NATIONAL CENTER FOR EARTHQUAKE
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State University of New York at Buffalo

A KNOWLEDGE-BASED APPROACH TO STRUCTURAL DESIGN OF EARTHQUAKE-RESISTANT BUILDINGS

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PREFACE

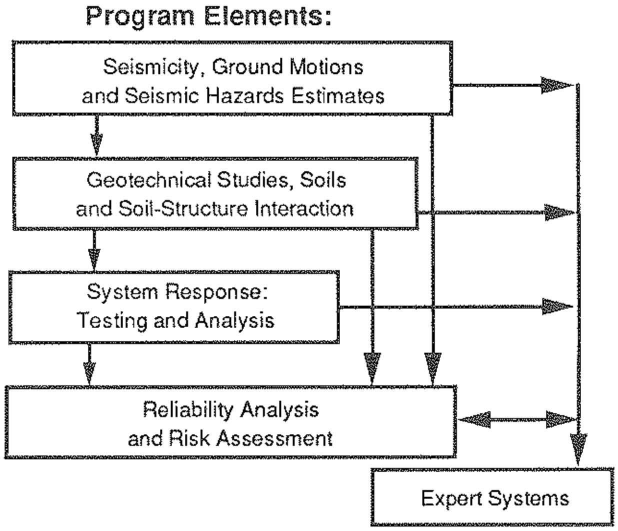
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 1, Existing and New Structures, and more specifically to expert systems development.

The long term goal of research in Existing and New Structures is to develop seismic hazard mitigation procedures through rational probabilistic risk assessment for damage or collapse of structures, mainly existing buildings, in regions of moderate to high seismicity. The work relies on improved definitions of seismicity and site response, experimental and analytical evaluations of systems response, and more accurate assessment of risk factors. This technology will be incorporated in expert systems tools and improved code formats for existing and new structures. Methods of retrofit will also be developed. When this work is completed, it should be possible to characterize and quantify societal impact of seismic risk in various geographical regions and large municipalities. Toward this goal, the program has been divided into five components, as shown in the figure below:



Tasks:

Earthquake Hazards Estimates,
Ground Motion Estimates,
New Ground Motion Instrumentation,
Earthquake & Ground Motion Data Base.

Site Response Estimates,
Large Ground Deformation Estimates,
Soil-Structure Interaction.

Typical Structures and Critical Structural Components:
Testing and Analysis;
Modern Analytical Tools.

Vulnerability Analysis,
Reliability Analysis,
Risk Assessment,
Code Upgrading.

Architectural and Structural Design,
Evaluation of Existing Buildings.

Expert systems constitute one of the important areas of research in Existing and New Structures. Current research activities include the following:

1. Evaluation of existing buildings in terms of seismic safety.
2. Design of new buildings both from the architectural and structural viewpoints.
3. Recommendations for the upgrading of deficient buildings.

The ultimate goal of projects concerned with expert systems is to construct practical expert system tools for the design of new buildings and for the evaluation of existing buildings, with the explicit consideration of expert opinion and uncertainties.

The development of a prototype program STRAKE is described in this report. This expert system program is intended for structural engineers and others interested in the design of earthquake-resistant buildings. The knowledge base has been assembled with the help of practicing engineers and it will be extended after a period of trial use by designers.

The Appendices (the user's manual; scenario for use; questionnaire for the knowledge base; sample rules; and additional figures) are not attached to this report but are available separately from NCEER.

ABSTRACT

The uncertainties in seismic design and the knowledge-intensive nature of the tasks involved suggest the need for a computer-based design aid to help structural engineers design earthquake resistant buildings. To this end, a prototype knowledge-based expert system (KBES) named CU-STRAKE has been developed. The KBES serves as an interactive consultant providing advice and recommendations for improving the design. A compilation of knowledge and expertise from a variety of sources is incorporated in the system. The knowledge base includes the seismic provisions of building codes, other existing information from design guides and technical documents, and lessons learned from post-earthquake studies. The CU-STRAKE system uses this knowledge to obtain estimates of seismic parameters, to check for compliance with the code regulations, and to obtain an overall evaluation of the building. The KBES, for example, provides feedback in cases where a few elements provide most of the torsional stiffness, and on such design features as large eccentricity and the presence of short columns. The knowledge base is organized in different levels of sophistication enabling the user to define the scope of the evaluation, ranging from a rapid check based on code regulations to a more comprehensive and detailed evaluation of the building.

The use of algorithmic functions for performing numerical computations is important for an engineering application such as seismic structural design. CU-STRAKE therefore combines the use of algorithmic functions for estimating numerical quantities with the knowledge-base rules of the system. In addition, the KBES makes extensive use of interactive graphics for providing a versatile and user-friendly environment. CU-STRAKE is implemented on engineering workstations with color graphics capabilities, and is provided with a menu-driven user interface. The use of graphics provides a convenient means of describing the building and of providing the system with the information needed to evaluate the building. The system presents a graphical view of the building and of the relevant design features.

The knowledge-based system described here is a model for an integrated design environment with knowledge-base rules, algorithmic functions, and interactive graphics combined to aid in the design process. It is believed that such a system can serve as a versatile and powerful design aid for practicing engineers in seismic design. Another of the benefits envisaged of such a system is its use as a 'front-end' for conventional computer-aided design (CAD), enabling the selection and effective use of CAD routines such as programs for static and dynamic analysis. It is also believed that the system can be used as an effective teaching tool for instruction in seismic design.

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We would also like to acknowledge the participation of several fellow researchers and many professionals in the development of the expert system described in this report. Through two workshops and a questionnaire we were able to benefit from their experience and improve CU-STRAKE. Of the large group that has participated, we would like to mention a few who spent considerable time in the effort: Thomas Sabol, Joseph Zona and Glenn Bell, Richard Niewiarowski, David Bonneville, Said Hilmy, Sigmund Freeman, Warner Howe, Charles Lindbergh, Bill Honeck, Stan Lindsey Associates, and Roberto Meli.

Finally, we would like to acknowledge the support of the following companies in the form of discounts on their products that were used in the research: Production Systems Technologies Inc., EXSYS Inc., IntelliCorp, and Digital Equipment Corporation.

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SECTION 1
INTRODUCTION

The design of buildings to resist earthquakes is a complex and challenging task involving a rich interplay of factors, many of which are not well defined or easy to quantify. While designing for earthquakes, the engineer must address the two-fold task of predicting the nature and intensity of seismic disturbances at a site (the 'demand'), and of estimating the seismic capacity of the proposed building (the 'supply'). Considerable uncertainty is involved in each of these tasks, and typically no clear and unique solution is available. Experienced engineers often rely on judgment and heuristic rules to aid them in making decisions.

Knowledge-based expert systems (KBES), a practical outcome of research in artificial intelligence (AI) in recent years, represent a potentially powerful means of applying AI technology to such domain areas as earthquake engineering. This new technology is rapidly being adopted for a range of engineering tasks requiring considerable expertise and domain knowledge. Previous advances in computer technology, in the form of improved algorithmic languages, database methods, computer-aided design (CAD) systems, and software tools for analysis, have benefited the civil engineering community over the years by enhancing the design process. Possible applications of the new technology of expert systems to civil engineering are now being investigated, and have met with some success in those areas which by their nature lend themselves to a knowledge-based approach. Typically these are areas that involve uncertainties and require intensive domain knowledge, and for which some degree of human expertise is required. The domain of earthquake engineering is such a field, in which much of the design process is non-algorithmic and not easily formalized. These characteristics of the domain, together with the underlying rationality of harnessing the latest advances in computer technology, indicate the desirability of investigating knowledge-based applications in the field of earthquake engineering.

1.1 Background on Expert Systems

The knowledge-based approach is an extension of, and in some ways a departure from, conventional programming techniques. Fundamental to the concept of expert systems is the idea of incorporating in a computer program the domain knowledge and expertise required to solve problems that traditionally require the efforts of human experts.

One definition of an expert system, attributed to Professor Edward Feigenbaum of Stanford University [1], is the following :

> ... an intelligent computer program that uses knowledge and *inference procedures* to solve problems that are difficult enough to require significant human

> expertise for their solution. Knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners of the field.

An inference procedure is the means by which an expert system derives information and draws conclusions by operating on the available data using a prescribed set of rules.

Expert systems have evolved from continuing attempts at computer modeling of human problem-solving techniques and strategies. A long-term objective of AI researchers is to impart some form of 'intelligence' to KBES computer programs, enabling them to perform human-like functions such as learning and arriving at generalizations, reasoning with incomplete data, improvising in some situations, and adapting to varying situations. These ambitious objectives form the basis of much of AI-related research, and have met with only limited success so far. A more modest view of expert systems, and one more in keeping with achievements to date in the field, is that they represent a novel and powerful approach to computer-based problem-solving, providing certain benefits in addition to those offered by algorithmic programs.

An expert system typically has four parts [2], as illustrated in Figure 1.1. The knowledge base contains the facts and rules that make up the expertise of the system, while the inference engine contains the inference strategies and controls for deriving information and drawing conclusions from the available data. The working memory is the repository of specific data pertaining to the problem being addressed. The user interface provides the communication link between the user and the expert system, enabling him/her to provide input to the program, obtain information and advice from the system, and examine the reasoning process. A possible extension and fifth feature of an expert system, also illustrated in Figure 1.1, is a built-in knowledge acquisition facility, which would enable the development and enhancement of the knowledge base, by adding new rules. Developing an expert system thus involves the accumulation and codification of the knowledge that makes up the knowledge base, and implementation of a suitable inference strategy, together with a convenient user interface [3].

1.2 Project Context and Objectives

The research described here is sponsored by the National Center for Earthquake Engineering Research (NCEER), and is being conducted as a cooperative effort involving several institutions, notably Cornell, Lehigh, and Carnegie-Mellon Universities. The research at Cornell University deals with the structural aspects of the design of new buildings, while the research at Lehigh University deals with architectural aspects, and the research at Carnegie-Mellon University concerns the seismic evaluation of existing buildings. Cornell University's research effort takes input from some other NCEER projects in progress at

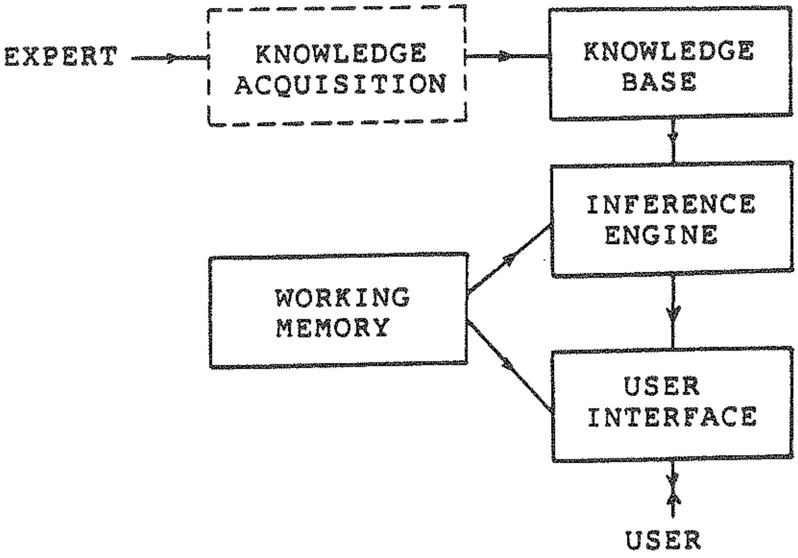


Figure 1.1: Typical Expert System Organization

Cornell, some involving experimental research, and others numerical modeling. The KBES development benefits directly from the concurrent research on the use of computers in earthquake engineering.

The main objective of this research is to investigate the knowledge-based approach as a means of enhancing the process of seismic design of buildings. Much of the practice of earthquake engineering involves decisions based on experience and in-depth knowledge of the domain. The use of a KBES is studied as a means of capturing the expertise from a variety of sources, and making it available to persons engaged in the seismic design process.

Building codes provide some of the requirements to be met by the proposed building designs. However, these specifications in several cases are only the minimum criteria to be met, and do not lead to the best design. Also, several of the code specifications are limited to fairly simple, two-dimensional building configurations; for complex or irregular structures it is often necessary to perform more comprehensive analyses. Further, it is widely acknowledged in seismic design that increasing the design forces to be on the safe side does not in itself ensure a good design. It is important to take into account several other factors contributing to the overall behavior of the building. There is thus a need for providing a more rational basis for the design, particularly when dealing with unusual structures. The use of a KBES is meant to supplement the building code provisions, improving on them where possible.

The development of a prototype KBES is undertaken as a part of this research to examine the validity and usefulness of the knowledge-based approach to earthquake engineering. The prototype development is also directed at evolving the appropriate methodology and techniques of expert-system development for this application.

1.3 Scope of the Report

The report describes an ongoing investigation of the knowledge-based approach to earthquake engineering. The various stages of the prototype development are described, together with the underlying motivation and approach. Section 2 outlines the fundamentals of the knowledge-based approach, and the motivation for this approach in the context of seismic design. The groundwork is laid in this section for the subsequent description relating to the development of the prototype. The different expert system shells investigated, and the preliminary versions of the KBES developed using these shells, are described.

Section 3 provides a detailed description of the prototype KBES, CU-STRAKE. The scope and the capabilities of the system are enumerated . An example of a building design is used to illustrate the consultation provided by the system, highlighting the important features of the program.

Section 4 gives a detailed account of the knowledge base which forms the heart of the system. The expertise from a variety of sources incorporated in the program is described. The different levels of consultation, including those implemented to date—the routine and specialized—are enumerated.

A technical description of the system is provided in Section 5, giving details about the overall strategy and organization of the program. The structure of the overall system, and its interaction with other related programs, is described. The hardware and software environments of the KBES are also described.

Section 6 summarizes the research in the project to date, suggests future areas for research, and makes recommendations for enhancing the system.

The User's Manual for the prototype KBES which describes the major features of the KBES and provides instructions on running the program, and a detailed design example, are available from NCEER under seperate cover. Also in that document are the contents of a questionnaire used to solicit expert opinion on important aspects of the seismic design of buildings, and some knowledge-base rules used in CU-STRAKE which exemplify the kind of rules used by the KBES in the reasoning process.

SECTION 2
A KNOWLEDGGE-BASED APPROACH TO EARTHQUAKE-RESISTANT DESIGN OF BUILDINGS

The preceding section introduced the expert-system approach as a new and potentially powerful problem-solving paradigm. The first part of this section deals with the nature and characteristics of expert systems, and how they differ from conventional (algorithmic) programs. This leads to a discussion of the motivation for this approach in the context of earthquake engineering. A description of the preliminary prototype systems developed using two expert system environments follows in the last part of this section.

2.1 The Expert System Approach

As mentioned in the previous section, the use of expert systems represents a different approach to problem-solving than that of conventional programming languages. Some of the background and methodology of expert systems is presented in this section, stressing the benefits of this approach, and the motivation for its use in earthquake resistant design.

2.1.1 Tasks in Expert-System Development

The four major tasks that are typically involved in the development process are knowledge acquisition, knowledge representation, implementation of an inference strategy, and design of an end-user interface [1].

1. Knowledge Acquisition

   This process of 'extracting' the relevant knowledge and expertise from a domain expert, and other sources, is the all-important first step in creating a knowledge-based system. This stage has a vital bearing on the performance and utility of the final system, for an expert system is only as good as the knowledge encoded in it. This stage is typically a difficult and tedious task, in the process of which the domain expert and the system developer (or 'knowledge engineer') interact extensively, and in the process get some understanding of each other's tasks and their mutual roles in the development process.

2. Knowledge Representation

   This is the process of formalizing the knowledge acquired in the preceding stage, and encoding it in an appropriate form so that the computer can access it and perform useful manipulations on it. The knowledge base is usually composed of several heuristics or rules-of-thumb, represented in the form of rules.

3. Implementation of an Inference Strategy

   This process involves the selection and implementation of a suitable inference strategy, i.e., some means of driving the reasoning process, enabling the system to derive conclusions from the data using the knowledge-base rules. The inference mechanism controls the program flow. The inference procedures commonly adopted are forward- and backward-chaining. In forward chaining, or 'data-driven' inferencing, the knowledge-base rules operate repeatedly on the data to derive as much information as possible, until no more rules can be executed. In backward (or 'goal-directed') chaining, the inference mechanism begins with a set of top-level goals, and tries repeatedly to satisfy sub-goals using the available data. Some expert systems allow a mixed inferencing strategy, with both forward- and backward-chaining.

4. Design of an end-user interface

   This is the process of designing and implementing a suitable end-user interface. This stage requires as input, information about the type and sophistication of the end-user, and his/her requirements of the system. The nature of the end-user interface varies widely from one system to another, depending on the requirements and objectives of the user. The interface may be graphical, or it may consist primarily of dialog at the keypad. The present system is equipped with a graphical, menu-driven interface.

2.1.2 Conventional Programming versus Expert Systems

The organization of an expert system as described earlier, with a separate knowledge base and inference mechanism, is one of the distinguishing features of an expert system [4]. Thus there are facilities for modifying and displaying the knowledge base, separate from the control or inference engine which executes the reasoning process. In the early stages, AI systems were encoded with general problem-solving strategies, but no domain-specific knowledge. This 'weak' approach was found to be insufficient for solving a majority of knowledge-intensive problems. The subsequent approach was to restrict the domain of KBES to specific areas instead of making them entirely general, and to provide them with more intensive knowledge and expertise specific to the field. Expert systems were thus provided with extensive domain expertise in addition to general problem-solving capabilities, making them more powerful and versatile.

Another useful feature distinguishing expert systems is the transparency of the knowledge incorporated in them. The domain-specific knowledge used in making decisions is explicitly coded in an expert system, and is in readable form, in contrast with some algorithmic programs which are 'black boxes' to the end-user. In addition, several expert systems have an explanation facility that allows the user to query the system and thereby learn about specific aspects of the reasoning process. Inexperienced users can therefore use this feature of an expert system to gain expertise in the application area.

Knowledge-based systems can be implemented initially using only a small portion of the ultimate knowledge base, and the knowledge base incrementally extended over a period of use without major restructuring. This allows the programmer to develop the system in stages, making the testing and debugging process more manageable. Also, since the system can be implemented at a fairly preliminary stage, the developers can begin to interact with the end-user community at early stages, and obtain feedback from them for directing the continuing development of the system. Further, the final system could be made so modular and user-friendly that it could be modified or updated by the practitioners who are the end-users, rather than by computer programmers.

2.1.3 Benefits of the Expert-System Approach

On account of these features of expert systems, their use is generally associated with the following benefits :

- transfer of expertise
- training of inexperienced persons
- transparency of the reasoning process
- highly interactive
- user-friendly interface
- incremental growth capability
- separation of knowledge base and control
- modeling of 'what-if' situations

However, the above features are not all exclusive to knowledge-based systems, with algorithmic programs increasingly tending toward more interactive and user-friendly environments. At the same time, knowledge-based systems in some fields are incorporating algorithmic capabilities to make them more versatile and effective. With this tendency toward a mixed strategy, the dividing line between expert systems and conventional programs is becoming a thin one, and much of the difference appears to be centered on the approach rather than the capability of the system. The future trend, according to Professor Steven Fenves of Carnegie-Mellon University [4], is in the direction of closer interaction between the two programming approaches :

> ... KBES environments will be more closely coupled with algorithmic programs which can supply the deep, causal knowledge. Thus, KBES will be increasingly used not as stand-alone programs, but as intelligent pre- and post-processors for existing programs, such as finite element analyzers or CPM schedulers.

This trend is reflected in the current development, in which the KBES forms a part of an overall CAD environment for earthquake-resistant design of buildings. The expert system component serves as the master controller, and is used to determine the flow of control in the program, and to coordinate the various program features. The CAD features in the program provide varied functionality, enabling the user to graphically define a building and to perform analyses. The KBES enables the user to recognize and exploit this functionality, and guides him/her through the relevant operations in the right sequence to arrive at a sound seismic design. The KBES is an 'expert system' to the extent that it is an interactive program, giving advice and recommendations that are based on the knowledge and expertise of experienced designers.

Several of the benefits associated with expert systems and their ease of user interaction, are reflected in this system, and in addition, this approach provides some benefits to the programmer in terms of ease of development. The rule-based approach is particularly useful in the solution of problems with a large number of conditionals [5]. When using an expert system, the developer does not have to keep track of these conditionals or explicitly specify program control at all stages. The rules are added to the program in an unstructured manner, and it is left to the interpreter of the inference engine to keep track of the rules and determine the proper sequence to execute them. This approach facilitates program modification and expansion, as the flow of control is determined by the inference engine.

The ability of expert systems to examine hypothetical ('what-if') situations is particularly useful in problems involving design and planning, and this feature is exploited in the present system. Using the change-and-rerun capability of the system, the designer can experiment with alternative design ideas and evaluate them in turn to arrive at the best design.

In addition, the concept of an 'open' system, allowing the end-user to modify the knowledge base and/or the inference mechanism, is a possible future extension of the program. This would provide the user with the flexibility to customize the system for compatibility with the design practices of his/her design office or environment, and to update the knowledge base to keep up with new technology and evolving practices. The techniques for implementing this capability for user-updating and modification are not yet well-established, though research is currently in progress in this area [6]. The idea of allowing the end-user to modify the system poses some serious questions about the competence and responsibility assumed of the user, and about who should be allowed to make changes to the program. There is some skepticism about the use of such a feature by average users [7].

2.1.4 Suitability of the Domain

The various features of expert systems just described are useful for applications such as the present one, involving design and planning. In addition, the following factors associated with the process of seismic design render it suitable for the expert-system approach :

1. Need to supplement building codes : Building codes provide designers with criteria to be met by the design; they do not provide much information on how to design the building for compliance with these criteria. Also, the code design is in some ways a 'minimum' specification and does not necessarily yield the most appropriate or optimum design. Further, some aspects of the design, particularly with respect to unusual structures, are not treated adequately by the codes. For these reasons, a prototype system is being developed to provide a more rational basis for the design by supplementing, and where possible improving on, the code specifications.
2. Nature of the domain : The domain of earthquake engineering is characterized by several features which make it suitable for an expert-system approach : it is knowledge intensive, involves a complex interplay of factors, and requires good judgment and expertise. Further, it involves uncertainty in estimation of seismic parameters, and is characterized by decisions based on heuristics or rules-of-thumb.
3. Need for an integrated design approach : Typically, expert systems deal with the solution of problems that are largely heuristic, as opposed to those that lend themselves to algorithmic solution. By the nature of the present domain, there is a need for both approaches at different stages of the design process. The prototype knowledge-based system developed can serve as an integrated design consultant, with both production rules and algorithmic functions, as well as extensive use of interactive graphics to aid in the design process.

2.2 Development of KBES Preprototypes

It was decided that the Cornell University prototype would be developed using a commercially available expert system shell or programming environment. Commercial development tools allow rapid prototyping and provide a range of useful features depending on the level of sophistication. These were favored over generic AI programming languages such as LISP and PROLOG, as it was believed that the greater generality provided by these languages did not adequately compensate for the added investment in time and effort of development using these languages. For the particular application at hand, it was concluded that the loss of generality associated with the use of an expert system tool would not be a serious handicap.

As a precursor to the prototype development it was decided that one or more preliminary prototypes would be developed, with the intent of gaining some experience with the basic methodology and techniques of knowledge representation and reasoning. A common strategy in expert system development, the preprototype is usually developed as a 'throw-away' system that serves to validate the knowledge-based approach for the particular application, and to illustrate the correct procedures as well as the pitfalls of the development process. The experience gained in this manner serves to guide the process of development of the final prototype. Specifically, the objectives of the preprototype development in the present case were the following :

1. Evaluation of commercial expert system shells and environments : Commercial expert systems of various kinds were examined and evaluated for the purpose of determining the best suited one for the current application. Also, the opportunity was utilized to gain some experience with the basic functionality of expert system shells.
2. Identifying the requirements and proposed usage of the system : For the development of a KBES to proceed effectively, the requirements and proposed usage of the system must be clearly identified. The process of development of a preprototype was to provide an opportunity for creating a typical scenario of the usage of the system, and in the process, arrive at the requirements and proposed usage of the system. The conclusions so obtained would then direct the development of the final prototype.

