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A mobile laboratory with an expert system for seismic assessment of buildings

M. Cadei, P. Panzeri, A. Peano & P. Salvaneschi
ISMES, Bergamo, Italy

ABSTRACT: A mobile laboratory, provided with a knowledge based system, is presented whose objectives are to support the procedures leading to the seismic assessment of masonry buildings and to suggest possible retrofitting strategies. The architecture of the laboratory and its functions are described with emphasis on the main parts of it: the hardware part, consisting of a vehicle, a special container, experimental equipment and electronic devices; the software part with a knowledge-based system, in particular, implementing models which describe, at different levels of abstraction and with qualitative and/or quantitative attributes, the structure and possible seismic behaviours of buildings.

1. INTRODUCTION

In the last few years, the importance of retrofitting existing buildings in order to obtain a uniform level of safety in case of seismic events has been widely recognized as a major problem in civil engineering.

The procedures required to establish a diagnosis and to suggest a therapy for a single building or for classes of buildings are complex and heterogeneous. They require both theoretical knowledge and practical experience because a building can be examined on the basis of direct observations, *in situ* or laboratory tests and numerical analysis. A rational way of operating requires a step-by-step economical evaluation of the risk related to the particular situation, the information obtainable by new tests and analyses, the improvements obtainable by different possible retrofitting strategies.

This strongly suggests the need for developing a facility to support this cognitive process. It has to help in data acquisition, storage and representation, in modelling, in simulation and evaluation, in decisions about retrofitting and in planning of activities.

2. OBJECTIVES

The objective of the research described in this paper is the design and implementation of a mobile laboratory able to support seismic assessment and planning of retrofitting for buildings.

The mobile laboratory is equipped with devices allowing to perform experimental tests for the acquisition of information related to the physical properties of the materials and to the structural features of the buildings.

The laboratory is also provided with software systems for data acquisition and management and for supporting the evaluation and planning process.

The whole research has been initially oriented to masonry buildings which represent a large part of the historical heritage in most European countries. It has however to be stressed that this research will produce a framework suitable to be extended to other different structural typologies.

3. STRATEGIES FOR USING THE MOBILE LABORATORY

In performing surveys for seismic assessment of buildings, three deepening levels have been identified:

- a first level allows, on large scale, the localization of the higher priority areas;
- a second level increments the needed knowledge and allows a more reliable evaluation. It is applied to smaller areas, localized in general by the first level, identifying higher priority buildings;
- a third level allows deeper detail in the seismic assessment of single buildings and their structural components.

The need in term of input data is greater and greater from the first to the third level. The first and second level require essentially visual inspection while experimental tests are necessary at the third level.

The general strategy leading the evaluation process should therefore consist of applying the evaluation at one level generating results and limiting the target for the more reliable but more expensive next level.

4. THE ARCHITECTURE OF THE MOBILE LABORATORY

The main requirement leading the design of the mobile laboratory was the integration of a knowledge-based decision support system with the test equipment generating input data.

The mobile laboratory, as shown in figure 1, consists therefore of a vehicle provided with a special container divided into two parts:

- a laboratory allowing the execution *in situ* of experimental tests on the materials and structural components and supplied with all the related equipment (also shown in the picture);
- an office provided with electronic devices such as data acquisition systems and a workstation, running the software system, with related peripherals (printer, plotter and so on).

