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Towards a knowledge-based system for seismic assessment of buildings

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A knowledge-based system, whose objectives are to support the procedures which lead to the seismic risk evaluation of buildings and to suggest possible retrofitting, is presented. The system architecture and its principal functions are described, with emphasis on the main part of the system: a model ("artificial world") which describes the structure and possible behaviors of the building and its environment, at different definition levels, with qualitative and/or quantitative attributes.

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.

The procedures required to establish a diagnosis and to suggest a therapy either for a single building or for classes of buildings, characterized on geographical bases or on the basis of common attributes, are complex and heterogeneous, requiring either theoretical knowledge and practical experience. A building can be examined on the basis of direct observations, in situ or laboratory tests and numerical analysis, and subsequently retrofitted; but a rational way of operating would require a step-by-step economical evaluation of the risk related to a vulnerable situation, the improvements obtainable by different possible interventions, a deeper knowledge obtainable by new tests and analyses.

For this kind of application, research and development in the expert-systems field initially produced associational/empirical systems (based on the so-called "shallow" knowledge).

This knowledge represents only a part of the knowledge needed to solve problems in many fields (civil engineering is among these). Limits and problems of first-generation expert systems have been clearly stated [8]. Second-generation expert systems are trying to combine associational/empirical knowledge and causal algorithmic knowledge (the so-called "deep" knowledge) [3].

This objective is pursued by the system described in what follows, through the creation of a model of the real world (an "artificial world" [5]) which has its own structure and can exhibit behaviors. Structure and behaviors are hierarchically defined at several depth levels [2].

OBJECTIVES AND KEY ISSUES

The objective of the research described in this paper is the design and implementation of a knowledge-based system with the following main features:

1. To support the evaluation of seismic risk and to suggest possible retrofitting interventions, both for single buildings and for classes of buildings.
2. To support data acquisition (planning surveys, measurements, and tests), and management (storing of information, generalization of knowledge from a specific building to groups of buildings).
3. To exert control over the use of a "movable laboratory" endowed with experimental and numerical facilities.

In a first phase of the project, the whole system will be oriented only to masonry buildings, and afterward extended to reinforced concrete buildings, monuments, lifelines, and so on.

The key issues of the research are synthetized in what follows:

1. Empirical/associational and causal knowledge and

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both qualitative and quantitative modeling are needed and have to be integrated.

2. The knowledge has to be organized in a hierarchical way: deeper levels of knowledge lead to deeper reasoning and more detailed and accurate conclusions. This is a common way of thinking for engineers.
3. The system architecture has to explicitly represent a hierarchical model of the world of interest and a set of reasoning agents working on the model.
4. From a technological point of view, the system development will lead to a hybrid system, mixing expert-systems technology, conventional technology (procedural languages, data bases and man/machine interfaces), and software engineering techniques. The aim is to build an industrial product able to help in solving a complex problem.

SYSTEM ARCHITECTURE

The system is built on three main layers (Figure 1):

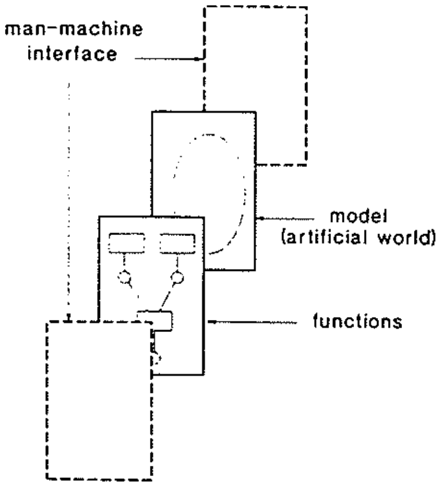
1. model or artificial world;
2. functions;
3. man–machine interface.

The artificial world depends on the situation or case to be dealt with. For example, it may be the model of a building, endowed with all of the "shallow" and "deep" knowledge on structure and behavior of the building itself, if the objective is the evaluation of the seismic risk of that single building, but it may represent the buildings of a village (or of a region) on the whole, as well.

The functions are possible operations related to the artificial world. Examples of functions are

getting information from the real world to refine the model;
simulating a seismic event on the model to evaluate the expected damage.

FIGURE 1. System architecture.



The man–machine interface allows the interaction between system and operator providing transparency to model and functions.

The structure of the artificial world and the related functions are shown in Figure 2:

1. The "artificial world *m*" is a model of a single building and its environment, while the "artificial world *M*" models a set of buildings, e.g., a village.
2. "*M*" and "*m*" are related by a load/save function which can move objects from one to the other and vice versa.
3. The "simulation function" can execute the model generating some damage from an earthquake.
4. The "evaluation function" gets information from "*m*" to produce a risk evaluation, with explanation, together with a list of possible improving interventions and their estimated cost.
5. The "updating function" modifies the attributes of the model "*m*" when more data are available from observations, measurements, and experimental tests.
6. The "output function" allows outputs for the representation of "*M*."
7. The "generalization function" generalizes some attribute value of specific buildings over whole classes (or subclasses) of buildings.
8. A "planner" makes decisions on the needed data acquisition, evaluation, testing, numerical analysis, and generalization of results, depending on budget, specific objectives, and general seismic protection philosophy. In other words, the planner acts as the control panel of the system, being able of suggesting a strategy, activating all of the system functions and collecting information related to the plan of action (through commands C1–C5 and status S1–S5 in Figure 2).

In what follows, some detail is given about the most important components of the system.

THE BUILDING MODEL

The building model collects the knowledge related to

the structure (e.g., the building elements and their relations);
the attributes (e.g., values coming from visual inspections, measurements, and tests); and
the behaviors (e.g., the physical processes related to the elements).

The model is built in a hierarchical way at different levels of abstraction and is able to be executed by a simulator.

