Structural Analysis Consultation System Developed by Use of Knowledge Bases and Symbolic Manipulation*

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An attempt is made to constitute an integrated consultation system for structural analysis. The objective at present is to furnish a prototype consultation system with the ability to recognize a structure and its properties in terms of the physical model and to predict the model response qualitatively. Elastic beams and plates are taken as the physical model. The system consists of the analysis knowledge base and structure-domain base of the physical model linked mutually by message communication and supported by the inference engine. The knowledge is stated in the form of the frame model. A symbolic processor is provided for the manipulation of equations and formulae. The inference engine is described in Prolog language. The system is implemented on a personal computer PC 9801 VX 2. The case studies of beam problems confirm the potential of the prototype system to evolve into sophisticated consultation systems for large computers in the future.

Key Words: Structural Analysis, Consultation System, Knowledge Base, Symbolic Manipulation, Inference Engine, Frame Model

1. Introduction

Numerical analyses have played an important role in structural design in recent years and are expected to assume greater importance in design by virtue of advancing hardware including pre- and post-processors and repletion of user interface. On the other hand, consultation systems for finite element methods have been developed as an application of artificial intelligence to the analysis^{(1)~(3)}, and expert systems have been introduced in the process of structural design^{(4)~(6)}. Attention has been paid to the fusion of artificial intelligence and computational mechanics, the emphasis being placed on the implementation of the knowledge of structural mechanics on computers⁽⁷⁾⁽⁸⁾. This tendency seems natural in view of the fact that expert systems were employed early on in the technology of safeguarding structural integrity⁽⁹⁾.

Present numerical analysis systems developed on the basis of the many numerical recipes and arts of scientific computing only recognize structures numerically, unlike the physical recognition employed by experts when discussing the propriety of analysis results. Integrated numerical analysis systems supported by the expertise of specialists can be expected to grow, as the faculty of experts for physical recognition is connected to the facility of computers for numerical analysis. The integrated numerical analysis system stated above requires the following functions:

(1) Ability to constitute such a computation model which can prescribe, execute and control the numerical calculation desired according to the mechanical and geometrical constraints and properties of the structure under consideration.

(2) Ability to recognize autonomously the relationship between the analysis results obtained by the computation model thus constituted and the engineering judgement of experts on the mechanical behavior of the structure in the similar manner and notion for recognition as of experts.

(3) Ability to properly execute numerical calculation based on the computational model so that

* Received 25th October, 1989, Paper No. 88-1012B

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experts can evaluate the analysis results adequately through a man-machine interface.

An attempt is made in this study to constitute a structural analysis consultation system using a physical model to realize the second requirement above. The physical model in this study follows the concept proposed by Fenves⁽²⁾, and is used to predict the response of the model qualitatively when analyzing mechanical structures. The consultation system is described in Prolog language and implemented on a personal computer PC-9801 VX 2. The consultation system consists of knowledge bases to collect fundamental knowledge of structural mechanics employed in structural analysis, the inference engine to solve problems autonomously by virtue of the knowledge bases and a symbolic processor provided to manipulate equations and formulae appearing in the inference process. The system is not complete at present, being still in the early stages of development. The scope of the physical model is confined to the problems of beams and plates due to the limitation in memory capacity of the computer used. The consultation system is able to define the configuration of structures including continuous beams in the frame of the small displacement theory of elasticity and to predict responses of the structure qualitatively by formulae. This paper shows that a knowledge of structural mechanics can be extracted from the consultation system with respect to the mechanical behavior of straight beams to verify the validity of the system constitution.

2. Knowledge and Inference in this Study

2.1 Knowledge representation using physical model

Program packages coded in the context of the finite-element method output the analysis results automatically in the form of numerals and graphics according to the element division and input such as the structural shape and boundary conditions. It is difficult however for the program itself to interpret the analysis results in conjunction with the physical properties of the structure, to alter the numerical model for the purpose of improving the analysis accuracy and to change the design of the structure for better performance. The basis of such intelligent treatment as physical interpretation and design change can be said to be the knowledge that represents a real structure by the physical model and carries out the analysis of the physical model. In many cases, the physical model means an assembly of the structure components whose shape is simplified and whose characteristics are expressed by formulae. The formulae of structural mechanics are the expression

of the mechanical and geometrical properties of fundamental structure component models in the form of equations. For instance, shearing strain γ is defined as

$$\gamma = \lambda/D$$

with respect to the shear λ for infinitesimal distance D . Experts memorize such a formula not as an equation but as a relationship between the parameters, hardly perceiving the importance of the formula expression. Such knowledge must first be accumulated for the consultation system.