Of the numerous commercially available expert-system tools, two were chosen for evaluation and preprototype development—Knowledge Engineering Environment (KEE) and EXSYS. The two are widely different systems, KEE being a high-end, sophisticated system running on LISP machines such as the Symbolics 3670, while EXSYS is a low-end PC-based system. Both of these systems are widely recognized in the expert system market for their capabilities at their respective levels of sophistication.

An initial version of the knowledge base for the preliminary structural design of buildings was developed and programmed in both KEE and EXSYS. The intention was to build a thin vertical slice, i.e., a knowledge base that could be used to carry the design all the way but only for limited options regarding structural types, details, and other factors. The comparison of the two shells was based on several criteria such as the power of knowledge representation, graphical capabilities, ease of interaction with external programs, and reasoning/inference mechanisms. Along with the evaluation of software, issues such as suitability of the hardware and user-interface design were to be addressed in the course of the preprototype development.

2.2.1 The CU-STRAKE Preprototype on the KEE System

KEE is a complex and sophisticated LISP-based programming environment. It is a hybrid system, offering a range of knowledge representation and inference techniques. The basic representational paradigm is frames, which unify the procedural and declarative expression of knowledge. KEE is an example of object-oriented programming. Facts and rules are represented as objects or frames that have labeled slots containing values. The inference mechanism may be either forward chaining ('data-driven') or backward chaining ('goal-driven'). KEE offers a rich graphical capability, with a variety of graphic icons and switches.

A preliminary version of the knowledge base was programmed in KEE, with a limited reasoning capacity for providing guidelines towards sound earthquake-resistant design of buildings. Some of the design recommendations were based on the 1987 SEAOC Code [8]. Figure 2.1 shows a typical screen of the preprototype on KEE, illustrating the use of inheritance hierarchies in the knowledge base.

The system was designed to primarily address the design of regular buildings, for which the static lateral procedure is applicable. The program dealt with the computation of the design base shear, as well as reasoning and recommendations relating to eccentricity and torsion effects. The system was designed to aid the user to identify potentially dangerous elements like short columns, unreinforced walls, and other brittle elements, and to caution the user accordingly. The system also used the first level Japanese Rapid Evaluation Procedure [9] to obtain the seismic index of buildings and to make a rough estimate of their seismic vulnerability.

The graphics capabilities of the KEE environment were used to provide convenient icons and switches for the interface. Graphical information about the building was not, however, used in the reasoning process. The rule base was organized into rule-classes, allowing localized reasoning over a selected set of rules. Further, inheritance among the building units was exploited to enhance the representation power and to minimize the entering of redundant information. Procedural commands were used in frame slots to set off programmatic commands.

2.2.2 The CU-STRAKE Preprototype on the EXSYS System

Concurrent with the development of a preprototype on the KEE system, a second preprototype was developed using the EXSYS system. The knowledge base used was much the same as that used with the KEE system. However, additional graphical capability was provided for this system using AUTOCAD, a PC-based tool for computer-aided drafting. EXSYS is an expert system shell enabling convenient and rapid prototype development. It is easy to use, and has a convenient interface, but has no graphical capability of its

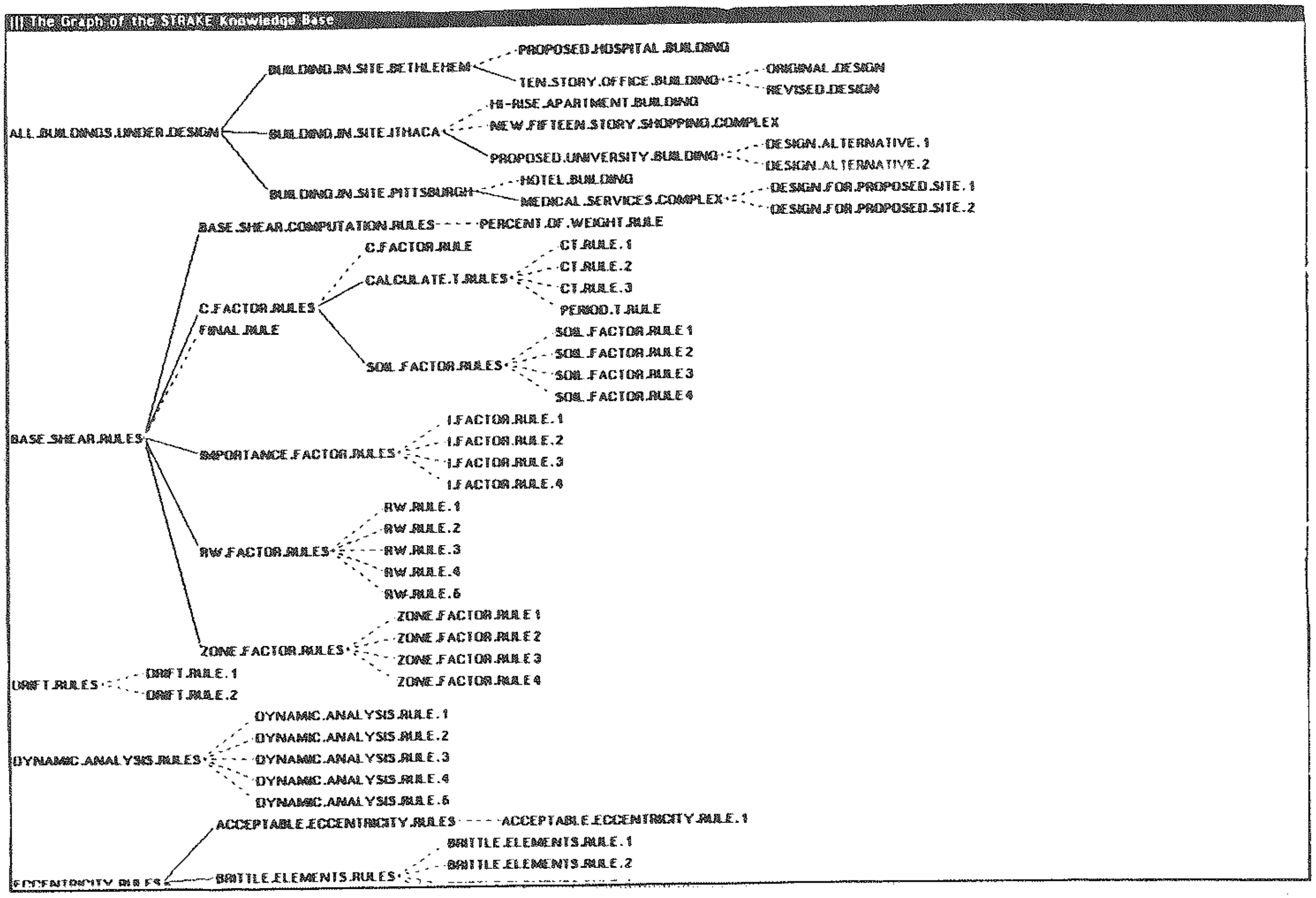


Figure 2.1: The CU-STRAKE Preprototype Using the KEE System

own. A useful feature of the software, however, is that it can easily be linked with external programs for numerical computations and graphics. The AUTOCAD program was used to provide graphical information to the system about the building being designed, and this information was used in the reasoning and the evaluation of the building. Some capability was provided in the system to go beyond the code specifications of design. As with the KEE preprototype, a 'thin-slice' knowledge base was used, and the system provided a capability of revising the design based on the recommendations of the system. Figure 2.2 shows some typical screens of the EXSYS preprototype during the consultation.

2.2.3 Comparison of the Two Programming Environments

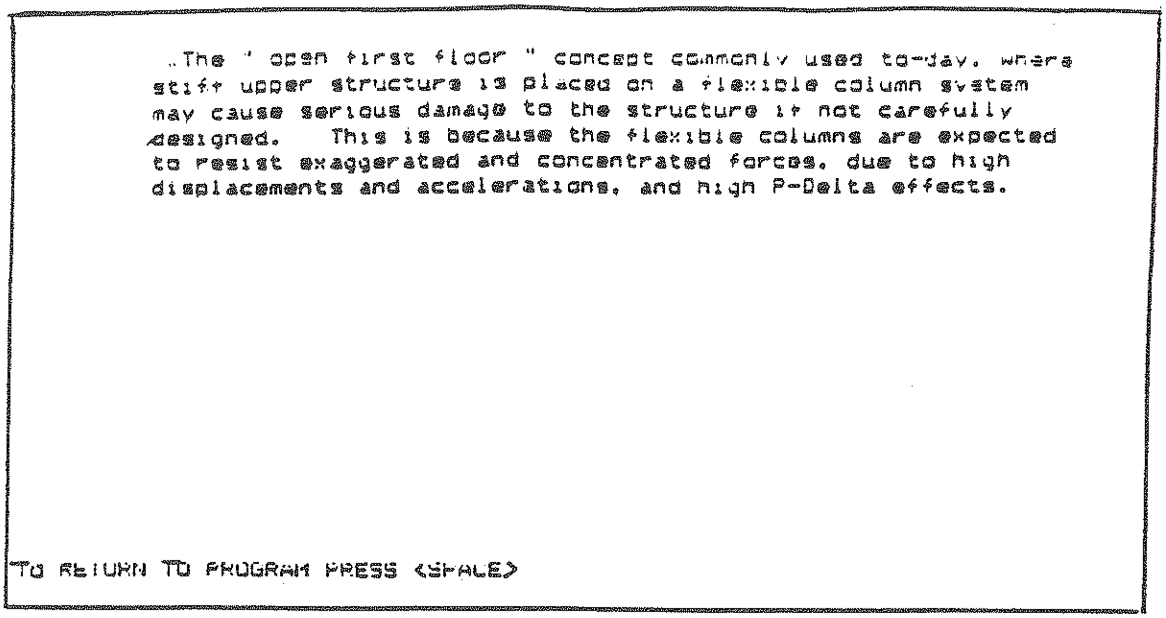
The development of the preprototypes using KEE and EXSYS served as a means of evaluating these environments and their suitability to this application. Several criteria were considered in evaluating the expert system tools, such as the power of knowledge representation, graphical capabilities, ease of interaction with external programs, and reasoning/inference mechanisms. Table 2.1 lists the important features of the two development tools.

The KEE environment has large system requirements, and calls for specialized hardware and a LISP environment. Hardware such as the Symbolics 3670, a LISP machine, is unsuitable from the perspective of the end-user; specialized hardware of this type is expensive, and is not common in structural engineering offices. The high cost of the KEE software makes it inaccessible to the smaller design offices. EXSYS, on the other hand, is available for PC's as well as VAX workstations, both of which are appropriate environments for structural engineering applications.

KEE is a sophisticated system, and requires significant training on the part of the developer as well as the user. EXSYS is a much smaller system, and is easy to develop applications on. The end-user interface is also straightforward, making it easy to use.

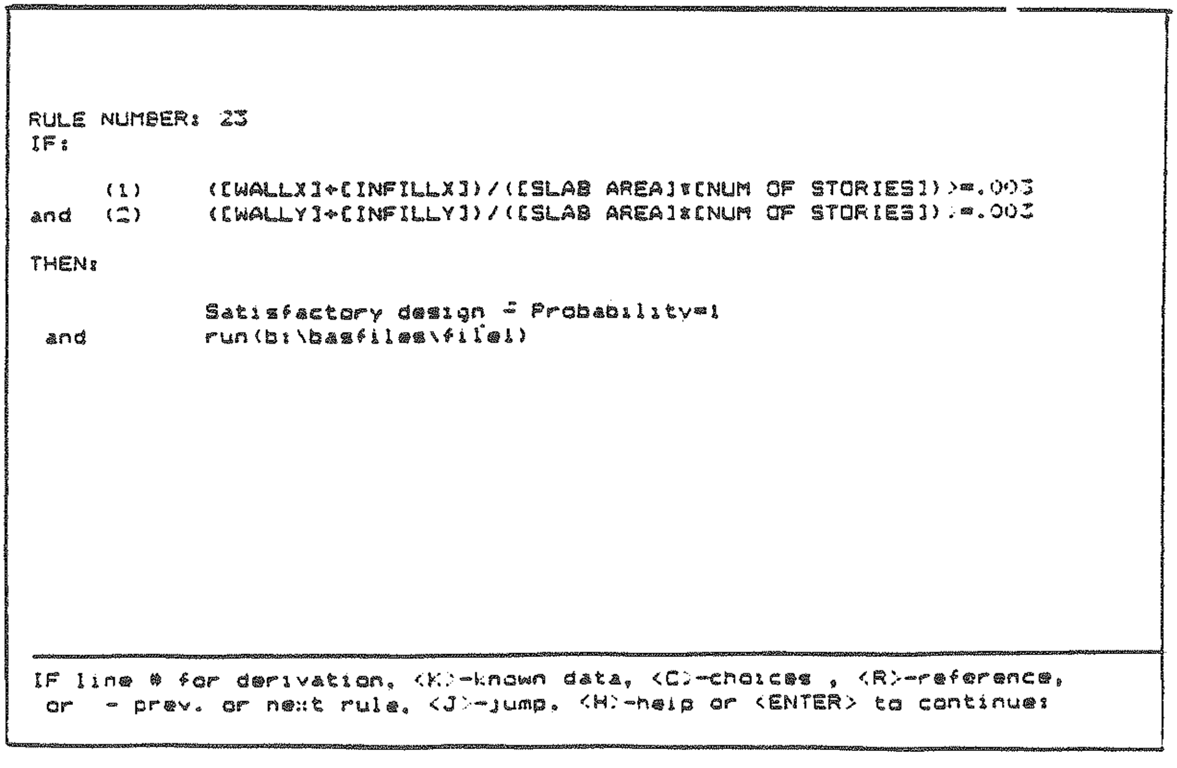
Of the two systems, KEE is a far more powerful tool for expert system development, allowing a rich representation of knowledge, making use of inheritance properties. KEE supports rule-based as well as frame-based representation schemes. It also allows more powerful inference schemes to be used, offering a choice of forward or backward chaining, or a mixed mode of operation. 'What-if' situations can be modeled by creating hypothetical contexts called KEEworlds. There is more flexibility in the reasoning, which can be localized to selected portions of the knowledge base.

In comparison, EXSYS is a more modest system, but one with impressive capabilities for its size and cost. EXSYS supports a rule-based representation scheme, and offers a choice of forward or backward chaining. The flow of control in EXSYS is predefined, and it does



```
  ..The " open first floor " concept commonly used to-day, where
  stiff upper structure is placed on a flexible column system
  may cause serious damage to the structure if not carefully
  designed.   This is because the flexible columns are expected
  to resist exaggerated and concentrated forces, due to high
  displacements and accelerations, and high P-Delta effects.

TO RETURN TO PROGRAM PRESS <SPACE>
```



```
RULE NUMBER: 23
IF:

     (1)     ([WALLX]+[INFILLX])/([SLAB AREA]*[NUM OF STORIES])>=.003
and  (2)     ([WALLY]+[INFILLY])/([SLAB AREA]*[NUM OF STORIES])>=.003

THEN:

             Satisfactory design = Probability=1
 and         run(b:\basfiles\file1)

IF line # for derivation, <K>-known data, <C>-choices , <R>-reference,
 or  - prev. or next rule, <J>-jump, <H>-help or <ENTER> to continue:
```

Figure 2.2: Sample Screens Showing the CU-STRAKE Preprototype Using the EXSYS System

not allow localized reasoning with small portions of the knowledge base. For studying alternative 'what-if' situations, there is a built-in feature allowing the user to change the values of certain parameters and rerun the sequence of reasoning.

KEE offers significant graphical capabilities. The system has two levels of graphics; at one level predefined graphic icons, meters and gauges are available for monitoring the values of attributes of the frames. At a lower level, the system's KEEpictures knowledge base allows the creation of a variety of graphical images using a set of primitives. EXSYS has no graphical features, but can be interfaced with external programs that provide the graphic capability. In general, both KEE and EXSYS can be conveniently linked with external routines to enhance their capabilities.

2.2.4 Conclusions Drawn from the Preprototype Development

The preprototypes developed using the two systems served as a preliminary test-bed for the knowledge-based approach being investigated. The process provided some insight into the basic methodology of expert system development, and also helped evaluate the available commercial development tools. A workshop held at Cornell University in August, 1987, on KBES in Earthquake Engineering, was used to coordinate the findings of various research groups and to make a decision about the future development systems to be used. Several considerations were taken into account, such as the suitability of the hardware for the end-user, and the capability for interfacing with external algorithmic programs. The latter capability was considered particularly important as the domain area by its nature requires the use of algorithmic methods to evaluate certain parameters. Also it was proposed to interface the KBES with graphical programs previously developed at Cornell, to provide input to the program, and enable static and dynamic analyses to be performed.

Based on these and other considerations, including the cost of the software, it was decided that the future development would proceed using the OPS83 programming environment. The KEE and EXSYS preprototypes were subsequently discarded, but the process of developing them provided valuable experience in the expert system methodology. Also, the process of evaluating the different shells helped in making a decision about the most appropriate environment for further prototype development. In addition, much of the knowledge base accumulated in the process could be used in the subsequent OPS83 prototype.

Table 2.1: Comparison of Expert System Shells – KEE and EXSYS

	KEE	EXSYS
1. HARDWARE	Symbolics LISP machine, engineering workstations - SUN, TI-Explorer, VAX.	PC-based. VAX versions also available.
2. PRICE	Commercial price $60000. No runtime license.	PC version for $395. VAX version for $5000 Run-time license for the PC for $600.
3. KNOWLEDGE REPRESENTATION	Supports rule- and frame-based representation schemes, with inheritance properties among frame elements.	Rule-based representation.
4. GRAPHICS	Has two levels of graphics; ready-made graphic icons and meters can be attached to frame slots and used to monitor slot values; at a lower level KEE allows the creation of a variety of graphical images from a set of primitives.	Does not support its own graphics, but can be interfaced with external graphics packages.
5. INFERENCE SCHEMES	Allows a choice of forward or backward chaining, or a mixed inference scheme.	Forward and backward chaining.
6. FLEXIBILITY OF REASONING	Reasoning can be localized to selected portions of the knowledge base. 'What-if' situations can be modeled using the concept of hypothetical 'KEEWorlds'.	Predefined flow of control. Has built-in feature to change parameters and rerun, to study 'what-if' situations.

SECTION 3

OVERVIEW OF CU-STRAKE: A KNOWLEDGE-BASED EXPERT SYSTEM FOR THE DESIGN OF EARTHQUAKE RESISTANT BUILDINGS

This section provides an overview of CU-STRAKE, a prototype KBES for seismic design of buildings. Various features of the prototype system are described, showing its capabilities and limitations. A typical scenario is presented using a case study to demonstrate the use of the system. A technical description of the system and the details of implementation form the subject of Section 5.

3.1 Scope of the Program

The CU-STRAKE prototype system is an outcome of a continuing research effort aimed at investigating the application of the expert-system approach to the practice of seismic structural design. The scope and organization of the system have been guided by the following objectives and considerations :

1. to validate the knowledge-based approach in the context of earthquake engineering; i.e., to verify the suitability of the domain and to establish the motivation for its use;
2. to use the development of the prototype as a means of evolving the appropriate knowledge base, methodology, and techniques of expert-system development for this application; and
3. to create and study the use of an integrated graphical environment for the definition, evaluation, and design of earthquake-resistant buildings.

While the KBES provides consultation and advice on several aspects of the seismic design of buildings, its recommendations are not to be considered the final word on the design, but rather as a supplemental resource for enhancing the design. The recommendations of the system currently pertain to the design of the building as a whole, rather than its individual components and detailing.

One of the primary objectives of the KBES development is to address some of the ill-structured and less routine aspects of the seismic design of buildings. It is intended to supplement building codes by aiding in the design of buildings not covered by the codes, and by providing alternatives to the code regulations that result in an improved design. Much of the knowledge base is therefore focused on features of seismic design that go beyond the recommendations of the building codes. It is widely acknowledged that in the seismic context using large design forces does not in itself ensure a good design. It is important to take into account other factors contributing to the overall behavior of the building. Thus the system stresses general aspects of good seismic design in addition to designing for the force level specified by the codes.

The KBES obtains information from the graphical definition of the building, and uses it to identify poor configurations and undesirable design features. The system cautions the user about the effects of such shortcomings in the design, and suggests alternatives to improve the design. The consultation of the system is organized in different levels corresponding to varying degrees of sophistication. The higher levels contain more specialized and 'expert' knowledge, while the lower levels deal with more routine aspects of the design. Presently two levels of evaluation have been implemented in the KBES—the first is used for performing a routine evaluation, and mostly concerns numerical computations, obtaining estimates of seismic quantities, and checking for compliance with some of the code provisions; the second level addresses those aspects of the design that are not covered by the codes, and are not otherwise well-documented.

Much of the first level evaluation, including the evaluation of seismic parameters such as the design base shear, is based on the Uniform Building Code (UBC) [10], and the SEAOC Lateral Force Requirements [8]. While some of the evaluation is based on these code regulations, the use of the KBES does not guarantee compliance with all the seismic regulations of the UBC, or any other code. The responsibility for ensuring compliance with the appropriate code is left to the user. The design process is interactive in nature, requiring active participation by the user in making design decisions. The user is expected to be a competent and responsible engineer, familiar with and experienced in structural design, but not necessarily with the seismic aspects of design. The KBES provides feedback on the design to the user in the form of estimates of seismic parameters, recommendations for revising the design, and in some cases a range of expert opinion on the appropriate action to take in dealing with some design aspects. The user then has the responsibility of taking an appropriate action based on the feedback of the system, or of selecting one of the alternatives presented by the system. The user also has the option of overriding the advice of the KBES, or of devising independent solutions to the design problem identified. The role of the KBES is therefore that of a 'surrogate consultant' rather than an autonomous decision-maker [11].

The CU-STRAKE system makes extensive use of interactive graphics for preprocessing, reasoning, and graphical display. The preprocessing capability is provided by the three-dimensional frame preprocessor, CU-PREPF [12], developed at Cornell University, and linked with the CU-STRAKE prototype. The preprocessor presents the user with a convenient means of providing input to the KBES graphically. However, this is not a mandatory form of input; if no graphical information on the building is available, the user can still proceed with the consultation, and any required input is obtained through user queries. However, without a full geometric description of the building, the KBES cannot easily reason on geometric data to obtain information needed for evaluation, a task which is simplified by using CU-PREPF to define the building.

Much of the knowledge base of the prototype system is applicable to buildings of various types, regular and irregular, in regions of high and low seismicity. The use of the graphical preprocessor for providing the building definition limits the user to those types of steel and concrete buildings that can be defined using CU-PREPF. Chapter 5 contains a brief description of the scope and range of applicability of CU-PREPF. Also, the estimation of some seismic quantities, such as the design base shear, is based on code formulas, and their applicability is limited by the range of validity of these formulas. However, the system provides alternatives to the code regulations which may lead to more conservative design choices.

Most routine and code-based provisions or design procedures are strictly applicable only to two-dimensional structures, and are based on assumptions of regularity and/or symmetry of the structure. Frequently these assumptions are violated for a building to meet its architectural or functional requirements. In these cases, three-dimensional seismic analysis and design may be required. The KBES in its present form does not have a built-in analysis capability for performing static and dynamic analyses; however, the building definition created using CU-PREPF may be used as input to one of two existing Cornell University programs, CU-STAND (static analysis and design) or CU-QUAND (earthquake analysis and design), which have three-dimensional analysis capabilities. More information on these programs, and the common databases used by them, is provided in Section 5. In the future, it is anticipated that these programs will be included as modules of the CU-STRAKE system providing the analysis capabilities for the KBES.

The KBES currently has no uncertainty mechanism for dealing with imprecise reasoning. The OPS83 programming environment used for implementing the system does not have a built-in uncertainty mechanism, but offers the flexibility for creating one. This is another anticipated future enhancement of the program.

During the consultation, the user can review the knowledge-base rules and obtain information about the reasoning process. At the present time the KBES does not permit the user to modify the knowledge base without modifying the source code containing the rules. A knowledge modification and acquisition facility may, however, be implemented in the future.