A detailed description of the model will be given in the following sections:

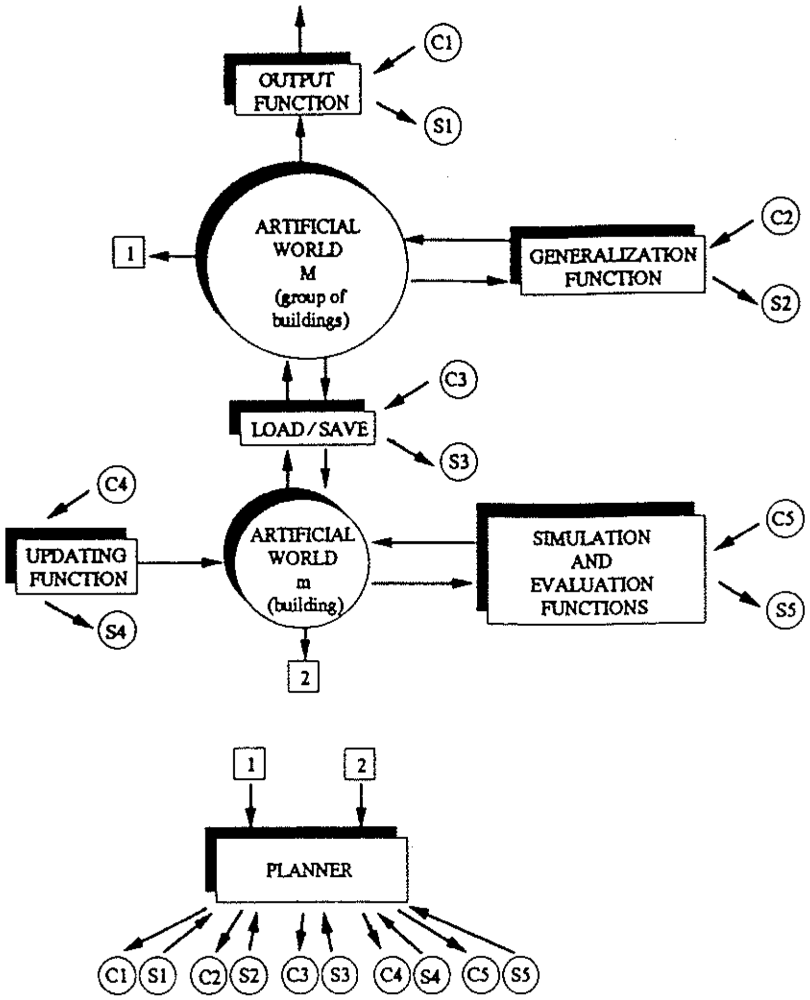


FIGURE 2. Artificial worlds and functions.

THE MODEL OF A GROUP OF BUILDINGS

A group of buildings is modeled as instances of classes of objects.

The classes are organized in a hierarchy where the more general class represents the generic building and subclasses represent building types.

Each single building is seen as a specific instance of one of the building types.

Class, subclasses, and instances are related through inheritance mechanisms.

All of the objects in the hierarchy have the same potential structure, attributes, and behaviors of the building model *"m."*

THE GENERALIZATION FUNCTION

The generalization function can spread the value of some attribute of specific buildings over whole classes or subclasses. This can be performed on statistical bases (when some information is available only for some building in a class, mean values can be generated and attributed to all other buildings) or on deterministic bases (if an expensive experimental test has been performed on a building, some results may be attributed to other buildings recognized by a generalization algorithm).

THE SIMULATION AND THE EVALUATION FUNCTIONS

The fundamental approach followed in the risk assessment is the separation between simulation and evaluation.

The simulation activity has the task of applying a seismic event to a building model to produce a possibly damaged model.

The evaluation activity is more complex, because it has to give a judgement on the output of the simulation activity. This implies some definition of undesirable states, some definition of the distance between the present state and such limit states, and some translation into economical values of such distances (social, historical, and moral considerations are influencing this translation).

The evaluation has therefore to be performed through the following steps:

1. Simulating a seismic event with the effect of generating new values of attributes.
2. Giving a judgement on the resulting damage in a gravity scale.
3. Giving a judgement on the safety level (distance), in a safety scale, taking into account the attributes of the social–economical system.
4. Discussing the judgements on the basis of the causal mechanism which generated them. The discussion is obtained going backward through the simulation. The discussion is important either to make possible to a human expert to check the "way of thinking" of the expert system and to give elements for another discussion, addressed at the next point.
5. Suggesting possible interventions with their approximate (average) cost, using suitable bases of knowledge. The need of interventions is also discussed by comparing their cost with the cost of the expected damage, in terms of cost of repairing. It has to be kept in mind that different costs of retrofitting interventions might correspond to the same level of expected damage (depending on the damage mechanism).

THE PLANNER

The planner has two main functions: the first one is related to the use of the artificial world "*m*", and the second one is related to the general strategy of the activities.

It has already been discussed that at a certain level of the model, it is possible to evaluate the expected damage, the seismic risk, and the cost of possible intervention.

It is obviously possible to obtain a more refined evaluation of all of them by new inspections, and/or experimental and/or numerical tests, but any possible refinement has a cost which can be quantified by entering the appropriate base of knowledge. Therefore the problem consists of deciding what is the benefit obtainable from a deeper knowledge in terms of probable reductions in the cost of the retrofitting interventions.

The main concept is that, at a poor knowledge level, the worst possible situation has to be adopted as true. On this basis, there is the possibility that an increment of knowledge may allow a lighter intervention. Therefore the probable economical saving which can be obtained (evaluated by running again the simulation with a different starting situation) has to be compared with the cost of the new knowledge.

In conclusion, the use of the artificial world "*m*" is governed by the principle of minimizing the probable total cost.

A secondary but important activity within this function consists of giving suggestions on the more suitable models depending on the available data (geometry, materials, stiffness, mass, connections, etc.).

The second function has the purpose of suggesting the best strategy to be followed on the whole depending on objectives of the survey, budget, and again available data (number of buildings, expected damage, computed risk, etc.). Clearly the strategy may be modified at each step of the procedure.