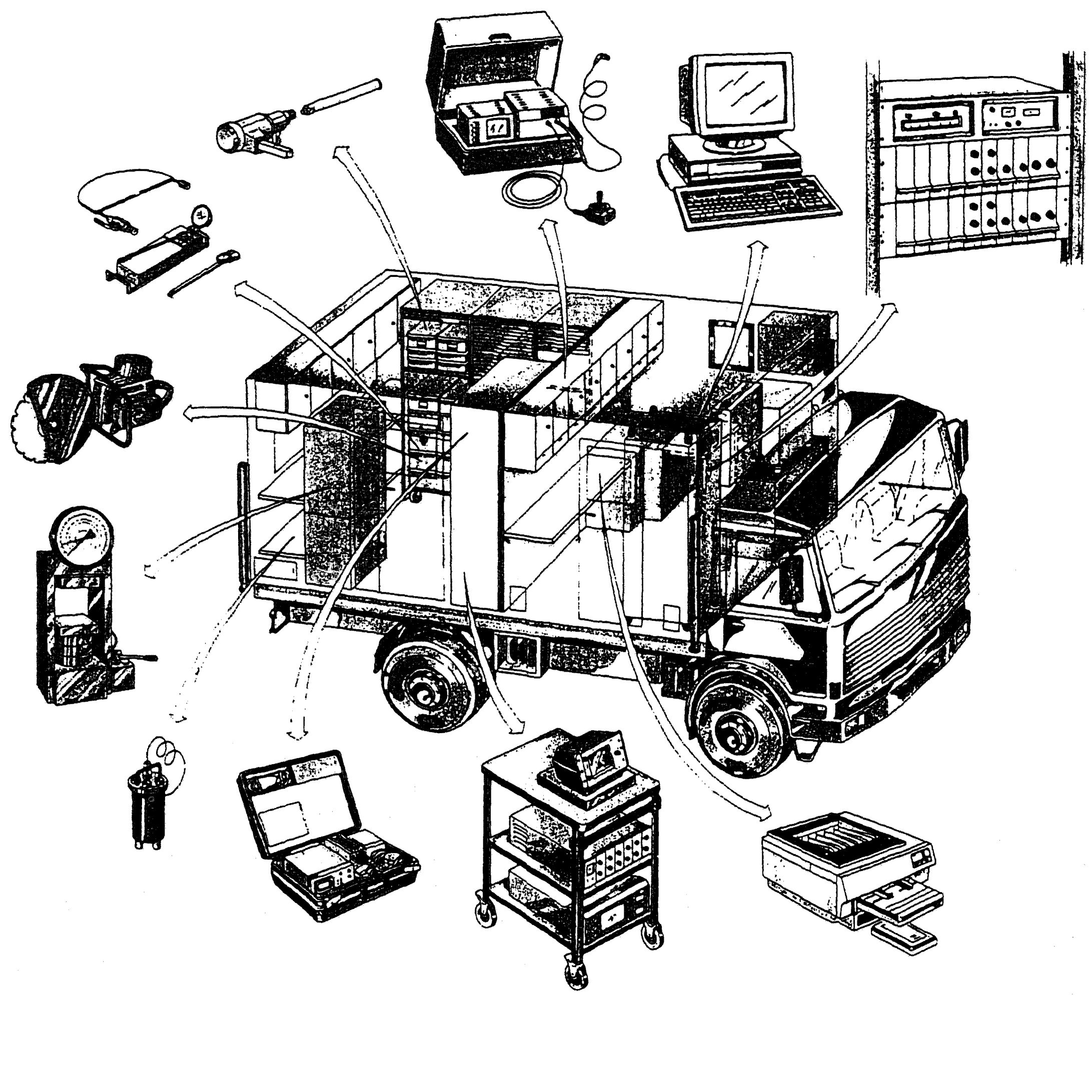
5. THE DATA ACQUISITION AND MANAGEMENT SYSTEM

The data acquisition and management system supports both static tests and dynamic tests (such as vibration test on floors or tie rods analysis) implemented on the mobile laboratory and generating the input data required by the decision support system. It includes a set of tools for reading, processing and presentation of signals and it also offers data base facilities.

Processing functions include statistics, analysis in the time domain and in the frequency domain, fitting, smoothing and filtering.

6. THE KNOWLEDGE-BASED DECISION SUPPORT SYSTEM

The software system, from a technological point of



view, is a hybrid system, mixing knowledge-based systems technology and conventional technology (procedural languages, data bases and man/machine interfaces) and is developed using software engineering techniques. It is built on three main layers:

- *models* of the physical world, collecting knowledge related to a single building or to all the buildings in a village (or a region);
- *functions* on the models, implementing possible operations related to them such as getting information from the real world, simulating a seismic event on a model to generate the expected damage, supporting in planning the use of different models and functions;
- *man-machine interface*, allowing the interaction between the system and the human expert at a proper conceptual level making as easy as possible the control over the decision process he is responsible of.

