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A COUPLED KNOWLEDGE-BASED EXPERT SYSTEM FOR DESIGN OF LIQUID RETAINING STRUCTURES

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Abstract

This paper describes a coupled knowledge-based system for the design of liquid retaining structures, which can handle both the symbolic knowledge processing based on engineering heuristics in the preliminary synthesis stage and the extensive numerical crunching involved in the detailed analysis stage. The prototype system is developed by employing blackboard architecture and a commercial shell VISUAL RULE STUDIO. Its present scope covers design of three types of liquid retaining structures, namely, a rectangular shape with one compartment, a rectangular shape with two compartments and a circular shape. Through custom-built interactive graphical user interfaces, the user is directed throughout the design process, which includes preliminary design, load specification, model generation, finite element analysis, code compliance checking and member sizing optimization. It is also integrated with various relational databases that provide the system with sectional properties, moment and shear coefficients and final member details. This system can act as a consultant to assist novice designers in the design of liquid retaining structures with increase in efficiency and optimization of design output and automated record keeping. The design of a typical example of the liquid retaining structure is also illustrated.

Introduction

Crack width control is imperative in liquid retaining structures, which are exposed to a corrosive environment. The design of these structures is quite specialized and requires assimilation of knowledge from heuristics, research findings and standard engineering methodology. It requires extensive studies of loading requirements, underground geotechnical conditions, wind force characteristics, load combinations, practical dimensions and distribution of reinforcement and concrete, material properties and the exposure environment. Moreover, deviations often exist between the assumed properties of components at the preliminary design stage and that at the detailed design stage. In such cases, re-analysis will be entailed and iterative steps such as numerical modeling, structural analysis and code conformance checking are usually involved. Existing computer models may be available to perform a particular task in the whole design process. It is difficult to code empirical rules or expert knowledge in a conventional algorithmic framework. The application of these individual programs requires the intensive knowledge of the structural designer and they are prone to human errors during the data transferring processes. Recent advances in artificial intelligence techniques have rendered it possible to incorporate the heuristic knowledge into the conventional algorithmic structural analysis models.

A knowledge-based system (KBS) is an interactive decision-making computer tool that mimics the reasoning processes of experts in a problem domain. Basic components of a KBS are system context, knowledge base, inference engine, knowledge acquisition, a user interface and explanation facilities. During the last decade, KBSs have been widely adopted to solve problems in many different disciplines (Chau, 1992; Chau and Anson, 2002; Chau

and Chen, 2001; Chau and Ng, 1996; Chau and Yang, 1992; Chau and Zhang, 1995; Maher, 1987; Shwe and Adeli, 1991). For application in engineering design, the KBS framework is in addition required to combine symbolic processing and extensive numerical processing. Examples of such systems by employing various representation schemes are INDEX (Kumar, 1995) and LADOME (Lin and Albermani, 2001).

The objective of this study is to develop a microcomputer KBS that can bring all the design stages together into a user-friendly environment. One of the primary motivations for implementing a KBS on microcomputers is the low cost and availability of sophisticated expert system shells for personal computers, which are widely available in the design office. This prototype system for design of liquid retaining structures, LIQSTR, can offer assistance and advice to the engineer in making decisions during design. Conventionally, design is considered to be a constraint-satisfying problem and it is cumbersome to effect the most structurally optimized solution. However, by adopting a coupled approach, the system solves this problem and provides a more rational basis for the whole process of structural design. Increases in efficiency, standardization and optimization of design output and automated record keeping are among the benefits of such a KBS.

The system can be used effectively by engineers of varied technical backgrounds. Novice designers can use it as a self-explanatory design system, supported by a combined factual/heuristic knowledge base. Experienced engineers can also use the system as a working tool to conduct the design in a more efficient and consistent way. It can also help engineering students to understand the expert approach and to acquire synthetic experience of the solution process. Besides, it can be a valuable research tool for evaluation and validation of the empirical rules and procedures embedded in design of liquid retaining structures.

System Development Environment

The KBS development environment for LIQSTR is VISUAL RULE STUDIO, which acts as an ActiveX Designer under the Microsoft Visual Basic programming environment (Rule Machine Corporation, 1998). VISUAL RULE STUDIO is an application development environment that combines expert system technology with object-oriented programming, a relational database, graphics capabilities and debugging tools. It furnishes a variety of knowledge representation schemes, inference mechanisms and capabilities to interface with external programs in a windows environment. Various types of displays, such as form, checkbox group, list box, command button, textbox, option button, picture box, etc., can be defined as different classes inheriting common characteristics and possessing their own special properties.

Architecture of System

A blackboard architecture (Engelmore and Morgan, 1988) has been adopted due to the nature of structural design, the expert system shell and its capability for coupling all design stages for liquid retaining structures. Under this model, the knowledge base comprises both declarative and procedural knowledge. This well-organized architecture furnishes communication between diversified knowledge modules involved in structural design process as well as facilitates future possible extension. Figure 1 shows the architecture of LIQSTR. The knowledge base is mainly composed of knowledge modules and the blackboard. Knowledge modules correspond to procedural expertise knowledge in solving design problem and are divided into two groups, namely, Design Process and Process Control. Message communications between Design Process knowledge modules and Process Control knowledge modules are effected via the blackboard.

The blackboard contains only declarative knowledge and is divided into two groups, namely, Design Entities and Design Stage. The Design Entities represent the breakdown of design concepts of liquid retaining structures. Each object in the blackboard incorporates some attributes, which are used to express the physical structural components, the facts used in the design, or the pertinent design entities entailed during the design solution process. The attribute can be defined as one of the following types, namely, compound, multi-compound, instance reference, numeric, simple, string, interval, and time. Fact about an attribute can be represented by facets, which design the inference strategy for processing an attribute.

A semantic network, as shown in Figure 2, illustrates the relationships among various objects in Design Entities and represents abstraction of the knowledge. The unique class in Design Stage includes several attributes that represent indicators tracking the current stage of every design context. The status or indicator of the attributes has to be one of the pre-defined values. The knowledge represented in this level will handle the order of execution via the Process Control knowledge modules, which are responsible for controlling the sequence of undertaking these tasks. Figure 3 shows attributes of the class Design Stage. An example of these attributes is “alternativeEvaluation”, which is of the compound type. During the design session, this compound type attribute must have one of the following values: “not completed” or “finished”. Both the initial and default values of this attribute are invariably defined as “not completed”. The search order is in the order of session context and then default value.