3.2 General Program Features

The CU-STRAKE system serves as an interactive consultant in the seismic design process by providing the user with convenient access to a database of knowledge and expertise in earthquake-resistant design. The system has a menu-driven interface, and makes use of graphics for the building definition and reasoning. It is assumed that at least a preliminary design of the building, such as one for wind loads, is available at the start of the consultation. In fact, several alternatives may be available as preliminary designs, and the KBES may be used to obtain feedback on each, and to determine the best design configuration. The building definition may be provided as graphical input to the program using CU-PREPF. The KBES obtains information about the building from the graphical data and uses it to evaluate the building from a seismic context. Information that cannot be obtained in this manner is obtained through user queries. During the consultation the system provides advice and recommendations on various features of the design. Based on the recommendations the user can revise the design and repeat the process until a satisfactory design is achieved. Figure 3.1 provides an overview of the design process using CU-STRAKE.

The feedback from the system, in the form of advice and recommendations, is used to improve the design of the building. Using the 'change-and-rerun' capability of the program, the user can make modifications to the design and re-evaluate it; the subsequent recommendations of the system can again be incorporated, and the new design evaluated once more. This process continues until a satisfactory design is obtained. The capability of some expert systems to model hypothetical ('what-if') situations is particularly useful in design and planning situations such as the present one, and is exploited in the CU-STRAKE system. This feature enables the user to explore different configurations and design possibilities, and the feedback from the system on each of these enables the user to select the most appropriate design choices.

An on-line HELP facility is available on all the menu pages of the program to provide information on the use of the program and about the functions available on each of the menu pages.

3.2.1 Layout of a Menu Page

The organization of the CU-STRAKE program is spread over several display screens or menu pages at different levels and with varying functions. Figure 3.2 shows the organization of the menu pages of CU-STRAKE. The general layout of a menu page and its different areas is shown in Figure 3.3. The program is menu-driven, and menu options are selected by clicking the mouse on the appropriate menu "button", which is simply a command displayed within a box on the screen. The menu buttons appear along the right edge of the

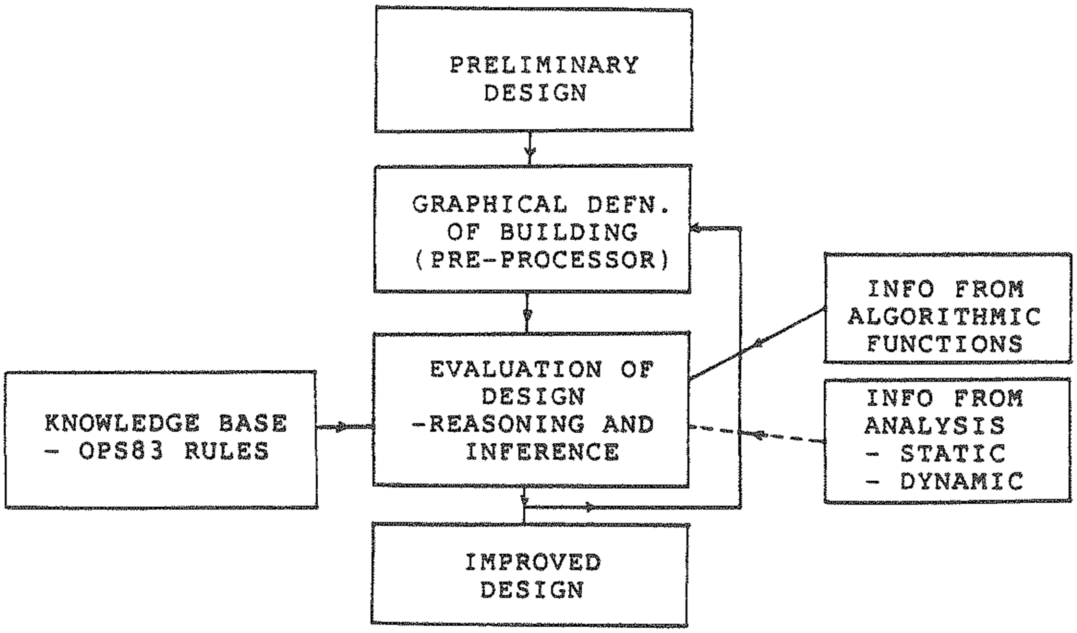


Figure 3.1: Overview of the Design Process Using CU-STRAKE

screen, and permit various operations from the different menu pages. Some menu buttons change from one menu page to another, and provide the functions relevant to the particular menu page they are on.

Some of the menu options are available from several or all menu pages. The HELP, PHOTO, RETURN/MAIN and QUIT commands are available on all menu pages as these commands may be required at any point in the program. The HELP command provides additional information about the functions on the particular menu page, and offers instructions on how to proceed with the evaluation. The PHOTO command is used to obtain hardcopies of the display screen. The RETURN/MAIN command is used to return from the current menu page to the previous level in the program; in some cases this is the MAIN page. The QUIT command enables the user to exit the program at any point.

The main display area is used to display information about the building under design, and for input/output during the consultation process. During some stages of the program, this area is composed of three subwindows (as in Figures 3.7, 3.8); the two upper windows are used for displaying information about the building, while the lower one is used for the dialog during the consultation. The upper left window displays a 3-dimensional graphical view of the building, if one is available; this is the case when the building definition has been created using CU-PREPF. The upper right window contains a tabular list of various attributes of the building and their corresponding values. This is a display of the information about the building in the format of the internal data structure (or 'working memory') used by the expert system in the reasoning process.

The title area at the top of all menu pages displays information such as the program name, the menu level and sublevel (if any), the username of the person running the program, the current date, and the problem name, if any. The information area at the bottom of the page below the main display window provides instructions to the user, and other information required to run the program.

3.2.2 Main Menu Levels in CU-STRAKE

The entry or main menu page, shown in Figure 3.4, provides access to each of the six main menu levels. If the HELP facility is invoked at this stage, the screen display shown if Figure 3.5 appears, providing information about the overall program and the functions of the six main menu levels. These menu levels and the operations that can be performed from them are :

1. INPUT STRUCTURE: - create a structure graphically, or read an existing file.
2. CONSULT–LEVEL I: - seismic evaluation, based on Code specifications and other well-documented seismic practices.

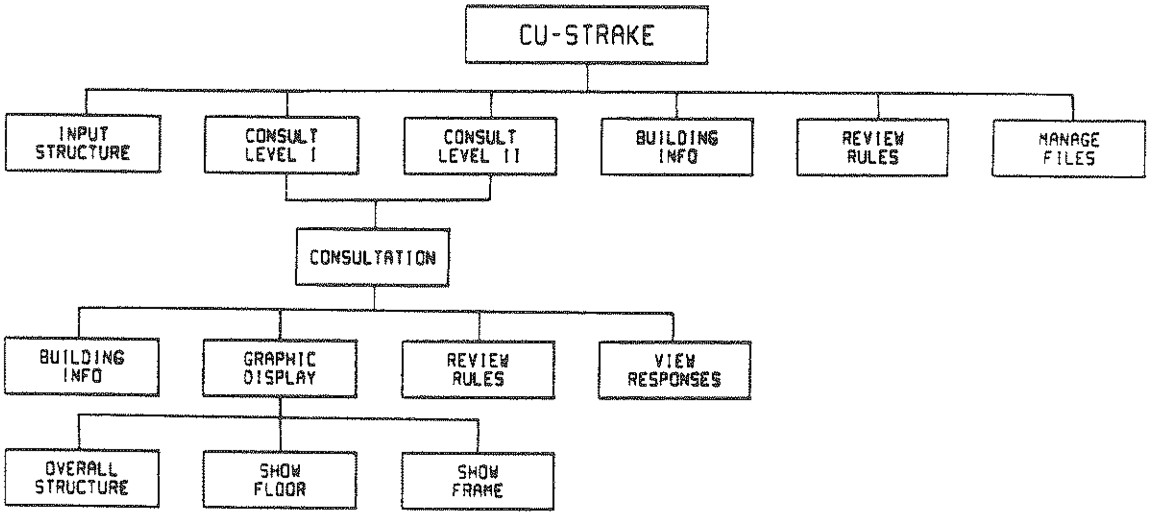


Figure 3.2: The Operation Structure of CU-STRAKE

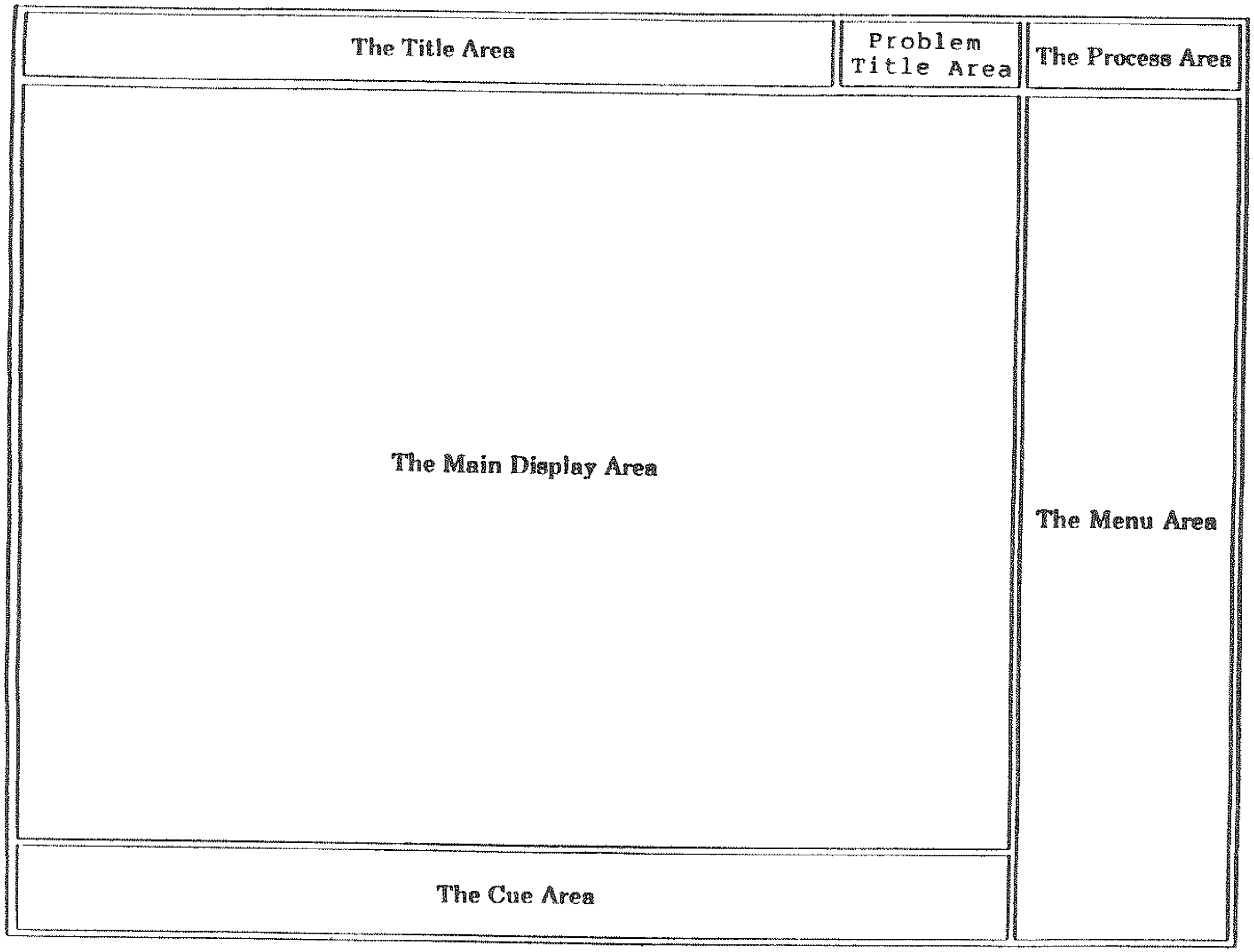


Figure 3.3: Layout of a Typical Menu Page of CU-STRAKE

3. CONSULT–LEVEL II: - consultation on seismic aspects not well-understood or well-established, or that are not adequately treated in the Codes.
4. BUILDING INFO: - operate on the building description data structure.
5. REVIEW RULES: - examine the rules forming the knowledge base.
6. MANAGE FILES: - read, write and delete files.

3.3 Case Study Scenario

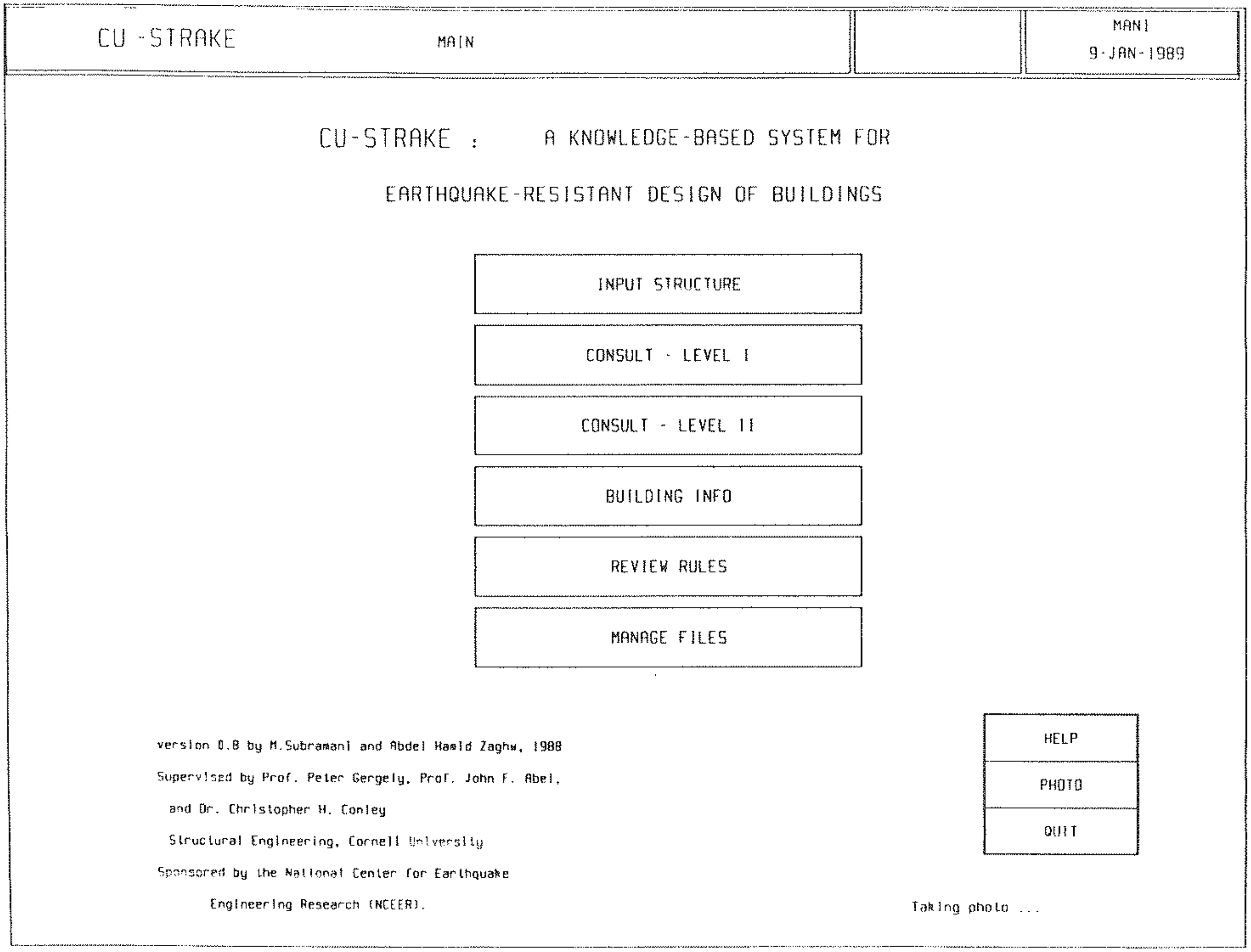
A case study is presented in this section to demonstrate the use of CU-STRAKE and to illustrate the various program features in some detail. The hypothetical building to be designed is a four-story framed structure to be located in Boston, Massachusetts.

Figure 3.6 shows a graphical view of the building in its preliminary form, which is provided as input to the system. The building is symmetrical, without offsets or other obvious irregularities. It may be noted that the walls of the building do not extend down to the first floor; this is not an uncommon arrangement, where walls are avoided in the first story level for functional reasons. However such an arrangement can be vulnerable during earthquakes as it results in a considerably less stiff first story. This effect, known as a soft first story, is identified during the second level of the consultation in CU-STRAKE. The building chosen is intended as a straightforward example to illustrate the various program features, without introducing much detail or complexity in the design.

INPUT STRUCTURE:

The first step in the design process is to provide the graphical definition of the building as input to the system. This is done from the INPUT STRUCTURE menu page. The layout of this menu page and the various menu operations available on this page are shown in Figure 3.7. As seen in the figure, the main display area of the screen is composed of three subwindows, labeled GRAPHIC DISPLAY, BUILDING INFO, and FILE LIST, to indicate their functions.

One may provide input to the system either by creating a graphical description of the structure using CU-PREPF, or by reading an appropriate input file, if one exists. It is presumed for the present example that the graphical data file has previously been created using CU-PREPF. When the user selects the READ command, the program requests him/her to specify what type of file to read in. Existing files are of two types—files with .DES extension are graphical data files created by the frame preprocessor, while files with .STRAKE extension ('Building Info' files) contain information about the building in the format of the internal data structure used by the KBES. In the present case, the '.DES file'

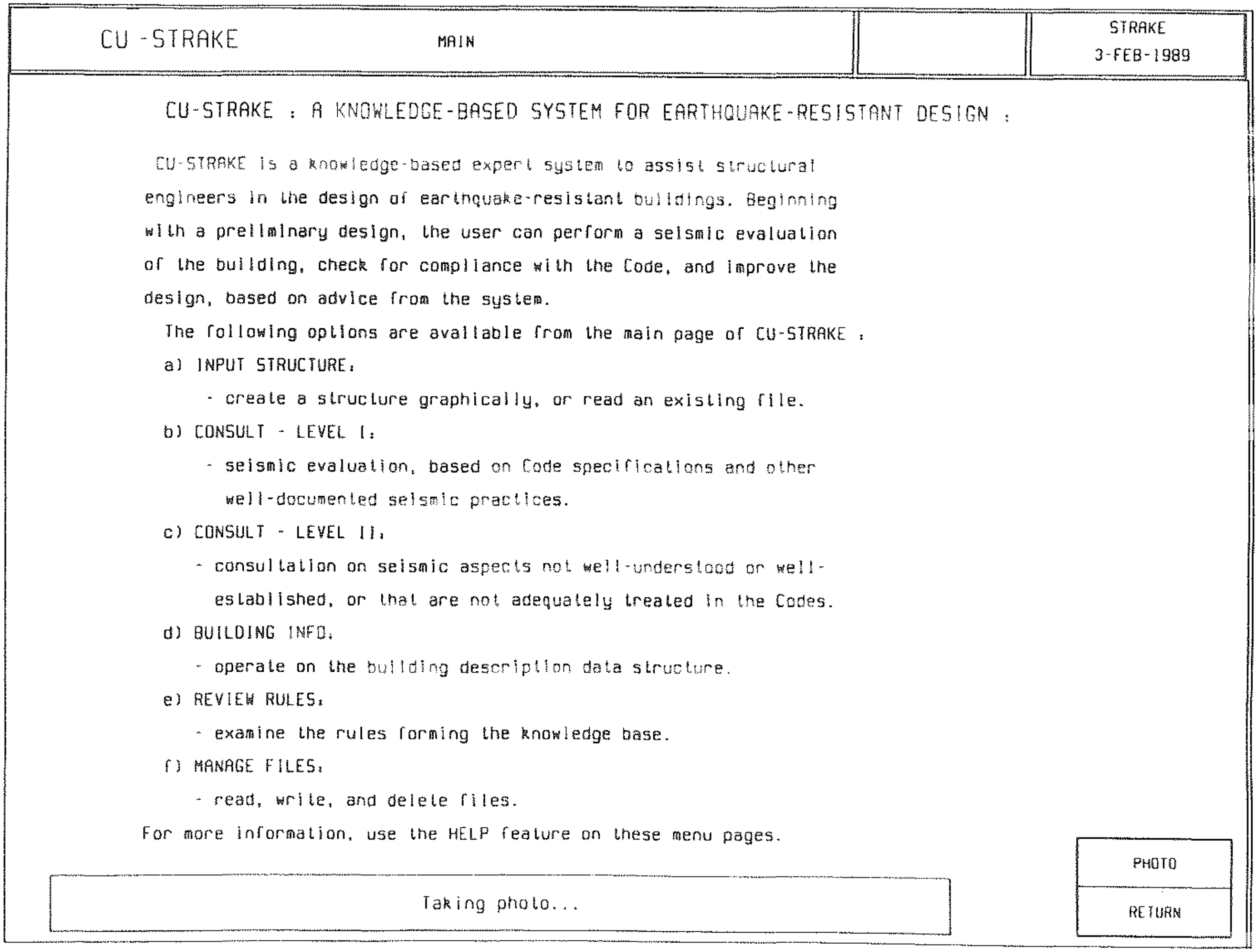


CU-STRAKE : A KNOWLEDGE-BASED SYSTEM FOR
EARTHQUAKE-RESISTANT DESIGN OF BUILDINGS

version 0.8 by M.Subramani and Abdel Hamid Zaghw, 1988
Supervised by Prof. Peter Gergely, Prof. John F. Abel,
and Dr. Christopher H. Conley
Structural Engineering, Cornell University
Sponsored by the National Center for Earthquake
Engineering Research (NCEER).

Taking photo ...

Figure 3.4: The MAIN Menu Page



CU-STRAKE : A KNOWLEDGE-BASED SYSTEM FOR EARTHQUAKE-RESISTANT DESIGN :

CU-STRAKE is a knowledge-based expert system to assist structural engineers in the design of earthquake-resistant buildings. Beginning with a preliminary design, the user can perform a seismic evaluation of the building, check for compliance with the Code, and improve the design, based on advice from the system.

The following options are available from the main page of CU-STRAKE :

a) INPUT STRUCTURE:
  - create a structure graphically, or read an existing file.

b) CONSULT - LEVEL I:
  - seismic evaluation, based on Code specifications and other well-documented seismic practices.

c) CONSULT - LEVEL II:
  - consultation on seismic aspects not well-understood or well-established, or that are not adequately treated in the Codes.

d) BUILDING INFO:
  - operate on the building description data structure.