The relations between the models and the functions are:

- a model (*m*) of a single building and its environment and a model (*M*) of a set of buildings (e.g., a village) are related by a *load/save function* which can move data between them;
- an *input function* allows input of values of the attributes of models and modifying them when more data are available from new observations, measurements and experimental tests;
- an *output function* generates reports and graphical representations of the models;
- a *generalization function* supports generalization of some attribute value of a specific building over classes of homogeneous buildings;
- a *simulation function* allows the simulation of a seismic event on a single building model generating an expected damage on it;
- an *evaluation function*, on the base of the output of the simulation, produces a ranking of the expected damage and an explanation of the structural features of the building responsible for it;
- a *retrofitting planner*, after simulation and evaluation, supports the planning of retrofitting;
- a *planner* supports decision making on the use of different models, data acquisition, evaluation and generalization of results, depending on budget, specific objectives and general seismic protection philosophy. It acts as the control panel of the system, being able of suggesting a strategy and activating all the functions.

Object oriented modelling is the base technique used in designing the software system implemented in C++ language and the shell NExpert Object on a SUN workstation.

In what follows, some detail is given about the employed modelling technique and the most important components of the software system.

6.1. State of the art in modelling masonry buildings

From the modelling point of view, the development of finite-element methods and the improvement of computer performance have allowed the analytical solution of complex civil engineering structures. Unfortunately, this is easily obtained only if a linear elastic behaviour of the structural elements is assumed. Moreover, computer programs which can deal with simple non-linear behaviours, as needed in seismic modelling, do exist, but the difficulties in getting the correct constitutive parameters are great. The results are therefore less reliable, more specialized users are required and, at the same time, the needed computer resources and the possible numerical difficulties significantly increase.

Masonry buildings are particularly affected by such situation, since the description of their geometry is less complex than the constitutive equations of the structural elements and of their interactions. The modelling of masonry buildings through finite-element analysis is therefore very complex or totally unsatisfactory.

The necessity of evaluating the seismic performance of large numbers of existing masonry buildings has therefore given a strong impulse to the development of associational/empirical expert systems. These, however, only represent a part of the knowledge needed to solve this kind of problems so that second-generation expert systems are trying to represent causal knowledge too (the so-called *deep knowledge*) (Chandrasekaran & Milne 1985).

In fact, engineering reasoning takes advantage of both associational/empirical knowledge and knowledge coming from domain theories, expressed using numerical procedures. Moreover, the engineer's evaluation is based on two key elements:

- *hierarchical reasoning*: reasoning with hierarchical models of systems;
- *causal mechanisms*: empirical knowledge and domain theories and both qualitative and quantitative information are used and interpreted in the context of causal mechanisms modelling the system behaviour.

These different types of knowledge have to be integrated (Fenves 1989).

The approach of model based reasoning and the work done in the area of reasoning about physical systems (Bobrow 1984; Chandrasekaran & Milne 1985) and cooperation between different types of knowledge and reasoning agents can be used as a basis for the integration.

6.2. The modelling technique

The formalization of the models for a single building required the development of a specific modelling technique and of the associated interpretations.

The key idea is that engineering hierarchical reasoning is based on causal mechanisms that can be generated by partitioning the space into discrete objects and the behaviours into discrete interacting processes on the base of the relevance principle (Forbus 1990). Within this framework, different modelling techniques (from associational/empirical models to finite elements methods) can be integrated.

A model of a physical system (a building) collects the knowledge related to:

- *structure*: describing its subsystems and relations (*is-connected-to* and *is-part-of* relations) between them;
- *attributes*: describing physical quantities and their values;
- *behaviours*: describing modifications of the structure and the values of attributes in time.

Each type of knowledge can be organized in a hierarchy, with different levels of abstraction:

- a structural hierarchy describes, at first, the system as a whole and then, in more detail, as a set of subsystems, parts of subsystems and so on;
- a hierarchy of attributes, moving from one level to another, can add more quantities or move from a qualitative to a quantitative description of (some of) them;
- a hierarchy of behaviours represents, at the top level, purely associative models and, at the lowest levels, very complex descriptions of causal mechanisms relating processes in different subsystems.

A combination of one level from each hierarchy is a model (*simple model*) of the physical system.

An *extended model* is a set of (more then one of) these simple models with dependencies among the values of attributes related to them. In it, the modelled system is simultaneously represented at different levels of abstraction. It allows to deal with incomplete knowledge or with the impossibility of using one abstraction level due to too much detail at lower levels and/or impossibility of describing all the processes of interest at higher levels.