Knowledge acquisition

Knowledge acquisition is the process of gathering of rules and facts from literature, including handbooks, standards and codes, and interviews with experienced designers of liquid retaining structures. Domain knowledge such as the minimum percentage of reinforcement, maximum percentage of reinforcement, minimum grade of concrete, etc. are then translated into rules or methods using an object-oriented representation. For instance, the following rule group, which is expressed using the Production Rule Language, represents knowledge on the determination of concrete tensile strength for different concrete grades.

!RULE GROUP: concreteTensileStrength OF BBSectionalProperties

RULE to find concreteTensileStrength : 1 of 3
IF concreteGrade OF BBSectionalProperties = 40
THEN concreteTensileStrength OF BBSectionalProperties := 1.75

RULE to find concreteTensileStrength : 2 of 3
IF concreteGrade OF BBSectionalProperties = 35
THEN concreteTensileStrength OF BBSectionalProperties := 1.6

RULE to find concreteTensileStrength : 3 of 3
IF concreteGrade OF BBSectionalProperties = 30
THEN concreteTensileStrength OF BBSectionalProperties := 1.45

Integration Methodology

Microsoft Visual Basic offers an interfacing facility in a fully integrated fashion. After the execution of the external algorithmic program, the KBS resumes its design session environment.

Finite element analysis program ABAQUS

The finite element package ABAQUS has both input and output files in ASCII format (Hibbitt et al, 1998). When the requisite input files have been prepared following model generation, the knowledge base calls the finite element program to perform the analysis. Through the interfacing module, the output data files are saved in the knowledge base for retrieval and manipulation. Accurate conversion of data format and correct mapping of character have to be attained during the data file preparation. The KBS is not only aimed to act as a front-end to this finite element analysis package, but also to encapsulate knowledge on the entire design process. During the member sizing process, in order to achieve the optimum design, structural re-analysis is very often inevitable. In these design cycles, the ensuing action to be taken by the system depends largely on message transfer amongst different components..

Numerical model generator and code conformance checking programs

Whilst existing algorithmic models generally deal with numerical data input only, the novice user usually finds it more convenient to express in a natural language. The numerical model generator converts these linguistic variables entered by the user in the knowledge base to numerical format conforming to stipulations of the structural analysis package. The code conformance checking program then checks the code requirements of BS 8007 (British Standards Institution, 1987). Apart from the finite element analysis, all number crunching and data manipulation procedures are written in Visual Basic. The communication between the programs and the knowledge base is performed mainly through the objects and attributes. The data can be used by all other components through the interfacing module.

Databases

External Access database files are accessed and updated whenever a consultation is made with the system. The database is composed of structural properties of reinforced concrete sections, moment and shear coefficients for various configurations in preliminary design, structural properties of proposed alternatives and final member details in detailed design. They provide useful information for decision-making and design of liquid retaining structures. The Data Control, which provides an efficient connection of the Visual Basic application to the databases, can open a specified database table or a set of records based on an SQL query on the database. Two key attributes of the Data Control are the DataBaseName property that specifies the name of the database and the RecordSource property that specifies the name of a table or a SQL query in the database. A Data-aware Control such as TextBox, DBGrid, etc., connecting fields of data in the database to the control, is then used to bind to the Data Control. Two key attributes of the Data-aware Control are the DataSource property that specifies the name of the Data Control and the DataField property that specifies the name of the field it is binding to.

Explanation system

Explanations of the reasoning process, liquid retaining structure types, procedures to take various design loading, various code provisions and expert comments regarding the design of liquid retaining structures are included in the explanation system of LIQSTR via the Help button. Explanation of the solution derived by the system is currently displayed by applying user interface facilities such as message boxes. The explanations consist of built-in specific texts together with associated values of design parameters generated by the knowledge base during system run time. Moreover, the user can get an explanation of the command button at any level of execution by viewing the *ToolTipText* with the mouse pointing over it.

User interface

The user interface allows the user to specify all design requirements and acquire the output results from the design consultation. The user can monitor the performance of the system during the design process through the interface. In fact, in most KBSs, it has been reported that a large part of the codes normally deal with the system-user interface (Kumar, 1995). In this prototype system, graphical user interfaces, consisting of layers of display screens and pop-up windows, are used for message transfer so that data handling has been greatly simplified. Contrary to traditional algorithmic models, the user has control over the sequence of actions during the design process subject to conformance with the Process Control knowledge modules.

System description of LIQSTR

The opening menu of LIQSTR is shown in Figure 4. When a command button is clicked, the value of the attribute attached to the command button is altered and the method associated with the attribute is executed, which in turn leads to changes in the display. Designing a liquid retaining structure involves the determination of a suitable configuration and selection of structural components according to both the design specifications and engineering practices. In this prototype system, three basic shapes, i.e. rectangular with one compartment, rectangular with two compartments and circular, and two layouts, i.e. underground and above the ground, are considered. The members are then sized for the imposed load, and wind load if any, on the structure. Structural optimization is considered in terms of the total costs of concrete together with reinforcement. Major design tasks performed by the KBS are preliminary synthesis, detailed specification, numerical model generation, structural analysis, optimized member sizing, and code conformance checking.

Preliminary synthesis

The preliminary synthesis stage of the design is begun with the geometrical and structural specifications. This includes the volume and height required, and also the width to breadth ratio for a rectangular tank. The system applies engineering heuristics such as span depth ratio, crack width computation and moment and shear coefficients for different length and width ratios to evaluate each alternative. Table 1 shows an example of such a heuristic design table showing the moment and shear coefficients for the vertical walls of rectangular shaped liquid retaining structures with different height and width ratios. The KBS selects proposed alternatives from a database containing characteristics of available reinforced concrete sections, which are defined by the concrete cross-sectional area composing of wall or slab thickness times unit metre length, reinforcement diameter as well as reinforcement spacing. In order to narrow the search space, it lists 15 most feasible reinforced concrete sections in order of priority based on minimum total material cost. The alternative with the minimum cost will be recommended by the system as the selected proposed alternative, but the user can still opt for overruling this recommendation. In fact, LIQSTR plays the role of a knowledgeable assistant in the decision making process by supplying details of the evaluated parameters. Heuristic rules reduce the amount of computations needed for preliminary design of members. In calculating the dead weight, the approximate weight of the member yet to be designed is initially estimated on the basis of the total gravity load supported by the structure and the span length of the structure. A more accurate estimate of the member weight is included after the first cycle of iteration.

