NEW PROFESSIONAL SKILLS FOR THE ECONOMIC ASSESSMENT OF SEISMIC PROTECTION SYSTEMS

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ABSTRACT :
This paper illustrate a public funded research project aimed at developing new professional skills for the economical assessment of building equipped with advanced seismic protection systems: base isolation and dissipative braces. Economic implications delay the application of innovative seismic technology. This aspect depends on the lack of performance assessment procedures able to formulate adequate cost/benefit evaluations. The purpose of this research is to outline a correct methodology necessary to study the economical implications when special innovative devices are used. The research is aimed at formulating methods for a correct assessment of the building seismic performance and damage probability connected with initial costs, rehabilitation costs and structural configuration, and to spread their knowledge. The project also provides for the education of an expert on building seismic performance assessment based on probabilistic concepts. Several potential users are expected for the outcomes of the project: individual structural engineers, suppliers of building products - including architectural, mechanical, electrical and structural systems and components - developers of building codes and design standards, educators, researchers, contractors, owners, lenders, insurers and decision makers

KEYWORDS:
Professional skills, innovative protection system, cost/benefit ratio, performance.

1. INTRODUCTION

Umbria Region financed with European founds a development program aimed at providing and strengthening the technological transfer to Companies, Universities and Research Centers in Umbria. The project is aimed at improving activities in the research sector and represents, in technological development area, the experience of the research activity carried out by young graduates. The goal of the project is to contribute to the strengthening of research activities by means of actions able to improve the opportunities for the entrance in the job world. This contribution also leads to increase the diffusion of advanced know-how and the worth of human capital. Umbria region financed singles research projects of young graduates by means of a public competition. The activities had to be carried out within a Company, University and public or private Research Center located in the Umbria region. Within this program a research proposed by the authors was financed and it was carried out at the Department of Civil and Environmental Engineering of the University of Perugia.

2. THE RESEARCH PROJECT

Within the financed project, a methodology, assessing the economical implications in the application of seismic protection systems, was developed. The goal of the research was to outline a procedure able to evaluate the economical profit deriving from the use of innovative protection systems in traditional building techniques. The goals of the research project and the development phases are illustrated in this paper.

2.1. Background
Fragile behavior characterizes many structural configurations of both new and existing buildings. This aspect limits their capacity to sustain severe earthquakes characterized by a strong energy contribution. Advanced seismic protection strategies are based on the use of innovative systems such as base isolation and dissipating

braces. These solutions allow for a reduction of the seismic input and produce a high dissipative capacity. Seismic protection systems have been used in many significant applications in the last two decades, also in Umbria region. The IERP building in Città di Castello (Parducci et al., 2001), the fire station's barracks in Foligno and the Emergency Management Agency buildings in Foligno (Mezzi, 1999) are some examples of the latest applications of seismic protection systems in Italy. Economic implications often delay the application of the innovative anti-seismic technologies. This aspect depends on the incorrect procedures adopted for the performance assessment that lead to an inadequate evaluation of the related cost/benefit ratio. The goal of this research is to outline correct methods for considering the economical implications of the use of innovative techniques, based on the use of special devices and materials to improve the building seismic behavior.

2.2. Goals

The fundamental goals stated in the research proposal are:

- defining the state of the art of the available advanced techniques for the seismic protection;
- analyzing the seismic behavior of structural configurations protected with various classes of advanced protection systems by means of a numerical simulation;
- identifying and developing procedures for a performance based seismic assessment for assisting designers and investors in making a decision;
- defining a probabilistic methodology for the correct identification of damage and a consequence in terms of three fundamental components: casualties, downtime and costs (initial, retrofitting and indirect costs);
- implementing numerical application, based on a structural analysis post-processor code, for the assessment of a performance curve in terms of the previously defined components.

The research aims at creating opportunities for interacting with various experts within the Umbria Region (both the Provinces of Perugia and Terni) involving the experience on design, numerical analysis and use of special seismic protection system and the knowledge on innovative material for applications in the structural field.