An example of a simple initial strategy might be as follows:

1. Perform a survey of all of the buildings, getting only qualitative attributes.
2. Run simulator and evaluator using the model at the simplest level.
3. Exclude the buildings with very low and very high risk from future testing (the meaning of "very low" and "very high" depends on the budget).
4. Get more information for the other buildings.
5. Generalize information.
6. Run simulator and evaluator at deeper levels.
7. Choose the buildings on which it is more convenient to get more information on the basis of cost/benefit evaluation (the number of the buildings depends on the budget).
8. Repeat steps 4–7 until a certain level of reliability of the evaluation is reached or until no more funds are available.
9. Generate the final output.

THE ENGINEERING CONTENT OF THE BUILDING MODEL

The core of the system is the multilevel model of a building.

In what follows, the engineering content of the model will be discussed in the context of the current state of the art.

STATE OF THE ART IN MODELING MASONRY BUILDINGS

In the last fifteen years, the development of the finite-element method and the improvement of the performance of the available computers have allowed the analytical solution (i.e., definition of the deformed shape and of the stress field) of complex and huge structures described in detail for what concerns geometry.

Unfortunately, this is easily obtained only if a linear elastic behavior of the structural elements is assumed. Computer programs which can deal with simple non-linear behaviors do exist, but the difficulties in getting the correct constitutive parameters greatly increase. The results are therefore less reliable and more specialized users are required. At the same time, the needed computer resources and the possible numerical difficulties significantly increase.

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

The necessity of evaluating the seismic performance of large numbers of existing masonry buildings has given a strong pulse to the development of simple models based on the empirical or intuitive evaluation of a series of favorable or unfavorable conditions combined with some rough estimation of the basic structural relation "strength > loading."

Examples of such methods are given in Refs. 1, 4, and 6; their basic philosophy can be summarized as follows:

1. The building is assumed to act as a rigid body.
2. A simple evaluation of the seismic vulnerability is given by the ratio of the total mass of the building and the total shear strength (the estimated strength multiplied by the total area of the masonry).
3. A check list is then compiled to evaluate the real ability of the building to behave as a box; examples of the items to be checked are

   quality of the connections between orthogonal walls;
   quality of the connections between floors and walls;
   and regularity in plan and in elevation.

4. The seismic vulnerability is eventually empirically evaluated through summations or products of the basic seismic coefficient (item 2) and of secondary coefficients (item 3) weighted by suitable factors.

Such methods are more appropriately used for vulnerability surveys of villages, urban areas or whole regions: their significance for what concerns each single building is debatable. Nevertheless, the attempt of somehow catching the physical behavior of the building is valuable and gives the hint for the development of more refined models where the accent is put on the comprehensive representation of the physical behavior rather than on a refined numerical description of the geometry of the building.

A PHYSICAL MODEL FOR MASONRY BUILDINGS

The model to be developed had to satisfy a series of requirements:

1. To allow many different levels of simulation, depending on the available knowledge and on the desired reliability of the results.
2. To maintain a clear physical meaning at any level of simulation.
3. To be able to mix quantitative and qualitative descriptions of the structural behaviors.

Three model levels have been presently implemented, with the following features.

Level 1

The descriptions of both the seismic action and the building are totally qualitative and based essentially on catalogue data.

The seismic input is defined by the seismic zone coefficient.

The parameters 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 building geometry; and
damage from previous earthquakes.

The seismic risk is evaluated on the base of empirical/associational rules.

Level 2

At this level, qualitative knowledge and behaviors descriptions are used to modify some simple quantitative evaluation of the seismic risk.

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

The building is conceived as a whole characterized by adjectives attributed to its structural elements: this level is similar, for what concerns data, to the method described in the previous section (a box-like behavior is assumed, the total shear resistance is compared with the expected horizontal force, and the ability of the building to act as a rigid body is checked).

The seismic risk is not evaluated through empirical-weighted summations or product, but discussing the most probable real response. In other words, any structural situation which is not likely to allow a rigid body motion is considered to be a possible cause of increased damage.

Note that, at this level, the adequacy of the model to represent the real building behavior can be directly evaluated by the planner.

The planner is therefore able to suggest if it is more convenient to use a more refined simulation or to retrofit some part of the building.

Level 3

The seismic input is defined by the peak acceleration, and two sets of response and input energy spectra, both as functions of the global displacement ductility. The use of the energy spectra is fundamental because for masonry buildings the duration of the seismic event is of great importance, even if low-peak accelerations are involved.

The overall response of the building is examined at first by considering the first period of vibration, as resulting from the reacting mass (mass of the longitudinal walls plus mass of floors and transversal walls as a function of the quality of wall-to-floor connections) and the gross stiffness of longitudinal walls.

A bilinear vertical distribution of the horizontal acceleration is assumed, defined by the ground acceleration, the acceleration of the center of mass as resulting from the previous point, and the top acceleration obtained by linear extrapolation, connecting the acceleration of the center of mass and the point of zero acceleration at the ground level.

The acceleration at each floor level is therefore obtained.

For each story high-wall, the possible damage is assessed.

The response of each floor is then examined, as a function of the ratio of floor to wall stiffness and of the quality of floor to wall connections.

The response of transverse walls is finally taken into consideration with the input accelerations obtained for each floor level (Figure 3).

Each of the steps enumerated may involve such 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 events (limit states) involving such phenomena are

flexural cracking, shear cracking, shear sliding, rocking for the in-plane behavior of walls;

flexural cracking, out-of-plane expulsion for the out-of-plane behavior of walls; and

frictional sliding or failure for wall-to-floor connections.

Each event is associated with a damage, a deterioration of strength, a deterioration of stiffness, and a local and a global ductility demand.

The sequence is therefore run several times, on an event-to-event research basis: the first (most probable) event is found; both the structure characteristics and the selected seismic spectra are changed, and the simulation is run again.