Detailed specifications

The selected alternative is specified in much greater details. In order to determine the structural response for the chosen configuration accurately, primary loading conditions, the

load combinations and the support conditions must be specified in detail. The system generates default loading and support conditions, which can be accepted or modified by the user. The user can also define specific load combination and wind speed. The system automatically calculates the structural dead weight and imposes it at the nodal points. The user is required to specify the imposed loads, which include the surcharge load and the level of liquid inside the tank. If the liquid retaining structure is chosen to be underground, the user is required to enter level of ground surface, level of water table, specific weight of soil and active soil pressure coefficient. If the liquid retaining structure is chosen to be above the ground, wind forces acting on the external surfaces of the structure are calculated according to the Code of Practice for Wind Effects in Hong Kong (Hong Kong Building Development Department, 1983). The design wind pressure profiles for various types of terrain have been calculated at different height based on the gust velocity in Hong Kong conditions. Various load combinations according to BS 8110 (British Standards Institution, 1985) are considered. For serviceability limit state, 3 load combinations, i.e., DL + WL, DL + LL, and DL + LL + WL, are considered, where DL represents dead load factor, LL stands for live load factor while WL means wind load factor. For ultimate limit state, 3 load combinations, i.e., 1.4DL + 1.4WL, 1.4DL + 1.6LL, and 1.2DL + 1.2LL + 1.2WL, are considered. The user can adopt another set of load factors by entering the required values on the screen as shown in Figure 5.

Structural analysis, crack width checking and optimization

In order to arrive at the optimized design solution, an iterative process is involved here. A detailed design analysis, which is involved mainly with computationally intensive numerical processing, is conducted to generate the structure with the minimum cost. Upon receiving messages from the knowledge base, a structural model is prepared by the model generator. The messages include the descriptions of configuration, structural dimension, support, wind loads, dead loads, member properties and load factors. Prior to the finite element analysis, LIQSTR generates the joint and member information of the liquid retaining structure automatically, thus relieving the user of the cumbersome task of manipulating a large amount of data manually. Heuristic knowledge is employed to generate joints and members information, which include joint numbering, joint coordinates, member numbering and member-joint connectivity data.

The created numerical model is especially tailor-made for the ensuing analysis employing the finite element package ABAQUS. The required input file format is quite complicated. It may require a structural engineer novice to the package a significant effort to manually generating input file successfully. Now, by using this KBS, the knowledge on the preparation of the input data file of a liquid retaining structure for ABAQUS analysis is represented symbolically. This results in both timesaving and avoidance of errors during data preparation or data transfer. The system evaluates the structural stability from the analysis results and furnishes post-processing for these results. Then it checks the structural members according to the relevant code of practice, BS 8007. The computed crack width has to be less than the prescribed crack width, which depends on the exposure environment. The crack width, C_w , is determined using the following formula:

$$C_w = \frac{3a_{cr}\epsilon_m}{1 + 2\left(\frac{a_{cr} - C_{min}}{h - x}\right)} \quad (1)$$

where a_{cr} = distance from the point considered to the surface of the nearest longitudinal bar (Figure 6); C_{min} = minimum cover to the longitudinal bar; ϵ_m = average strain at the level considered; h = overall depth of the member; and x = depth of the neutral axis.

The average strain at the level at which cracking is being considered, is given by

$$\varepsilon_m = \varepsilon_1 - \varepsilon_2 \quad (2)$$

where ε_1 = the strain at the level being considered = $\frac{(h-x)f_s}{(d-x)E_s}$; ε_2 = the strain due to stiffening

effect of concrete; f_s = service stress in tension reinforcement obtained from finite element analysis; E_s = modulus of elasticity of steel; and d = effective depth. Besides, the strain in tension reinforcement is not allowed to exceed $0.8f_y/E_s$.

For crack width C_w of 0.2 mm,

$$\varepsilon_2 = \frac{b(h-x)^2}{3E_s A_s (d-x)} \quad (3)$$

For crack width C_w of 0.1 mm,

$$\varepsilon_2 = \frac{1.5b(h-x)^2}{3E_s A_s (d-x)} \quad (4)$$

where b = width of the section; and A_s = area of tension steel.

The optimized reinforced concrete section obtained is then compared with the initial section used in the structural analysis. If they are not the same, the next design cycle, which involves model generation, structural analysis and code conformance checking, is invoked again using the new section. Typically this phase of design involves several iterations. Once final design result is achieved, the system will present a summary of the final design and generates a printed design report. Figure 7 is the flowchart showing the structural optimization procedure. The optimum values obtained from interactive optimization can then be added to the knowledge base of the system, which is effectively extended by the knowledge acquired through machine experimentation. Machine learning can be effected since the final optimum structural section from the finite element structural analysis is added to the database containing the heuristics during the preliminary design. The system can also be used as a means for testing the available empirical knowledge since the heuristic moment and shear coefficients during the preliminary design stage can be validated with the model run.

Case study

A case study on a typical liquid retaining structure is used to demonstrate the application of LIQSTR. The spatial requirements of the structure are as follows:

Shape = rectangular with two compartments

Volume = 100 m^3

Depth = 5 m

Breadth/width ratio = 1.2

Location = above ground

Exposure condition = severe

Based on these geometric constraints and crack width requirement, the KBS performed a preliminary synthesis using heuristics. According to the span lengths of the structure, the system searches the databases on moment and shear coefficients and on sectional properties and proposes 15 feasible proposed configurations in order of priority of minimum costs.

During this preliminary synthesis, the system suggests an initial member thickness of 225 mm with reinforcement diameter 10 mm at 100 mm spacing as the most suitable alternative. As shown in Figure 8, the proposed alternative include the alternative number, slab thickness, bar size, bar spacing, bar area, span depth ratio and the total material cost. The total costs of the suggested feasible alternatives are listed in ascending order. The user can choose between system's selection and user's selection through an option button with a corresponding evaluation message displayed. In this case, the system's selection is opted. The default design parameters are adopted and shown as follows:

Concrete grade = 40
Reinforcement grade = high yield steel
Concrete cover = 40 mm
Aggregate type = granite
Temperature variation = 15 °C
Unit cost of concrete = \$3000 per m³ of concrete
Unit cost of reinforcement = \$500 per tonne of reinforcement

Detailed design specification, as shown in the following, is input for the selected alternative prior to detailed design and analysis.