2.3. Market

The purpose of the "advanced seismic protection" is the design of new buildings and the retrofit of existing ones with "compatible" strengthening and "controlled" cost, allowing for the safeguard of human life and reduction of damage, with the consequence of saving costs for successive repair or replacements. The establishment of a specific knowledge of methods for a correct assessment of the building seismic performance and for defining the probability of damage connected with the initial cost, the rehabilitation cost and the structural configuration, is the result expected from this research. Several potential users are expected for this product: individual structural engineers, suppliers of building products, including architectural, mechanical, electrical and structural systems and components, developers of building codes and design standards, educators, researchers, contractors, owners, lenders, insurers and decision makers.

2.4. Feasibility, coherence and congruity

The feasibility of the research project, related to the goals already defined, is associated with the following factors:

- formation, curriculum, experience and competence of the researcher;
- experience, cultural level of the host's operating context;
- limited operative tools.

The research project is aimed at providing the formation of competence on the assessment of the building seismic performance to a person skilled on probabilistic approaches. The host structure is the Civil and Environmental Engineering Department of the University of Perugia, where there are various experts on structural analysis, seismic response of structures, soil behavior and traditional and innovative materials. The proposed project looks absolutely compatible with the subject competence and within the host context. This aspect guarantees the feasibility of the project within the defined period and its implementation in the referred sector represented by civil engineering in general. Indeed, the research project's application involves all the civil constructions (buildings and infrastructures) subjected to seismic damages.

2.5. Phases and expected results

The research project is carried out through three fundamental phases, each including a number of research lines, as shown in Figure 1.

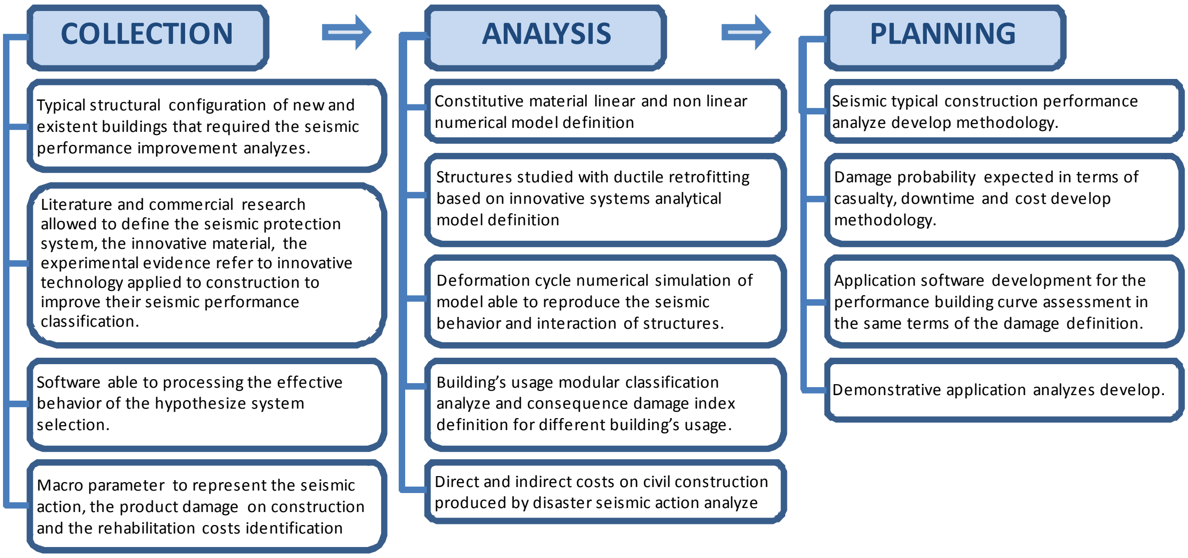


Figure 1 Phases and actions of the research project

The expected results are:

