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Publication of this paper sponsored by Committee on General Structures.

Application of Expert Systems in the Design of Bridges

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ABSTRACT

The principles of artificial intelligence have been used to develop an expert system for the design of bridge superstructures. The expert system developed, a Bridge Design Expert System (BDES), applies the ideas of artificial intelligence to the bridge design process. The result is a practical system capable of aiding any bridge designer. BDES at its preliminary stage considers superstructures of short- to medium-span bridges. It designs for structural steel and prestressed concrete girders. The developed BDES is a valuable design tool, but, more important, it has shown the potential applications of expert systems in bridge design.

The application of computers in engineering has aided in the solution of numerous problems. This is especially true for problems of analysis for which programs have been constructed to assist the engineer in determining stresses, strains, and strengths of structures. Computer systems are also available to aid in detailed drafting. However, computer applications for decision making in design problems have been limited. Programs to aid the designer proceed through different phases of the design process have been developed, but programs to carry out the entire design decision-making process are scarce. The designer is required to make various decisions throughout the design process (1,pp.3-6). Design decisions may include selecting feasible structure types, making appropriate approximations and assumptions, and sizing individual members to satisfy the design criteria. Such problems are "ill-structured" and are not well suited for conventional programming procedures (2).

However, a program capable of proceeding through the entire design process has been developed by applying a relatively new technology called expert systems. Expert systems, also called knowledge- or rule-based expert systems, are intelligent computer programs that are capable of solving practical problems that have heretofore been considered difficult enough to require human intelligence for their solution (3). The developed expert system, Bridge Design Expert System (BDES), was constructed to explore the applications of expert systems to the design of bridge superstructures.

EMERGENCE OF EXPERT SYSTEMS

Interest in developing expert systems has greatly increased in recent years because of their advantages over more conventional computer programming procedures. The following table gives some expert systems and the problem domain that they attempt to address (3,4).

Expert System	Domain
MYCIN	Medical diagnosis
DENDRAL	Organic chemistry
MACSYMA	Symbolic mathematics
HEARSAY II	Speech understanding
PROSPECTOR	Exploratory geology
GENESIS	Genetic engineering

However, because the idea of expert systems is quite new, their potential use in many areas has not yet been investigated. This is certainly true for civil engineering applications, and especially in the area

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of transportation engineering. The following table gives some engineering expert systems along with their problem domain.

Expert System	Domain
HI-RISE	Building design
FAX	Failure analysis
SAGE	Structural analysis
BDES	Structural design

EXPERT SYSTEMS

Expert systems attempt to model the problem-solving expertise of a human expert within a particular field. This requires representing specific knowledge or expertise of an expert as well as general problem-solving strategies. In knowledge-based expert systems, the expert's knowledge is stored in the system's knowledge base. This is analogous to a data base in a conventional program. The problem-solving strategy involves drawing inferences and controlling the reasoning process (3). These strategies comprise the inference procedure of an expert system. The inference procedure is included in what has been termed the expert system's "inference engine" (3,4).

The knowledge base includes two different types of knowledge: factual and heuristic (3,4). Factual knowledge can usually be found in textbooks and other references and hence is common knowledge (3,4). For example, in BDES factual knowledge may include AASHTO requirements, material properties, and potential superstructure designs typically used. Factual knowledge is referred to as simply the "facts."

Heuristic knowledge is mostly private knowledge that experts have gained through experience (3). This knowledge is characterized by rules of good judgment, rules of good guessing, rules of plausible reasoning, and rules of thumb. These rules model the decision expertise the expert uses to solve the problem. This heuristic knowledge is represented in the form of rules and is thus referred to as the "rules." Rules in BDES may be used to select the superstructure type, determine the girder spacing, or decide between a simple or continuous span design.

KNOWLEDGE-BASED EXPERT SYSTEM

Figure 1 shows a schematic representation of a knowledge-based expert system. The figure illustrates that a user of an expert system may be an expert or a nonexpert. The analogy in BDES is the experienced bridge designer as the expert and the novice engineer as the user.