Support specification = fixed
Surcharge load = 10 kN/m²
Level of liquid = 5 m
Wind load determination = found by system
Terrain type = general terrain
Top level = 5 m
Load combination = default load combinations
(1.4DL + 1.4WL/ 1.4DL + 1.6LL/ 1.2DL + 1.2LL + 1.2WL)
Number of elements per surface = 100 (10x10)

Figure 9 shows the screen displaying the execution of the finite element package, in which the total number of nodes and elements are computed automatically to be 366 and 350, respectively. The iterative process of numerical model generation, structural analysis, code conformance checking and optimized member sizing is undertaken. Finally, the system finds out that a member thickness of 300 mm with reinforcement diameter 25 mm at spacing 225 mm is the optimum section. Figure 10 shows the member sizing record of the recommended section, which includes slab thickness, reinforcement diameter and spacing. The designed bending moments at serviceability and ultimate limit states and the designed shear force at ultimate limit state are also shown. Table 2 tabulates the comparison between the moments and shears in preliminary synthesis and in the final design. Although the values are basically of the same order of magnitude, there still exist some rooms for improvement on accuracy of the values from heuristics in preliminary design, given the lack of details at that stage. As such, the values acquired from the final design, together with detailed specifications, can be added to the knowledge base to improve the existing heuristic knowledge.

Conclusions

A coupled microcomputer KBS on design of liquid retaining structure (LIQSTR) was implemented to combine expert knowledge with object-oriented programming, graphics capabilities, KBS technologies, conventional algorithmic models and relational databases under a windowing environment. It can act as a repository of empirical knowledge provided

by experienced specialists. It not only reduces time and effort in design of various structural elements of liquid retaining structures, but also offers assistance and explanations to the user. The prototype system undertakes all major design stages including preliminary synthesis, detailed specification, numerical model generation, nonlinear finite element analysis, code conformance checking, and optimized member sizing. Moreover, it has been shown that machine intelligence can be introduced into the KBS in addition to the knowledge acquired from the human experts and the literatures. From this point of view, the system will be an ideal research tool to validate and enhance our empirical knowledge, which in turn may lead to more efficient and optimized structural design.

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<i>b/a</i>	<i>Moment Coefficients</i>		<i>Shear Coefficients</i>	
	M_h	M_v	V_h	V_v
0.5	9	15	16	20
1.0	29	35	23	32
1.5	42	60	26	41
2.0	62	86	25	46
2.5	76	108	27	48
3.0	89	126	31	50
4.0	101	148	34	50
5.0	103	158	35	50

Notes:

a = vertical height (in m); b = horizontal width (in m); w = specific weight of liquid (in N/m³)

M_h = horizontal moment coefficient; M_v = vertical moment coefficient

V_h = horizontal shear coefficient; V_v = vertical shear coefficient

Moment = moment coefficient x $wa^3/1000$ (in kNm/m); Shear force = shear coefficient x $wa^2/1000$ (in kN/m)

Table 1. Moment and shear coefficients for a vertical wall of rectangular shaped liquid retaining structure with topside free and the other three sides fixed

	<i>Preliminary design</i>	<i>Detailed design</i>
SLS moment	34	50
SLS shear	69	164
ULS moment	47	60
ULS shear	95	197

Table 2. Comparison between moments and shears in preliminary synthesis and in detailed design for the case study

