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A Knowledge Based System for Deriving Qualitative Seismic Behavior

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1 Introduction

The analysis and design of complex or critical facilities, such as tall buildings, nuclear power plants, offshore structures, or cable stayed bridges requires that, in general, these facilities be made safe against the effect of earthquake induced loads. With the advent of digital computers it was possible to perform large scale computations to simulate the effect of dynamic loads on structures. Currently a number of sophisticated computer programs exist that allow us to perform analysis and design of complex structures. However, none of these programs have any reasoning capability. Users of numerical packages must anticipate the behavior prior to analysis. The purpose of the analysis is usually to confirm the anticipated behavior. Furthermore, responsibility for validating the computer outputs lie entirely with the user. Ideally, a program should not only perform numerical analyses, but also provide expert advice by communicating through a natural language and continue to improve its performance by acquiring new knowledge.

In this paper we describe the architecture of QSEIS, a system implemented in C and Prolog, that derives the qualitative behavior of structural systems under seismic loads from structural descriptions based on heuristic expert knowledge and qualitative reasoning capabilities. We believe that in order to build intelligent systems, it is essential to incorporate the fundamentals or the basic knowledge of a domain in the knowledge base. Furthermore, in order to ease the task of manipulating the knowledge base it is desirable to provide a natural language interface. In addition, to improve the performance of the system with time, automated mechanisms for knowledge acquisition need to be incorporated in the framework. The architecture of QSEIS incorporates all of these features and presents an integrated framework for intelligent problem solving.

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2 Expert Consulting Systems

Current rule based expert systems are inadequate for exhibiting truly intelligent behavior because they usually do not attempt to incorporate the fundamental premises of the given domain. For example, SACK [2] contained rules that suggested analysis procedures of complex structures, yet did not possess elementary knowledge of mechanics such as the cause-effect relationship between torsion, force, and moment arm. A lack of understanding of the underlying physics of a problem is responsible for limiting the performance of these systems. In addition, these KBES cannot reason about the behavior of physical systems in a qualitative manner, as experienced engineers normally do. Furthermore, these programs suffered from a lack of generality. A small addition to the program often involved a complete rewriting starting with the data structures. Indeed, a general knowledge base that could be applied to multiple domains, even when they are closely related, is still lacking. QSEIS attempts to overcome these shortcomings by using a knowledge base that contains the general principles or the fundamental knowledge of the domain which can be augmented incrementally. The qualitative behavior is derived through causal relationships between the various entities in the database. The details are discussed in subsequent sections.

3 Engineering Problem Solving

To appreciate the various reasoning mechanisms that are involved in an actual engineering problem, such as in the domain of earthquake resistant analysis and design, let us consider the structural system as shown in Figure 1. From the drawings in Figure 1 an experienced engineer might reason as follows, even before he performs any detailed calculations:

The height to depth ratio of the structure seems to be quite large and therefore there is a possibility of large overturning moments. The shear walls have large openings and hence the structure will primarily behave as a frame and be quite flexible. A heuristic rule for obtaining the fundamental period (T) of a structure that acts as a moment frame is \( 0.025 \times 300^{\frac{3}{4}} \) which yields 1.8 seconds. Now since a frame behaves as a shear beam, the higher modes are likely to correspond to time periods which are approximately \( T/3 = 0.6 \) seconds, \( T/5 = 0.36 \) seconds etc. Since the plan is almost regular, it is sufficient to consider modes of vibration corresponding to 1.8 and 0.6 seconds to estimate forces and deflections. The overturning moment is likely to be higher than usual since the lateral distribution will be nonlinear instead of being almost linear. The slight non-symmetry of the plan shape will cause some non-uniformity in the distribution of lateral forces which in turn will cause torsion. Since the shear walls have large openings, there is a possibility of serious degradation of performance due to the torsion. The columns in the first story are very tall and this would cause very large drift in the first floor which might cause non-structural damage. The coupled shear walls are not identical in nature, i.e., they possess different stiffnesses. This will cause large forces in the links and since some of the links are not restrained laterally, there is a serious possibility of their buckling ... ...
The above example suggests the following types of knowledge structures and reasoning mechanisms that the engineer utilizes: *Heuristic knowledge* - if the building behaves as a moment frame then the fundamental period of the structure is $0.025 \times 300^{3/4}$; *Qualitative analysis* - the slight non-symmetry of the plan shape will cause some non-uniformity in the distribution of lateral forces which in turn will cause torsion; *Analogical reasoning* - since a frame behaves as a shear beam the higher modes are likely to correspond to time periods which are approximately 0.6 second, 0.36 seconds, etc.; Here an analogy is made between the frame and the shear beam, since the higher modes of a shear beam are likely to correspond to time periods which are approximately 0.6 second, 0.36 seconds, etc., the modes of the frame are likely to have similar characteristics; *Approximate Quantitative Analysis or back of the envelope calculations* - involve calculating stiffness distribution, estimating structural period, estimating lateral load distribution etc.

