STRUCTURAL ANALYSIS CONSULTATION

USING ARTIFICIAL INTELLIGENCE*

R. J. Melosh and P. V. Marcal
MARC Analysis Research Corporation

Les Berke
Flight Dynamics Laboratory, Wright Patterson Air Force Base

ABSTRACT

This presentation reports on implementation of engineering consulting for structural analysis using the concepts of artificial intelligence. It describes a knowledge base for the consultation and illustrates the use in sample engineering problems.

The primary goal of consultation is definition of the best strategy to deal with a structural engineering analysis objective. The knowledge base to meet the need is designed to identify the type of numerical analysis, the needed modeling detail, and specific analysis data required. Decisions are constructed on the basis of the data in the knowledge base - material behavior, relations between geometry and structural behavior, measures of the importance of time and temperature changes - and user supplied specifics - characteristics of the spectrum of analysis types, the relation between accuracy and model detail on the structure, its mechanical loadings, and its temperature states.

Existing software demonstrates the feasibility of the approach, encompassing the 36 analysis classes spanning nonlinear, temperature affected, incremental analyses which track the behavior of structural systems. It provides consultation, in an interactive environment, which can identify an effective analysis strategy in consultation times ranging from two to twenty minutes.

INTRODUCTION

The choice of the analysis strategy to use in computer simulation of a structural-mechanical system is important and difficult. The choice is important because it can affect required human and computer resources for engineering by an order of magnitude. The choice is difficult because there are a wide variety of analysis strategies and tactics.

*This research was sponsored by the Advanced Research Project Agency in conjunction with the Flight Dynamics Laboratory of Wright-Patterson AFB, Dayton, Ohio. Work was performed in cooperation with Bob Englemore, Lew Creary, and Jim Bennett of the Stanford Heuristic Programming Laboratory.

The concepts of artificial intelligence which encompass knowledge-based consultation (heuristic programming) offer a basis for automating the decision process. The central idea is to imbed the knowledge needed for the decision in a data base which can be particularized and manipulated during a user-computer interchange. In this "consultation", the computer system plays the role of consultant.

Heuristic programming can be based on a production rule system. Here the data base is made up of a collection of rules. Each of the rules describes some aspect of the knowledge of the "world" being considered. The rules are stated as a number of premises followed by conclusions. This results in an open system where the connectivity between the rules is implied and sought out by the program logic.

The consultation proceeds from rule to rule. At each rule every premise is resolved by means of previously accumulated consultation data or by questions to the user.

The approach has been used successfully in a number of disciplines. Feigenbaum, Buchanan, and Lederberg [1] describe a chemical spectrometry consultant. In this case the software leads to evaluating the chemical nature of a substance working from mass and nuclear spectrometry input. Shortliffe [2] describes a bacterial infectious consultant, MYCIN. This software addresses diagnosing infections based on patient data and prescribing treatments with the best prospects of success for the patient.

This paper describes an implementation of the concepts for selecting analysis strategy and tactics using a general purpose computer program like MARC [3]. It characterizes the knowledge base used for consultations and illustrates use of the base in a consultation.

STRUCTURAL MECHANICS CONSULTATION

The Mathematical Model

In order to provide the flexibility to take into account different behavior patterns in different portions of the structure, the model data is thought of as a number of substructures or regions. The behavior pattern may be estimated by using either a simple model or by direct questions to the user. For this reason the substructure is not restricted to a particular area of a structure but may overlay with other substructures.

In this pilot project we have provided simple models which depend on formulas and we require that the burden of describing the substructure data be placed on the user. It is, however, easy to visualize a scenario in which an increasing number of rules are added until a stage is reached where the consultant takes over most of the job of model idealization.

The consultant asks for data defining the material, general geometry, and boundary conditions for each substructure. It uses these data and its mathematical models to estimate stresses and deflections for the substructure. The behavior of the complete structure is determined as the peak relative stress and deflection behavior of all the substructures. Based on these peak responses, knowledge of the available analysis strategies, and user defined analysis requirements, the consultant recommends an analysis approach.

The substructure is a geometrically contiguous region of the structure composed of a unique material and with a unique set of kinematical boundary conditions. With this definition, the user can reduce his structure to substructures in a number of ways with the objective of insuring that he represents the most aggravated stress and displacement conditions.

Figure 1 illustrates some of these possibilities. Figure 1(a) depicts the conventional substructure concept of finite element analysis. Here the structure is divided into nonoverlapping regions. Every part of the structure falls into a substructure or onto a boundary shared by substructures. Figure 1(b) shows substructuring using overlapping substructures and exclusion of parts of the structure from a substructure. Figure 1(c) illustrates a decomposition into two particular parts of the structure to permit selecting the peak responses from two different models of the substructure's kinematic boundary conditions.

The engineer indicates the overall geometry and kinematic boundary conditions of an envelope model of the substructure. He describes geometry by defining the length, width, and (indirectly) depth of a rectangular prism which can just enclose the substructure. He indicates edges of the prism, which are supported either by adjacent substructures or external restraints. The engineer synthesizes the total loading for a substructure from one or more loadings. He constructs a loading from a number of point and/or distributed loading components.