Whether the user is an expert or not, the system must require input from the user to begin. The input, represented here by the problem statement, consists of all engineering data required to state the problem for the expert system to solve. The problem statement basically symbolizes the memory that stores the problem data.

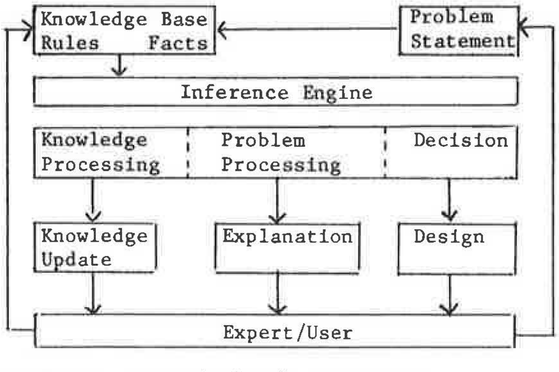

FIGURE 1 Knowledge-based expert systems.

The expert system now combines the data of the problem statement with the facts and rules contained in the knowledge base. The rules in the knowledge base use the problem data and the facts of the knowledge base to draw inferences and solve intermediate steps leading to the final design decision.

The inference engine uses control procedures to draw appropriate inferences. Drawing inferences in an expert system simulates the expert's reasoning process. Reasoning requires processing the problem and the problem expertise to make decisions.

Inference procedures typically use if-then rules to model the decision making of the expert. If-then rules state that if a certain condition or set of conditions is true, then a particular conclusion becomes true. The knowledge base may contain many if-then rules and thus require the inference engine to provide a suitable strategy to control the selection of appropriate rules.

Ideally the inference engine should trigger rules that generate decisions comparable to those that the expert would make at any point in the solution process. The control procedures must therefore find a way to systematically proceed from the initial problem state to the final goal. The solution or goal in many problems, including design, requires searching many possible outcomes until one satisfying the goal is found. The inference engine continues using rules to search for a solution until the solution has been found.

Figure 1 shows three outputs to the expert/user. These include solution, explanation, and knowledge update. The solution output is obviously the desired solution to the problem. However, the user may wish to know more than just the final solution. The user may want to know how or why a certain conclusion was reached. The explanation output represents this feature. All expert systems do not give explanations of why or how they reached a certain conclusion. However, this feature is obviously quite desirable.

The knowledge update output represents an ideal feature by means of which the expert system can learn from its experience and thus suggest ways to the user (expert) for updating the knowledge in the knowledge base. The expert user can then update that knowledge. Of course the expert user may still update the knowledge base or enter new knowledge without this feature.

ARTIFICIAL INTELLIGENCE SEARCH STRATEGIES

Artificial intelligence has developed efficient strategies for solving search problems. Most notable are "breadth-first" and "depth-first" search processes using forward and backward chaining strategies (5,6). Breadth-first and depth-first differ in the way they proceed through a search space. A search space includes all possible outcomes at each stage of the solution process. This can be viewed as a treelike structure that contains at the top the initial state and at the bottom many goal or solution states. Levels in the middle of the structure correspond to intermediate solution states along some path to the goal state. A breadth-first search proceeds down the structure one level at a time examining each intermediate state of the next level to decide what is the best path. A depth-first search assumes one path and proceeds down it until it either determines that that path will not lead to a solution or reaches the final goal state.

Forward chaining starts at an initial state and infers intermediate subgoals in an orderly fashion until the final goal is found. Backward chaining assumes a goal and attempts to verify the assumed goal by attempting to proceed backwards to the initial state. Forward chaining is useful when many goal states are possible and backward chaining is useful when a few goal states are possible.

IMPLEMENTING AN EXPERT SYSTEM IN BRIDGE DESIGN

Implementing an expert system in bridge design first requires identifying the knowledge of the bridge design process to use to build and develop a knowledge base. Steps in the bridge design process (design procedure) are shown in Figure 2. Knowledge used in each step of the process is also displayed.