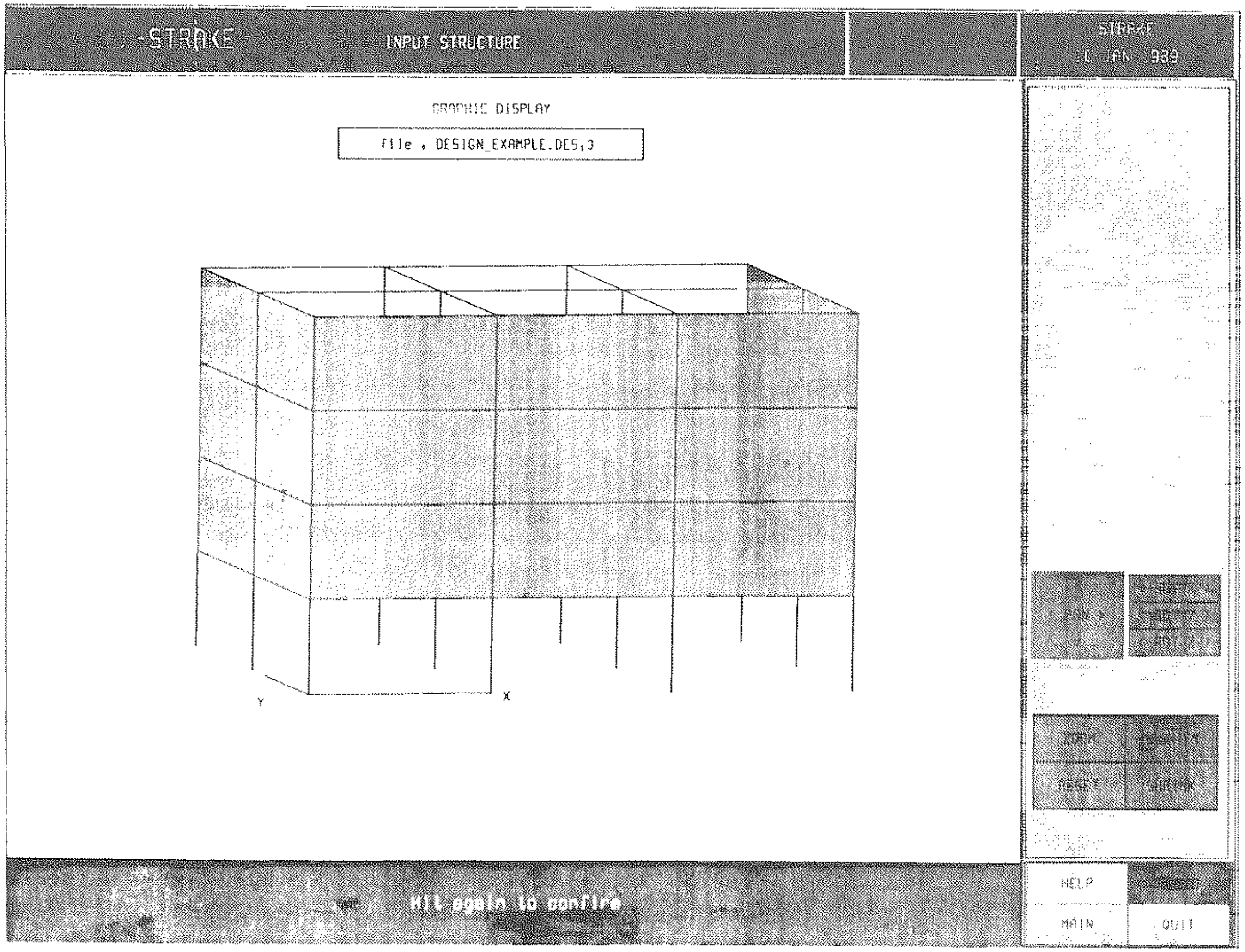
e) REVIEW RULES:
  - examine the rules forming the knowledge base.

f) MANAGE FILES:
  - read, write, and delete files.

For more information, use the HELP feature on these menu pages.

Taking photo...

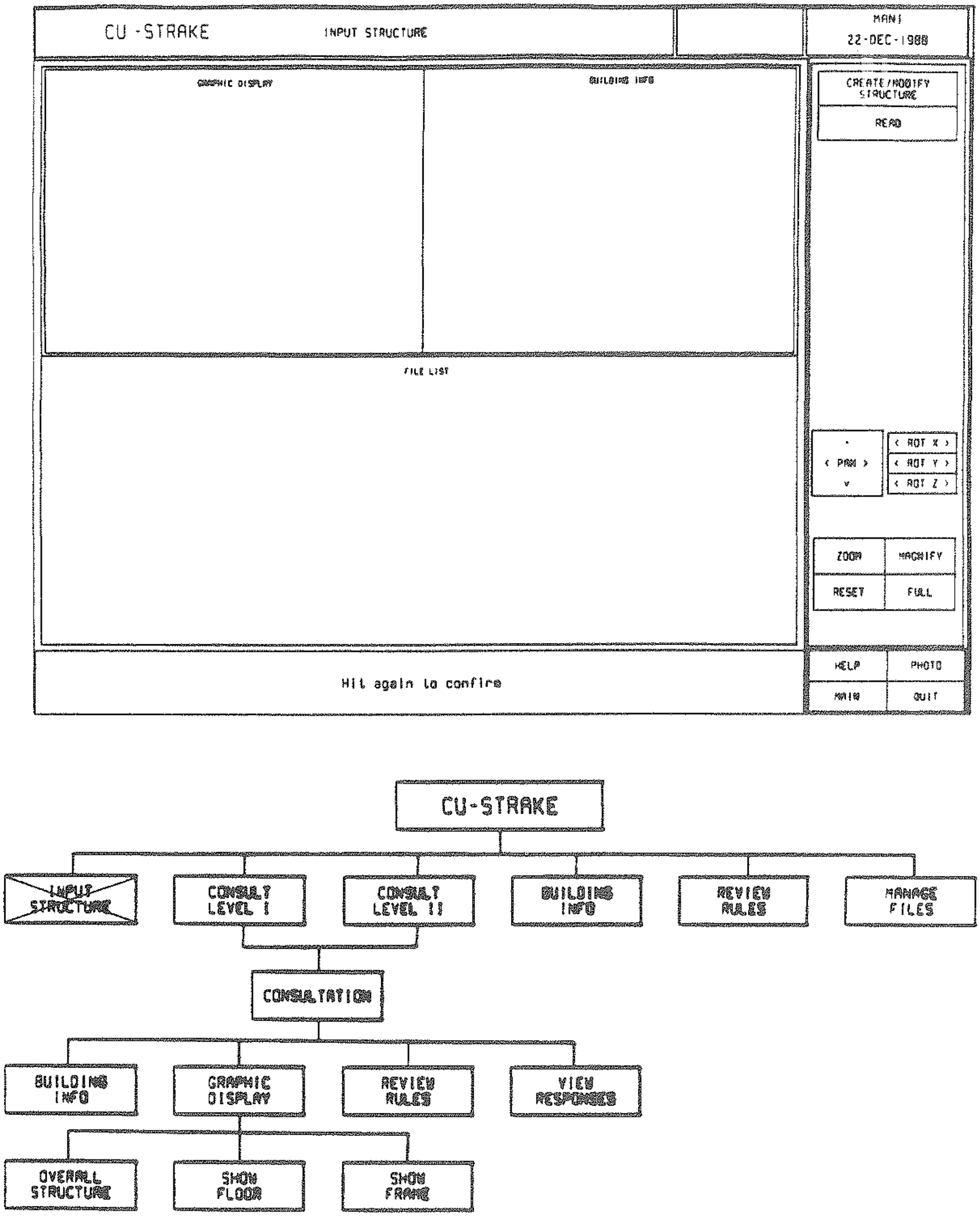
Figure 3.5: The HELP Mode in the MAIN Menu Page



file , DESIGN_EXAMPLE.DES;3

Hit again to confirm

Figure 3.6: Graphical View Showing the Preliminary Design of the Building



Hit again to confirm

Figure 3.7: The INPUT STRUCTURE Menu Page

option is selected since a graphical definition of the building is to be read in. When this selection is made, the KBES scans the default directory for files of the desired type, and lists all such files for the user to select one. Clicking on the appropriate filename directs the program to retrieve the corresponding input file and obtain the information about the building. Once this is done, the information pertaining to the building is displayed on the screen. A graphical view of the building appears in the GRAPHIC DISPLAY subwindow, while a list of the building attributes with some of their values is shown in the BUILDING INFO window (Figure 3.8).

The geometric manipulation commands in the menu button area may be used to rotate, zoom, or pan the view of the structure. It is also possible to scroll up and down the BUILDING INFO table to view the various attributes. It is seen that only a few of the attributes have known values at this point—these pertain to geometric data about the building which has been inferred from the graphical input. Other information which could not be obtained from the graphical data, such as the seismic zone and the occupancy type of the building, is obtained by the KBES during the consultation by querying the user. The corresponding slots in the BUILDING INFO table are filled as this information becomes known.

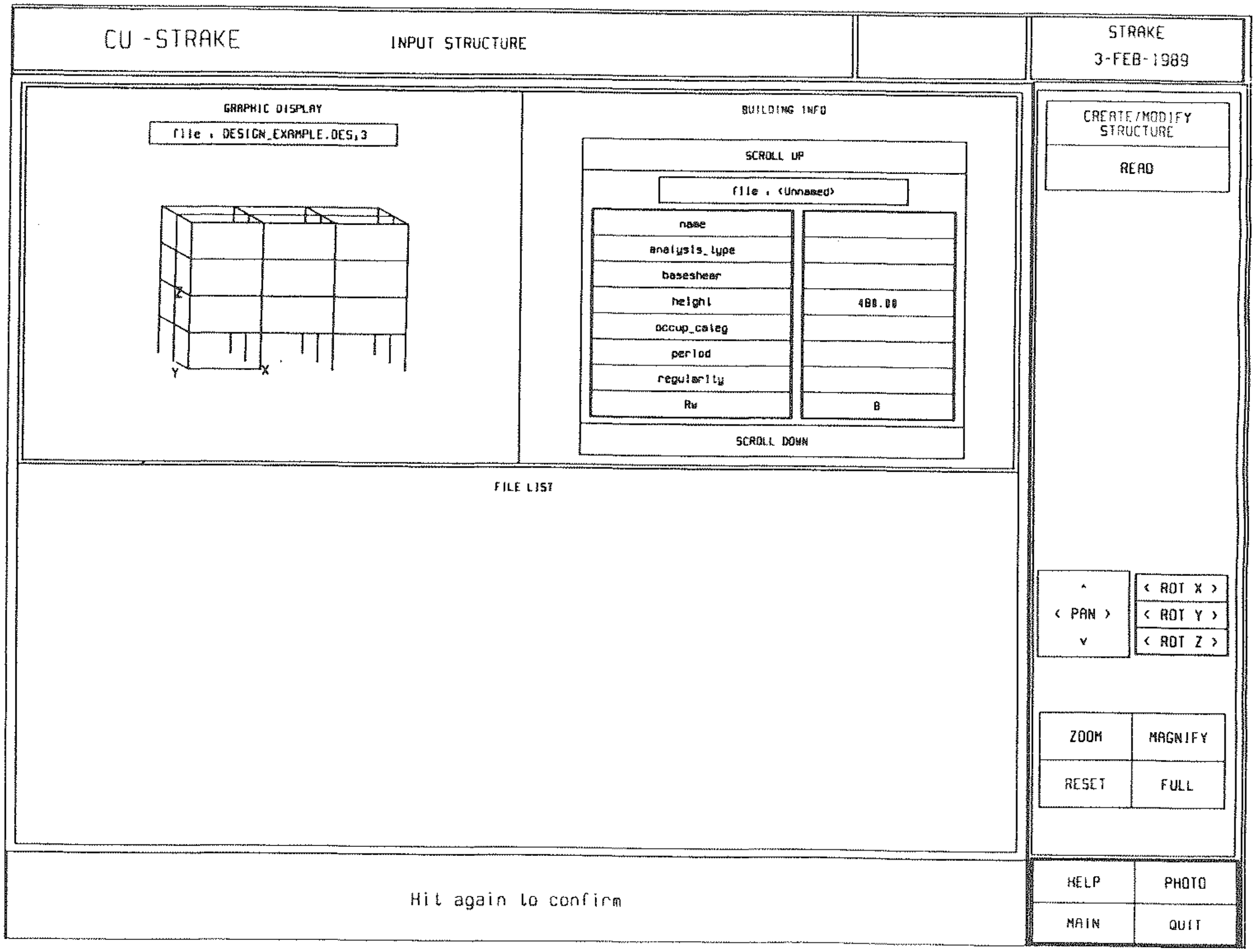
Having defined the building to be used in the evaluation, one can now proceed with the seismic design process. Returning to the main menu page, one may select one of two levels of consultation. The two levels differ in the scope of their evaluation and the level of complexity incorporated in them. The sections of the knowledge base incorporated in each of the levels of consultation, and the motivation for such an organization of the knowledge base, are discussed in Section 4.

CONSULT–LEVEL I:

The first of the two levels of consultation implemented to date is CONSULT–LEVEL I, which deals with the more straightforward aspects of the design including the estimation of seismic parameters and checking for compliance with some of the code provisions. The knowledge base for much of this level of the consultation is based on building code provisions and well-documented procedures.

The first menu page in the first level evaluation (Figure 3.9) provides a range of options for defining the scope of the evaluation. These are :

1. Period evaluation
2. Base shear estimation
3. Story drift



file : DESIGN_EXAMPLE.DES;3

file : <Unnamed>

name	
analysis_type	
baseshear	
height	400.00
occup_categ	
period	
regularity	
Rw	0

Hit again to confirm

Figure 3.8: The INPUT STRUCTURE Menu Page after Reading an Input File

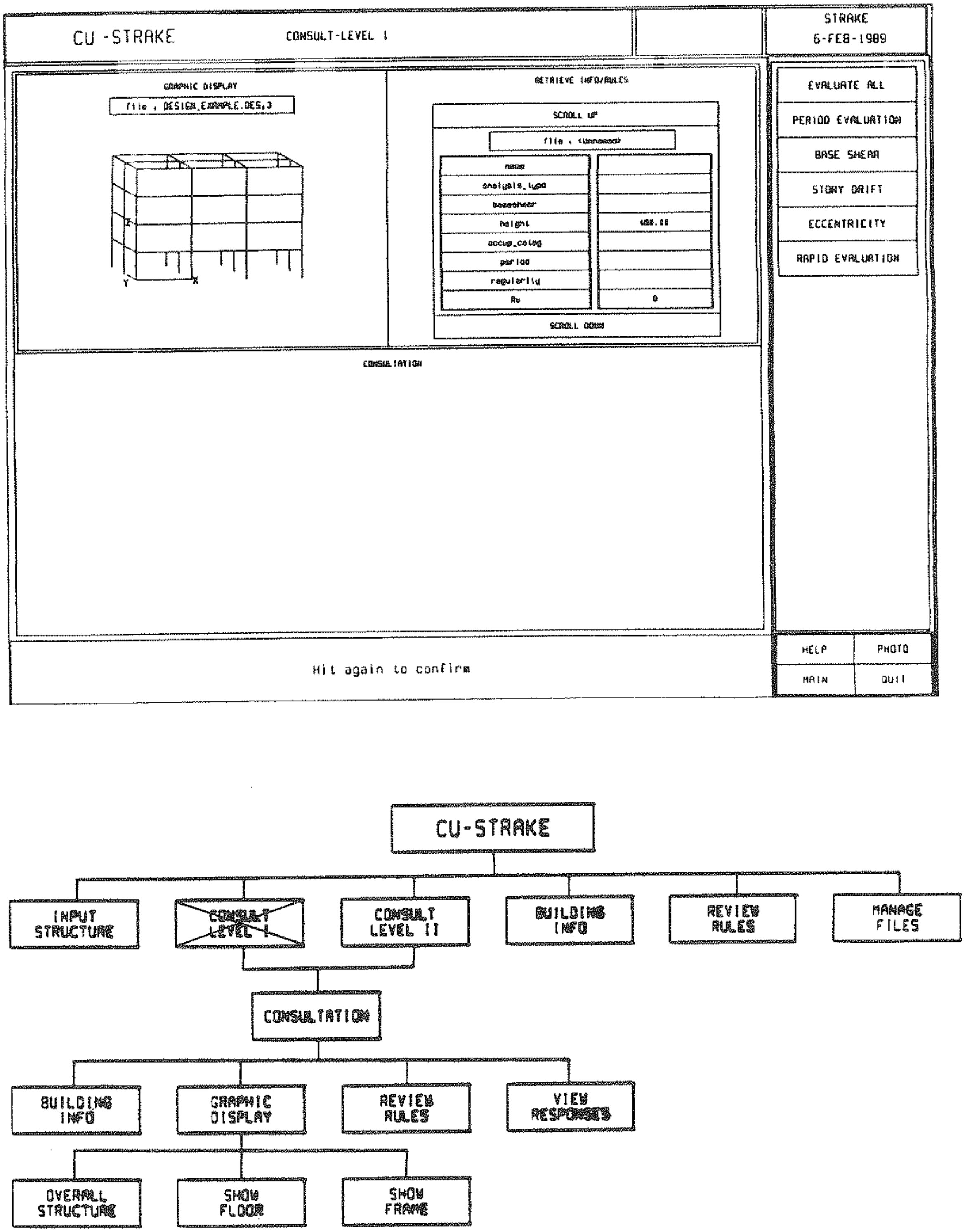
4. Eccentricity and torsion effects
5. Japanese Rapid Evaluation Procedure

The Japanese Rapid Evaluation Procedure [9] provides an approximate means of estimating whether a building design is safe, based on the available area of walls to provide the lateral shear resistance. More information on this approximate method is provided in the discussion of the knowledge base in Section 4. The EVALUATE ALL option on this menu page may be selected to go through all of the above evaluations.

1. Period evaluation: When the PERIOD EVALUATION option is selected, the CONSULTATION menu page appears, from which the rules can be executed to perform the evaluation and reasoning. The menu options on this page are shown in Figure 3.10. The user can proceed with the evaluation either by stepping through the rules, or by executing them all at once. The other buttons on this menu page allow the user to switch to one of the other menu pages associated with the graphical display or the information in the RETRIEVE INFO/RULES window, which contains the BUILDING INFO data structure, and can also be used for reviewing the knowledge-base rules. Any one of the three subwindows in the main display can be made active at any time by clicking on it, enabling the user to then perform operations related to the particular window.

When the EXECUTE ALL RULES option is selected at this point, the rules associated with the estimation of the building period are executed and the fundamental period is obtained as 0.32 sec. This is an approximate value based on the formula in the 1988 UBC. The user is referred to other more comprehensive methods such as the Rayleigh method to obtain a better estimate of the period. The Rayleigh method is not currently available in CU-STRAKE, but is likely to be added in the future, once the program has a static analysis capability.

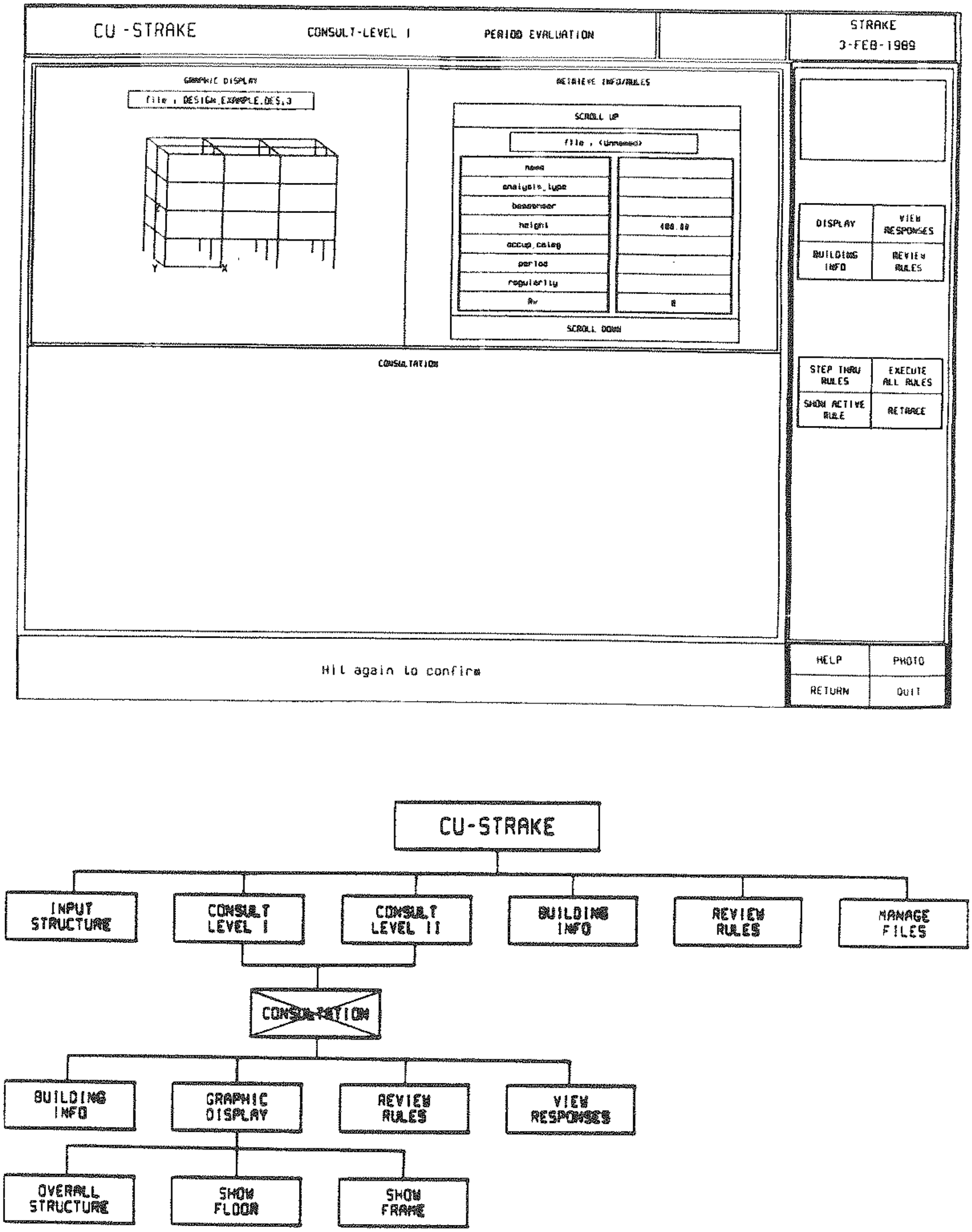
2. Base shear estimation: The next step in the evaluation is the determination of the design base shear. When this operation is selected with the EXECUTE ALL RULES option, the KBES proceeds to execute all the rules necessary to obtain an estimate of the base shear. In the course of this evaluation, the KBES queries the user for any information that is required for the evaluation and is not otherwise available to the program. The first of these is the seismic zone, which is given as 2 (for the site in Boston, Massachusetts). Next, the user is asked to specify the occupancy category of the building, which is required to determine the importance factor used in the base shear evaluation. The building is specified here as belonging to the standard occupancy category. The KBES next requests the user to select the soil type of the building site—the four soil types listed correspond to those defined in the 1988 UBC. For the present case, the soil type selected is 2, which implies a soil profile with dense or stiff soil conditions, where the soil depth exceeds 200 feet or



name	
analysis_type	
baseshear	
height	488.00
occup_categ	
period	
regularity	
Rw	0

Hit again to confirm

Figure 3.9: The CONSULT–LEVEL I Menu Page



name	
analysis_type	
baseshear	
height	400.00
occup_categ	
period	-
regularity	
Av	0

Hit again to confirm

Figure 3.10: The CONSULTATION Menu Page

more. The value of the design base shear for the building is now obtained as 145 kips. The distribution of this force over the height of the building is also obtained, and is displayed graphically. Also, based on the information about the building, the KBES determines that, in accordance with the code requirements, the static lateral force procedure is adequate for this building, and no dynamic analysis is necessary.

3. Story drift: The next step in the first level evaluation of the building is to obtain estimates of the interstory drifts. This evaluation is performed for a particular floor of the building—at present this is the first floor, which is the 'current' floor by default. When the corresponding rules are executed, the KBES provides estimates of the story drift for this floor. Two approximate methods are available in the system for estimating the story drift. One of these is based on a rapid evaluation procedure outlined in ATC-14 [13], while the other is based on a spring model to estimate story stiffnesses. These methods, and their range of applicability are discussed in detail in the discussion of the knowledge base in Section 4. The first method is applicable to steel or concrete moment-resisting frames only, and is not suitable for buildings such as the present one, which have shear walls. The KBES recognizes this and consequently does not use the ATC formula but provides an estimate of the story drift based only on the approximate spring model.