1) Technological transfer: associated to the diffusion of methods for the application of seismic protection systems.
2) Human resource development: associated with the experience related to the design and analytical simulation of the seismic behaviour of advanced protection systems.
3) Scientific relevance: associated to the study of the behavior of seismic improvement systems representing the state-of-the-art in this sector.
4) Other competencies involved: the involvement potential levels, with regards to the competences present in the Campus of Perugia and Terni of the University of Perugia, are referred to the competence on new materials and systems.
5) Potentiality to create research and development: advanced techniques of seismic protection based on "new devices" and "new materials" are the subject of the research and offer new possibilities for further studies. A correct cost-benefit evaluation in the use of seismic protection systems should push the development and application of innovative constructive technologies.
6) Potential social and economical impact: the goal of the advanced "seismic protection" is the safeguard of human life and the damage reduction with the consequent reduction of repair or replacement cost.

2.6. Possible occupational consequence

Two areas for the application of the research project outcomes were hypothesized. The methodology represents a direct application of the seismic performance assessment and an actual scientific experience for accounting the economic impact of new design strategies. The obtained knowledge has a large group of users (designers, building officials, developers, owners, lenders, insurers, tenants) who are required to make decisions on acceptable performance for an individual building or a broad class of buildings. Consequently, it includes the effective and significant possibility of developing consulting and training activities oriented to technical specialists.

Moreover, broadening the use of special seismic systems will indirectly increase the development of consulting and design companies, contractors expert in seismic device application, consulting companies expert in seismic performance assessment and cost-benefit optimization of buildings in seismic areas. New professional skills are also required, making evident the positive impact on the employment of graduates in technological sectors.

3. PROGRESS STATUS

During the development of the research project some reports were produced to illustrate the obtained results. In this chapter the content of these reports is briefly resumed. Other reports are presently under preparation and they will be ready in October 2008, when the project will come to an end.

3.1 Collection phase

The first activities of this project phase included the characterization of typical structural configurations and a selection of calculation code by means of a research on the existing literature. The research on new and existing buildings allowed for the creation of a structural configurations' classification based on geometric properties and seismic performances, titled *"Abacus of structural configurations"*. The possibility of conceiving particular structural configuration of buildings, thanks to the application of new seismic protection technologies, is outlined in this report. Indeed the global morphology and the structural configuration do not influence the seismic response, because the seismic performance is fundamentally related to the presence and location of devices. Technical and commercial information on innovative devices used to improve the building seismic performances are set out in another report titled *"Technologies for improving the building seismic behavior"*. In this report, information on the devices' characteristics, application, Italian and world producers, price, if available, are set out.
Subsequent activities focused on the classification of computer codes for the structural analysis. In particular, the report titled *"Comparison of the available commercial software for structural modeling"* classifies the codes able to process the effective behavior of considered systems. Four classes of codes are pointed out:

- Commercial: codes created to analyze, design and optimize structural elements. They are characterized by user-friendly interfaces and allow to obtain output information in form of drawings and computational reports. Some of them allow to model seismic devices.
- Scientific: codes without a user interface created especially for analyzing structures. They are usually able to carry out static and dynamic, linear and non-linear analyses. Moreover, they allow sophisticated modeling to define non-linear performing elements reproducing the seismic protection system devices and the structural plastic hinges.
- Hybrid: codes characterized by a simple user interface, having a powerful solving core, able to perform any type of analysis, but not to produce output in terms of drawing or computation reports.
- General purpose: codes oriented to various sectors of the engineering (mechanical, hydraulic, industrial and civil), that can reproduce almost every structural situations, but require the acquisition of a complex know-how.