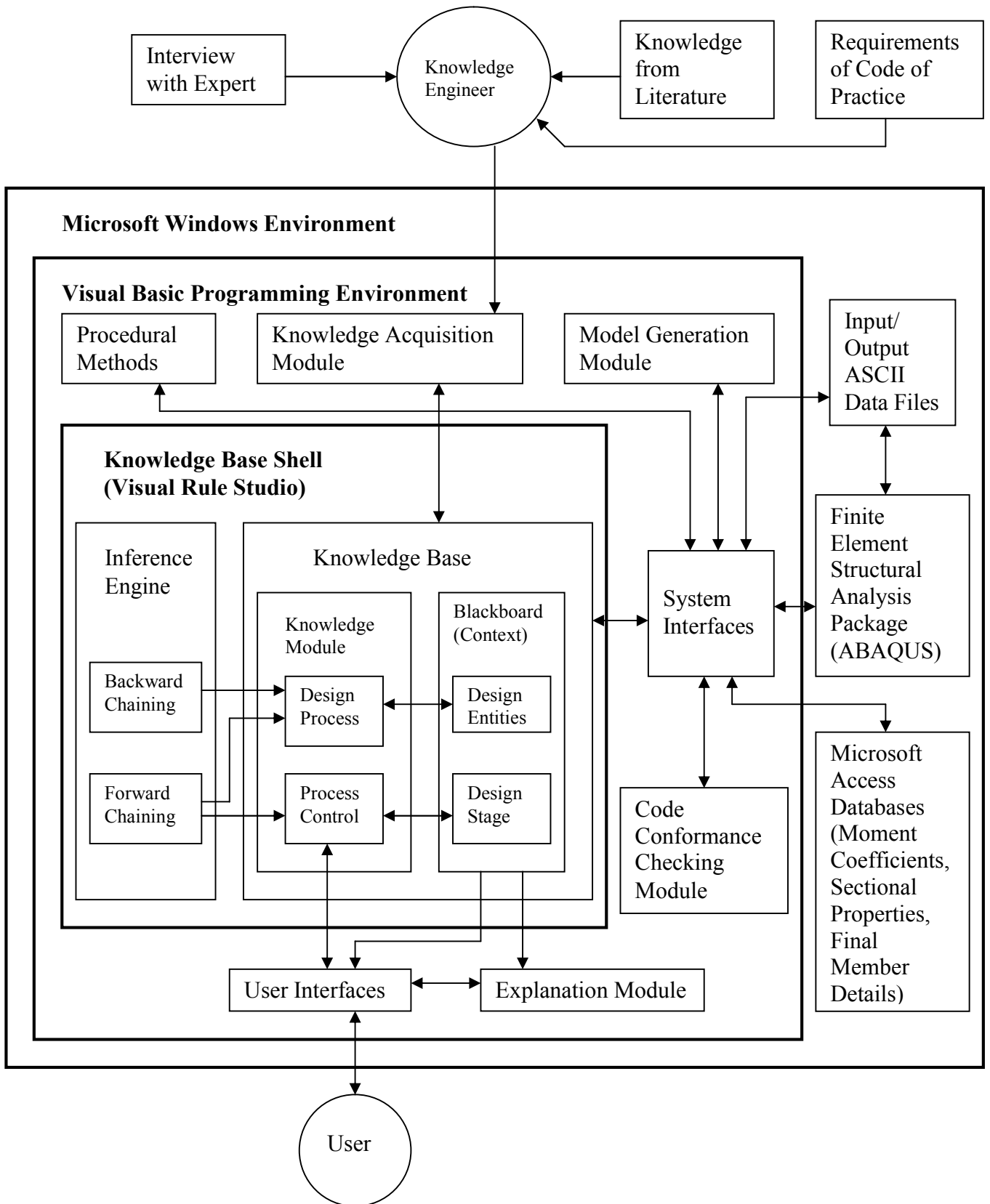


Figure 1. Architecture of the coupled knowledge-based system

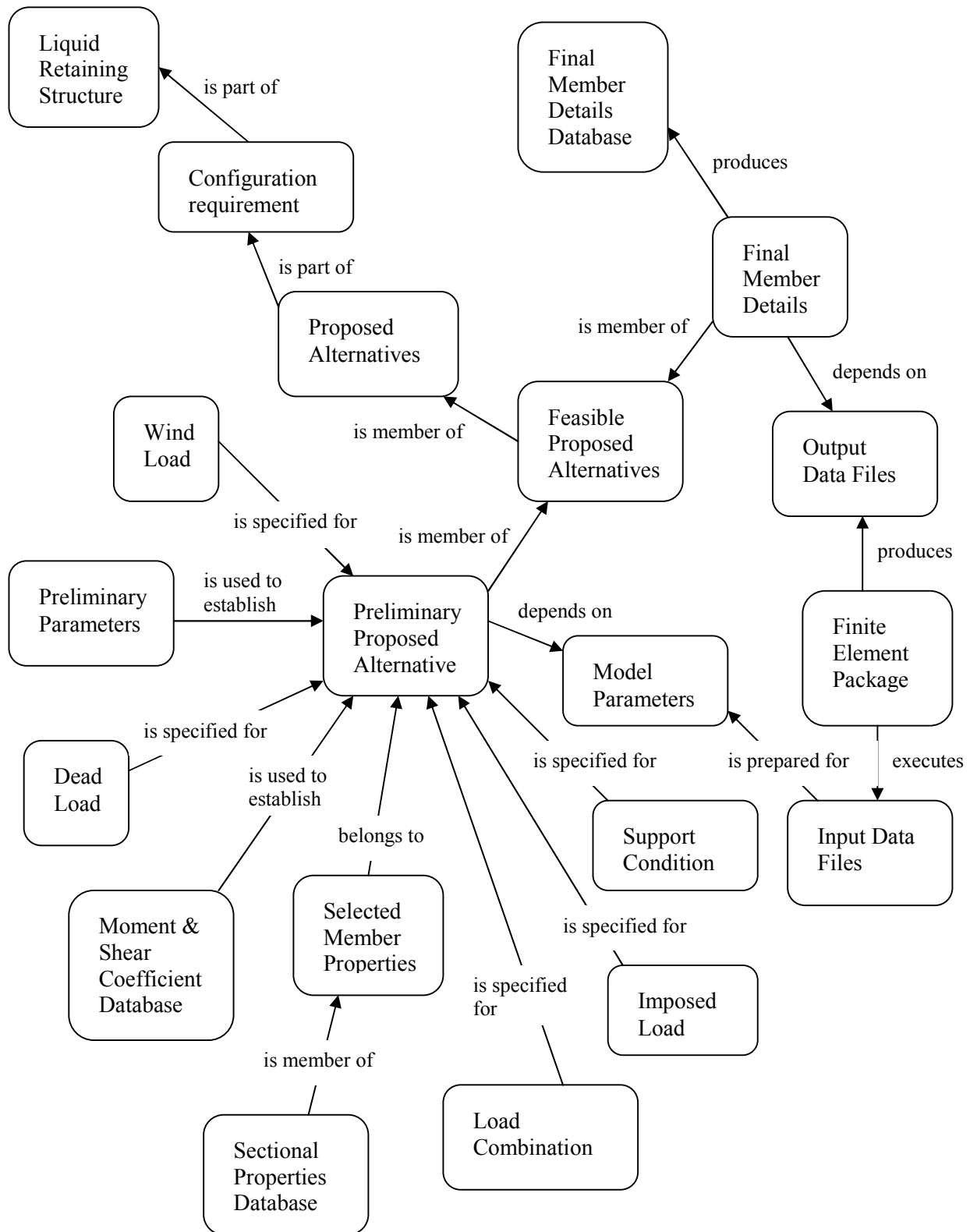


Figure 2. Semantic network representing objects and their relationship in the blackboard

```

CLASS DESIGN_STAGE
  WITH structuralSpecification COMPOUND
    not specified,
    specified
  WITH imposedLoad COMPOUND
    specified,
    not specified
  WITH windLoad COMPOUND
    not specified,
    specified
  WITH loadCombination COMPOUND
    not specified,
    specified
  WITH modelSpecification COMPOUND
    specified,
    not specified
  WITH supportSpecification COMPOUND
    specified,
    not specified
  WITH crackWidthCheck COMPOUND
    not executed,
    complete
  WITH analysisAndMemberSizing COMPOUND
    not ready,
    finished
  WITH restartApplication SIMPLE
  WITH alternativeEvaluation COMPOUND
    not completed,
    finished
    INIT not completed
    DEFAULT not completed
    SEARCH ORDER CONTEXT DEFAULT
  WITH memberSizingRecord COMPOUND
    not produced,
    produced
  WITH finalMemberDetail COMPOUND
    not produced,
    produced
  WITH designSpecification COMPOUND
    not completed,
    completed
  WITH designReport COMPOUND
    not generated,
    generated