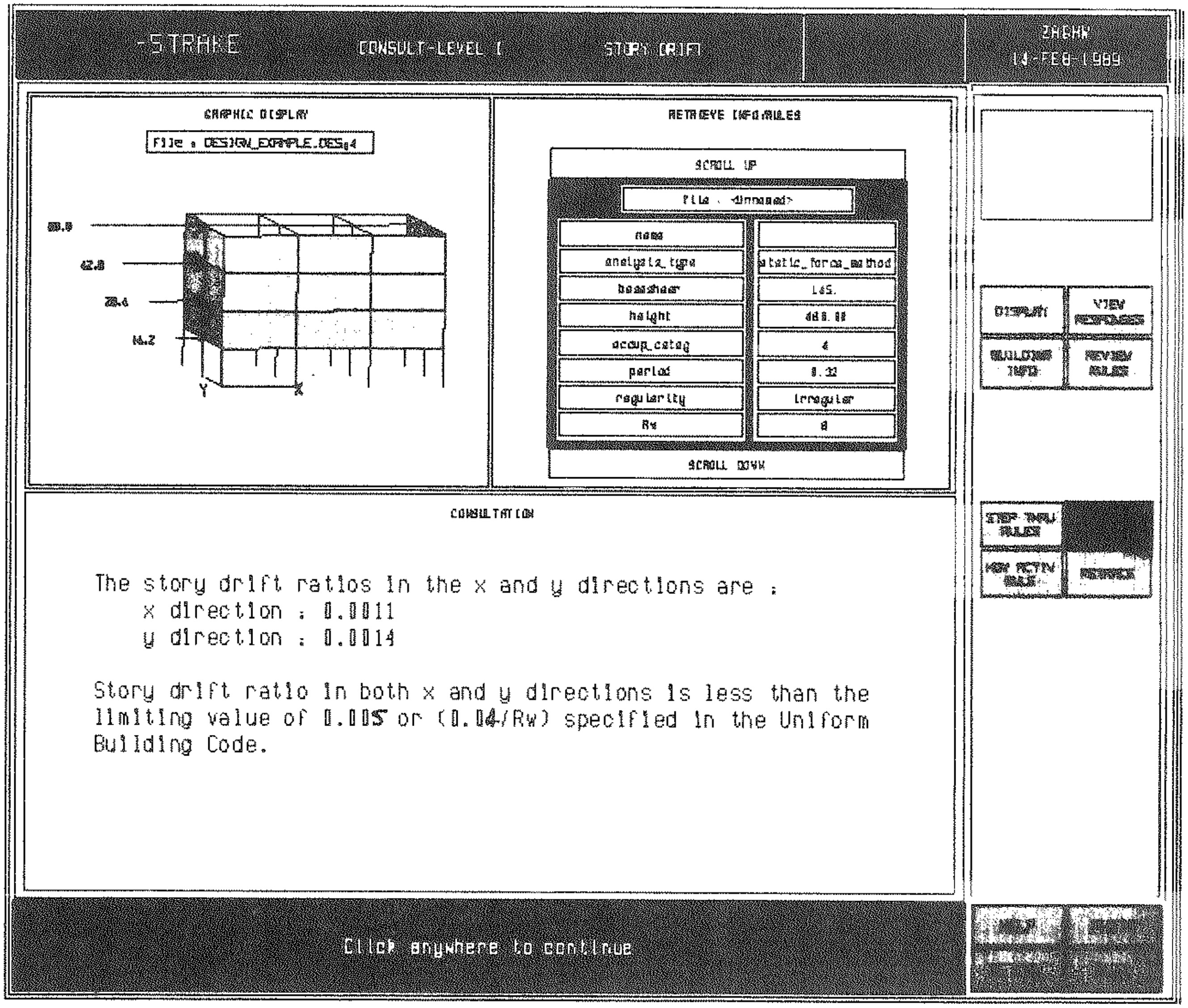
The story drift ratios obtained for the first floor of the building using the approximate spring method are the following :

x-direction = 0.0011
y-direction = 0.0014

The display of this information on the screen during the consultation is shown in Figure 3.11.

In cases where both the methods for drift estimation are applicable the KBES provides two sets of estimated drift values, one corresponding to each method, and allows the user to specify which of these estimates to use. The user can then select either method, or instruct the system to calculate the drifts by both methods and use the more critical values.

The story drift ratios of 0.0011 and 0.0014 obtained for the present case in the x- and y-directions respectively are both well within the allowable range of 0.005 or $(0.04/R_w)$ specified in the UBC for buildings less than 65 feet in height. The story drifts for the other floors may be checked in a similar way by modifying the floor number in turn to each of the other floors and repeating the evaluation. This is done by switching to the BUILDING INFO menu page and changing the floor number using the MODIFY STRUCTURE DESCRIPTION command. When the drift estimation is repeated for each of the other floors of the building, it is found that the story drifts are within the code limits in all cases.



name	
analysis_type	static_force_method
baseshear	145.
height	468.00
occup_categ	4
period	0.32
regularity	irregular
Rw	8

The story drift ratios in the x and y directions are :
x direction : 0.0011
y direction : 0.0014

Story drift ratio in both x and y directions is less than the limiting value of 0.005 or (0.04/Rw) specified in the Uniform Building Code.

Figure 3.11: Feedback from the KBES Showing Estimates of the Story Drifts

4. Eccentricity and torsion effects: The next option in the first-level evaluation deals with identifying different types of irregularities in the building and the consequent scope for torsional effects. The system checks for vertical as well as plan irregularities. The plan eccentricity is calculated for each floor as the distance of the centroid of the floor from its center of rigidity. If the eccentricity exceeds 20% of the larger plan dimension of the building, it is considered irregular. Also, if there are any soft stories in the building, it is considered irregular on the basis of vertical variation in stiffness. In the present case, the first floor is found to have no plan eccentricity as the frame itself is symmetrical and the walls do not extend to the first floor. The upper floors are more asymmetrical but their eccentricity ratio does not exceed 0.2. However, the building is found to have a soft first story as the stiffness of this story is reduced significantly as a result of discontinuing the walls at this level. The building should therefore be treated as irregular on the basis of vertical irregularity.

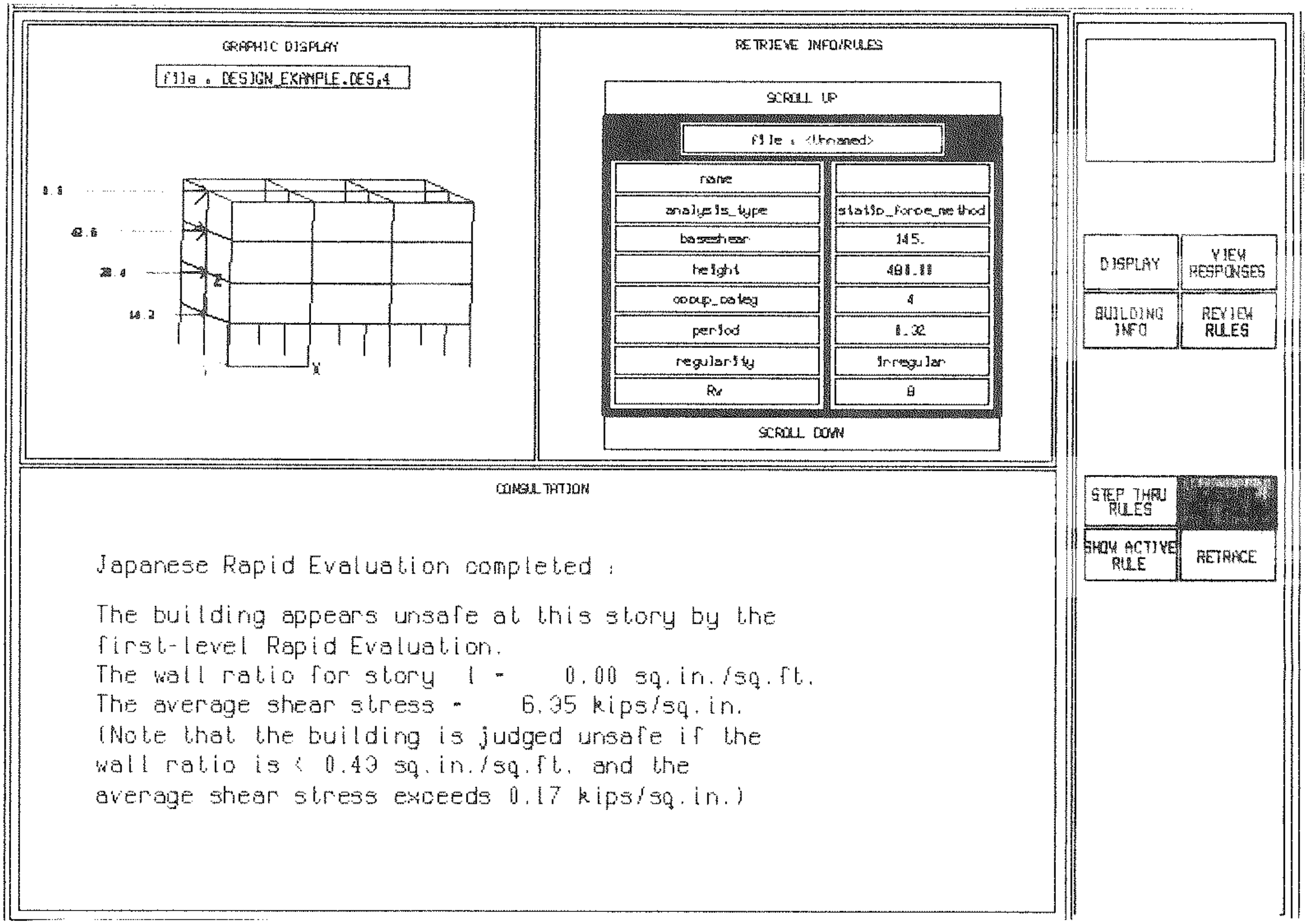
5. Japanese Rapid Evaluation Procedure: The final operation in the first level evaluation is the first level of the Japanese Rapid Evaluation Procedure (JREP), which provides a quick check on whether the building design is likely to be safe, based on the available area of walls at various floors to provide the lateral shear resistance. The check in this case fails for the first floor, as there is no available wall area at this level, and the average shear stress, based on column areas, is higher than a limiting value (Figure 3.12). The check is then repeated for other floors, and it is found that these floors appear safe by the first level JREP.

This concludes the first level evaluation of the building, in which estimates of various seismic quantities were obtained, and some of them checked against limiting values. The only deficiencies noted in the design were the soft first story and the fact that the first story fails the first level JREP on account of its lack of walls or sufficient column area.

During or after completion of the first evaluation, one may wish to make use of other menu options such as those available on the BUILDING INFO and REVIEW RULES menu pages, to obtain additional information, modify the building description, or examine the knowledge-base rules.

BUILDING INFO:

By selecting the BUILDING INFO command from the CONSULTATION menu page one can operate on the internal representation of the structure. The options on the BUILDING INFO menu page can be used to review the working memory of the system, and to perform operations such as modifying or deleting the structure description, and saving the current state of the working memory to a file. The ability to modify the internal representation of the structure provides a convenient and powerful way of accessing the building information



name	
analysis_type	static_force_method
baseshear	145.
height	481.88
occup_categ	4
period	0.32
regularity	irregular
Rv	8

Japanese Rapid Evaluation completed :

The building appears unsafe at this story by the
first-level Rapid Evaluation.
The wall ratio for story 1 = 0.00 sq.in./sq.ft.
The average shear stress = 6.35 kips/sq.in.
(Note that the building is judged unsafe if the
wall ratio is < 0.43 sq.in./sq.ft. and the
average shear stress exceeds 0.17 kips/sq.in.)

Figure 3.12: Feedback from the KBES Based on the JREP

stored in the system. One use of this feature is to study hypothetical ('what-if') situations; for example, the user can perform repeated evaluations of the structure and evaluate different configurations or design possibilities by merely modifying the relevant attributes in the internal representation of the building. Also, any incorrect input to the program on the design attributes of the building can be corrected using the facility for modifying the structure description.

REVIEW RULES:

The commands in the REVIEW RULES menu level are useful for obtaining information about the knowledge base and gaining insight into the working of the KBES. The features of this menu page help in making the reasoning process more transparent, and consequently the KBES less of a 'black box'. The commands on this menu page can be used to determine how the KBES derived certain information, and how it arrived at its conclusions. The facility can also be used like an explanation facility, to determine why certain data asked of the user is relevant to the evaluation, and how it impacts the overall reasoning process.

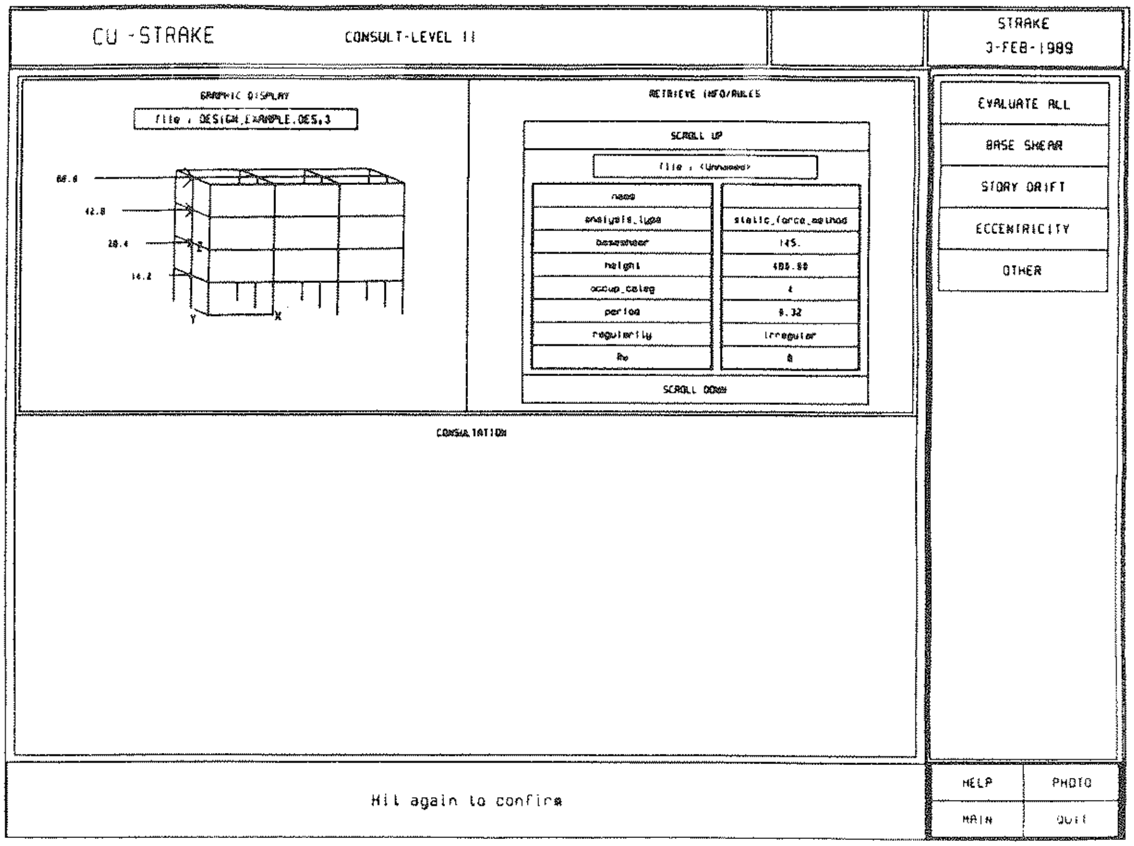
CONSULT–LEVEL II:

The second level consultation is directed at ill-structured and less routine aspects of the seismic design of buildings. Most of the evaluation at this level is for irregular structures, and is aimed at identifying and suggesting remedial action for the design deficiencies of such structures.

The menu options on the first page of the second level consultation are shown in Figure 3.13. Some of these options are also available in the first level evaluation; however, in the second level more options are available to the user to modify or override the code-based values used in determining some of these quantities. The BASE SHEAR and the STORY DRIFT commands allow the user to override the code values used in the first-level evaluation of these quantities. For instance, in the base shear evaluation, instead of picking one of the seismic zones identified in the code, the user may assign weight factors or probabilities to different seismic zones (Figure 3.14) to reflect the 'degree of belief' that the building site is in that zone. The corresponding zone factor is then an interpolated value, or weighted average lying in between the code values.

The STORY DRIFT option may be used to determine the story drift and to check the values obtained against user-defined limits, instead of the code-specified values used in the first-level consultation.

The ECCENTRICITY option is used to determine whether the stiffness asymmetry of the floors of the building exceed a maximum permissible value (30% of the plan dimension). A histogram is also displayed, showing the range of expert opinion on the limiting value of



name	
analysis_type	static_force_method
baseshear	145.
height	400.80
occup_categ	4
period	0.32
regularity	irregular
Rw	8

Hit again to confirm

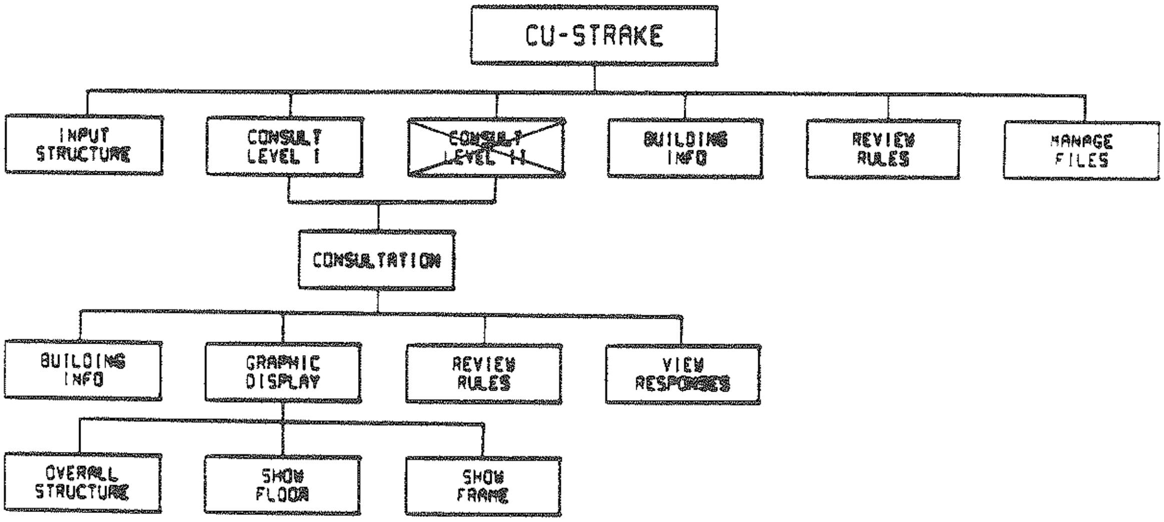
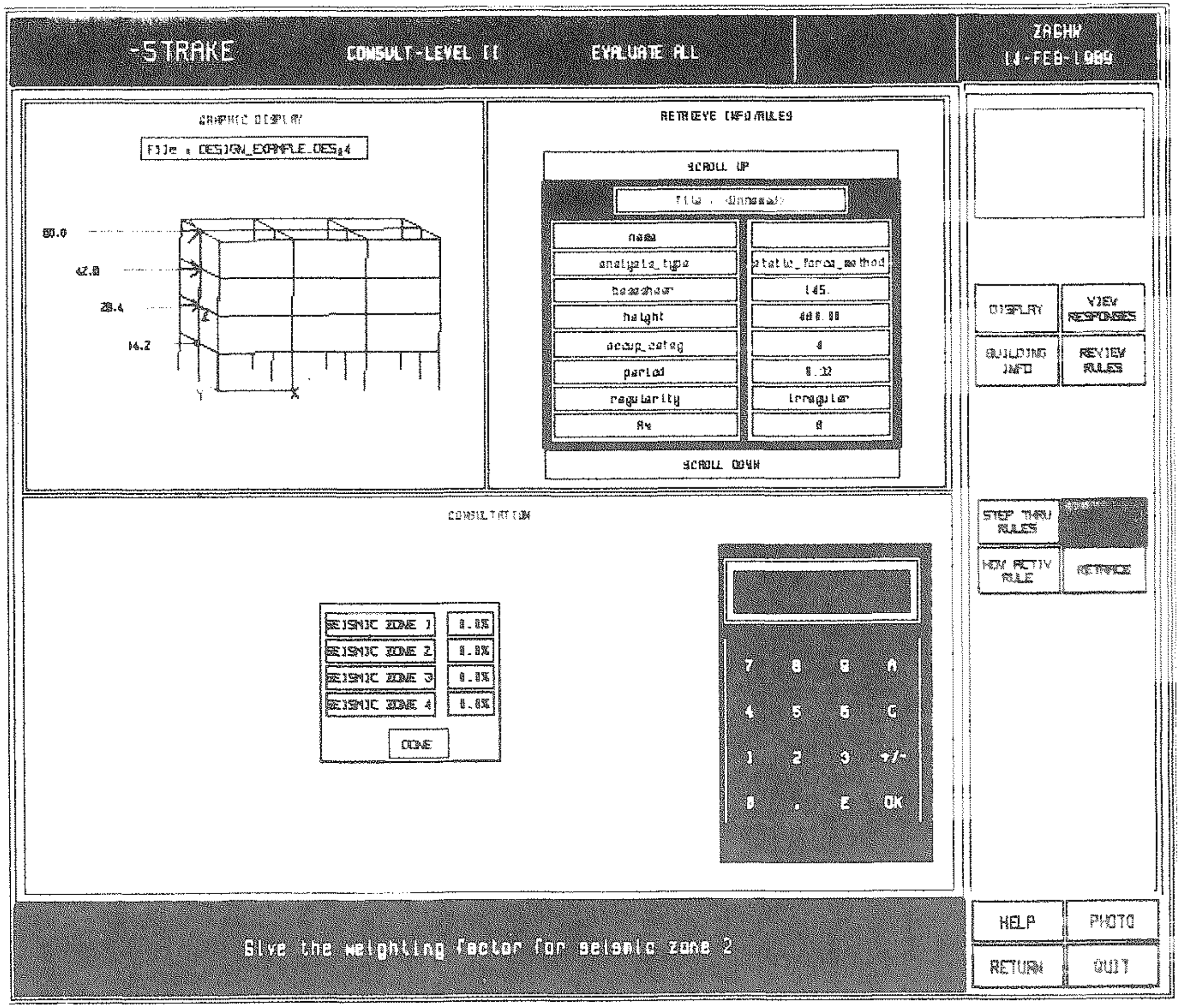


Figure 3.13: The CONSULT–LEVEL II Menu Page



File : <Unnamed>

name	
analysis_type	static_force_method
baseshear	145.
height	480.00
occup_categ	4
period	0.32
regularity	irregular
Rw	8

SEISMIC ZONE 1	0.0%
SEISMIC ZONE 2	0.0%
SEISMIC ZONE 3	0.0%
SEISMIC ZONE 4	0.0%

Give the weighting factor for seismic zone 2

Figure 3.14: Assigning Weight Factors to Seismic Zones in CONSULT–LEVEL II

the acceptable eccentricity as a percentage of the plan dimension. For the present building the KBES determines that the stiffness eccentricities of the floors of the building are less the limiting value.