In the last part of the phase, the macro parameters representing the seismic action, the building damage and the rehabilitation costs are identified. The information were collected in the report *"Seismic action, damage and cost parameters"*. Seismic scales give an exhaustive measure of the earthquake intensity, but the qualitative or macro-quantitative representation of the action cannot be correlated to damage indicators. Characteristic parameters of the ground motion cannot be utilized to assess the expected potential damage without considering an assessment of the structure seismic response: the representation of the seismic event should be related to the chosen type of design analysis. Procedures are provided for three different types of seismic performance assessments. The "intensity-based assessment" provides for the estimates of the probable casualties, direct economic losses and downtime, when the building experiences a ground shaking represented by a predefined acceleration response spectrum. The "scenario-based assessment" provides for estimating the losses of a building subjected to a ground shaking resulting from a specified earthquake scenario, defined by the magnitude and distance from the site. The "time-based assessment" provides estimates of the probability of experiencing a given level of consequences over a specified period of time, considering all the earthquakes that may occur in that period and the probability of each one. All the three different methods require the definition of the seismic action in terms of acceleration applied at the base of the structure. Damage statuses are defined by global parameters and the criteria reported in (ATC58, 2005) can be utilized to classify them. It is possible to distinguish various indexes: global and local, probabilistic and deterministic, structural, economical and those based on the analysis type. Finally the consequence macro-parameters are classified in three classes that are not mutually independent. The first one groups together the parameters related to the direct economic losses, retrofitting costs, downtime and casualties. The second class accounts for parameters related to damage of historical and monumental building that represents a cultural loss. The last class account for consequence related to psycho-moral damage of the occupants.

3.2 Analysis phase

Dynamic analyses were carried out on device models, on fixed base configurations and on structural configurations equipped with innovative devices, by means of the previously selected software. In this phase, some of the devices described in the cited report were analyzed using numerical models. The selected innovative seismic protection systems were the base isolation and dissipative bracing. For the last one, the hysteretic, elastomeric and viscous fluid variants were considered. The sample structure used for the evaluation consisted of a 2-bay 4-story plane frame. The structure was designed according to the Italian guidelines and using the data detailed in the report titled *"Comparison of the output obtained by numerical simulations"*. In this report, input and output analysis data are reported and a comparison among the behaviour of different protection systems, is presented. The achieved results were then utilized to develop the subsequent phases, in particular, the cost assessment of the expected damages.
In the second part of the analytical phase, a direct cost assessment methodology was developed. The results were applied to compare the retrofitting cost associated to conventional structures and to the same ones assembled with innovative systems. The retrofitting costs of r/c columns were considered in the proposed methodology for identifying the costs associated to a seismic event. In the report titled *"Expected damage correlated to the seismic action and building usage"*, the procedure for assessing the direct costs, depending on the damage level, is described. The probability associated to particular damage states is expressed by means of fragility curves that allow for establishing a correlation between seismic demand and structure response. The fragility curves take into account the uncertainties in geometry and material characteristics. The proposed methodology is limited to reinforced concrete frame structures in which the deformation levels, associated to the seismic response of columns, have a fundamental role in the damage assessment of the complete structure. With these assumptions, it is possible to simplify the problem and to focus the procedure on the assessment of the seismic performance of a single r/c column. The structural response is strongly influenced by the uncertainties due to the material characteristic and executive modalities. The seismic response could be different even if the shear-type behavior is assumed. It is possible to record a variation in the column local drift at the same story caused by variations due to the node stiffness and torsion effects. Damage states are expressed in terms of the only relative top/bottom displacement. A static non-linear analysis with assigned displacement allows to check the element stress state. Therefore, the damage states are expressed by local stress or strain and by the consequent retrofitting works. The use of a fiber model is fundamental in checking the evolution of the stress/strain status of the constitutive material.
Successively, consequence functions correlate damage and losses. The consequences of a damage state, defined in a prefixed class of losses, are expressed by means of probability density functions. The goal of the study is to develop families of consequence functions conceived for different performance groups or different building usages. The proposed procedure requires to edit forms, in which parameters, descriptions and necessary indications for the consequence assessment are required for all the performance groups and for each structural and non-structural element.
The costs chosen in the price list are a fundamental matter in assessing the retrofitting evaluation. The period for making repairs works represents the downtime. The costs of the interruptions of the building use, depending on the downtime, must be added to the direct costs as a building usage function. Inexorably, indirect economic losses are associated to downtime and these losses may be even more relevant than the direct repair costs.