The previous example suggests that there is a need to incorporate mechanisms in computer programs that attempt to achieve expert problem solving capability in engineering. Since SACON's knowledge base consists of simple heuristic rules and does not incorporate any of the reasoning mechanisms that have been described earlier, it is insufficient for serious engineering problem solving. In the implementation of QSEIS, an attempt has been made to incorporate heuristic knowledge, qualitative reasoning and approximate quantitative analysis. QSEIS, however, does not have any means of reasoning by analogy.
4 Architecture of QSEIS

The schematic sketch describing the overall process of engineering problem solving is shown in Figure 2. The shaded region in the Figure 2 corresponds to the implemented architecture of QSEIS. The main modules of QSEIS include a knowledge base, a learner and a user interface.

4.1 Knowledge Base

The knowledge base can be thought to incorporate three types of knowledge: Heuristic knowledge, Qualitative knowledge and Quantitative knowledge. Heuristic knowledge is used to determine whether the structure conforms to some accepted guidelines, such as Applied Technology Council guidelines [1]. In case the system finds potential problems, it will inform the user. Although the analysis using heuristic knowledge may suggest that the structure does not violate accepted guidelines, there may be some problems that can be detected through commonsense reasoning. This type of reasoning is provided by the knowledge structures at the qualitative level. Finally approximate quantitative methods are available in the knowledge base to estimate periods of vibration, lateral load distribution, etc. At present QSEIS does not incorporate numerical methods, such as the finite element method, to perform detailed quantitative analysis.
4.1.1 Heuristic Knowledge

A large amount of information exists about the effect of dynamic loads on structural systems such as those due to earthquakes. Reports and guidelines from a number of organizations such as the Applied Technology Council [1], clearly document the effect of the various factors such as shape, size, components, etc. on the dynamic behavior of the structure during an earthquake. Similarly, well established criteria exist in the literature about the seismic performance of various facilities, risk levels at different sites, ductility characteristics, analysis and design methods, etc. It is necessary to take into consideration all of the above factors in order to ensure a proper design. The location of the site decides the effective acceleration, effective velocity and the risk level associated with the site. The purpose of the structure and its location together decide the seismic hazard level for which it needs to be designed. In the case of buildings, seismic performance groups have been established depending on the nature of the facility. The seismic performance group in which the facility belongs and the risk level associated with the site together decide the appropriate framing systems and analysis and design procedures that are necessary for the facility. The selection of the framing system, the analysis, and the design procedures are also dependent on the geometric features of plan elevation and materials used in constructing the facility. Heuristic knowledge is represented using a collection of frames [9] and rules. Typical frames are:

**Structure:**
- **type:** building
- **purpose:** hospital
- **location:** California
- **vertical elevation:** vertical elevation-1
- **plan:** horizontal plan-1

**Vertical-Elevation-1:**
- **height:** 500 feet
- **width:** 100 feet
- **symmetry:** does not exist
- **vertical setbacks:** exist
- **mass distribution:** non-uniform

Following are some examples of rules (the acronyms in the parenthesis are used in the graphical representation in Figure 3):

*If*

the hazard exposure group of the building is 3 AND (SHEGIII)
seismic index of location is 4 (INDEX4)
*then*

the required seismic performance category is D. (SPCATD)

*If*

seismic performance category of the building is D (SPCATD) AND
the height of the structure is greater than 160 feet (HTGT160)
Figure 3: Inference Network for Part of Rule Base

then

the appropriate structural system is either a dual system (DUALSYS) OR
a special moment frame system. (SPMOMFR)

If

seismic performance category of the building is D (SPCATD) AND
horizontal plan of structure is irregular (IRRPLCONFIG)
then

it is necessary to perform a three dimensional dynamic (DYNCON)
analysis.

If

seismic performance category of the building is D (SPCATD) AND
horizontal elevation of structure is irregular (IRRELCONFIG) AND
the plan of the structure is regular (REGPLCONFIG)
then

it is necessary to perform at least a modal analysis (MODAN)
of the structural system.

Figure 3 depicts part of the rule-base in the form of an inference network. The top
level hypotheses in the sample inference network determine whether an appropriate
structural framing system has been selected. Although Figure 3 illustrates part of a knowledge-base related to buildings, the issues that influence the seismic behavior are general in nature. The knowledge structures used in the system are sufficiently general and can address other constructed facilities such as bridges, dams, etc.