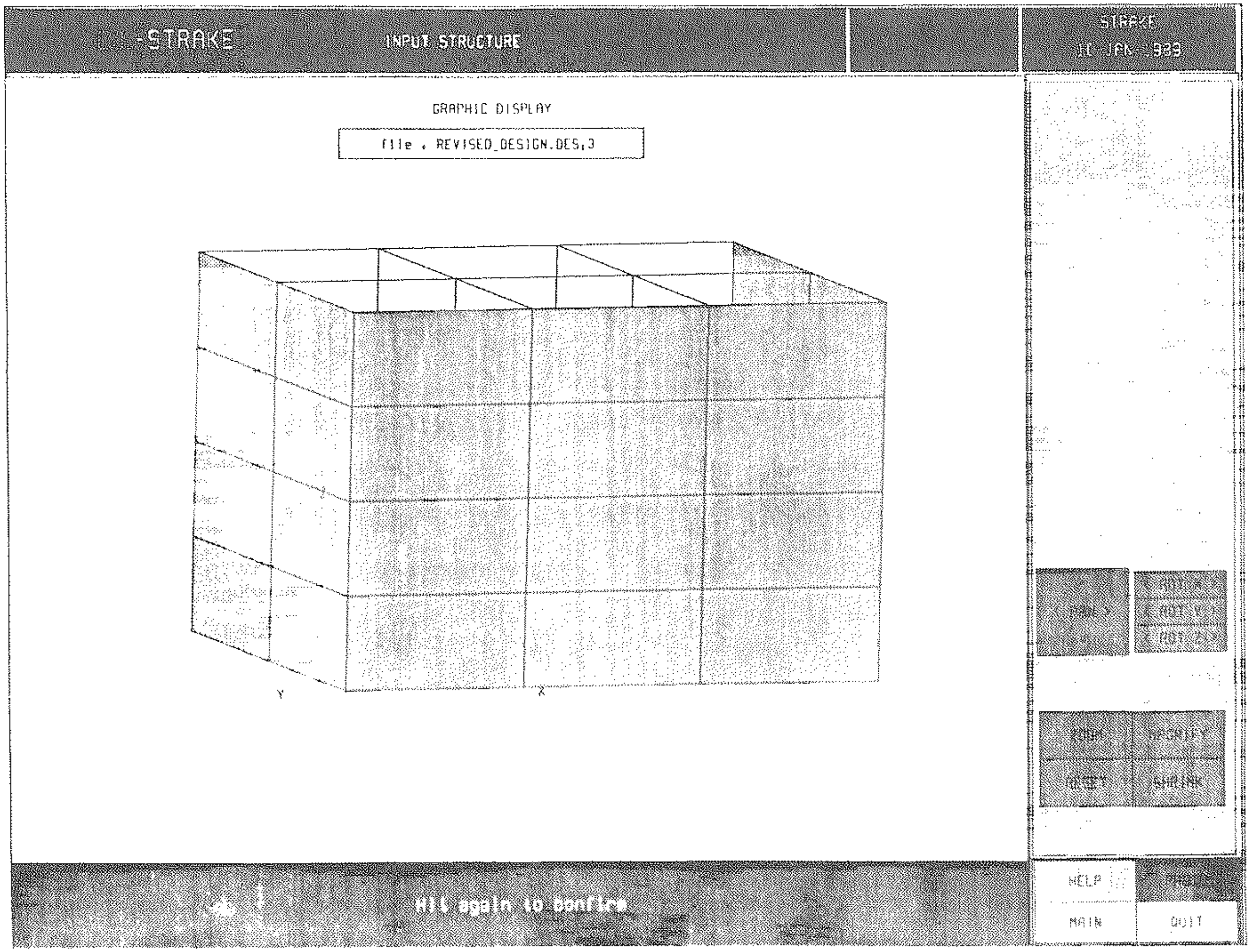
When the OTHER command in the CONSULT–LEVEL II menu page is selected, followed by the EXECUTE ALL RULES command, the KBES performs checks for various possible deficiencies in the design. The KBES identifies the first floor as being a 'soft story', where a soft story is defined as one in which the lateral stiffness is less than 70 percent of the stiffness of the story above. The KBES warns the user about the vulnerability of soft stories under seismic excitation, and recommends that greater lateral stiffness be provided at this level. This may be done either by extending the walls down to the ground level, or by increasing the stiffness of the columns. The KBES then advises the user to ensure that short columns are not present in the design as they are particularly susceptible to brittle shear failure under seismic loads. If short columns are present in the design, the KBES recommends that the columns restrained by partial-height walls be designed for a shear corresponding to the moment capacity of the column, i.e., a design shear of about 1.3x$(2M_u/L)$, where M_u is the ultimate moment capacity of the column, and L, its effective (restrained) length. The KBES performs a redundancy check to examine whether the torsional stiffness of the structure at the current level is concentrated in too few elements, as the failure or degradation of such elements under seismic loads can significantly affect the building response. For the present building, it is found that there is an adequate number of elements at the current level of the building contributing to the overall torsional stiffness.

The user is asked to specify whether any walls of unreinforced masonry are present in the design. If this is the case, the KBES advises the user to estimate the effect of these walls on the response of the structure, by performing the analysis twice, once including the stiffness of these walls, and again without including them; in this manner it is possible to obtain some bounds on the predicted response of the building.

In summary, the primary design deficiency exposed by the second level consultation is the soft first story, which needs to be redesigned for greater lateral stiffness. Recall that the first story also failed the Japanese Rapid Evaluation Procedure in the first level evaluation because of the lack of wall area on this floor. Based on these effects, it is decided that the walls of the building be extended down to the ground level. This is done using the CU-PREPF program to modify the graphical definition of the building to include walls at the first level. Figure 3.15 shows a graphical view of the revised design of the building. After assigning the appropriate geometric and element properties for the revised design using CU-PREPF, the new data file is read in as program input, and the checks for the Japanese Rapid Evaluation and soft stories are repeated. It is now found that the wall area on the first floor appears adequate for safety according to the JREP; also the soft story effect of the first floor has been removed. The other evaluations performed with the original design are then repeated for the building to ensure adequacy of the revised design.

MANAGE FILES:

Before exiting the program the user may want to save the current state of the working memory in a file, so that the same state can be read in automatically at a later date. The MANAGE FILES menu page contains functions to perform file-related operations such as reading input files and saving information to files. The SAVE command is used to write the current BUILDING INFO data structure (i.e., the existing working memory data structure) to a STRAKE file. The present attributes of the building are stored in the file in an appropriate form for performing reasoning. This file can be read in at a later time to set up the building with the current attributes directly without having to go through the consultation again.



file : REVISED_DESIGN.DES;3

Hit again to confirm

Figure 3.15: Graphical View Showing the Revised Design of the Building

SECTION 4
THE KNOWLEDGE BASE OF CU-STRAKE

The preceding sections established the motivation for the knowledge-based approach to seismic design of buildings and illustrated some of the capabilities of the CU-STRAKE prototype system. This section discusses the background knowledge and expertise on which the reasoning capabilities of the system are based. The first subsection discusses some general aspects of the design of earthquake resistant buildings and presents some commonly accepted guidelines for use in the seismic design process. The sections which follow discuss the knowledge base used in the CU-STRAKE prototype system. The content of the knowledge base and the various sources from which it is compiled are presented. The organization of this knowledge in the prototype system and the representation strategy adopted are detailed.

4.1 Background on Seismic Design

Earthquakes represent a major form of natural calamity with vast potential for causing loss of life and property. The design of buildings to resist damage due to earthquakes is a complex and challenging task, and while significant advances have been made in the science, it is still uneconomical to attempt to design buildings to survive severe earthquakes without suffering any damage. The widely accepted objective of earthquake resistant design for common types of structures is to enable them to respond to frequent, moderate earthquakes without suffering significant damage, and to exceptional, severe earthquakes with some damage, but without collapse or loss of human life [14]. Based on this underlying objective, the task of designing earthquake resistant buildings is a demanding one that consists of producing structures having an optimum combination of such seismically important properties as strength, stiffness, energy-absorption, and ductile-deformation capacities that enable them to withstand the effects of seismic disturbances [15].

Earthquakes are associated with the release of enormous amounts of energy from the earth's crust, and this energy is transmitted through the earth's crust in the form of seismic waves emanating from the location of the energy release. The effect of these seismic waves on buildings is to cause vibratory movements of two distinct types : up-and-down (vertical) and back-and-forth (horizontal). Of these, the effect of the horizontal motion is more significant as it tends to disturb the stability of the building, causing it to overturn or collapse sideways. This effect of an earthquake is often modeled in the form of lateral forces acting on the structure to produce roughly the same effect, and the main problem of seismic building design is then considered as the problem of bracing the building against these lateral forces [16]. This is particularly important since many buildings are commonly designed to resist vertical (gravity) loads, and thus can survive vertical earthquake loads, but they are not designed to resist horizontal earthquake loads.

While it is important to provide buildings with the capability to resist the appropriate level of lateral forces by designing a strong and reliable lateral force resisting system, this does not in itself constitute a sound overall design. Various other considerations need to be addressed in order to achieve a good design. It is of fundamental importance to provide adequate, well thought-out, stress paths to ensure that the design forces can be transmitted down to the foundation. Particular care should be given to ensure the integrity of the structure and that the various parts of the building function effectively as one unit. In order to achieve a reasonable degree of seismic safety, it is desirable to provide as much ductility as possible in the building, so that it can absorb energy through inelastic deformations if necessary [17]. However, since ductility results in large deformations, the structure should be checked for instability and for non-structural damage due to excessive deformations.

Another vitally important consideration in the design is the provision of redundancy. Since the nature and magnitude of the actual forces, as well as the nature and response of the structural system, are not known accurately, it is important to anticipate and provide for the possibility of failure of some structural elements in a large earthquake. Provision of a high degree of redundancy provides some protection against the failure of a single element resulting in a progressive collapse. Other factors, such as the quality of the materials and construction also affect the seismic capacity of the building.

The design guidelines mentioned here constitute only a few of the numerous aspects to be considered in the seismic design process. Table 4.1 lists some guidelines for seismic design associated with some of the important design features [17]. Building codes provide the seismic requirements to be met by the design, and form one source for guidelines on seismic design. The aim of the CU-STRAKE prototype is to design buildings using some of the code provisions, but in addition, to deal with several other aspects of the overall design, and improve on the code design where possible. Several sources of information relevant to this objective are available in the literature, and are presented briefly in the following section.

4.2 Knowledge-Base Sources for CU-STRAKE

The field of earthquake engineering encompasses a rich and diverse body of domain-intensive knowledge. The knowledge base of the CU-STRAKE prototype incorporates a depth of knowledge and expertise from a variety of sources, including earthquake reconnaissance reports, in-house experience, research at Cornell University involving experimental investigation and numerical modeling, and building codes and related documents.

The recommendations of buildings codes such as the 1988 UBC [10] and the SEAOC Lateral

Table 4.1: General Guidelines for Seismic Design

1. Assure symmetry of mass and stiffness.
2. Keep distress out of connections and columns (put hinges in beams).
3. Provide energy absorption capacity (ductility).
4. Avoid structural discontinuities.
5. Reduce weight.
6. Avoid brittle failure of stiff elements (walls, braces). Consider the stiffness of secondary elements.
7. Provide a second line of defense (e.g., walls with ductile frame).
8. Limit inelastic deformations to reduce nonstructural damage and to avoid large P-delta moments.
9. Consider stress reversals (e.g., reinforced concrete, trusses).
10. Use dynamic analysis to obtain the distribution of forces in unusual structures.
11. Try to carry lateral loads with members not supporting vertical loads.
12. If structure is on the right of the peak of the spectrum, ascertain that all stiffnesses were considered; if on the left side, consider loss of stiffness and climbing on curve.
13. Consider local soil conditions, especially in fills and soft basins.
14. Assure good workmanship and inspection.
15. Allow distance between dissimilar elements to prevent knocking.
16. Consider cost of repair and cumulative effects.

Force Recommendations [8] are included in the KBES, and provide some basic guidelines for the design. The recommendations of these, and similar documents, constitute directives for use by the less knowledgeable and less expert individuals engaged in the practice of seismic design. However, there are many limitations associated with the use of the building codes. The concepts on which the code provisions are based are often not explicit in the codes, and so they may not be adequately understood by less experienced persons applying these to practical problems. Also, several of the assumptions on which the code provisions are based may not be explicitly stated [14]. In addition, the applicability of the code may be restricted to certain types of buildings and structural systems, and it is important to be aware of these restrictions. Thus, code provisions usually provide minimal, rather than optimal, requirements, and result in a legislated minimum acceptable, rather than best possible, design. The aim of the CU-STRAKE KBES is therefore to use the building codes as a basis for some of the evaluation, but in addition to supplement these provisions with a depth of knowledge from a variety of other sources.

Several other sources are used in the development of the knowledge base, to supplement the code provisions. The commentaries to the UBC and SEAOC codes provide some background and additional information on the use of these codes. The seismic design provisions laid out in other documents by organizations such as the Applied Technology Council (Report ATC-3-06 [18]) and the Building Seismic Safety Council (NEHRP Recommended Provisions [19]) are also used to enhance the knowledge base of CU-STRAKE. Earthquake damage and reconnaissance reports form another valuable resource for knowledge base enhancement. Publications such as "Reducing Earthquake Hazards–Lessons Learned from Earthquakes" [20] provide valuable feedback and experience from previous occurrences of earthquakes, and the resulting damage. These and several other sources of expertise are used in the knowledge base of CU-STRAKE, and reference is made to them at the appropriate time, in later sections on the content of the knowledge base.

The feedback from practicing engineers engaged in seismic design constitutes an important part of the knowledge base of CU-STRAKE. Several aspects of the design were identified that were considered ill-structured, or on which experts were found to disagree. A questionnaire based on such design aspects was mailed to a group of practicing engineers, and their responses used to enhance the knowledge base.

4.3 Knowledge-Base Organization and Representation Strategy

The knowledge base of CU-STRAKE is organized in different levels of depth or sophistication to enable the user to select the features or options he/she would like to include in the evaluation, and thereby provide greater flexibility in the design process. As illustrated in Section 3, this feature of the system can be used in the interactive design process to determine whether to perform a simple, code-based evaluation, or to address some of the more sophisticated aspects of the design. In the latter case, the user can specify the degree of sophistication desired in the evaluation by selecting the appropriate level of reasoning. The underlying motivation for, and some of the useful features of this organization of the knowledge base are listed below :

1. The basic objective of this organization is to separate the knowledge base into different levels of sophistication, allowing the user to select the level of detail to be employed in the evaluation. This determines the scope of the evaluation, in a range from a straightforward to a more detailed and comprehensive approach. The user can specify in this manner whether or not to include controversial and less established aspects in the design, on which expert opinion differs, and for which no consensus may be available.
2. This means of knowledge representation provides for a logical and understandable organization of the knowledge base features. The lower levels of the knowledge base deal with a smaller range of design features, and may be considered subsets of the higher levels. The higher knowledge base levels differ from the lower ones primarily in the following ways :
    (a) Greater level of detail in the design.
    (b) More options to the user to modify the default parameters and limiting values; these are predetermined in the lower levels.
    (c) Additional design features that are not included in the lower level evaluation.
3. This method of knowledge base organization provides scope for future enhancements and modifications. A logical extension of the existing knowledge base is to incorporate higher levels, dealing with more sophisticated design aspects. Also, it raises the possibility, at a future date, of allowing the user to customize the knowledge base by specifying how many of these levels to have, and what sections of the knowledge base to incorporate in each.

Table 4.2 shows the organization of the knowledge base in three different levels in its current state. At the present time, much of the first two levels have been implemented in the KBES. The system thus has the capability to perform reasoning on those aspects of the knowledge base contained in these two levels. The knowledge base incorporated in these two levels is discussed in detail in the following two subsections. The features listed under Level III represent some of the intended future enhancements to the prototype system, some of which are likely to be incorporated in the imminent future, such as the static analysis capability. The list of anticipated enhancements listed under Level III is by no means complete, nor is it certain that all of these will eventually be implemented in that Level. Other features and enhancements will in time be added to this and the other levels, and in addition more sophisticated levels may be created.

4.4 Knowledge Base–Level I

The first level of the knowledge base deals with the more routine and well-defined aspects of the design, and is based primarily on building code provisions. The evaluation at this level follows a fairly rigid, predetermined sequence, and is used to obtain a rapid evaluation of the building. The user has few options at this level to modify the provisions incorporated in the KBES, or to make use of any in-house expertise to override the recommendations of the system. As listed in Table 4.2, and elaborated on in the description of the system's capabilities (Section 3), the main features available in Level I of the evaluation are :

1. Period evaluation
2. Base shear estimation
3. Story drift estimates
4. Eccentricity and torsion effects
5. Japanese Rapid Evaluation Procedure (JREP) [9]

4.4.1 Period Evaluation

The present method of period evaluation in Level I is based on the simple code formula in the 1988 UBC (Method A, Section 2312(e)2B), which gives an approximate estimate of the period based only on the building height and the type of structural frame :

$$T = C_t h_n{}^{3/4} \tag{4.1}$$

in which

T = fundamental period of vibration of the building, in sec.

C_t = 0.035 for steel moment frames

= 0.030 for reinforced concrete moment frames and eccentric braced steel frames, or

= 0.020 for all other buildings.

h_n = height of the building in ft.

Table 4.2: The Knowledge Base Levels of CU-STRAKE

Level I	Level II	Level III
Period Evaluation - Code formula		Rayleigh method, eigenvalue analysis.
Base shear evaluation - Code method	Options to modify/override the code values : - probabilistic input of the seismic zone. - choice of different methods for incorporating soil effects; checking the potential for liquefaction. - modifying the R_w factor to a value different from the code value. - estimates of mass: choice of live loads, snow loads, etc., to include in the overall mass estimate.	Design base shear by dynamic analysis. Soil-structure interaction studies.
Story drift : obtain estimates of the story drift by two methods - option to user to select which value to use; drift estimate is checked against the allowable drift ratios in the code.	Drift estimates by the two methods; user has the option to select which estimate to use; user is also given the option to override the drift limits in the code, and to supply his own limits.	Drift estimates by performing analyses.

Table 4.2 (cont'd): The Knowledge Base Levels of CU-STRAKE

Level I	Level II	Level III
Eccentricity and torsion: pre-defined limits for acceptable eccentricity and for identifying a building as irregular.	Histogram showing the range of expert opinion on the limiting values of the acceptable eccentricity; option to override the default limits.	Other means of detecting irregularity in the building; geometric irregularity, offsets in plan, etc.
Japanese Rapid Evaluation Procedure (JREP): - for buildings with walls; check against the pre-defined limits in the method.		JREP with limits modified for U.S. context. Higher levels of the evaluation.
	User given option whether or not to include the out-of-plane stiffness of structural/infill walls.	
	Flag undesirable/unacceptable design combinations and suggest modifications.	
	Identify and flag soft story feature in the design; warn of possible consequences and suggest means of fixing this condition.	

Table 4.2 (cont'd): The Knowledge Base Levels of CU-STRAKE

Level I	Level II	Level III
	Check the design for adequate redundancy, i.e., whether there are too few elements contributing to the torsional stiffness in a particular direction.	
	Warn the user of the problems associated with short columns and advise against having such elements; also to ensure adequate shear strength in such elements so they don't fail in brittle shear.	
	Warn the user about the potential for failure of any walls of unreinforced masonry in the building.	
		Use of analysis capabilities for obtaining estimates of the drift, period, design base shear, etc.
		Uncertainty schemes and imprecise reasoning; fuzzy sets(?)

Method B in the code gives a more rigorous procedure for estimating the period of a building, based on the Rayleigh Method, which requires an estimate of the elastic deflections of the floors. This method has not been implemented in CU-STRAKE to date, but this procedure is to be added once the program has a static analysis capability.

4.4.2 Base Shear Estimation

The design base shear is obtained by the equivalent static lateral force procedure outlined in the UBC (Section 2312(e)2A) :

$$V = \frac{Z\,I\,C}{R_w}\,W \tag{4.2}$$

in which

Z = Seismic zone factor, obtained from the seismic zone map of the United States and Table 23-I, UBC 1988.

I = importance factor to take into account the occupancy type of the building (Table No. 23-L of UBC, 1988).

R_w = Response modification factor, to account for ductility in the structure, among other effects. Obtained from Table No.23-O of UBC 1988).

W = Total seismic dead load of the structure.

C = Numerical coefficient determined from the following formula

$$C = \frac{1.25\,S}{T^{2/3}} \tag{4.3}$$

in which

S = site coefficient obtained from the table in UBC for the particular type of soil conditions (Table No. 23-J in UBC 1988).

T = fundamental period, in sec., obtained by the code formula given earlier.

The total design base shear obtained using the above formula is then distributed over the various levels of the building in accordance with the following formula :

$$F_x = \frac{(V - F_t)\, w_x\, h_x}{\sum_{i=1}^{n} w_i\, h_i} \tag{4.4}$$

in which

V = the design base shear

F_x = the force at the level designated as x

F_t = the concentrated force at the top of the building given by the following formula :

$$F_t = 0.07\, T\, V \tag{4.5}$$

in which T is the period obtained earlier, and V, the design base shear.

w_i, w_x = that portion of the total seismic load, W, which is located at or is assigned to level i or x, respectively

h_i, h_x = height in feet above the base to level i or x, respectively

The above static force procedure for the design base shear is applicable to a limited range of regular and low-rise buildings. For more unusual or irregular buildings, the dynamic lateral force procedure should be followed. More details on the static force procedure outlined above, and its range of applicability, as well as on the dynamic force procedure, are available in the 1988 UBC and the commentary to the SEAOC Recommendations. At present only the static force procedure has been implemented in the CU-STRAKE system. The dynamic force procedure is an intended future enhancement, planned for the third level of the knowledge base.

4.4.3 Story Drift Estimates

Story drift is the displacement of one level relative to the level above or below, due to the design lateral forces. Large interstory drift may cause excessive nonstructural damage. The 1988 UBC specifies that the calculated story drift should not exceed $0.04/R_w$ nor 0.005 times the story height for buildings less than 65 feet in height. For buildings greater in height, the drift should not exceed $0.03/R_w$ nor 0.004 times the story height. The first level evaluation in CU-STRAKE checks the story drift against these code limits; the user does not have the option to override them. At present the story drift is estimated by two approximate methods which do not involve actual analyses. They are based on empirical formulas typically used to obtain a rough estimate of the drift rapidly. The formulas used by the two methods to estimate the story drift are :

1. ATC Drift Formula

The story drift, D, at any level of a moment-resisting frame is estimated by the following formula, given in the Report ATC-14 [13] :

$$D = \frac{k_b + k_c}{k_b\,k_c}\,\frac{h}{f}\,V_c \qquad (4.6)$$

in which

f = a factor that depends on whether the building is a steel or a concrete moment-resisting frame.
= 348000 for steel moment-resisting frames, and
= 36000 for concrete moment-resisting frames
k_b = (I/L) of beam
k_c = (I/L) of column
h = story height in inches
I = moment of inertia in in^4
L = center to center length, in inches
V_c = average shear in each column in kips.

It is important to note that the ATC-14 Report and the procedures suggested therein are strictly intended for evaluating existing buildings. Some of the methods, such as the story drift estimate described above, may therefore not be altogether appropriate for use in the design of new buildings, or may need to be modified accordingly. Also, the formula shown above is applicable only to steel or concrete moment-resisting frames, and not to buildings with shear walls.

2. Approximate Method based on a Spring Model

In this method the drift is estimated by dividing the story shear by the approximate stiffness of the floor, where the stiffness is obtained using the model shown in Figure 4.1. The stiffness of columns is obtained by multiplying the stiffness, assuming fixed-fixed end conditions, by a modification factor which is intended to account for the actual fixity and the scope for rotation at the ends of the column. The following formula is used for the modified column stiffness, K_m :

$$K_m = m\,\frac{12\,E\,I}{h^3} \qquad (4.7)$$

in which

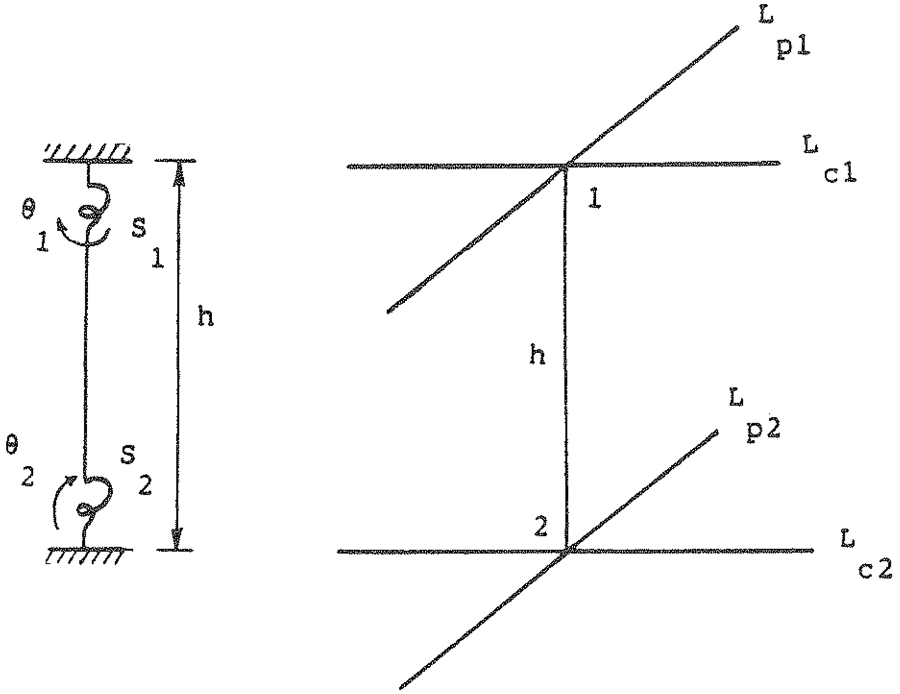


Figure 4.1: Model Used in Approximate Method for Estimating Drift

$$
\begin{aligned}
m &= \frac{4\,S_1\,S_2 + K\,S_1 + K\,S_2}{3\,K^2 + 4\,K\,S_1 + 4\,K\,S_2 + 4\,S_1\,S_2} \\
S_i &= n^b_{ci}\,(\frac{3\,E\,I_b}{L_{ci}}) + n^b_{pi}\,(\frac{G\,J}{L_{pi}}) \\
n^b_{ci} &= \text{number of beams coplanar with the column} \\
 & \quad \text{and framing into joint i} \\
n^b_{pi} &= \text{number of beams perpendicular to the} \\
 & \quad \text{column and framing into joint i} \\
L_{ci} &= \text{length of the coplanar beams at joint i} \\
L_{pi} &= \text{length of the out-of-plane beams at joint i} \\
K &= \frac{4\,E\,I_c}{h}
\end{aligned}
$$

The spring stiffnesses S_1 and S_2 can be adjusted to accommodate a variety of fixity conditions, thus modifying the effective column stiffnesses. For instance, the spring stiffness S_2 can be set to infinity for the first story to account for complete fixity at the lower end of the column. The above formulas can then be used with the new values for the spring constants in the stiffness evaluation and the estimation of the story drift.