```

Figure 3. Characteristics of class design stage

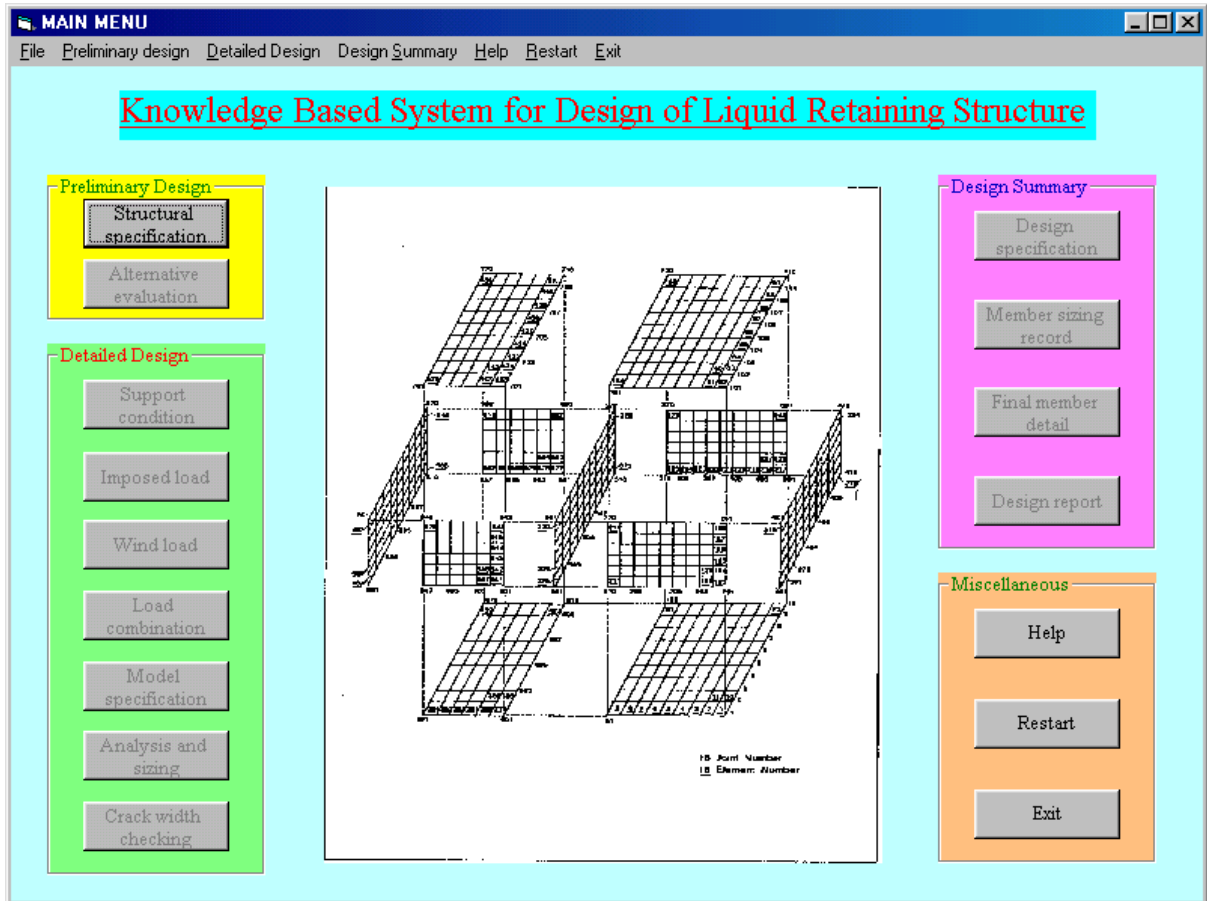


Figure 4. Screen showing the main menu

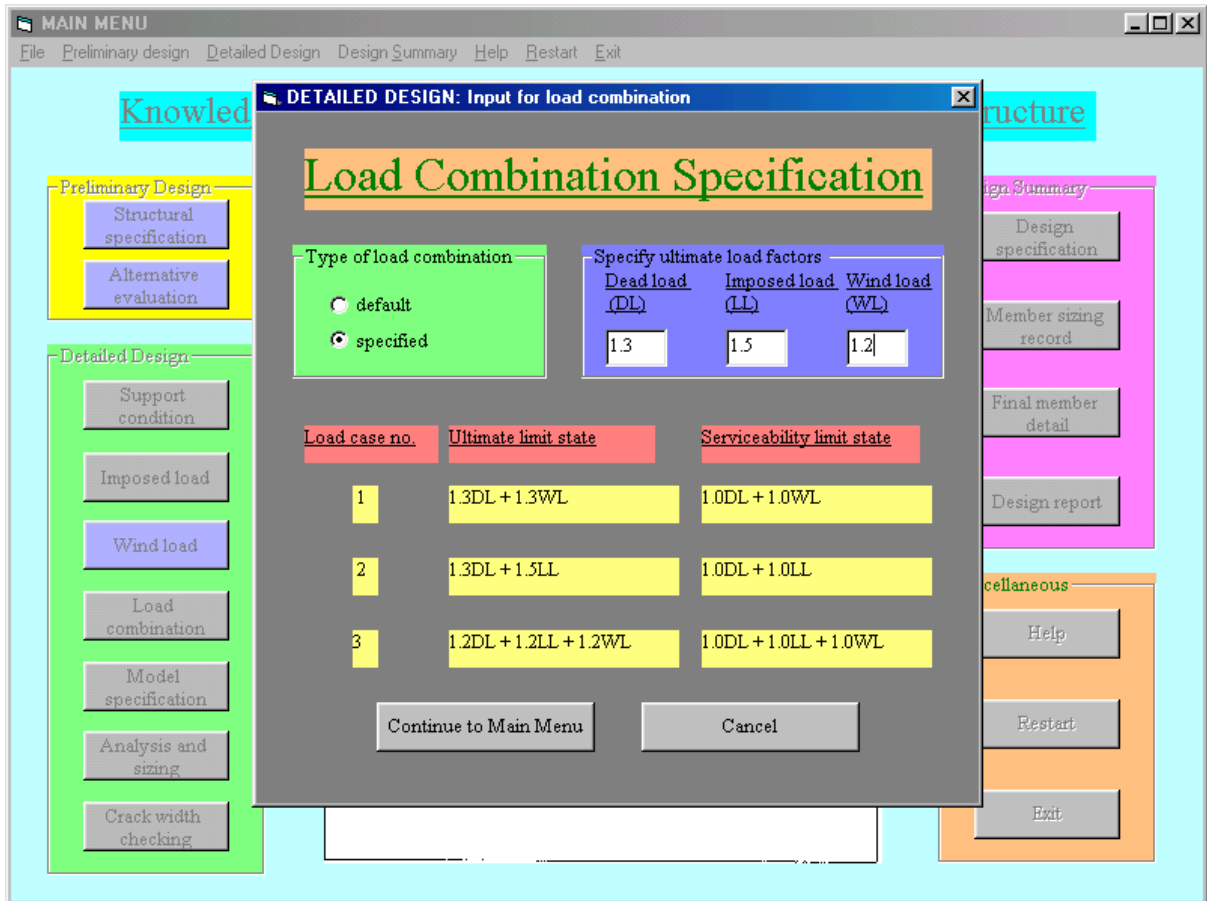


Figure 5. Screen showing input of specified load combination overriding the default values