2.2 Inference by means of physical model

The inference using the physical model indicates such a process that a particular relationship between the parameters is obtained as desired after forming and testing successively a connecting link between the parameters according to the properties of the physical model used. In this study, the inference is processed by transforming the formula that expresses the properties of the physical model according to the function of the parameters. The process enables the consultation system to infer cooperatively the solution of the problems posed by engineers so that the engineers can grasp the responses of the structure qualitatively.

2.3 Knowledge of structure components

The physical model expressing the properties of the structure is taken as one of the fundamental structure components such as straight beam, rectangular plate and circular plate. The knowledge of mechanical and geometrical properties of the components can basically be given in the form of differential equations. The consultation system expresses the knowledge through the frame model and formulae. Complicated structures are represented by the physical model generated by combining the structure components.

3. Knowledge Base System EXSTRA

The consultation system constituted in this study is called EXSTRA hereafter, an abbreviation of EXpert system for STRuctural Analysis. The knowledge of the geometrical properties of the structure components is described by the frame model and employed as the structure-domain knowledge base. The inference is due to the message communication between the frames. The knowledge of mechanical properties of the structure components is given in the form of differential equations and formulae and is employed as the analysis knowledge base. The inference is carried out by successive connection and transformation of the parameters in the equations and formulae. The inference engines in the two knowledge bases can call each other, and a symbolic processor is added to deal with symbolic manipulation of equations. The EXSTRA system is shown in Fig. 1. The

contents are described in the following.

3.1 Structure-domain knowledge base and inference engine

The structure-domain knowledge base is expressed by the frame model in EXSTRA. A property of the structure components is assigned in a frame. A frame consists of multiple slots. When a property is expressed in detail by low-ranking properties, they are described in the slots of the frame. The inference is carried out by repeating the mutual communication of messages between the frames until a solution to the problem posed is obtained. In case the solution cannot be found within a frame, the inference is extended further by sending messages to the other frames to the search for the solution. Figure 2 is a schematic diagram of the inference by means of the message communication.

The parameters of the geometrical properties of the physical model are defined in the structure knowledge base of the frame model. The structure knowledge base contains general knowledge of such data as figures, units, vectors and coordinates in addition to the knowledge of beams and plates. Not only such items that are given in industrial standards and handbooks, but also procedural knowledge such as the calculation of moment of inertia of area can be described in the structure knowledge base. Figure 3 shows a representation of the knowledge of a straight beam as one of the structure components.

Fig. 1 EXSTRA system

Fig. 2 Inference in structure-domain knowledge base

The domain knowledge base has the function of defining the position and boundary conditions of the structure components in the domain where the structure can exist. The position and topology of the structure can be described by the global coordinate system. Each component has the local coordinate system defined individually and is distinguished on the basis of its position and direction relative to the global coordinate system. The relationship to the other components and connecting conditions at the boundaries are described in the specified frames for points and planes in order to impose the geometrical boundary conditions. The global coordinate system is shown together with the local coordinate system in Fig. 4.

The inference engine formed for the structure-domain knowledge base has the following capabilities:

- (1) Ability to define the detailed specifications of the structure components.
- (2) Ability to respond to inference corresponding to the messages in regard to the specified structure and fundamental structure components.

The first function is equivalent to filling out the

Material

(a) Physical model of beam

(b) Hierarchical representation of beam knowledge

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kb_s(structural classification,[beam (B),
[[principal axis(coordinate,X),end],
[line axis(line,C),end],
[material(material,M),end]]).
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(c) Representation of beam by knowledge base

Fig. 3 Knowledge of beam

blanks in the specification format of the structure with actual parameters in order to describe the specifications of the structure. The latter function is equivalent to the extraction of required data by the designer at the time of structural analysis from the data base in which the specification format is input. The messages stand for the question in regard to the physical model. In EXSTRA, when such a question as the value of Young's modulus along the principal axis of a straight beam A or the value of the moment of inertia of area of a straight beam B is inquired in the format similar to Japanese language, the inference engine outputs the answer retrieved from the structure-domain knowledge base.