The accuracy of the method has been compared with more rigorous analysis methods, and it appears that the story-drift estimates obtained by this method for the first few stories are in reasonably close agreement with those obtained by static analysis. The correlation in the first few stories is particularly relevant as these are in many cases the critical stories for drift.

4.4.4 Eccentricity and Torsion Effects

Eccentricity, or asymmetry, in a building is an indication of the potential for torsional effects. Plan eccentricity is one of the various types of irregularity identified in UBC 1988. Thus it is important to check for eccentricity in a building to determine the scope for torsional effects and establish whether the building should be treated as irregular.

The plan eccentricity of a particular floor of a building is obtained in CU-STRAKE as the distance between its center of mass and its center of rigidity (or center of stiffness) (Figure 4.2). This marks the offset in the line of action of the lateral forces from the center of mass, and is an important determinant of the extent of torsional moments [21]. The x- and y-coordinates (x_s and y_s respectively) of the center of stiffness of a floor are obtained by the following formulas :

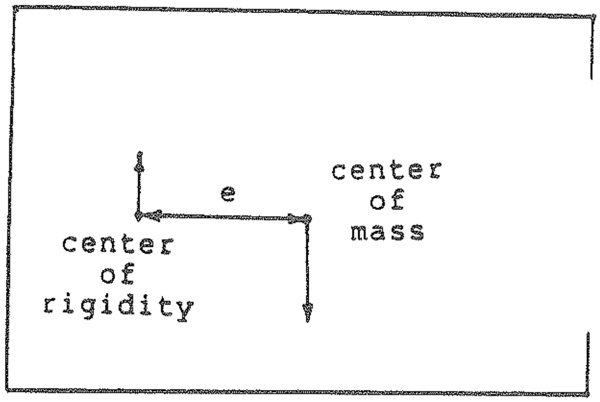


Figure 4.2: Plan Eccentricity Resulting from Asymmetry in Stiffness

$$\begin{aligned} x_s &= \frac{\sum_{i=1}^{n} k_y\,(x)}{K_y} \\ y_s &= \frac{\sum_{i=1}^{n} k_x\,(y)}{K_x} \end{aligned} \tag{4.8}$$

in which

k_x = stiffness of an element (beam/column/wall) in the x-direction

k_y = stiffness of an element (beam/column/wall) in the y-direction

x = x-coordinate of the centroid of the element

y = y-coordinate of the centroid of the element

K_x = total stiffness of all elements in the x-direction $= \sum_{i=1}^{n} k_x$

K_y = total stiffness of all elements in the y-direction $= \sum_{i=1}^{n} k_y$

When information about the building is provided graphically using the frame preprocessor, CU-STRAKE can perform an evaluation of the building on a floor-by-floor basis, and obtain information about the eccentricity of each floor. When the eccentricity ratio in either of the principal directions is greater than 0.2, the building is classified as irregular. The user is informed that much of the first-level evaluation is therefore not strictly valid for this building, and should be supplemented by more comprehensive evaluation. If the eccentricity exceeds 30%, the KBES informs the user that the eccentricity exceeds the maximum permissible value, and recommends reducing the asymmetry in the stiffness.

The eccentricity limits for designating a building as irregular (20%) and for the maximum acceptable eccentricity (30%), are predetermined in the first level evaluation. In the second level evaluation, however, the user is given the opportunity to modify or override these limits based on his/her expertise or on the practice followed by the particular design office. Also, the KBES currently has the capability to identify stiffness irregularities, but not geometric irregularities. For instance a building having an unusual shape or offsets may not be identified by the KBES as irregular if the stiffnesses of the elements are symmetrically distributed. The capability for this kind of geometric and spatial reasoning may be incorporated in the future in one of the higher knowledge base levels.

4.4.5 Japanese Rapid Evaluation Procedure

The first (elementary) level of the Japanese Rapid Evaluation Procedure (JREP) [9] has been implemented in Level I of the CU-STRAKE knowledge base. This method attempts to classify a building as seismically safe or unsafe, using some simple indices associated with the available cross-sectional area of walls and columns, and the average shear stress at any level of the building. The basis of this method at the elementary level is that the available area of walls in a building is a useful index of its capacity to withstand an earthquake because of the shear resistance offered by these walls to the lateral forces resulting from the earthquake.

The seismic quantities used in the first level of the JREP are the following :

Wall Ratio : The wall ratio is defined as the horizontal cross-sectional area of walls in one principal direction divided by the total floor area above the story being considered. The ratio is measured in cm^2/m^2 in the original method, as practiced in Japan. Here it is taken in units of in^2/ft^2.

Average Shear Stress : This is the other major quantity used in the JREP, and is calculated as the total weight above the story being considered divided by the total horizontal area of columns and walls in one principal direction. It is regarded as the average shear in all vertical elements resisting seismic loads due to a uniform horizontal acceleration equal to the acceleration due to gravity.

The first level JREP identifies a 'safe' range for the values of the above two quantities. This method suggests that buildings with wall ratios greater than 0.43 in^2/ft^2 are generally safe, and that buildings with wall ratios less than 0.43 in^2/ft^2 and average shear stress greater than 0.17 $kips/in^2$ are generally vulnerable. These limits are used in the KBES to obtain a rough idea of whether or not a building is safe.

The knowledge base presently utilizes only the first level evaluation of the JREP, based on the simple indices described above. A more comprehensive evaluation, involving calculation of the 'seismic index' [9], is available in the higher levels of the JREP. This represents a possible future enhancement of the Rapid Evaluation Procedure in the knowledge base. Further, the procedure described above was developed for use in the Japanese context, and is likely to be too conservative for use in the United States. The method may therefore need to be modified in order for it to be more effective and appropriate for use in this country.

4.5 Knowledge Base–Level II

The knowledge base at the second level provides a more sophisticated evaluation than the first level, with a greater depth of knowledge as well as more options for the user to exercise his/her own judgment and contribute to the decision-making process. This level deals with aspects of the knowledge base which require more judgment and expertise than the first level, in which the evaluation was mostly numerical and the procedure widely accepted. The scope of the reasoning in the second level evaluation is expanded to include the treatment of those areas for which no clear consensus exists; hence the recommendations at this level are more advisory in nature, and because of the lack of consensus, may not be widely acceptable. The user is therefore provided the option in many cases of overriding the recommendations of the KBES if he/she has other sources of informed opinion and/or greater confidence in an alternative course of action.

Many of the recommendations included in the second level of the knowledge base are based on the opinions of practicing experts in the field of seismic design, obtained as feedback from the questionnaires mailed to them. As mentioned earlier, the first level of the knowledge base can be considered a subset of the second and higher levels. Thus the various options encountered in the first-level evaluation are also available in the second level with additional options enabling the user to modify some of the code values or to override the recommendations of the KBES.

These additional options include :

1. Base shear Evaluation :

In the second-level evaluation, the user can modify several of the code-specified values based on in-house experience and interpretation of the code regulations. Thus the user can modify some of these values while continuing to comply with the code requirements :

a) The seismic zone of the building site may not be known precisely, and without doubt. In the second level evaluation, the user is provided the facility to input the seismic zone non-deterministically. This is done by assigning 'weight' factors ('probabilities') to each of the seismic zones, which represent the degree of certainty on a scale of 0–100 that the seismicity of the zone corresponds to that particular value. This is essentially a generalization of allowing the user to interpolate between two seismic zones in cases where the building site lies near the border between two zones. When weight factors are assigned for different zones in this manner, the zone factor used in obtaining the base shear is thus an intermediate value lying between the code-specified values.

b) In the first-level evaluation, the site coefficient, S, is based on the four soil types identified in the 1988 UBC. In the second level, the user is given the option to select one of two methods—either the UBC method just mentioned, or a second method based on a previous code, which determines the value of S as a function of T/T_s, where T is the fundamental period of vibration of the structure and T_s is the natural period of the soil. T_s depends on the shear velocity of the soil, and for a single-layer soil profile is given by the following formula :

$$T_s = \frac{4H}{V_s} \tag{4.9}$$

in which

H = depth of the (single) soil layer

V_s = shear velocity of the soil

(H and V_s in consistent units).

As shown in Table 4.3, the site coefficient in the new code is obtained directly from the table, and depends on the type of soil profile. In the earlier method, the site coefficient was obtained from a curve such as the one shown in Figure 4.3, and depended on the ratio T/T_s. It is to be noted that in both these methods the site coefficient represents site effects, not soil-structure interaction. However, the second method, involving the T/T_s ratio, goes a little further in accounting for the interaction effects, by relating the site and structure periods via this ratio and using it indirectly to determine the extent of amplification. On comparing the site coefficients given by the two methods, from Table 4.3 and Figure 4.3, it is seen that the maximum value of S from the previous (T/T_s) method is 1.5, while the site coefficients in the new code range from 1.0 to a maximum of 2.0. Hence, the T/T_s method is less conservative in cases where the new method gives a site coefficient greater than 1.5. The T/T_s method is therefore relevant only in cases where the new code gives a site coefficient less than 1.5.

Much discussion has been centered on the relative merits of these two methods, and the choice of procedure for including the soil effects. Some feedback on this was obtained through the questionnaire used to solicit the opinion of practicing engineers. One of the shortcomings identified by respondents to the questionnaire in connection with the T/T_s method is that frequently T_s, required for this method, is not accurately known. The formula for determining T_s is dependent on the shear velocity of the soil, which may not be available to the user. Also, T_s is often available as a range rather than a specific value, and the range may in some cases be comparable to the period of the structure itself. In such cases the use of the T/T_s formula is rendered ineffective and it is preferable to use the new code formula instead.

The two methods for incorporating site effects, as mentioned above, do not account for soil-structure interaction effects [22]. The capability to model soil-structure interaction comprehensively is an important and desirable enhancement to the KBES, and is likely to be incorporated in one of the higher levels of the knowledge base in the future.

Another important effect associated with the soil is the potential for liquefaction of the soil. The second level of the knowledge base is to include a check for the liquefaction potential based on an empirical method [23]. The method requires knowledge of certain properties of the soil, such as the type and depth of the soil layer, the shear velocity, and the threshold shear strain. When some of these properties are not known, default values may be used, which represent typical values for the soil. The following formula gives the value of the threshold acceleration a_t for a given site, above which liquefaction can occur :

$$\frac{a_t}{g} = \frac{\gamma_t \, (G/G_{max})_t}{g \, Z \, r_d} \, V_s^2 \tag{4.10}$$

in which

γ_t = threshold shear strain
(range of γ_t : 1x10^{-4} to 3x10^{-4}
typical value : 1x10^{-4})

g = threshold shear strain
= $32.2 ft/sec^2$

r_d = coefficient to account for the flexibility
of the soil (range : 0.92–1.0; typical value : 1.0)

Z = depth of the layer at which liquefaction may occur

Table 4.3: Site Coefficients
(Table No. 23 J in UBC 1988)

Type	Description	S Factor
S_1	A soil profile with either: (a) A rock-like material characterized by a shear-wave velocity greater than 2,500 feet per second or by other suitable means of classification, or (b) stiff or dense soil condition where the soil depth is less than 200 feet.	1.0
S_2	A soil profile with dense or stiff soil conditions, where the soil depth exceeds 200 feet or more.	1.2
S_3	A soil profile 40 feet or more in depth and containing more than 20 feet of soft to medium stiff clay but not more than 40 feet of soft clay.	1.5
S_4	A soil profile containing more than 40 feet of soft clay.	2.0

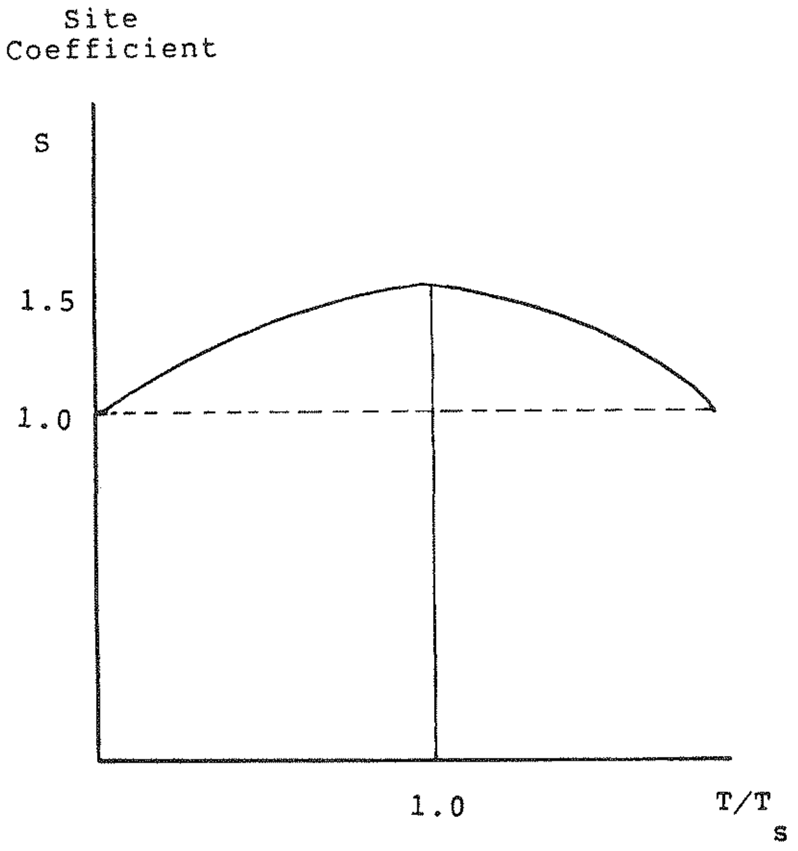


Figure 4.3: Variation of Site Coefficient with T/T_s

V_s = shear wave velocity, obtained from a table containing typical values for different types of soils

G/G_{max} = modulus reduction factor at the threshold strain γ_t

$$= \frac{\text{secant shear modulus associated with } \gamma_t}{\text{shear modulus measured at small strains}}$$

The ground acceleration for the particular site can be compared with the threshold acceleration given by the above formula to determine whether liquefaction of the soil is likely.

c) The R_w factor in the code formula for the base shear is a response modification factor that reduces the force level to account for ductility and other effects. The code specifies a wide range of R_w values, ranging from 4 to 12, for different types of framed or shear-wall buildings with widely differing ductilities. It is believed by some that the higher values of R_w in the code sometimes overestimate the ductility of the building, and therefore err on the unconservative side. These values are based on the assumption that careful detailing and a high degree of ductility are provided. However, since the detailing requirements are not explicitly stated in the code, and may not be understood by less experienced practitioners, the requirements may not be met in the design.

Also, the R_w factor is intended to account for several effects leading to a reduction in response. However, the code value depends only on the type of structural system of the building and does not take into account differences associated with the geographic location and seismicity of the region. Performance requirements for different seismic zones are different, as are the construction practices. Therefore some experienced users may wish to use a value of R_w that takes this effect into account.

The factors discussed above indicate that the R_w factor given in the code may need to be modified in some cases to better approximate the actual response. The second level evaluation in CU-STRAKE provides the user the option to modify the code value of R_w to a more conservative value in cases where he/she considers the code-specified value too high, or when it is desired to capture in the R_w value other effects such as the variation in construction practices with geographic location. Based on a survey of expert opinion, the effects described above, as well as others, are brought to the attention of the user by the KBES; he/she is then given the option to modify the value if a better estimate is available. If not, the default value is used, which is the value obtained from the code.

d) The seismic dead load, W, used in the base shear determination, includes the total dead load and a proportion of the live load, depending on the use of the building. The code specifies a minimum of 25 percent of the floor live load for storage and warehouse occupancies. Since the live load for these types of occupancies is present most of the time, a higher proportion of the live load may be preferable. Also, the extent of the snow load to include in the seismic dead load may vary considerably depending on the geographic location and the period over which the snow load is expected to be present. The user is reminded of these considerations in assigning the seismic dead load for the building, and is permitted to assign the floor loads accordingly.

2. Story Drift

The UBC specifies limits on the calculated story drift, but states that these limits may be exceeded in cases where the greater drift can be tolerated by both structural and non-structural elements that could affect life safety. The second level of the knowledge base enables the user to design a building with greater calculated drift than the code limits, if the condition stated above can be met.

Also, the user may in cases wish to have stricter drift limits than those required by the code. This may be the case when designing special structures, or to protect the contents of buildings such as museums and hospitals, housing articles such as precious artifacts and scientific or medical equipment. The user may therefore use the option in Level II to reduce the allowable story drift.

The story drift estimates are at present obtained approximately using empirical formulas. Better estimates of the interstory drifts can be obtained by performing static analyses using the design lateral forces. It is anticipated that this utility will be provided in Level III of the evaluation once the KBES has a static analysis capability.

3. Eccentricity and Torsion Effects

In the first-level evaluation, predetermined limits for the eccentricity are used to classify a building as irregular or having excessive plan asymmetry. In the second level, these limits are not fixed but can be modified by the user based on in-house experience or other knowledge. A range of expert opinion is presented to the user in the form of a histogram showing the distribution of the limiting values of the plan eccentricity, and the user can assign an appropriate value based on this feedback. The plan eccentricity is used to indicate the possibility of torsional effects.

The potential for torsional effects can also be determined by performing simple eigenvalue analyses to detect torsional modes of vibration. This useful facility may be incorporated in one of the higher levels of CU-STRAKE once a dynamic analysis capability is added.

4. Out-of-Plane Stiffness of Walls

The second level of the evaluation provides the user the option of whether or not to include the out-of-plane stiffness of walls in the stiffness computations. It is found that experts have differing opinions on whether to include the out-of-plane flexural stiffness of various types of walls in the stiffness computations. While there is no clear consensus on this, many feel that infill walls that are isolated from the structural frame should not be included, but that in most cases the out-of-plane stiffness of shear walls should be included in the design.

5. Undesirable Design Combinations

Most building designs have some features in them that are not desirable from a seismic standpoint. However, in isolation these may not be critical to the overall safety of the structure. When a combination of these design deficiencies occurs simultaneously, however, the overall response of the building may be adversely affected. The CU-STRAKE prototype attempts to flag some such combinations of design deficiencies and bring to the attention of the user the possibility of failure of the building under seismic loading. Various such combinations have been identified based on feedback from seismic designers. These include:

- high eccentricity together with the presence of relatively weak elements contributing to the torsional stiffness.
- significant irregularity in the design, especially in high seismic zones.
- presence of soft stories and brittle elements which are susceptible to collapse under cyclic loading.

6. Soft Story

A soft story is one that has significantly less stiffness than the other stories of a building. This feature typically occurs at the first story, where shear walls or other bracing elements are discontinued for functional or aesthetic reasons. Figure 4.4 shows such an instance of a soft story in the first floor. The soft story also occasionally occurs at a higher floor when there is a major stiffness discontinuity.

It has come to be recognized that buildings with soft stories are highly vulnerable under the effect of earthquakes. Several instances of failure of such buildings have been recorded in past earthquakes [20, 24]. The stiffness discontinuity with height often directs forces to places where the strength is minimal. It is therefore preferable to have fairly uniform buildings without abrupt changes in stiffness or strength.

In CU-STRAKE, a soft story is identified as one in which the lateral stiffness is less than 70 percent of the stiffness of the story above. The KBES uses the graphical information about the building to obtain the lateral stiffness of the stories, and to then determine whether there are soft stories. If any soft stories are found, the fact is brought to the attention

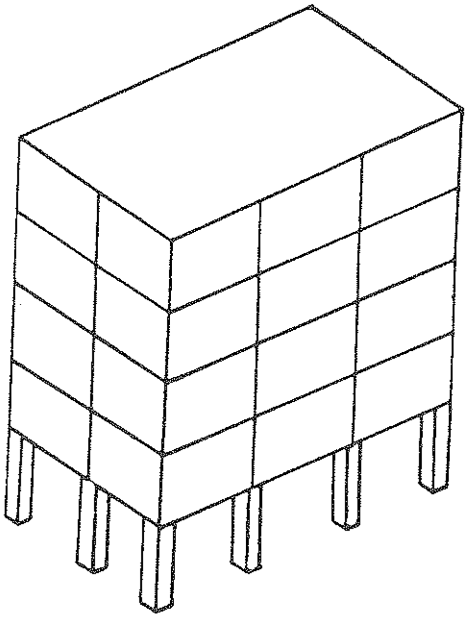


Figure 4.4: Soft First Story

of the user, with a recommendation to modify the design by providing additional lateral stiffness to the story either by extending the walls to that story, or by having heavier column sections.

7. Redundancy for Torsional Effects

The provision of adequate redundancy is an important consideration in the design of a building for seismic loads. The designer must anticipate and provide for the possibility of failure of some structural elements in an earthquake. The CU-STRAKE system assists the user in part with the check for redundancy by examining the contribution of various vertical elements to the overall torsional stiffness. This is done by evaluating the torsional stiffness in each direction ($k_x(y)$ and $k_y(x)$) for each element, and comparing the values so obtained with the overall torsional stiffness in that direction($\sum_{i=1}^{n} k_x(y)$ and $\sum_{i=1}^{n} k_y(x)$). If any element is found to contribute more than 50% of the total torsional stiffness, it is taken as a sign of inadequate redundancy and the user is advised to revise the design, distributing the stiffnesses more equally among the various elements.