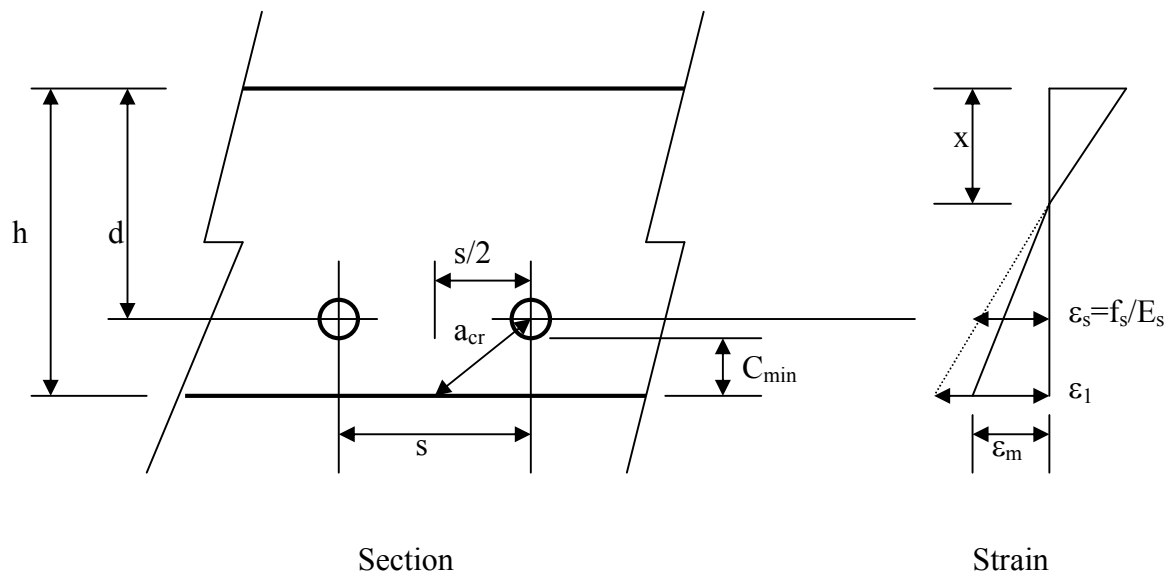


Figure 6. Design parameters in crack width calculation

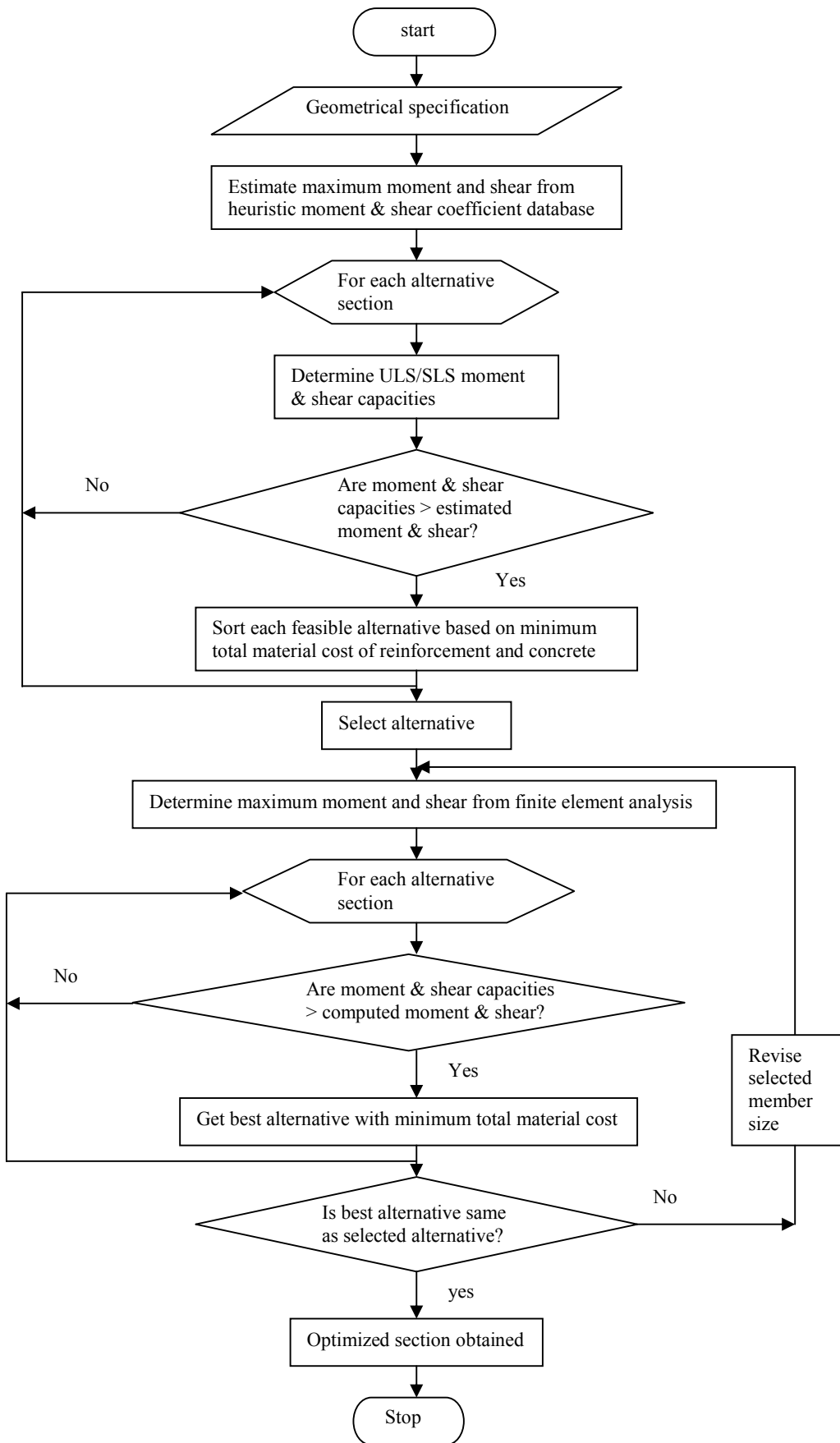


Figure 7. Flowchart showing the structural optimization procedure

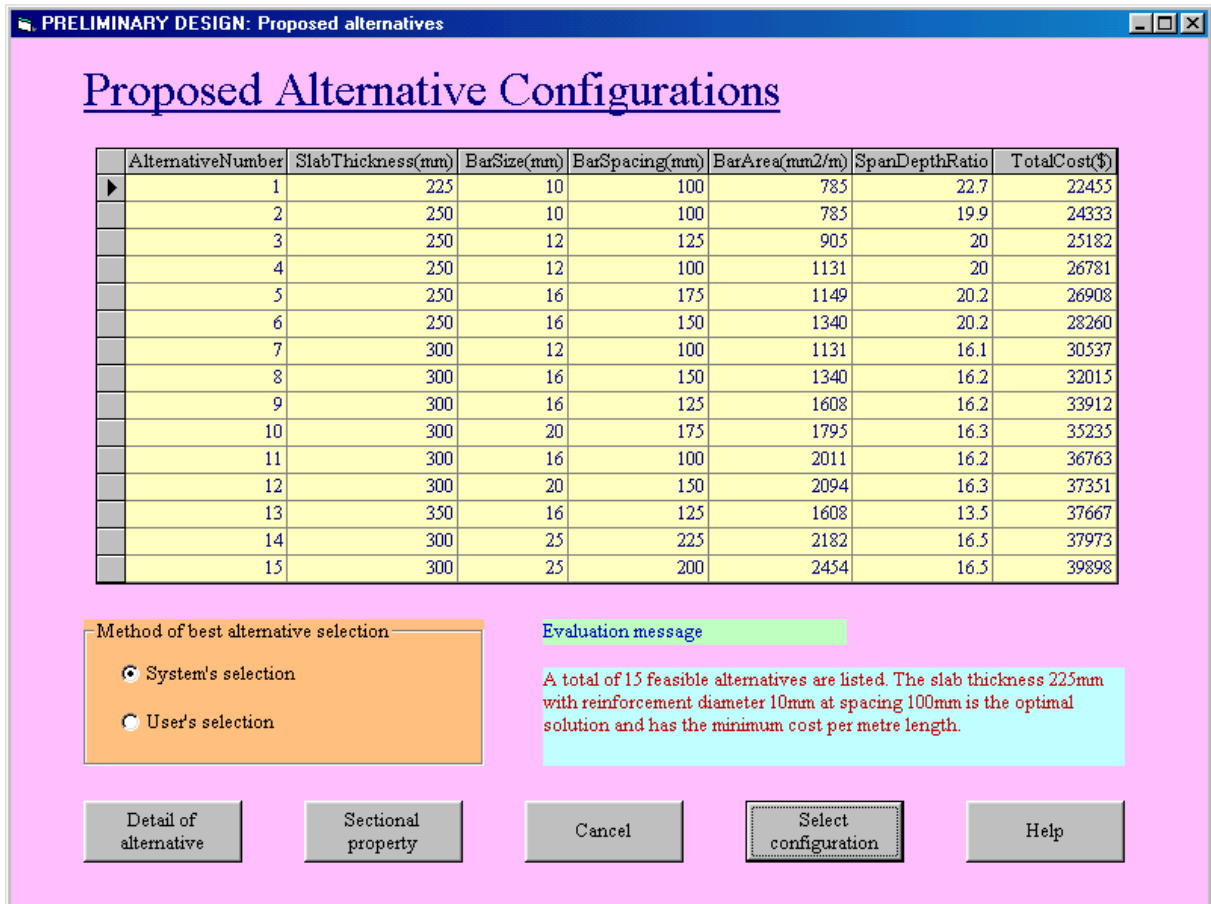