The end of the simulation is reached when a steady-state motion is expected, 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.

THE FORMAL REPRESENTATION OF THE MODEL

The formalization of the engineering model required the development of a specific modeling technique and of the associated interpretations.

The key idea is that engineering hierarchical reasoning is based on causal mechanisms. Causal mechanisms are generated by partitioning the space into discrete objects and the behaviors into discrete interacting processes. Within this framework, different techniques to model processes (from empirical/associational models to FEM) can be integrated.

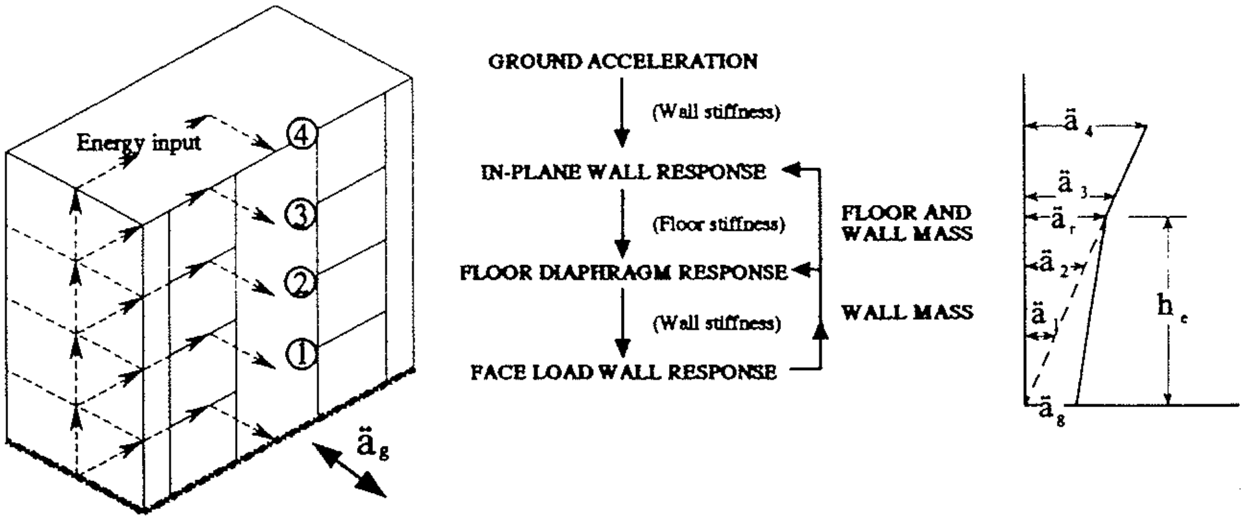


FIGURE 3. Basic assumptions for the definition of the response of a masonry structure.

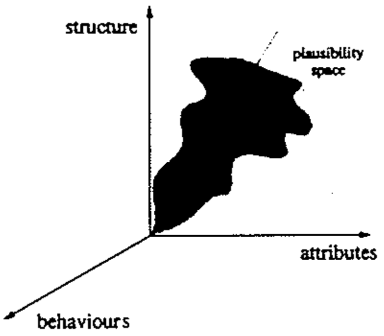


FIGURE 4. The three-dimensional space of the model.

THE MODELING SPACE

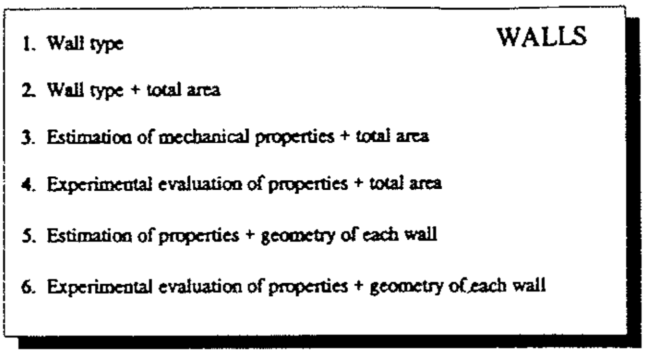
A system model collects the knowledge related to

structure (components and connections);
attributes (whose values are obtained from measurements and tests); and
behaviors.

Each type of knowledge can be organized in a hierarchy resulting in a three-dimensional modeling space (Figure 4) where a specific model can be represented by a point (or a set of points). Different points are characterized by the fact of having more or less information, of using a more or less refined structure, or of simulating a more or less complex behavior.

Generally, any improvement requires the investment of funds, either to acquire or to manipulate more information.

Obviously, it is not possible to reach any desired point in the space, but restrictions do exist (e.g., a numerical simulation might require certain quantitative data), so that suitable strategies are needed to govern the movement within a plausibility space.



WALLS

1. Wall type
2. Wall type + total area
3. Estimation of mechanical properties + total area
4. Experimental evaluation of properties + total area
5. Estimation of properties + geometry of each wall
6. Experimental evaluation of properties + geometry of each wall

FIGURE 6. A hierarchy of attributes.

The evaluation function can be applied to any plausible point in order to produce risk assessment and a discussion of the interventions.

Figures 5–7 show examples of possible hierarchies along the three axes of the modeling space.

For the specific application three models have been implemented (Figures 8–10). These correspond to the three levels described earlier.

MODELING STRUCTURE AND ATTRIBUTES

The structure is modeled by components and connections where components are classified into elements (e.g., walls) and interfaces (e.g., wall–floor interfaces).

Components have attributes and values and are organized in classes (e.g., the class of walls) and instances (e.g., a specific wall).