3.3 Planning phase

In the last phase the PADD (Probabilistic Assessment of Direct cost and Downtime) toolbox was implemented to perform the damage and loss analyses. The damage analysis results are used in the proposed application to calculate the direct and consequent economic losses, associated with the building retrofitting and downtime.

4. ABSTRACT OF RELEVANT RESULTS

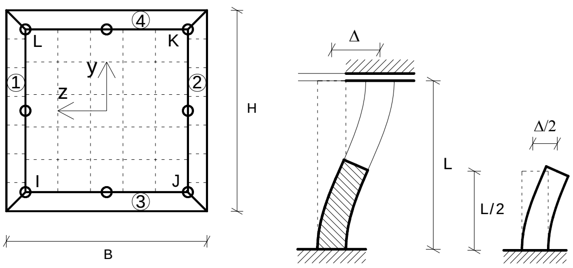
For the sake of brevity, this paragraph only illustrates some relevant results obtained during the analytical phase. Probabilistic correlation between damage and seismic demand in r/c structures (Botta & Mezzi, 2008) is the first result outlined herein. The second step refers to an assessment of the retrofitting cost. A combination of the two procedures allows to obtain the direct costs associated to a particular structure for a defined seismic performance level.

4.1 Damage state definition

The deformation limits associated with the seismic performance of r/c columns represent a fundamental issue in the definition of the performance criteria of r/c structures of any shape and dimension.
The method used to assess the probabilistic correlation between the damage and seismic demand in r/c structures is based on the definition of the drift limits of the columns at different performance levels. The story drift ratio is therefore the referred Engineering Demand Parameter (EDP), which assumes different limit values at various damage levels. Considering the scattering characterizing the materials and geometrical properties of the columns, the drift limits should be determined in a probabilistic manner. The final purpose of the performance-based method is to assess a Consequence Parameter (i.e. the retrofitting cost) of a r/c structure for various damage levels, expressed by the stress or strain status at relevant points.
Current guidelines usually propose five performance levels for structures, namely: fully operational, operational, life safety, near collapse and collapse. In order to perform an economical assessment, some predefined performance levels are grouped together, basing it on the costs to be sustained for the necessary works associated to structural damage. Crushing of compressive unconfined concrete and 1 mm residual crack widths, may be used to define the functional performance limit state because damage up to this degree may be repaired at a relatively low cost and without major interruption to the normal functions of the building. The initial cracking of the concrete cover and the yielding of the longitudinal bars are included within this damage level. The second level corresponds to the status in which the confined concrete reaches the ultimate compressive strain or the longitudinal reinforcement at the tension side reaches the ultimate tensile strain. It primarily depends on the quantity of reinforcement (fragile or ductile collapse). Hoop fractures and buckling of the longitudinal bar are included within this damage level. Important retrofitting work is necessary and involves an interruption of the building's occupancy. The last damage level consists of the collapse or near-collapse status of the element.

4.2. Fragility curves of damage states

A r/c cantilever element having half the height of an interstory column was assumed, simulating one half of the expected fixed-end deformed shape (Figure 2). A static non linear analysis is carried out increasing the lateral top displacement whilst checking the strain-stress state at specific points at control sections.
A refined sectional analysis program (OpenSees, 2000) was used, based on a fiber-element model. The cross-section was divided into fine strips parallel to the axis (Figure 2), the confined concrete core, cover regions and bars were modeled separately by means of various constitutive stress–strain laws (the Kent-Park law for the concrete and the elastic-plastic law for the steel). Structural uncertainties were considered by means of random extraction, assuming log-normal distributions of the relevant geometrical and mechanical parameters. Figure 2 reports the statistical parameters used, which were obtained from the existing literature.