Figure 8. Screen showing the selection of proposed alternative

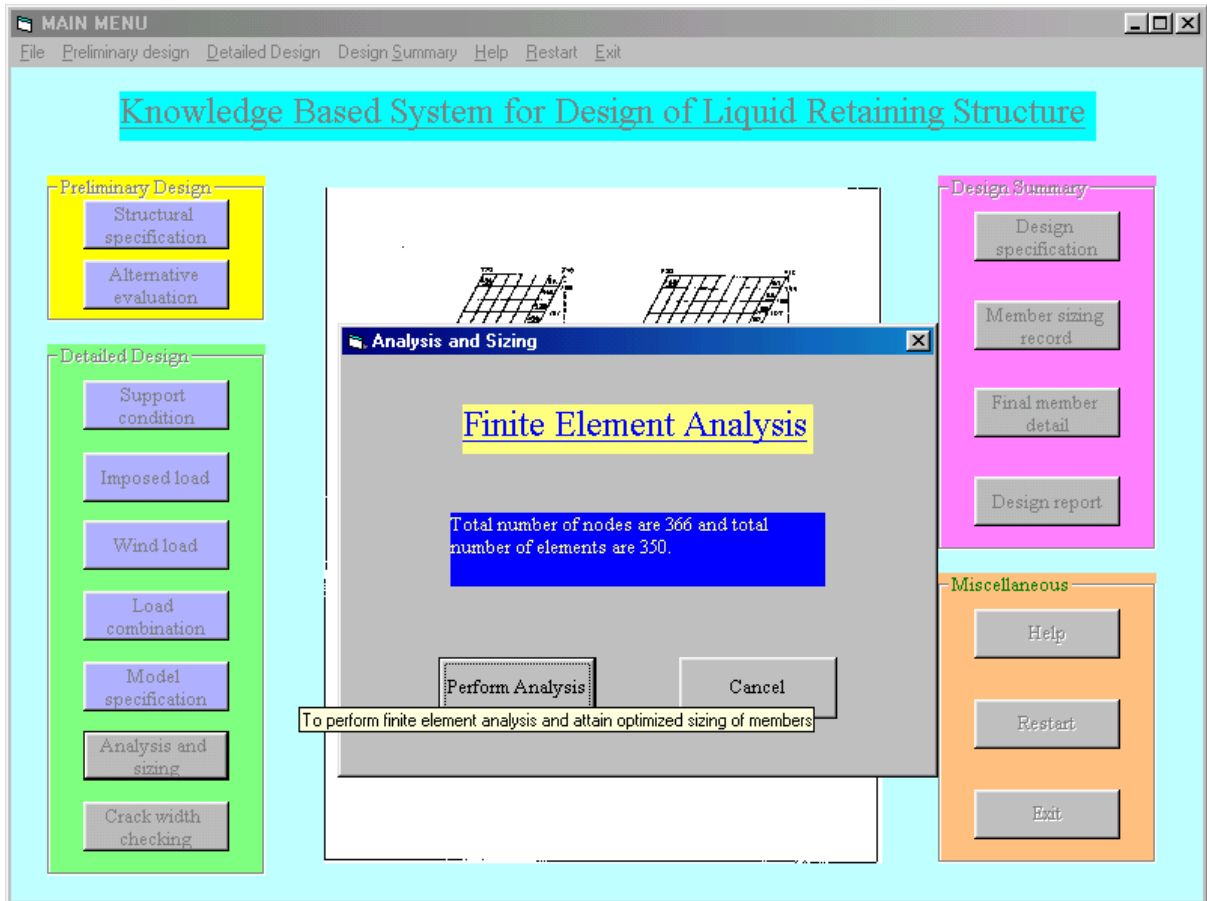


Figure 9. Screen showing structural analysis by finite element package



Figure 10. Screen showing the best member sizing record