In our modelling formalism, the structure is modelled by instances of subclasses derived from three classes (in the object oriented modelling sense):

- *elements*, representing subsystems (e.g., walls);
- *connections*, representing physical connections between subsystems;
- *interfaces*, representing contact parts, having their own attributes and behaviours, between subsystems (e.g., wall-floor interfaces).

Both elements and interfaces belong to the *components* super class and have attributes and behaviours.

Stimuli (e.g., a force) are a class of attributes which, at a definite time, can be marked by a *token* (a value is present) or not (no value), while *properties* (e.g., a friction coefficient) are attributes always having a value.

It is possible to express dependencies between the values of different attributes, even belonging to different components and different simple models in the same extended model, so that, changing one of them, the other is immediately modified too. That allows description of physical laws and representation of quantities at different levels of abstraction.

Behaviours are modelled so that each component expresses one or more *processes* (e.g., a process modelling the shear sliding of a wall) which can be activated by stimuli and influenced by properties. Each process is characterized by:

- a *precondition on the existence of input stimuli*;
- a *precondition on the values of input attributes*;
- a *body*.

When the preconditions are true (some cause is present and some threshold is overcome), the process can start, removing the tokens from input stimuli and executing the body. This is a computation, expressed, in general, by a mix of associational/empirical rules, procedures and calls to external programs, generating new stimuli and values of properties. In such a way, associational/empirical and procedural knowledge can be mixed and quantitative and qualitative computations can be mixed as well.

A process can be graphically represented as a rectangle, while stimuli and properties are circles connected to them by oriented arcs representing input and output relations. The result of linking different processes is a net embedded in the components. Starting from a set of initial stimuli, the net can be run simulating the system behaviour (from an earthquake to a damage).

6.3. The models of a single building

Three models of a single building, at different levels of abstraction, have been created.

The first and second models respectively correspond, as concerns input data, to the first and second vulnerability assessment forms by the Italian Gruppo Nazionale per la Difesa dai Terremoti (CNR/GNDT 1986).

6.3.1. Model 1

The building is modelled as one element and the description of both the seismic action and the building attributes are totally qualitative.

The seismic input is defined by the seismic zone coefficient while the properties used to characterize the building response are:

- date of construction in relation with the date of enforcing a seismic design for the site of the building;
- materials and construction typology;
- regularity of the geometry of the building;
- damage from previous earthquakes.

The expected damage is qualitative (*low damage*, *medium damage*, *high damage*) and evaluated on the basis of associational/empirical rules.

6.3.2. Model 2

The seismic input is defined by a peak acceleration obtained from catalogue data.

The building is conceived as one element: a box-like behaviour is assumed and the total shear resistance is compared with the expected horizontal force.

The ability of the building to act as a rigid body is also checked: any structural situation which is not likely to allow a rigid body motion is considered to be a possible cause of unreliability of the model.

6.3.3. Model 3

This is an extended model so that the building is simultaneously modelled at three abstraction levels. It provides a very detailed description of the non-linear mechanical behaviour of the structural elements and the connections between them. That allows the analysis of damage processes inside single elements and the generation of a diagnosis in term of structural features and physical properties of the materials responsible for them.

At the first level, the building is modelled as one element and the associated behaviour assumes a one-degree-of-freedom model.

At the second level the building is modelled as composed by macro elements (one component for the foundation, each wall, floor and the related interfaces).

At the third level each wall is described as composed by end-walls (between floors).

The processes at level 2 and 3 model the transmission of motion and energy through the components and phenomena as amplification or attenuation of motion and energy dissipation (from the point of view of the excitation or acting stimulus) and damage to structural elements (equivalent to energy dissipation from the point of view of the building). Examples of damage processes are, related to the in-plane behaviour of a wall, flexural cracking, shear cracking, shear sliding and rocking.

The simulation is started by putting values into the earthquake attributes of the *geological structure* and these stimuli are propagated through the first abstraction level. The resulting effects related to the *building* are inherited, through attributes dependencies, by the building components (level 2) and the simulation goes on.

When some damage process is activated, according to the time ontology (event to event search), the simulation is stopped and the resulting properties in the lower levels are summarized, through dependencies, to the upper levels. For example, when a damage process is activated in a *wall*, the stiffness property of the *building* is changed too.

The simulation is run several times (each time starting from the previously generated status) and the end is reached when a steady state motion is reached, either because of the low level of the forces developed by the input acceleration or because of convergence between the input and the dissipated energy (see Salvaneschi et al. 1990 for more details).