3.2 Analysis knowledge base and inference engine

The analysis knowledge base is made to provide the knowledge of the governing equations that express the mechanical properties of the fundamental structure components, various formulae of structural mechanics and the conditions demanded at the time of their application. The inference engine carries out the analysis until the parameters and conditions inquired by the question are satisfied by using the knowledge stored in the analysis knowledge base. The following rules are provided so that the governing equations and formulae (called equations in general hereafter) can be expressed in as similar a format with symbolic or numerical expression as possible and can be processed easily by the inference engine of the analysis knowledge base:

- (1) The equations are to be solved with respect to a particular parameter, and the parameter is set as a variable on the left-hand side of the equation.
- (2) An equation is transformed into the forms in which all the parameters are solved and appear on the left-hand side
- (3) An equation number is assigned to an equation.

An example of an equation described in the analysis knowledge base is given below.

Examples:

— a formula of straight beam —

Fig. 4 Global coordinates and local coordinates

$$\sigma = My/I \quad (1.1)$$

expr([[skin stress,1], [bending moment*distance from axis, moment of inertia of area]], [1,1])

— an equation of beam deflection —

$$V = F(L^3/2 - 3L^2x + x^3)/6EI \quad (14.1)$$

expr([[[deflection, 1], [force*(L^3 + L^2*x*(-3) + x^3), moment of inertia of area * Young's modulus*6]], [14,1])

The inference engine of the analysis knowledge solves problems by employing the equations according to the imposed conditions and rules so that the prescribed analysis message (a goal to solve a certain problem, that is, what is inquired after) is satisfied. The features of the messages used in the process are as follows:

(1) The procedures to analyze the function of a particular parameter under the given conditions can be expressed.

(2) The goal can be expressed multiply so that a certain parameter can be used successively in subsequent analyses.

(3) It is possible to prescribe a format by which a particular parameter can be expressed explicitly. The basic format of the analysis message is as follows:

goal(goal variable, (condition 1, condition 2.....))

In the above, the goal indicates the name of the parameter demanded, the goal variable is the name of the variable into which the analysis result is input, and the condition fields describe the conditions imposed at the time of the analysis. Example:

Find the deflection angle (*i*) of a beam at the location of $x=L/2$ in such a format that the moment of inertia of area (*I*) is included explicitly.

.....deflection angle(*i*, ($x=L/2$, $I=I$))

The inference procedure for the problem solution takes the following path:

(1) Search is made for the equation that has the parameter expressing the analysis goal on the left-hand side.

(2) An examination is conducted to see whether all the parameters on the right-hand side of the equation satisfy the conditions given by the analysis message. Any variable which satisfies the conditions is eliminated from the conditions.

(3) As for all the parameters which fail to satisfy the conditions, the above procedure is repeated under the assumption that the parameters fit the subsequent goals.

(4) The problem is regarded as solved when all the conditions of the analysis message are satisfied.

(5) In such cases that no equations exist with

respect to a particular parameter, the selection of the preceding equation is judged to be wrong, and backtracking is carried out to select the other equations.

(6) The answer is obtained by substituting the conditions of the analysis message into the equation retrieved.

(7) In such cases that the goal is expressed multiply, both the conditions of the analysis message used in the preceding states and the parameters which express the goal at the state are added to the conditions of the analysis message for the subsequent states.

Figure 5 depicts the procedure of the inference by EXSTRA for the problem to express the bending skin stress of a beam b in width and h in depth as the function of a position x .

4. Symbolic Processor SYMPRO

The symbolic processor to be used in the consultation system needs the ability to manipulate numerical expression in terms of symbols algebraically and to support the input and output by means of files and graphic output. Easy access to various procedures and packaging of particular procedures are needed for the processor in order to carry out multiform procedures in the system. The software for symbolic manipulation now on the market such as MACSYMA, REDUCE and muMATH hardly are able to satisfy the above requirements. Thus a symbolic processor is made on trial to meet the necessities of symbolic manipulation in the consultation system. The symbolic processor is called SYMPRO hereafter.

The functions installed in SYMPRO are the four fundamental rules of arithmetic and expansion of equations written by use of symbols, finding of common factors in equations, transformation and differentiation and definite integrals of some simple equations, reduction of a fraction to the lowest terms, separation and replacement of variables, solution of small-sized simultaneous linear equations and solution of boundary value problems of several simultane-

Fig. 5 Inference process of equation

ous differential equations.