The second task is to develop suitable inference procedures to process the knowledge. Different procedures could be used. However, a strategy that best simulates the reasoning process of the bridge designer should be identified.

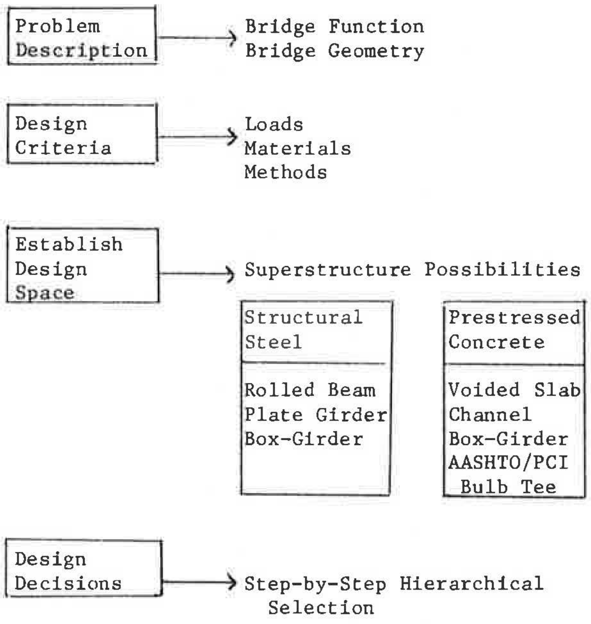

FIGURE 2 Design procedure.

KNOWLEDGE OF THE BRIDGE DESIGN PROCESS

Establishing the information or data needed to adequately describe the problem is the first step. Bridge geometry and bridge function give this information. Bridge geometry includes bridge length, width, height, and skew. The number of lanes, the number of spans, and the lengths of the spans are also part of the geometry input. Bridge function describes the reason for constructing the bridge (e.g., to cross over another roadway, to cross over a stream). Information describing the problem is design specific and is therefore required input by the user. This information is thus not part of the expert system's knowledge base.

The next step in the design process represents factual knowledge stating the constraints and criteria to which the design must adhere. The loading, material properties, and method of design to be used must be established. For example, the method of design could consist of either load factor or working stress.

The next step shown in Figure 2 refers to the establishment of the design space. The design space represents all possible bridge superstructure designs. Examples of structural steel and prestressed concrete superstructures included in the design space of BDES are shown in Figure 2 (6-9). Figure 3 illustrates further the design space for structural steel. The figure shows a treelike structure in which levels of the tree correspond to different design characteristics.

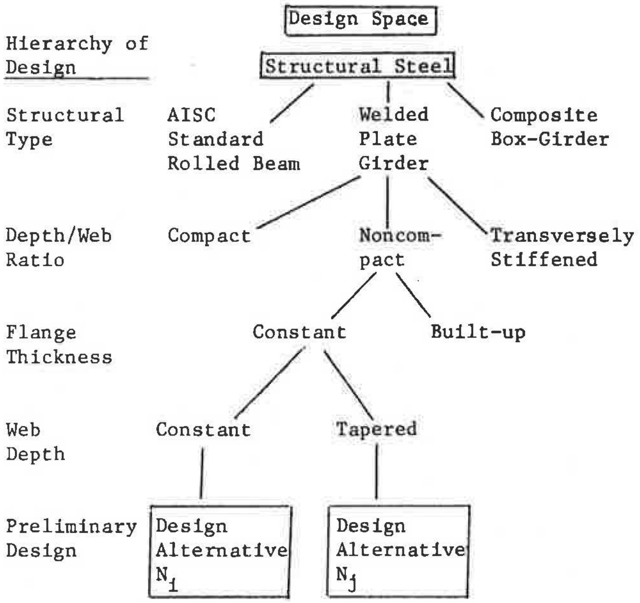

FIGURE 3 Design space.