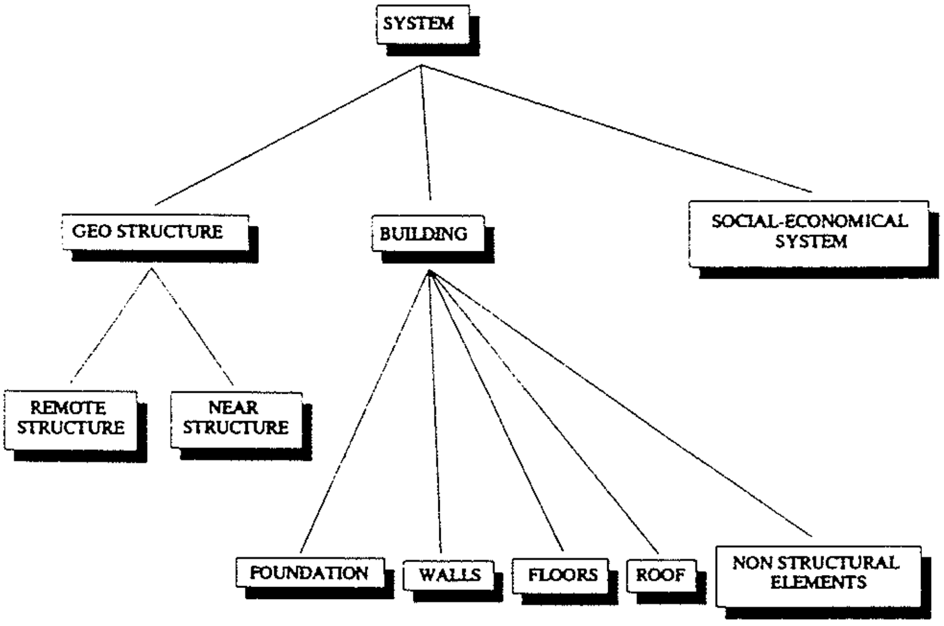


FIGURE 5. A structure hierarchy.

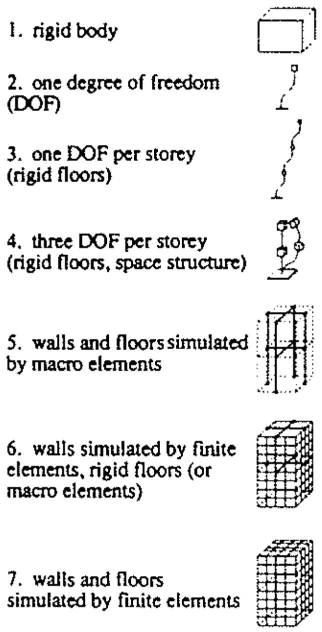


FIGURE 7. A hierarchy of behavioral models.

Connections express possible physical connections between components.

MODELING BEHAVIORS

Each component can express one or more elementary processes (e.g., a process modeling the shear sliding of a wall), which can be activated by stimuli (e.g., a force). When a process is activated, its behavior can be influenced by properties (e.g., friction coefficient) where stimuli and properties are both component attributes.

An elementary process can be graphically represented as a rectangle, whereas stimuli and properties can be represented as circles and connected with oriented arcs representing input/output relations.

The resulting graph can be interpreted in a way similar to a Petri Net [7] where each process contains

a precondition on the existence of input stimuli;
a set of predicates on values of input properties and stimuli; and
a body.

When the precondition and the predicates are true, the process can start, removing the input stimuli and executing the body.

The body can be a set of empirical/associational rules (e.g., the process in the component "building" at Level 1), or a mixing of procedures, rules, and calls to external programs.

In such a way, empirical/associational knowledge can be mixed with causal knowledge and quantitative and qualitative computations can be mixed.

The execution of the body can generate new stimuli and properties values.

The result of linking different elementary processes is a net of processes embedded into the components (e.g., Figure 11). Starting from a set of initial stimuli, the net can be run simulating the system behavior from an earthquake to a damage.

SIMPLE AND EXTENDED MODELS

Both the Level 1 and 2 models represent a point in the structural axis of the modeling space. Note that the Level 3 represents three contiguous points (we define this type of model as "extended model") where the building is simultaneously represented at three levels of abstraction and the simulation runs across the levels.

COMMUNICATION BETWEEN MODELS

Different models can communicate through inheritance functions and synthesis functions.

Using inheritance functions, a more detailed model can inherit attribute values from a less-detailed model, whereas through synthesis functions, attribute values can be summarized and communicated from a more detailed to a less-detailed model.

Similar functions do exist, between different abstraction levels, in extended models not only to communicate property values but also to communicate stimuli.

At Level 3 (Figure 10), for instance, the simulation runs from the upper to the lower abstraction level (through stimuli inheritance) with a predefined path, and the resulting modifications of building status are synthetized to the upper level (through synthesis functions).

TIME ONTOLOGY

The problem of dealing with time when a seismic event is simulated through static relations is obviously a difficult task which can be faced only by defining a different ontology of time.

In regard to this, the well-known event-to-event research method has been applied: of course 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).

Another problem related to time, which has been previously addressed, is the need to take into account the earthquake duration. This has been done by considering the input energy spectra, which can be regarded as an integral of the product of ground acceleration, building mass, and building velocity over time.

