn into plastic hinges.(see Fig.3)

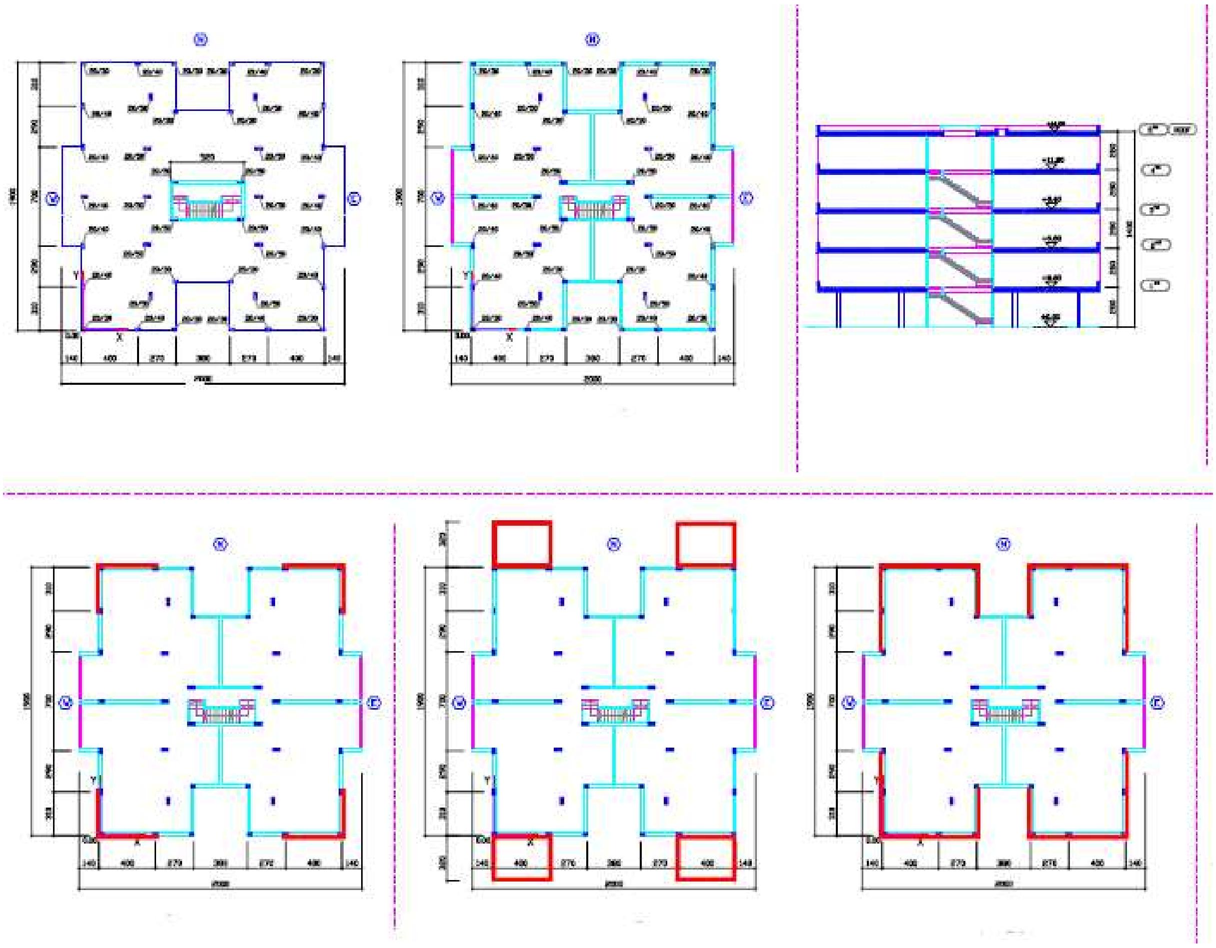

Fig. 3 The Retrofitting Case. Three Solutions of Strengthening

Three strengthening solutions have been indicated in Fig. 3:

1- Partial R.C. shear wall added at the corners of the structure
2- Four R.C. boxes built from shear walls
3- R.C. shear walls cast along the perimeter of the building.

The strengthening walls have been reinforced according to confining demands to increase the ductility of the entire structure.

The analysis for the initial structure and for the strengthened solutions was made by means the SAP2000 routine according the performance method. One of the strengthened solutions is visualized in Fig. 4.