The many characteristics allow for a great multitude of potential designs. Establishing the design space provides the designer with all the possible solutions to the design problem. It should be pointed out that this step does not represent an input, action, or decision in the design process. However, this step is shown to stress that the designer must be aware of all of the possible superstructure designs. It should be noted that the design space represents factual knowledge in the knowledge base. This is true because the different designs in the design space are typically used standard designs.

The design process must now begin making decisions that will ultimately lead to a final design. The design decisions in themselves constitute a series of steps. Each step requires drawing inferences to make appropriate selections given some discrete set of choices. These steps are normally performed in a generally fixed sequence thus creating a hierarchy of selections. Figure 4 shows the steps contained in the design decisions. These include selecting a set of promising and feasible design alternatives, sizing the members in the alternatives, and comparing the alternatives to select a preliminary design. A structural analysis step is shown to emphasize that analysis may play a role in the design decisions.

Selecting a set of promising and feasible design alternatives requires heuristic knowledge. Rules of thumb, rules of good judgment, and rules of plausible reasoning govern decisions about appropriate selections. Typical rules include decisions to choose between steel or prestressed concrete; among a compact,

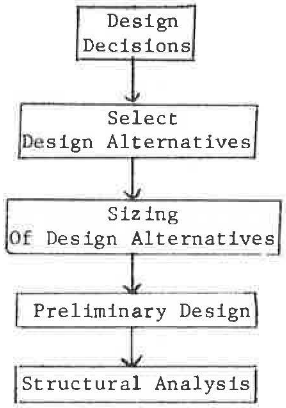

FIGURE 4 Design decisions.

noncompact, or stiffened web; or between a constant or built-up flange section. Some rules may be documented and practically universally used. However, many rules comprise the knowledge that the bridge designer has gained with experience.

Sizing the members of the design alternatives is another step that requires heuristic knowledge. In this step rules of good guessing are used to design members of the design. Typical rules include rules for selecting girder depths and spacings, web and flange dimensions, and slab thickness.

Comparing the design alternatives to select a preliminary design is also governed by rules. It should be clear that one rule used in this step is to select the "best design." However, the best design selected by one designer may not be the best design selected by another. The reason is that designers use many different rules to quantitate the affects of aesthetics, environmental concerns, and local economics.

The next step in the design process is to structurally analyze the selected design alternatives. The analysis uses mostly factual knowledge regarding common and documented procedures to find the stresses, deflections, and so forth.

INFERENCE AND CONTROL IN BRIDGE DESIGN

Heuristic knowledge is easily cast into a form of if-then rules that implies a modus ponens inference strategy (3,5). This strategy uses logical if-then rules to draw inferences and hence make decisions. For example, in BDES a typical inference can be made to select a potential superstructure type using the following rule:

> If: Span length is less than 80 ft,
> Then: Consider a rolled beam.

Note that the rule only infers considering a rolled beam, it does not use a rolled beam. This example illustrates a few key points. First, many conditions may have to be true in order for a certain decision to be reached. For example, conditions other than the fact that the span length is less than 80 ft will have to occur before a rolled beam becomes the selected design. Second, a rule drawing an inference does not have to dictate a decisive action; it may instead prompt a tentative decision. Eventually, with enough rules, a final decision can be reached. Although not evident in this example, it should be pointed out that the decisions reached by rules may themselves be conditions for new rules.

The control strategy must now be selected to process the rules in such a fashion as to eventually produce a final design. A breadth-first search using forward chaining appears to be most appropriate for a design problem. The large number of possible outcomes (final designs) favors the forward chaining process. The selection of the design types, characteristics, and sizes proceeds in a systematic order thus prompting the need for a breadth-first strategy.

Figure 3 shows the advantages of using a breadth-first search. Breaking a design into a hierarchy of design characteristics allows rules pertaining to each characteristic to be grouped. A group of rules can then be examined to select a particular design characteristic at each level in the hierarchy. After all characteristics have been examined, a design alternative has been found.