Regarding to the time modelling, the *event to event* research method has been applied. In this ontology, when a simulation on the model is started, no time interval elapses until a significant event (a damage) is reached. The *first* event is not necessarily the first to happen in time, but rather the one which requires the lowest *load multiplier* (in a sense, it is the most probable).

6.4. The retrofitting planner

After simulation and evaluation, this function supports the choice of the best intervention techniques in term of lowest cost/performance ratio and of feasibility of the implementation (depending on the structural features of the building and its geographical position).

6.5. The planner

With a certain model, it is possible to evaluate the expected damage, the seismic risk and the cost of possible intervention for a building. At a poor knowledge level, however, the worst situation has to be considered as true so that there it is possible that a more refined evaluation, based on a more detailed model, may allow a lighter intervention. The probable economical savings which can be obtained have therefore to be compared with the costs, in terms of new inspections and experimental tests, of the knowledge needed by the refined model.

The first task of the planner is supporting the use of the models on the base of the principle of minimizing the probable total costs.

The second activity of the planner consists of suggesting the best strategy to be followed on the whole depending on the objectives of the survey, the budget and the available data (number of buildings, expected damage, computed risk, etc.).

7. EXPERIMENTAL EQUIPMENT AND TESTS

The key issues in selecting the experimental tests provided by the laboratory were:

- to generate all the input data required by the seismic assessment software, particularly model 3;
- to ensure reliable and really interesting information;
- to provide quick and low costs tests and analysis;
- to limit weight and volume of related devices;
- to limit electric power required;
- to allow execution of the tests on site, particularly on a building in an old urban nucleus.

Table 1 shows the list of the experimental tests provided by the mobile laboratory and their relation with the physical parameters directly or indirectly estimated.

Some information are generated by more than one test allowing different strategies to be employed in different cases depending on the structural features of the building and the operative conditions. Sometimes, nevertheless, redundant tests will be needed in order to ensure maximum reliability of data.

Table 1. Experimental tests provided by the mobile laboratory.

TEST	PHYSICAL PARAMETERS / STRUCTURAL FEATURES
flat-jack test	state of existing stress, longitudinal elastic modulus, Poisson ratio, compressive strength
shear test along the mortar layers	shear strength of mortar-masonry joint, friction angle, masonry cohesion
centered compression on a panel	compressive strength of masonry, longitudinal elastic modulus, Poisson ratio
diagonal compression on a panel	tensile strength of masonry, shear modulus
hammer test on the mortar layers	compression strength of mortar layers
Bond-Wrench test	flexural tensile strength
compression of a brick (or core)	strength in compression of bricks (or cores)
point load test	tensile strength of bricks or mortar layers
vibration test on floors	in plane floor rigidity, floor-walls connection effectiveness
static load test on floors	floor-walls connection effectiveness
tie rods analysis	effectiveness of tie rod tension
sonic test	presence of anomalies, areas of deterioration, voids, crumbling
thermography	test of the internal structure (arches, beams, hidden openings, chimneys...)
endoscopy	internal structural characteristics, voids and fissures in the masonry
removal of panels from the site then shear-compression test in a laboratory	shear strength of masonry, tangential elastic modulus

8. CONCLUSIONS, CURRENT AND FUTURE DEVELOPMENTS

The need of support to the seismic assessment and retrofitting of buildings is dictated by the complexity of the problem and by the heterogeneity of the involved knowledge. A mobile laboratory being developed for this purpose has been presented. It integrates a knowledge-based decision support system with equipment for data acquisition about structural features and properties of the materials.

As regards the software system, the modelling technique, the simulator, the models and a part of the user interface have been implemented, while other components of the system (the evaluator, the retrofitting planner, the model of groups of buildings and the output function) are under development. The models 1 and 2 are being tested on about 1000 masonry buildings and the model 3 is being tested comparing the results with data obtained by laboratory tests. These are performed, on a *shaking-table*, simulating an earthquake on scale masonry buildings.

The uncertainty aspects of the knowledge and the evaluation process have been up to now ignored, but they will be one of the fundamental tasks to be faced in the future development of the research, together with the extension to other kinds of buildings and structures such as reinforced concrete frame buildings and bridges.

The implementation of a prototype of the whole mobile laboratory has been activated and a laboratory test of the equipment and software is scheduled. It will be followed by a final check on site.

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