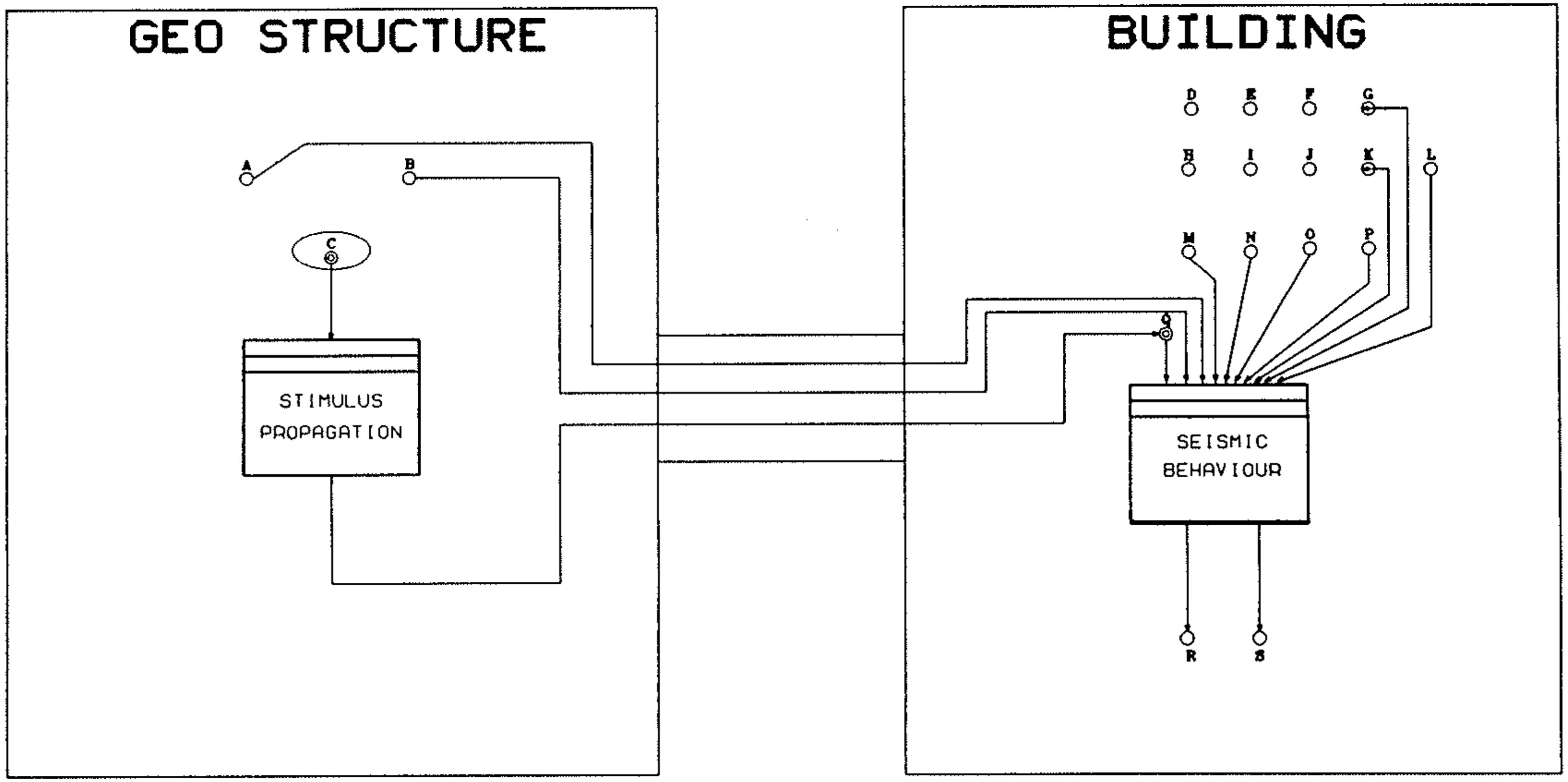


FIGURE 8. The model—level 1: A, date of seismic assessment; B, seismicity; C, earthquake; D, wall quality; E, wall damage; F, wall damage extension; G, wall behavior; H, floor quality; I, floor damage; J, floor damage extension; K, floor behavior; L, roof quality; M, building age; N, intervention type; O, intervention age; P, elevation regularity; Q, earthquake; R, vulnerability index; and S, damage index.