The initial structure, according the performance analysis proved to be unsuited for the considered excitation with no performance point to show the intersection between the capacity and the demand. This analysis leads to the conclusion that it is necessary to strengthen the structure against the horizontal load which according the statistics may occur soon. The result of the performance analysis is given in Fig. 5 where it may be seen the fact that the demand is greater than the structural capacity. Fig. 6 stands for the analysis of one of the strengthened solutions. As result of the analysis one may remark that the demand and the capacity curves intersect at the performance point proving the stability of the strengthened structure.

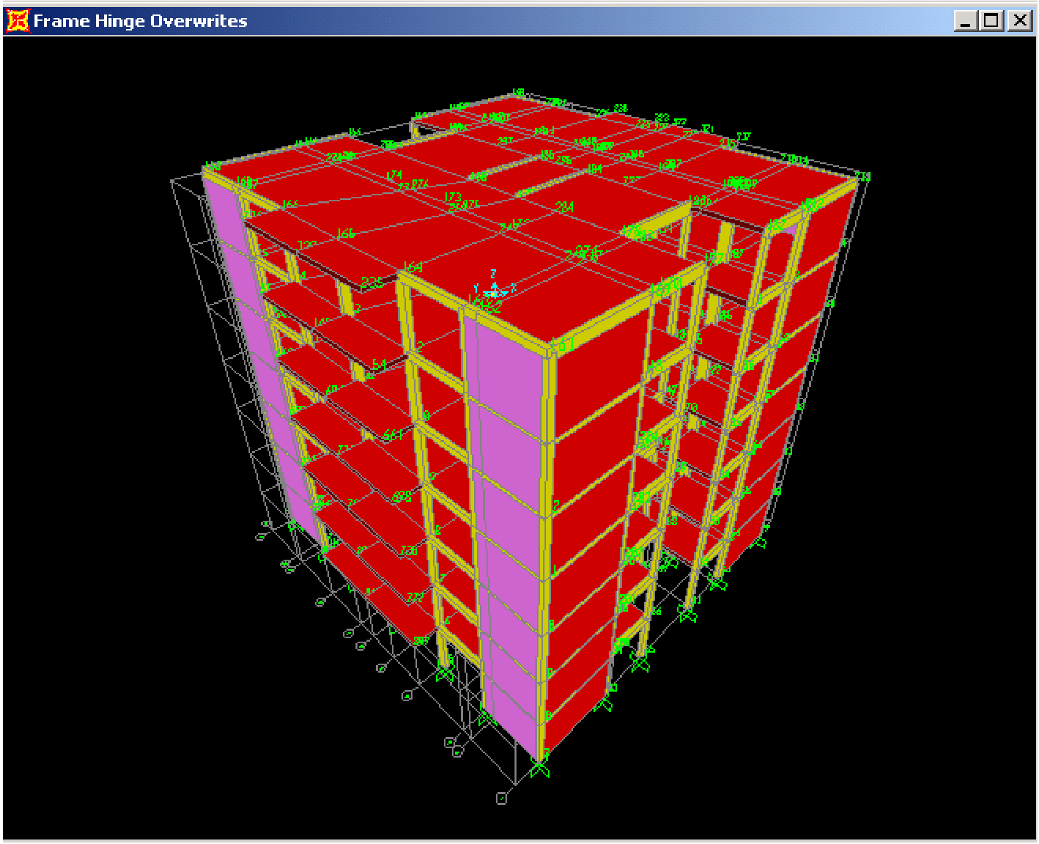

Fig. 4 Solution with shear walls at the corners

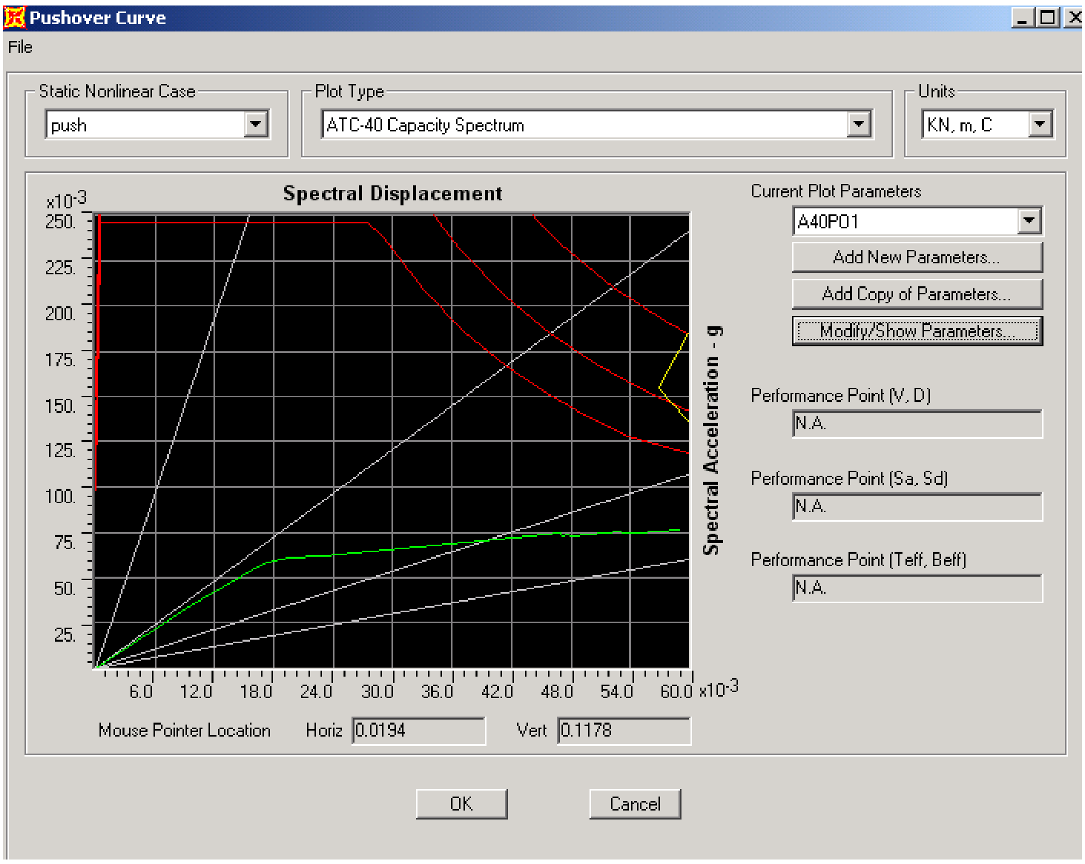

Fig - 1Performance analysis of the initial structure

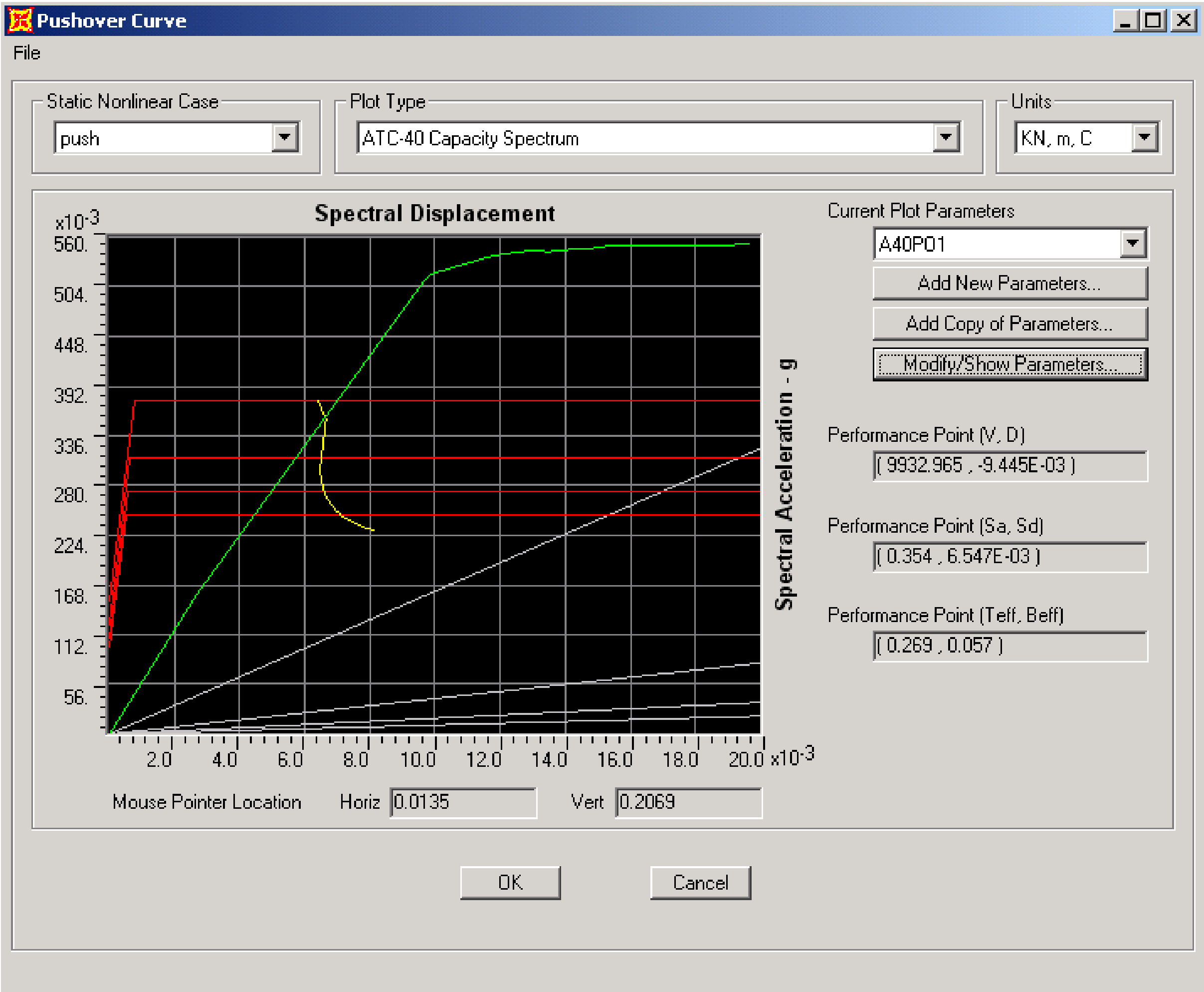

Fig. -6 The strengthened solution performance analysis

The performance point indicates the values of the base share (V= 9932kN), the top displacement (D=9.45mm), the effective oscillation period of the structure (T=0.269sec) and the considered effective damping (B=0.057).

This method is defined as NLSA – Non-Linear Static Analysis and gives an indication about both the behavior of the initial un-strengthened structure and the performance of the structure to be strengthened.