	Parameter	Mean	st.dev.
f_c	*Concrete compressive strength (MPa)*	33	4.52
ε_{1c}	*Concrete compressive strain (‰)*	2	0.2
f_y	*Reinforcing bar yield strength (MPa)*	478.8	28.7
E_s,	*Reinforcing bar Young modulus (MPa)*	206000	6800
B	*Section Depth (mm)*	401.6	6.35
H	*Section Hight (mm)*	401.6	6.35
c	*Cover (mm)*	28.1	4.20
s	*Distance hoop (mm)*	100	5.90
e_a	*Eccentricity axial load (mm)*	10	6.10

Figure 2 Column section. Element model. Mean and standard deviation of the parameters

During the analysis, the stress/strain values at three control points on the section, representative of the status of the concrete core, concrete cover and tensile bar, are monitored. It is possible to establish the story drift ratios corresponding to the damage states by means of an automatic procedure. A characterization of the section curvature at various damage states is also computed, as shown in Figure 3.

Two hundred simulation runs are carried out at two axial force levels (expressed by the ultimate force ratio ν=0.2 and ν=0.4). Each model is defined by a random assumption of its geometric and mechanical parameters. A log-normal PDF is assumed for representing the distribution of the drift ratio corresponding to the damage states: carried out Kolmogorov-Smirnov tests confirm the assumption. The results are expressed in terms of fragility curves (Figure 3), that define the CDF of the story drift ratio corresponding to the type of damage: the curves appear very steep for the light damage states.

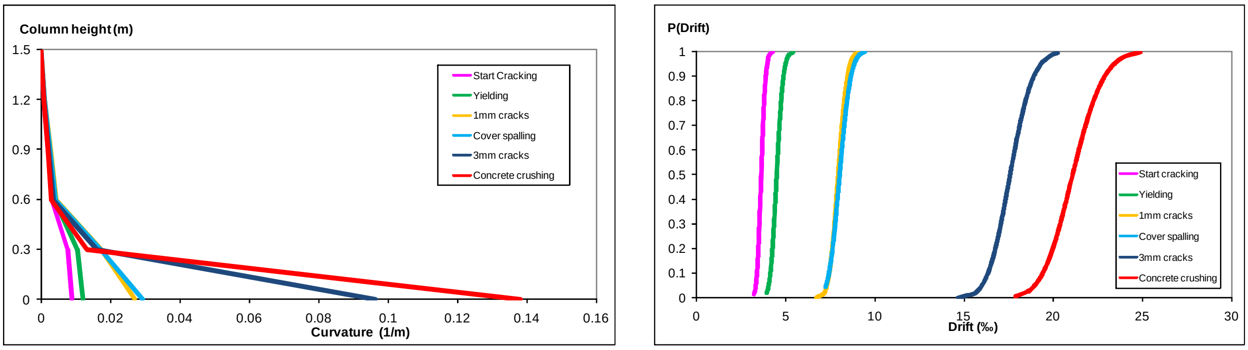


Figure 3 Section curvatures values along the column for various damage states. Fragility curves (axial force ratio ν=0.2) (Botta & Mezzi, 2008).

4.3. Direct cost procedure assessment

Performance groups can be identified within a construction. They are collections of homogeneous components and systems, defined to monitor the damage sustained by the building for a particular earthquake realization. In general, performance groups are pointed out to address specific needs of an assessment. Generally, performance groups include components that will experience the same, or very similar demands, will be damaged by the same type of demand (e.g. interstory drift), will have similar damage states, and have similar fragilities. For each performance group, two or more damage states must be defined. There is always the potential for a "no damage state" and a "complete damage" state. The probability that the components in a performance group will be damaged to a given or more severe state of damage is obtained from the fragility functions. The probability, at a given demand, that the components in a performance group will be damaged to, but not beyond a given damage state, D_i, is given by reading vertically in the fragility curve from the value of the demand and subtracting the probability of exceeding damage state, D_{i+1} from the probability of exceeding damage state D_i. The damage states are defined in terms of either the degree or scope of repair (for direct economic losses and downtime) or percentage of building collapse (for casualty computations). For direct economic loss assessment, a list of required repairs, should the damage state occur, is prepared. This list of repairs, or bill of repairs, depends on the actual physical material quantities comprising all of the components in the group. The repairs that represent the damage states are specific quantities of material and labor required to return the entire group to a pre-event condition. For direct economic losses the consequence function consists of appropriate unit costs, which are dependent on the repair measure quantities tabulated in the total damage state. This function assumes that, for any repair measure, there is a maximum unit cost that applies for quantities up to a limiting lower amount. For greater quantities the unit cost diminishes linearly until a limiting higher quantity is reached. Beyond the higher quantity limit a minimum unit cost applies. The generalized cost function represents a median estimate of repair cost, given a total damage state. Uncertainty associated with contractor efficiencies, market pricing conditions, labor availability and similar factors is represented through a distribution around this median value, represented by the repair cost dispersion. Thus for any set of demands this distribution can be used to treat the unit costs as a random variable.