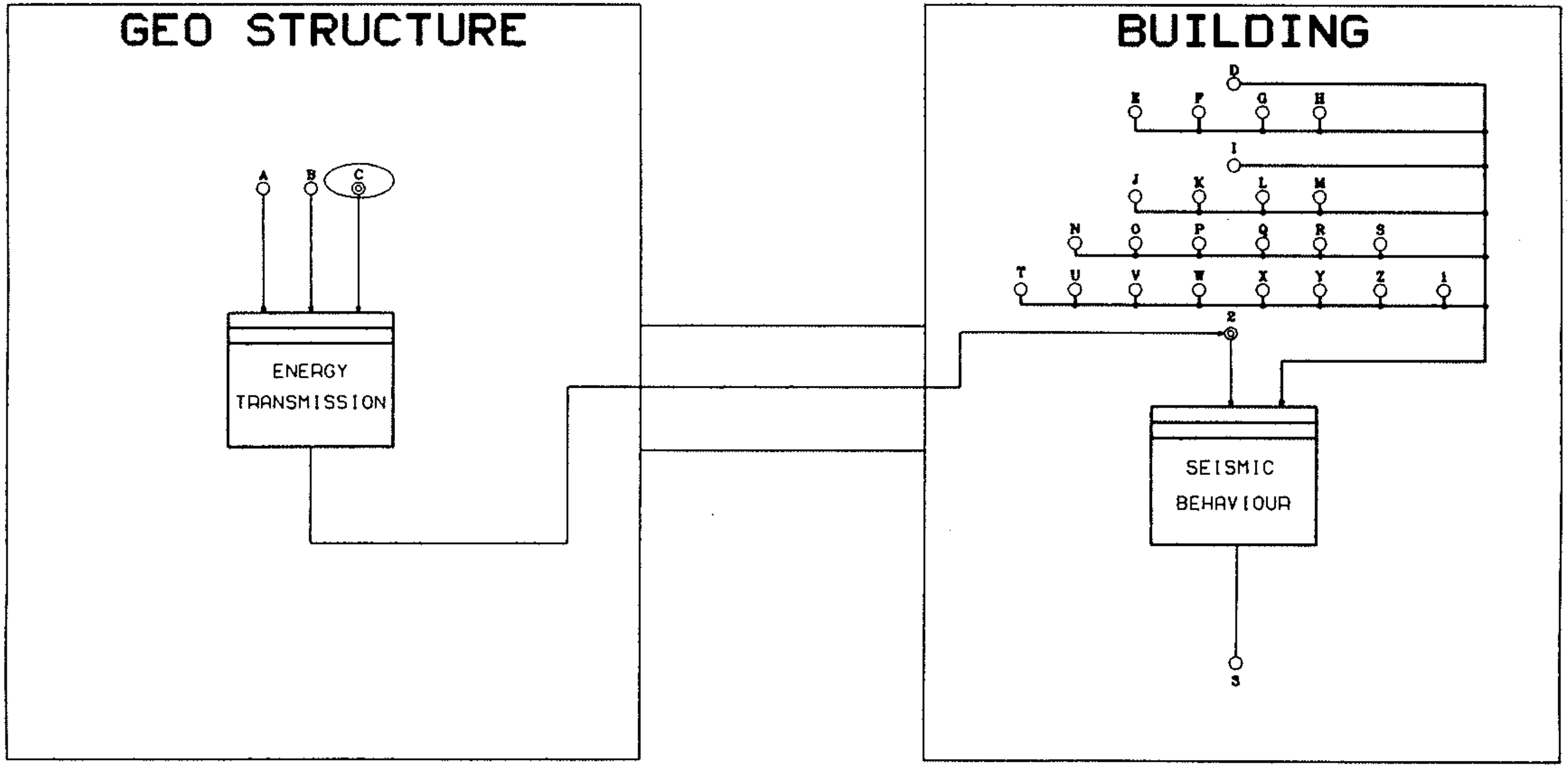


FIGURE 9. The model—level 2: A, seismicity; B, soil type; C, earthquake; D, max. difference of foundation height; E, x area; F, y area; G, shear resistance; H, masonry density; I, wall–floor connection quality; J, floor type; K, % rigid and well-connected floors; L, stagger floors; M, floor permanent load; N, roof type; O, presence of perimetral beams; P, presence of ties: Q, roof permanent load; R, support length; S, roof perimeter; T, A/L ratio; U, B/L ratio; V, % increase/decrease mass; W, T/H ratio; X, % porch area; Y, number of floors; Z, total covered area; 1, mean floor height; 2, peak acceleration; and 3, damage.

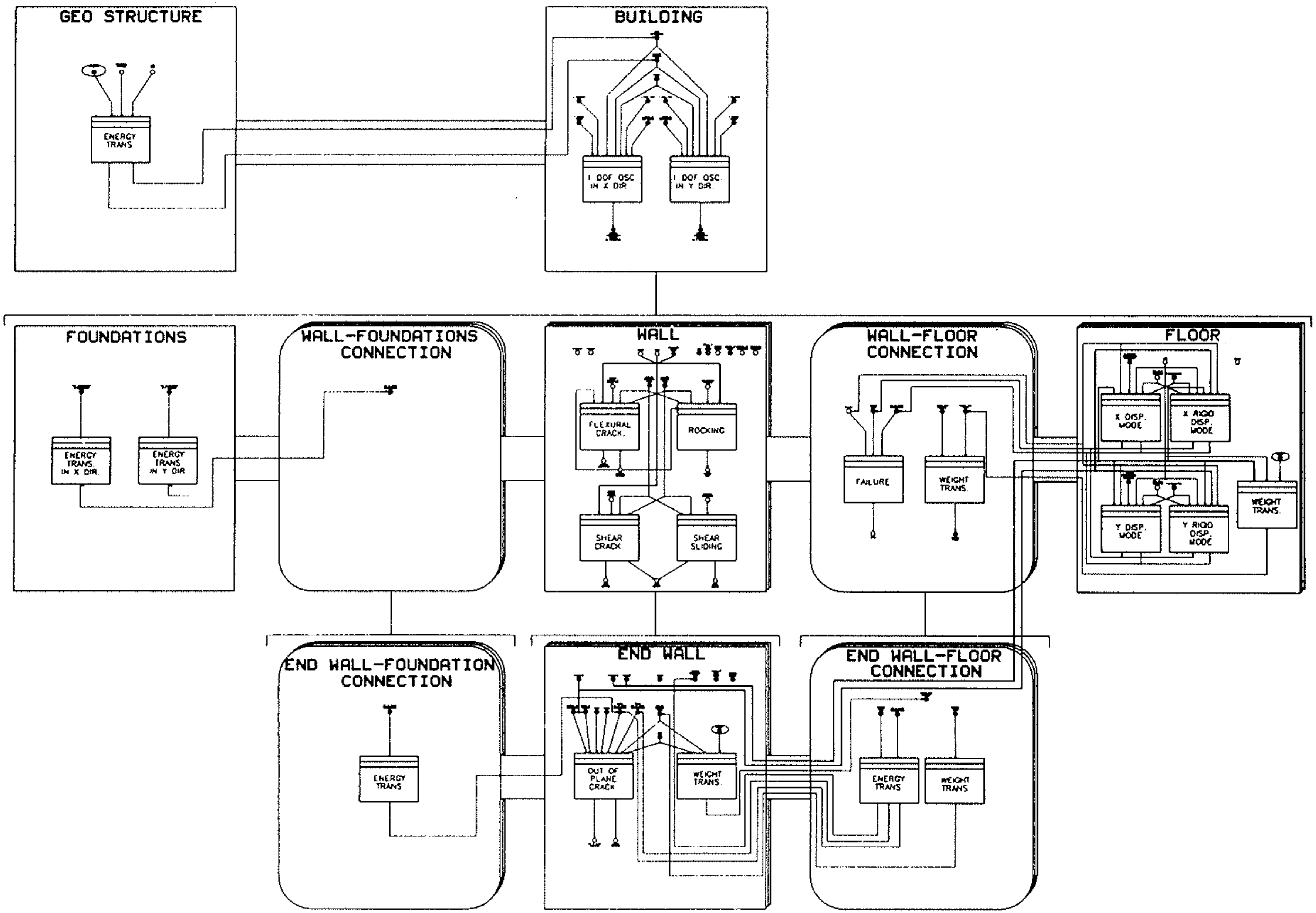


FIGURE 10. The model—level 3.