4.2 Qualitative Reasoning in QSEIS

QSEIS derives the abstract qualitative behavior using causal reasoning. Causal reasoning, as the name suggests, is essentially a reasoning methodology based on cause and effect relationships between the various entities in a given domain. Causal knowledge is modeled as a network of nodes representing states or various kinds of events with links representing varieties of causal relationships. A causal link specifies the cause-effect relation between the cause (antecedent) and the effect (consequent) states. In earthquake engineering, in addition to well defined heuristics, there are a number of qualitative issues that play a significant role in behavior of a structure during an earthquake. While many of these may seem to be obvious, and are rather clear to an experienced engineer, it is difficult to implement such reasoning mechanisms in a computer program. Many of these qualitative issues can be thought to require engineering judgment which is very difficult to model and implement once a domain gets sufficiently large and complex. The importance of this aspect of knowledge becomes apparent when one considers, for example, the effects of the plan shape on the dynamic behavior of the structural system. If the plan is too long, it is possible that differential movements can cause disastrous effects. Such knowledge is not written explicitly in the codes, since it is considered obvious. Furthermore this particular fragment of knowledge is applicable to a number of areas in mechanics. Causal reasoning provides a richer representation of the fundamental premises of the domain and provides a detailed explanation of the derived behavior.

Figure 4 shows two planes - the dependency plane and the causal plane - as related to the domain of seismic analysis. The dependency plane shows dependency relationships between various entities. Following are some causal associations, depicted pictorially in Figure 4, that are utilized in assessing the qualitative structural behavior.

A rapid change of curvature causes stress-concentration. Openings in structural elements cause reduction in their stiffness. Deflection due to bending may cause rotational inertia of masses to be considered. Significant reduction in stiffness cause large deflections. Nonstructural elements cause increase in stiffness of the overall structure. An increase in stiffness cause reduction in fundamental period of response of the structure. A reduction in fundamental period will cause increased lateral force. An increase in fundamental period will cause higher modes of vibration to participate. Participation of higher modes will cause non-linear distribution of lateral force. A non-linear distribution of lateral force will cause force distribution to increase more rapidly with height. A higher force near the top will cause larger overturning forces. Large deflections cause non-linear behavior. Structural deflections depend on stiffness distribution. Significant difference in horizontal displacements cause large axial forces in members. Large axial forces cause buckling of members if they are not laterally restrained.

In QSEIS, causal relationships are expressed using predicates. The following example illustrates how the presence of various predicates cause the assertion of new predicates in the database.
The above example illustrates the following causality: The presence of reentrant corners and unsymmetry in plan causes torsion. Torsion in turn causes the modes of response to be coupled. The aspect ratio of the elevation, being large, causes a higher number of modes to participate in the dynamic response.
4.3 Knowledge Acquisition and Learning

Even in the early days of expert system development, it was clear that a large amount of domain specific knowledge was essential for high performance of expert systems [4]. However, assembling and modifying a large knowledge base manually is not a trivial task. In a sufficiently large system, the internal representation of the data structures and their interrelationships is very complex. It is difficult for a human being to keep all this in his memory. Furthermore, as the system evolves, managing the changes and refinements requires significant effort. These considerations provided the impetus to automate the process of knowledge acquisition.

QSEIS learns incrementally from knowledge provided by the user. Thus, learning in QSEIS is essentially knowledge acquisition. Knowledge acquisition can be viewed as learning by role, i.e., learning by being told. QSEIS allows incremental acquisition of facts and rules which are used in the future to derive the qualitative behavior. A new fact or rule is stated in English from which QSEIS automatically generates the internal representation. Furthermore whenever a new rule is fired, it is ensured that this rule does not introduce any inconsistency.

4.4 User Interface

User interfaces play a very important role in the acceptance of computer aided software by engineers. QSEIS provides a sophisticated user interface that allows three types of input: 1) menu-driven, 2) restricted natural language, and 3) user sketched diagrams. Typically when QSEIS asks a question to the user, it displays a list of options through a menu. The user responds by selecting an appropriate item from the menu. The natural language interface, which is based on definite clause grammar, comes into play when the user wishes to ask QSEIS a specific question. The natural language input is useful since it does not restrict the user to follow specific formats for inputting. Finally, engineering knowledge is often best conveyed through drawings. Features such as symmetry, aspect-ratio, bracings, re-entrant corners, setbacks, soft story, etc., can be extracted directly from engineering drawings. QSEIS allows the user to input sketches of plan, elevation and structural system from which relevant features are recognized.

5 Conclusions

Intelligent behavior is based on the ability to derive qualitative behavior based on the fundamental premises of a domain. An effective way to derive such a behavior is by using causal reasoning which is shown to be a practical methodology for deriving qualitative behavior. Statements describing the cause-effect relationships between different entities can be made in first order predicate logic. It is an effective formalism for describing a wide variety of declarative statements which can be stored in a general knowledge base. Database manipulation is facilitated by natural language understanding capability based on definite clause grammar. Grammar rules are easily expressed using Horn clauses. Incremental knowledge acquisition and conflict resolution capabilities allow the system to acquire new facts and rules which can be used in future to deduce appropriate conclusions.
References