BRIDGE DESIGN EXPERT SYSTEM

BDES designs superstructures of short to medium span. The potential designs comprise practically all designs normally used today. Possibilities may include structural steel or prestressed concrete with either simple or continuous spans.

BDES is highly user interactive with graphic capabilities to aid in input and output. The system requires the bridge geometry as minimal input. However, the user may intervene at each step of the design process to alter assumed facts. Graphic displays guide the user in inputting geometry. Graphic output displays various cross sections to illustrate clearly the designs generated by BDES.

BDES requires the bridge geometry as discussed previously. Figure 5 shows a graphic output of the bridge geometry. The geometry input is flexible in that it allows the user a choice between entering the width or the number of lanes. The system will suggest a width using assumed values of shoulder, median, railing, and lane widths.

The reason for constructing the bridge, bridge function, is another input to the system. Bridge function dictates vertical clearance requirements. For example, in North Carolina the clearance must be from 16 ft 6 in. to 17 ft 0 in. for bridges crossing over Interstate highways (10).

The environment may affect the selection of materials. For example, North Carolina suggests using ASTM A588 unpainted steel except in highly corrosive environments (11). Thus BDES requires information regarding the environment.

Assumptions regarding materials, loading, design method, and other constraints and criteria are incorporated in BDES. However, assumptions may be changed by the user to allow for maximum flexibility. A typical assumption might include an AASHTO HS 20-44 loading. Only one method of design, load factor, is used in BDES.

BDES now begins making design decisions using the rules. A set of design alternatives is generated first. More than one alternative is usually generated because not enough knowledge is known at this point in the design process. For example, it may not be clear whether a rolled beam or an AASHTO-PCI prestressed concrete girder is the best design for a simple span length of 60 ft. Alternatives may be similar except for one particular characteristic, such as a plate girder with and without transverse stiffners. In BDES each is considered a separate alternative. However, there is enough knowledge to guarantee that only a small number of alternatives will be generated.

The next step in BDES is to size the members for each alternative in the set just created. The main structural members are sized along with the slab

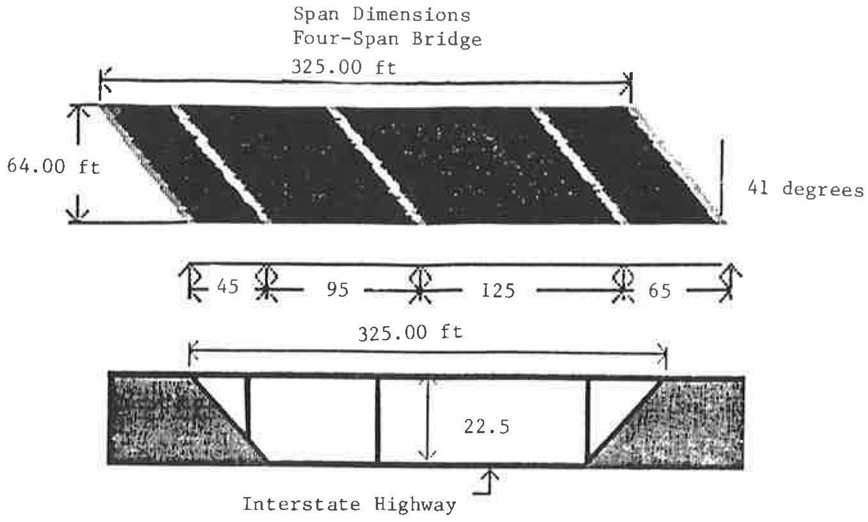

FIGURE 5 Bridge geometry.

thickness (all designs assumed a reinforced concrete deck). The spacing of the members is also generated. Rules are used to make good guesses of the member dimensions. This process proceeds in a systematic order using breadth-first search strategy similar to the process for determining the set of design alternatives. The hierarchical design is required because sizing some dimensions depends on other dimensions. For example, the web depth is found first with a rule that uses the span length. Then the web thickness is found with a rule using the web depth as a condition. Specifically, in the design of a compact plate girder the web thickness will be limited by AASHTO code requirement 10.48.1(b) (12). This requirement specifies the maximum depth-to-thickness ratio allowed for a compact section.