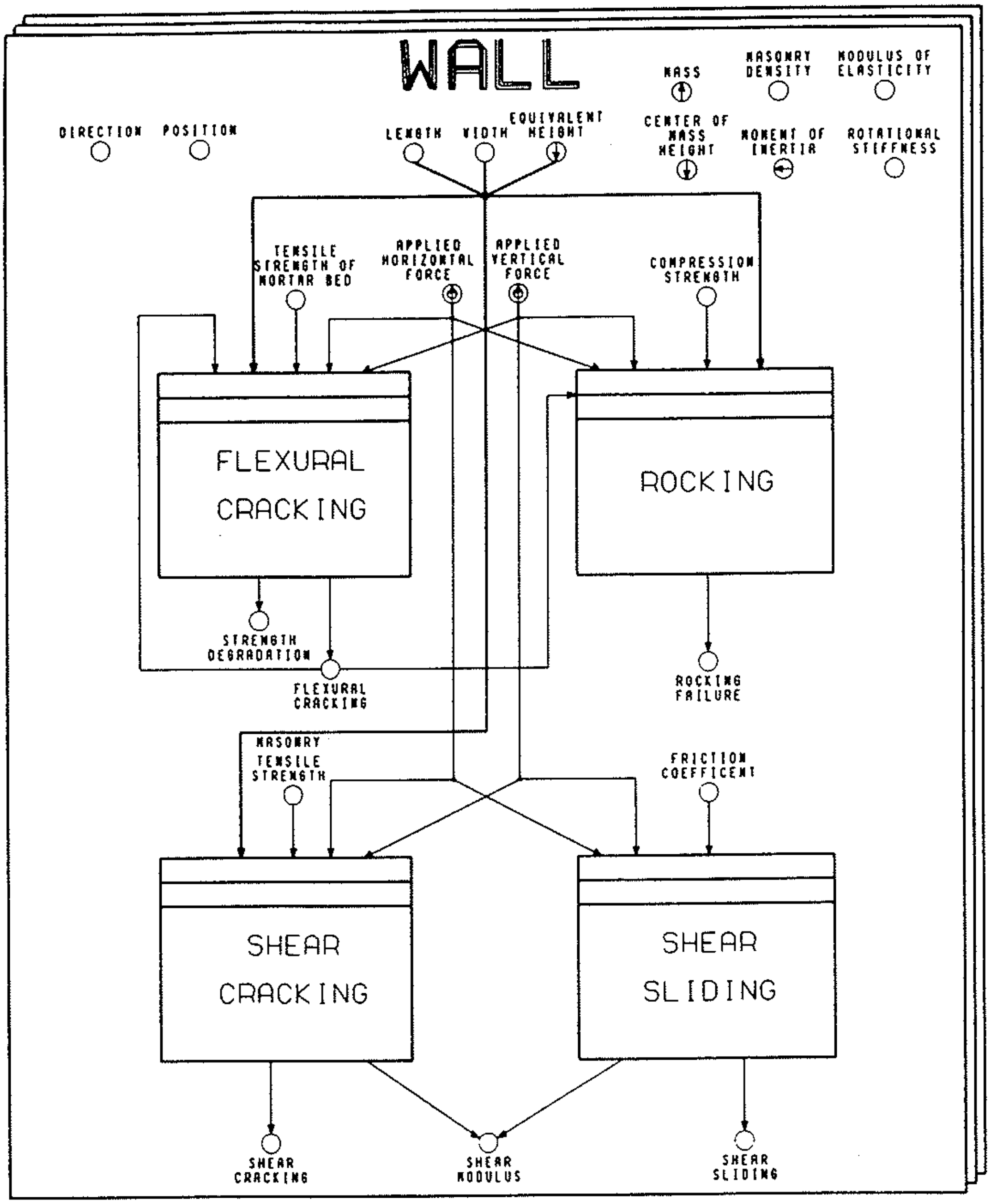


FIGURE 11. Level 3. The objects class "wall."

SOFTWARE ENGINEERING AND DEVELOPMENT OF THE SYSTEM

The system resulting from what has been previously described is a complex hybrid system, in which some parts are based on classic software techniques and some others are based on artificial-intelligence techniques.

The problems in designing, developing, and documenting such systems are not different from the problems usually faced in software engineering.

The main choices for the development of the system have been as follows:

1. The development process is based on step-by-step iterations on a prototype, with a series of phases for each step.
2. At each iteration some chapter of a project file is

generated or updated; all of the documents related to the project are collected within the file.

The main chapters are

definition and modeling of the context of use of the system;
definition of the objectives;
modeling of the system with respect to the problem (independently on the implementation);
translation into the implementation environment;
implementation; and
evaluation.

It has to be emphasized that the modeling of the system does not depend on the specific knowledge-representation techniques of the expert system shell that will be used. It is only in a second stage that the system model is translated into the specific languages (e.g., frames and rules).

Petri nets are the base technique used to model the system; other techniques are used within the nets.

The system described is under development using NEXPERT OBJECT™, C language, X-Window System™, and ORACLE™ dbms under SUN™ workstation/UNIX™.

CONCLUSIONS

The need for artificial-intelligence techniques to face the problem of seismic assessment and retrofitting of building structures has been proven to be justified either by the complexity of the problem and by the heterogeneity of the involved knowledge. A knowledge-based system being developed for this purpose has been presented, discussing the main aspects of the general philosophy, the structural modeling, and the formal representation. The present studies are limited to masonry buildings. The product promises to be an effective and versatile tool, but some fundamental part has still to be implemented, such as the planner and the man–machine interface.

A final answer on the usefulness of the system will be possible only after some successive phase of calibration and validation, which are being started in parallel with the completion of the system.

Eventually, it has to be noted that the probabilistic aspects of the knowledge and of its processing have been up to now completely neglected. The treatment of the uncertainties related to the whole process of risk assessment and seismic retrofitting of buildings will be one of the fundamental task to be faced in the future development of the research, together with the extension to others kinds of buildings and structures, such as reinforced concrete frame buildings and bridges.

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