A simple procedure has been coded in the ambient (Matlab, 2004), allowing for the assessment of direct costs.

The user inputs the exceeding probability of the damage states obtained by the fragility curves computed at the previous step. Once known the column geometry and variability of the repair cost, the code is able to provide for the repair cost and downtime. A sample form of the user interface is reported in Figure 4.

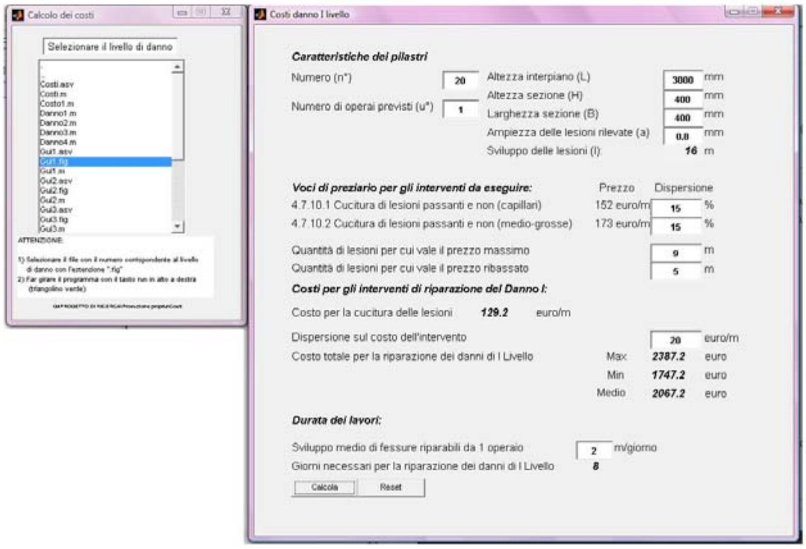


Figure 4 Direct cost and downtime assessment procedure: user interface *(in Italian)*.

CONCLUSIONS

The research project will come to an end in October 2008. In the last three months a collection of reports, final revision and updating will be produced. The research project can be considered positively developed. The knowledge achieved and the product documentation allows the granted graduate paper author to possess new professional skills in economical assessment of seismic protection systems.

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REFERENCES

ATC58 (2005). Guidelines for Seismic Performance Assessment of Buildings. 25%draft. Applied Technology Council

Botta, M., Mezzi, M. (2008). Probabilistic correlation of damage and seismic demand in R/C structures. Int. fib symposium 2008. Amsterdam, Nederland

Matlab - The language of technical computing (2004). The MathWorks, Inc.

Mezzi, M. (1999). Demonstrative Project for the Application of Seismic Isolation in Umbria After the 1997-98 Earthquakes. Intern. Post-SMiRT Conf. Seminar on Seismic Isolation, Passive Energy Dissipation, Cheju, Korea.

OpenSees - Open System for Earthquake Engineering Simulation (2000). Pacific Earthquake Engineering Research Center (http://opensees.berkeley.edu)

Parducci, A., Mezzi, M., Federici, L., Mascelloni, S., Pacchiarotti, A. (2001). The Base-Isolated Buildings of Ierp in Città di Castello. 7th Intern. Seminar on Seismic Isolation, Passive Energy Dissipation , Assisi, Italy