BDES must now select one of the design alternatives. The selected design alternative is governed by the "least weight" design. The "weight" of a design alternative includes the material weight plus "equivalent weights" to account for the differences in fabrication or construction costs, or both. Material weights are obviously easily calculated. Equivalent weights are found by equating x number of pounds of material to unit values of different design parameters. For example, BDES assumes 700 lb of steel for each field splice (13). The user may input several different equivalent weight conversions: the user might equate x number of pounds of steel per linear foot of weld.

BDES now selects the least weight design and verifies its adequacy by structural analysis. The analysis checks for all AASHTO code requirements. Included in BDES are also requirements dictated by North Carolina (11).

Figure 6 shows the design recommendation generated

Superstructure Characteristics

Material Type	Girder Type	Span Type	Length	Web	Flange	Depth
Structural Steel	Plate Girder	Simple Span 2	125 ft	Compact	Built-Up	Constant

Preliminary Design Data

Girder Spacing	No. of Girders	Top Flange Plate		Web Plate		Bottom Flange Plate	
		Width	Thickness	Depth	Thickness	Width	Thickness
12.50 ft	5	11 3/4 in.	1 1/8 in.	60 in.	1 1/16 in.	16 3/16 in.	1 1/8 in.

Flange Build-Up

Width	Bottom Flange Thickness	Length	Width	Top Flange Thickness	Length
11 3/4 in.	1/2 in.	56.3 ft	11 3/4 in.	1/2 in.	56.3 ft

FIGURE 6 Preliminary design alternative.

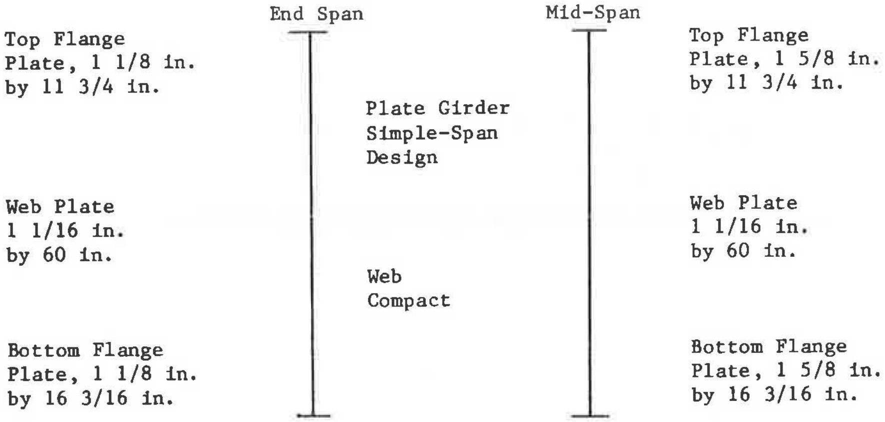

FIGURE 7 Girder cross section.

by BDES corresponding to the geometry displayed in Figure 5. Figure 7 shows a typical graphic output of the girder cross sections for this design.

If the recommended design satisfies all requirements, BDES will advise the user that the design is usable. If the design does not meet required specifications, BDES will let the user know why the design was not acceptable. However, at this time BDES does not redesign. The next phase in developing BDES would thus be to incorporate redesign rules.

CONCLUSION

Great potential exists for the use of expert systems in design problems. The bridge design expert system developed, BDES, has certainly shown this potential. BDES has demonstrated that expert systems are well suited for "ill-structured" problems. Capturing the knowledge of the bridge designer and integrating it with a workable inference procedure has resulted in a system capable of making intelligent design decisions.

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Publication of this paper sponsored by Committee on General Structures.