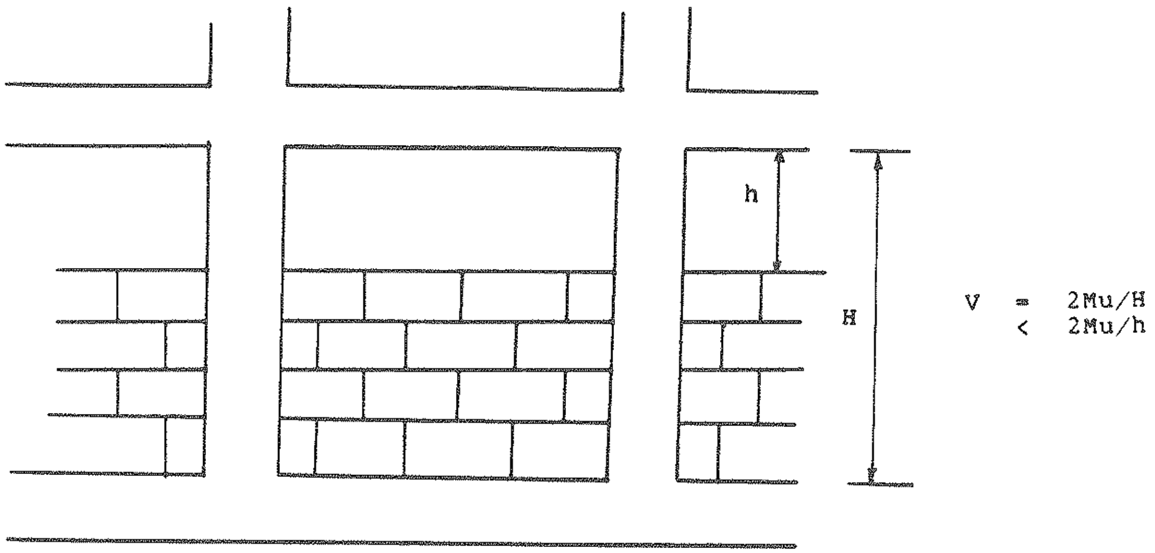


Figure 4.5: Short Column Resulting from Masonry Infill

8. Short Columns

Short columns, or 'captive columns', refer to columns in the building whose effective length has been reduced by the presence of confining walls of reinforced concrete or masonry. Because of the reduced effective height, such columns are sometimes subject to lateral shears greater than those anticipated initially, and in excess of their shear capacity. Figure 4.5 illustrates the short column concept. A column designed with a shear capacity of $2M_u/H$, corresponding to the ultimate moment capacity M_u of the unrestricted column, may in fact come under larger shear forces, equal to $2M_u/h$, if the column is restricted to a free height of h by the presence of restraining walls. Such columns are prone to brittle failure under seismic loads, and have frequently been instrumental in the eventual collapse of a building [24]. The CU-STRAKE system warns the user of the vulnerability of short columns in the design, and advises him/her to check the design carefully for the presence of such elements in the design. If short columns are present, the user is advised to either modify the design by removing the constraining walls, or to provide the column enough reserve strength to take the higher shear forces. In the latter case, the column must have a shear capacity at least equal to $2M_u/h$, corresponding to the ultimate moment capacity of the short column.

9. Unreinforced Masonry

Walls of unreinforced masonry are highly vulnerable to damage during earthquakes, and their failure early in the earthquake can significantly change the response of the building and cause eventual collapse. Several previous earthquakes have supported this observation, and it is generally agreed that unreinforced masonry of any kind should be avoided in seismic design. In fact, the use of unreinforced masonry is now forbidden in high seismic zones in the U.S.

CU-STRAKE informs the user about the problems associated with brittle walls of unreinforced masonry, and advises him/her to check for the presence of these in the design. Where present, it recommends that the design be revised to avoid having such walls, especially if the site is in a region of high seismicity.

SECTION 5
TECHNICAL DESCRIPTION OF THE CU-STRAKE PROTOTYPE

This section discusses the details of the implementation of the CU-STRAKE prototype, including a description of the hardware and software environments, the organization and overall strategy of the program, and the knowledge representation techniques adopted. The description of the prototype in this section is of a technical nature and is intended to supplement the description given in the preceding sections, which was aimed at presenting an overview of the capabilities and organization of the KBES.

5.1 Hardware and Software Environments

The design of the KBES is aimed at providing the user with a convenient, user-friendly, and versatile system that represents an effective environment for performing the seismic design of buildings. Accordingly, the selection of the software and hardware environments for implementing the KBES has been guided by the following considerations :

1. Suitability of the programming environment from the perspective of typical structural engineers engaged in the process of seismic design of buildings.
2. Interaction with algorithmic programs; compatibility with, and ability to utilize, existing capabilities for structural analysis and design.
3. Flexibility and power of knowledge representation provided by the expert system environment; suitability of the features of the expert system for the particular application at hand.
4. Convenience and ease of use of the KBES in the interactive design process.

The CU-STRAKE prototype is implemented using the OPS83 programming language [25] in the VAX/VMS environment, and runs on engineering workstations (VAXstations) with color graphics capabilities. For ease of use, the system is provided with a convenient, graphical, menu-driven interface. The graphical displays are provided using the commercially available HOOPS color graphics software [26]. The KBES also makes use of functions written in the C programming language to perform numerical computations and other operations more suited to an algorithmic approach. The KBES thus provides a synthesis of expert-system features with conventional algorithmic functions to create an integrated design environment controlled by the user from the expert-system module.

The particular choice of hardware is motivated by the convenience and versatility of color graphics workstations, and their increasing use in the engineering workplace. Also, several structural analysis and design programs at Cornell University have been previously implemented on the workstations, and by using the same hardware the KBES can exploit some of the capabilities of these programs. At present the KBES is implemented on an 8-bit plane color graphics environment; in the future it may be made portable to 4-bit plane and monochrome systems as well.

The selection of a suitable expert-system environment for KBES development constituted an important step early in the implementation process. The development of the preliminary prototypes using the KEE and EXSYS environments (Section 2) provided a learning experience to gain insight into the methodology of expert-system development in general, as well as the nature and characteristics of the domain of earthquake engineering. They also provided insight into the particulars of organizing and representing the domain knowledge. In addition, a Workshop on Expert Systems in Earthquake Engineering was held at Cornell University in August 1987. Discussion and feedback from the participants at the Workshop also contributed to the process of selecting a suitable environment for KBES development.

The choice of the OPS83 programming language for implementing the KBES was based on several of its features, described here. OPS83, a second-generation expert-system language, is an enhanced version of OPS5 [27, 28]. It is a rule-based production system based primarily on forward chaining. In addition to the rule-based component, OPS83 also supports the ordinary imperative programming paradigm of languages such as C and Pascal. The OPS83 language itself is C-based, and the choice of this programming environment was in part due to its capability for easy interfacing with algorithmic programs written in C and other programming languages. The availability of OPS83 for the VAXstation environment also favored the choice of this programming language. Some of the features provided by other commercial expert-system shells, such as a built-in mechanism for handling uncertainty, are not available in OPS83; however, the language provides the developer the flexibility to program these features independently. This results in greater development time in some cases, but is less constraining. The availability of a version of OPS83 for personal computers (PC's) also raises the possibility of implementing the KBES on the less expensive PC's. Rule execution in OPS83 is much faster than in several other commercial shells, as the rules in OPS83 are compiled directly into machine code and simply executed at run-time; the greater speed makes it feasible to deliver substantial systems on PC's.

The HOOPS color graphics software, used to produce the graphical displays in CU-STRAKE, is available on license from Ithaca Software, and is a powerful and flexible graphical tool. The HOOPS software is also available for a PC.

5.2 Program Organization and Control

The CU-STRAKE prototype, as described above, is composed of several program modules, some heuristic and others algorithmic. The main section of the program is implemented in the imperative component of the OPS83 programming language. It is this program section that initiates the execution of the program. The OPS83 production rules in the KBES form the basis for the reasoning and inferencing of the system. These rules, together with some other OPS83 functions, control the program flow in CU-STRAKE. Several algorithmic functions written in C are called at various points in the program to perform numerical calculations and derive other information. C functions are also used to draw and manage the graphical menu pages of the KBES that form its user interface.

Knowledge representation is achieved using OPS83 rules, together with other OPS83 and C functions. The rules are organized in separate files to distinguish between the routine and the more specialized levels of consultation. The rules represent the knowledge acquired from a variety of sources including earthquake reconnaissance reports, in-house experience, input from structural engineers by means of a questionnaire, and various building codes and related documents. The sources and content of the knowledge base were discussed in detail in the previous section. The rules control the program execution by including, in the rule outcomes, function calls to OPS83 and C functions as required at various stages of the program. The user is prompted for input about the building, or for other information only when this information is required for the reasoning, and is not otherwise available, for example from the graphical database.

5.2.1 The Use of Graphics in CU-STRAKE

The extensive use of interactive graphics is a distinctive feature of the CU-STRAKE prototype. The system relies heavily on its use of graphics to obtain information about the building, perform reasoning, and to integrate the program as a whole via the menu-driven user interface. Specifically, the use of graphics serves the following purposes in CU-STRAKE :

1. User interface

   The menu-driven interface of the program serves to integrate the different components of the system, and provides the user a convenient means of switching between different options and exercising control over the program.

2. Preprocessing

   The use of graphics to provide input to the program is a particularly useful feature of the program. This is a convenient way of describing the building, and provides the program with necessary information about the building to perform reasoning.

3. Reasoning and inference

   The program uses the graphical description of the building to arrive at estimates of relevant seismic parameters and to perform related reasoning. Calculations based on the graphical data help in evaluating the building design.

4. Display of information

   The graphical view of the building under consideration aids the designer in understanding the behavior of the building. The display of relevant information about the particular floor under consideration, or the distribution of the design base shear over the height of the building also enhance the design process. Further, graphical views are used to bring to the attention of the designer typical design features such as soft stories, which are potentially dangerous.

5.2.2 Interaction of Program Modules

The CU-STRAKE prototype consists of a central OPS83 program module, together with several other program modules which perform a variety of functions relevant to the reasoning process. An overview of the KBES and its component modules was presented in Figure 3.1. As displayed in the figure, the KBES uses information from an external program for graphical preprocessing developed at Cornell University; also, other programs for static and dynamic analysis are to be linked with the expert system in the future.

CU-PREPF :

CU-PREPF [12] is a graphical preprocessor for defining three-dimensional framed buildings. It is a fully interactive program for the definition of two- and three-dimensional framed structures: geometry, boundary conditions, member properties, and loads. Particular facilities are provided for steel frames, including AISC section tables. In addition, structural and infill walls, as well as beam and column sections, of reinforced concrete can be defined using CU-PREPF.

CU-STAND :

CU-STAND [29] is a fully interactive program for the analysis and design of statically loaded two- and three-dimensional steel framed structures defined by CU-PREPF. Analysis options include linear elastic, geometrically nonlinear, and material nonlinear. The program provides integrated graphical postprocessing (moment diagrams, deflected shapes, etc.) and printed output. Design options include AISC LRFD specification formulas for reviewing and refining trial designs.

CU-QUAND :

CU-QUAND [30] is a fully interactive program for the earthquake-resistant design of two- and three-dimensional framed structures defined by CU-PREPF. Analysis options include equivalent static loads, modal analysis (time history or response spectrum), and direct time history analysis. Design checks include AISC LRFD formulas. The program provides integrated graphical postprocessing.

Of these, CU-PREPF is currently linked as a module in CU-STRAKE. CU-STAND (static analysis and design) and CU-QUAND (earthquake analysis) are not currently available as modules of CU-STRAKE; however, a building model created using CU-PREPF can be used as input to these programs for static or dynamic analysis, as these programs work with a common database.

A graphical definition of the building to be designed is only one way of providing input to the KBES. When a preliminary design of the building is available, the use of the graphical preprocessor presents a convenient and effective means of defining the building. However, the user can also choose to proceed without a graphical input file, in which case all information needed for the reasoning will be obtained by the program by querying the user. The principal data structure used by the KBES in the reasoning process is one of the kind displayed in Figure 5.1. The figure displays information about the building in the format of the internal OPS83 data structure (or 'working memory element'). The various attributes of the building, and their values if known, are listed. The data structure includes some attributes pertaining to the structure as a whole and others that are specific to a floor. The organization of some of the information on a floor-by-floor basis provides a convenient means of performing an evaluation of the seismic quantities that are floor-specific, such as the inter-story drift and the plan eccentricity. The checks for these quantities must therefore be repeated for each of the floors of the building.

When a graphical definition of the building has been created, the information from a graphical ('DES') file is made available to the KBES by means of a translator program which obtains the necessary information and stores it in the corresponding working-memory or 'STRAKE' data structure. Figure 5.2 shows the interaction of the different program modules linked with the expert system, and their use of DES and/or STRAKE files. The translator built into CU-STRAKE currently allows only one-way information transfer, from the DES file to the STRAKE file. It is anticipated that at a later stage of development of the program, the translator will enable either file-type to be translated into the other.

```
(building
    name = ||;
    analysis_type = ||;
    baseshear = 1.33200703636859e+02;
    height = 4.80000005441019e+02;
    occup_categ = 4;
    period = 5.56689441204981e-01;
    regularity = ||;
    Rw = 6;
    seismic_zone = 2.00000007548260e+00;
    short_columns = ||;
    soft_story = ||;
    soil_type = 2;
    struct_system = |moment_resist_frame|;
    struct_type = |steel_moment_frame|;
    unreinf_masonry = ||;
    weight = 1.80279003906250e+03;
    floor_num = 1;
    eccentr_ratio = 0.00000000000000e+00;
    floor_area_above = 1.29600000000191e+06;
    JREP_aver_shr_str = 4.76423549652100e+00;
    JREP_wall_ratio = 0.00000000000000e+00;
    redundancy = |yes|;
    story_drift_ratiox = 0.00000000000000e+00;
    story_drift_ratioy = 0.00000000000000e+00;
    wall_area = 0.00000000000000e+00;
    wall_col_area = 2.83799987793434e+02;
    weight_above = 1.35208996582218e+03;)

 FILE : REVISED_DESIGN.DES;1
```

Figure 5.1: Building Information Stored in OPS83 Format

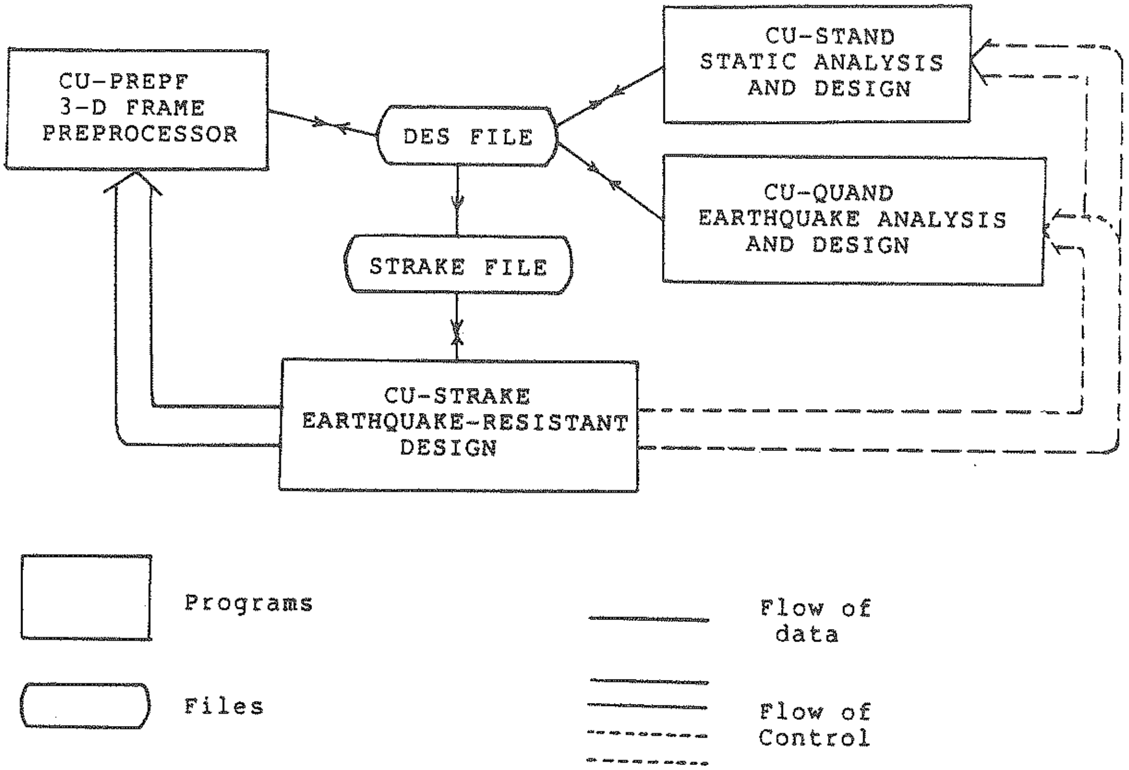


Figure 5.2: Interaction of Analysis and Design Programs

SECTION 6
CONCLUSION

6.1 Summary

The outcome of the first two years of research aimed at investigating the application of knowledge-based expert systems to the design of earthquake resistant buildings is described here. The study served as a means for breaking ground in this area, and coming to terms with some of the benefits as well as limitations of this approach. While it is recognized that the research is still at a relatively early stage with considerable scope for further work, it is believed that several benefits have accrued from the research to date, and that it has been successful in meeting several of its initial objectives. The progress made, and the objectives realized in the research to date, are summarized below :

1. The research serves as an investigation into the applicability and usefulness of the relatively new technology of knowledge-based systems to the domain of earthquake resistant design of buildings. The process served to demonstrate the validity of the approach and the suitability of the field of earthquake engineering as a domain for expert-system development. As is often the case with an emerging technology in the early stages of its inception, wide-ranging claims have been made about the versatility and power of expert-systems, many of which appear to overstate their case. The present research helped to recognize some of the more realizable benefits of this approach for the particular application at hand.

2. The research serves as a 'first cut' at the process of developing expert systems for earthquake engineering applications such as the present one. Different aspects of the development have been investigated, and the experience so gained provides some useful guidelines and insight into the development process. Issues such as the hardware and software environments for such an application, and their suitability from the perspective of the proposed end-user, have been addressed. Interaction with the intended user community at various stages of the research has helped to keep the development in line with its eventual objective of providing practicing engineers with a useful and versatile tool for seismic design.

3. An important outcome of the research has been the development of a knowledge base of expertise and judgment for use in seismic design. The process of knowledge acquisition and representation has involved extracting the useful knowledge from different sources, and formalizing the design knowledge and rules-of-thumb used by experienced practitioners into a set of production rules that constitute the knowledge base. The knowledge base sources include earthquake reconnaissance reports, building codes,

and feedback from practicing engineers by means of a questionnaire soliciting their opinion on various aspects of seismic design. A modest-sized knowledge base has been compiled in this manner and organized in different levels of sophistication for greater flexibility in the reasoning. While the knowledge base is by no means complete, the present organization represents a useful subset of the domain expertise, and leaves room for future enhancement. Enhancements to the knowledge base are possible either by adding more levels of sophistication, or by providing more knowledge/expertise in the existing levels.

4. The implementation of the KBES helps demonstrate the benefits of an integrated design environment, combining conventional algorithmic techniques with the heuristic and advisory capabilities of expert systems. The prototype makes extensive use of interactive graphics for defining the building, and for obtaining information about it for reasoning, as well as for providing a convenient, menu-driven interface.

The research into the knowledge-based approach indicates the potential for the use of this approach for enhancing the process of seismic design. Several benefits have been identified with the application of expert systems to this domain area. The fundamental motivation for the knowledge-based approach arises from the nature of the field of earthquake engineering, and the need for expert judgment in the design process. It is to be noted that while the present development represents the successful application of the expert-system approach to a particular engineering field, it cannot successfully be extended to all or most other engineering applications. While there are other engineering disciplines which can benefit from the approach, it is believed that for several others, the approach would not produce any substantial benefits. The key to the distinction lies in the nature and characteristics of the particular engineering discipline. It is recommended that the algorithmic method of solution be retained for applications that do not warrant a different approach. Domain areas which are ill-structured and not easily formalized are the ones that are suited to expert-system applications.

One of the benefits of the knowledge-based approach identified in the course of this research is the use of a KBES as a 'front-end' for conventional computer-aided design (CAD). As demonstrated in part by the CU-STRAKE prototype, the KBES can be used as the main driver in a program that can access various CAD routines, and which guides the flow of control between the different component modules as required during execution of the program. In this respect the KBES plays the role of a master program that supplements the use of CAD programs, and enables them to be used more effectively.

Another useful conclusion of the research is that the preferred hardware/software environment for engineering applications such as seismic design is one that is in common use by the end-user community, or represents the likely environment, in the near future, for engineering applications in that discipline. In this way the developer can ensure compatibility of the KBES with existing programs for engineering analysis and design. The usefulness of the KBES is enhanced by enabling it to work with existing programs commonly used in the domain area. Thus the KBES can be used to enhance and supplement, rather than replace, the existing capabilities in the particular domain.

6.2 Suggestions for Future Development

The present stage of development of the prototype leaves room for future growth in several directions. These can be separated into

a) Enhancement of earthquake design capabilities, and

b) Enhancement of expert-system features.

6.2.1 Enhancement of Earthquake Design Capabilities

The table in Section 4, showing the organization of the CU-STRAKE knowledge base (Table 4.2), provides a good starting point for possible future enhancements to the system. As indicated in that table, the knowledge implemented in the KBES is a subset of the domain expertise, and some of the knowledge-base aspects, particularly those listed under Level III in the table, represent possible future additions to the program. In addition, other levels may be added in time, and/or more knowledge incorporated in the existing levels.

The design capabilities of CU-STRAKE can be considered to be composed of (1) analysis capabilities, and (2) advisory functions.

In terms of analysis capabilities, an important and desirable future addition to the program is to incorporate static and dynamic analysis capabilities. As mentioned earlier, this extension is planned for the near future. The existing Cornell University programs, CU-STAND and CU-QUAND, for static and dynamic analysis/design respectively, are to be linked with the expert-system module to provide the analysis capabilities. The addition of these capabilities will make the system considerably more versatile and robust. More comprehensive treatment of several features of the design would become possible. For instance, the Rayleigh Method for estimating the fundamental period of the building can be used to obtain accurate estimates of the period fairly easily. Also story drift estimates corresponding to the design lateral forces can be obtained more accurately by static analysis. The dynamic analysis capability could enable more realistic modeling of the response of buildings to the seismic input. The design base shear can be obtained using dynamic analysis, so enhancing the usefulness of the KBES in treating irregular and unusual types of structures. The eigenvalue analysis capability can be used to obtain good estimates of the period, and also to check for the presence of torsional modes of vibration. Another possible extension of the system is to include a comprehensive treatment of soil-structure interaction.

Enhancements need to be made also to the advisory capabilities of the system, by incorporating more expert knowledge in a variety of areas. One method of acquiring this expertise is by close interaction with experienced practicing engineers, either by means of a questionnaire, or on a more long-term basis by involving them actively in the continuing development of the system. The use of a questionnaire has been tried earlier as a source for expertise, and was found to provide much useful knowledge. The technique can be made more effective by extending the scope of the questionnaire to include knowledge-base aspects not yet implemented, and by targeting a larger sample size than that used earlier. Active involvement of practicing engineers in the development process is desirable for the purpose of obtaining feedback at various stages on their requirements of the system and how the KBES can be designed to achieve them. Incorporating a knowledge acquisition facility as part of the expert system would greatly enhance this process of active involvement of practicing engineers in the development process by providing a mechanism by which their domain expertise and feedback can be effectively captured in the system.

6.2.2 Enhancement of Expert-System Features

1. Knowledge acquisition : the addition of a knowledge acquisition facility is a possible future enhancement that would enable the creation of new knowledge base rules internally. This would facilitate the process of transferring knowledge from the domain expert, and of representing this knowledge in an appropriate form for use in reasoning.

2. User modification of knowledge base : Many believe that the effectiveness of a KBES can be enhanced by providing a facility for 'customizing' the knowledge base, or modifying the rules based on the experience and design practices of the particular design office. It is to be noted that a utility for customizing the knowledge base in this manner, without modifying the source code, is not commonly available, and may need to be developed. Some research into ways of doing this is currently under way elsewhere [6]. It is also mentioned in passing that a utility for user modification of the knowledge base raises some serious questions about who should or should not be permitted to modify the existing knowledge base.

3. Uncertainty handling : the provision of some form of imprecise reasoning is an important feature that needs to be added to the system. This is particularly the case for a domain such as earthquake engineering, which is characterized by considerable uncertainty in loading as well as response parameters. Different methods for handling uncertainty are available for use with expert systems [31, 32, 33]. These alternative methods, including the use of

certainty factors [31] and fuzzy set theory [34], may need to be investigated before deciding which method to adopt.

4. Synthesizing expert opinion : a utility for incorporating the opinions, often divergent [35, 36], of domain experts may be useful in dealing with the more ill-structured aspects of the design. A facility like this would enable the developer to input the results of surveys of expert groups, and come up with recommendations in the appropriate form. Thus in cases of common consensus the utility might lead to a single recommendation, but in cases where there is disagreement a histogram may be generated showing the user the range of expert opinion.

5. Comparing alternative designs : a facility for summarizing and comparing the benefits and defects of alternative design proposals for a building would be of help in enabling the user to select the most appropriate or optimal design. Beginning with two or more alternative design proposals, the user can evaluate each one and use a utility such as this to view simultaneously the relevant information about each design and arrive at the best configuration.

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