The expression of equations in SYMPRO is given below.

expr([[[left-hand numerator, left-hand denominator],
[right-hand numerator, right-hand denominator],...,equation number]]).

Example ; $\gamma = \lambda/D \cdots \cdots \text{expr}([[[\gamma, 1], [\lambda, L]], \text{ex} - 1)$.

5. Analysis of Beams by EXSTRA

Three examples of the analysis by EXSTRA are described in this section. The structure components in the examples are processed by 25 frames and the equations are dealt with by 30 numerical expressions.

1) Find the bending moment and deflection of the cantilever beam as shown in the upper part of Fig. 6.

The procedure of how the answer is obtained is shown in the lower part of Fig. 6.

2) Find the characteristics of the bending moment in a straight beam deflected so that the neutral axis has a constant radius of curvature.

Find bending moment (M) for constant curvature R
analysis message : bending moment

(M , [curvature= R])

knowledge bending moment = I -moment of inertia of area*stress/distance from axis
.....1

knowledge stress = Young's modulus*distance from axis/curvature2

BOUNDARY CONDITION :

w1 = 0
w2 = 0
f1 - f2 + fg = 0, []
m2 = 0, [x2 = L]
m1 = m2, [x1 = L, x2 = 0]
i1 = 0, [x1 = 0]
i1 = i2, [x1 = L, x2 = 0]
v1 = 0, [x1 = 0]
v2 = 0, [x2 = 0]
v1 = v2, [x1 = L, x2 = 0]

w1 = 0 -[ex_1-[c(1),1]]
f1 = $\frac{fg*3}{-5}$ -[ex_1-[c(1),2]]
m1 = $\frac{fg*(L+x1*-3)}{5}$ -[ex_1-[c(1),3]]
i1 = $\frac{fg*x1*(L*-2+x1*3)}{e*i*10}$ -[ex_1-[c(1),4]]
v1 = $\frac{fg*x1^2*(L+x1*-1)}{e*i*10}$ -[ex_1-[c(1),5]]

Fig. 6 Inquiry of bending moment in beam

answer bending moment = I -moment of inertia
of area*Young's modulus/ R

bending moment is
proportional to Young's modulus
proportional to moment of inertia
inversely
proportional to R

3) Design the width of the beam of question 1 so
that the bending skin stress takes a constant value,
and find the width at $x=L/2$.

Find beam breadth (b) under conditions of
stress=constant, distance from axis=depth/2, x
= $L/2$

analysis message : breadth(b , [stress=constant
stress, distance from axis
=depth/2, $x=L/2$])

knowledge I -moment of inertia=bending moment
*distance from axis/stress1

knowledge bending moment=force* $x/1$ 12

answer breadth= $1*force*3/constant$ stress**
(depth,2)

breadth is
proportional to force
proportional to beam length
inversely proportional to half-depth
proportional to constant stress

6. Conclusions

A consultation system is developed in this study
to predict the responses of structures qualitatively on
the basis of a knowledge that interprets the behavior
of structures according to the corresponding physical
model. In the consultation system, the geometrical
properties of the physical model are expressed by the
frame model, and the mechanical properties are de-
scribed by equations. The process of solving problems
is regarded as the transition process of chain applica-
tion of equations to the goal state. EXSTRA and
SYMPRO systems are constructed to realize the tran-
sition process in the inference engine. The analysis
goal is expressed by the format of the analysis mes-
sages so that various conditions required to obtain the
answer can be imposed definitely. The findings and
result of the study are concluded as follows :

(1) It is possible to constitute systems with simi-
lar abilities to recognize actual structures like experts
by means of the inference due to the combined knowl-
edge of the geometrical properties and mechanical
properties of the physical model (fundamental struc-
ture components).

(2) It is confirmed that well-posed problems can
be evaluated and answered qualitatively by chain

application of knowledge representation in the form
of equations. This implies the importance of the sym-
bolic representation of knowledge and indicates the
usefulness of the symbolic processor in expert systems.

(3) Fundamental structure components are cho-
sen as the physical model in this study. The notion of
elements in the finite- element method is similar to
that of the physical model in consultation systems.
This implies that the methodology examined in this
study can be applied to consultation systems for finite
element analysis.

(4) This study shows that some simple problems
of elastic beams can be answered autonomously only
by the knowledge described in the system. This sug-
gests that an autonomous and integrated numerical
analysis system can be formed which can support
specialists of structural analysis.

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