More exactly, the behavior of these two stages may be visualized by means of the R.H.A. (Response History Analysis) which is a lengthy and intricate process with results that are more exact but require intense search. This analysis is required in case of the implementation of a certain solution which was chosen by means of the N.L.S.A.

6. STRUCTURAL RETROFITTING BY THE HEURISTIC APPROACH

Heuristic approach means that the optimal solution is found by means of a learning process. This is the reason that huge efforts are made to improve the existent codes and the analysis methods. Books, scientific papers, conferences aim improvements in the design process. Each major destructive event, natural or manmade is followed by intense research to study the causes and to find the best defense against the loss. The topics of most of the conferences refer to:

- Lessons from Damaging Earthquakes
- Engineering Seismology
- Geotechnical Earthquake Engineering
- Dynamic Analysis of Structures and Seismic Codes
- Experimental Mechanics, Control of Structures and Structural Health Monitoring
- Seismic Retrofit of Structures and Protection of Historic Buildings
- Societal, Economical and Managerial Aspects

Heuristic approach leads to the optimal solution by conducting an evaluation of the proposed solution. A series of principles have been defined and their application leads to the project improvement for finding the best solution. Some of the principles were defined by Jakob Nielsen. These principles may be very general for a specific field like structural engineering or struchese principles may be very general for a specific field like structural engineering or structural retrofitting the evaluation must be more specific. The main usability problems may refer to:

- The definition of the expected earthquake
- Closeness to the active fault (distance to the Hypocenter)
- The geological characteristics of the soil
- The structural features of the analyzed building
- Use of the existent codes or proposals of improvement
- Soil Structure Interaction issues.
- Etc
- Not last the esthetics of the new or the retrofitted buildings.

7. CONCLUSIONS

This method is not new, it leads to a solution during a learning process.

The found solution may be analyzed by evaluators while the shortcomings can be reveled.

Evaluators can belong to various fields of activity but their findings can lead to significant improvements.

Heuristics is based upon experience, artificial intelligence, brain storming for solving the problem.

The need of the best solution justifies use of a variety of strategies, heuristics among them.

8. REFERENCES

[1] G. Polya, How to Solve It, Princeton University Press 1945
[2] J. Nielsen, Usability Engineering, Morgan Kaufmann, San Francisco, 1993
[3] S. Lagomarsino, Damage assessment of churches after L'Aquila earthquake(2009), Bull. Earthquake Eng. (2012), Springer
[4] ASCE/SEI 41-06, Seismic Rehabilitation of Existing Buildings, ASCE 2007
[5] SI-413, Seismic Design of Structures, the Standards Institution of Israel.
[6] SI-2413, Guidelines for Seismic Resistance Assessment and for Strengthening of Existing Structures, the Standards Institution of Israel.