Using this data, the consultant models the substructure as either a network or a continuum. Network models imply beamlike behavior. Continuum models imply platelike behavior. The cross section of a substructure may be treated as solid or thin-walled. In a solid section, all the material in the section resists loading. In a thin-walled section, that part of the material resisting loading is centered near the boundaries. A solid bar and a hollow tube illustrates the solid and thin-walled section, respectively.

Table 1 defines some of the formulas used for the plate model. These formulas estimate peak stresses and relative deflection considering the number of edges supported, the geometry of the panel, the material stiffness, the form of the cross section and the location and magnitude of loadings.

Figure 2 shows the relationship of the parts of the structural model. The stresses and deflections due to each loading component are added to determine stresses and deflection bounds for a particular loading. Behavior of loadings is combined assuming that each loading is statistically independent to arrive at limiting response estimates for each substructure. The analysis strategy is then determined by considering the most severe stress state and deflection change for any of the substructures of the structure.

Consultation Knowledge Base

The existing knowledge base provides for selecting one of 36 analysis strategies. These encompass nonlinear analysis of structures whose equilibrium equations are time independent and imply that the structure is fabricated and loaded at room temperature (21 C). If nonlinear analysis is not a constructive conclusion, the consultation recommends linear analysis.

Table 2 names the specific analysis strategies distinguished in the knowledge base. Distinction allows the user to consider substructures to be formed of any one of eight materials (three grades of aluminum, three of steel and two of concrete). Each substructure may be approximated by one of three construction models, have one of four support conditions, and be loaded by any number of distributed and/or point loads using any number of loading components to represent a loading.

The knowledge base consists of about 170 rules. These lead to valuing up to 140 consultation parameters. Using this data base, a typical consultaton (2 substructures, 3 loadings, 2 load components) requires about 25 minutes at an interactive terminal.

Table 3 defines the principal parameters of the consultation and their relation to the context tree. Valuing these parameters leads to values for the primary solution strategy variables:

Type of nonlinearity:	Geometric, material, both, boundary nonlinearity, geometric and boundary, material and boundary, all.
Itegrity goal:	Behavior, stability, both.
Integrity concern:	Local (stress exceedance, cracking...), global (deflection exceedance, stiffness degradation...).
Loading Type:	Cyclic, noncyclic.

Other parameters of the knowledge base define consultation interpretations for mathematical operations associated with the anatomical model.

A typical rule used in the consultation is given below. A rule consists of one or more if statements followed by one or more conclusions. The rule shown illustrates how considerations of accuracy, stress, and number of loading cycles interact with known data in determining the types of behavior which will justify analysis.

Typical Consultation Rule

- If the material is high strength steel
- If substructure non-dimensional stress is greater than .7
- If required analysis accuracy is less than 30 percent
- If number of cycles of loading is less than 10,000
- Conclude fatigue is a problem for the substructure

COMPUTER PROGRAM LOGIC

A computer program directs the manipulation of the rules and the engineer-consultant dialogue. The rule manipulation is sequenced to fulfill the consultation goal rule which requires that all data needed by the rules be accumulated before an opinion is offered. Through the dialogue, the consultant obtains data from the engineer whenever previously supplied user data or rule conclusions are unavailable.

The dialogue also permits the engineer to interrogate the consultant. The engineer can prompt an explanation of why a particular piece of data is required, how a particular conclusion was reached, and what rules and conclusions are available. Thus he can determine whether the knowledge base is appropriate for the particular problem in mind.

The principal tasks implemented by the computer code are as follows:

1. Determine areas of interest by keywords.

2. Find a rule with a conclusion pertaining to the keyword of interest.

3. Initiate processing of this rule:

   A. Process the next premise. If the premise is negative, terminate processing of rule and return to 2. If all premises have been processed, store the conclusion and proceed to 4.

   B. Check if this premise can be processed by using data and conclusions acquired from previous rules. If yes, conclude the processing of premise and return to A. If no, proceed to C.

   C. Ask for the required data from the user and return to A. If no, return to process another keyword. If all rules pertaining to the keyword have been processed, proceed to 5.

4. Print out conclusions of the consultation.

The following additional optional tasks may be requested by the user:

5. Develop an explanation of the reason for any question being asked by the consultant. (This requires particular printing of information on the current argument context and the particular rule being exercised.)

6. Explain how a particular conclusion was reached. (This requires reviewing the history of the consultation with respect to rules used in arriving at the conclusion.)

7. Detail what keywords are handled by the program. (This requires scanning and printing of conclusions in the knowledge base.)

8. Detail each rule. (This requires printing each rule when it has been fully exercised so the engineer can appraise the logic with respect to his problem.)

9. Allow an expert in the technical area, who knows little about the coding of the program, to enter and/or change rules in the course of building experience with the program.

ILLUSTRATIVE CONSULTATION

The following provides the computer printout for a consultation.

The program asks preliminary questions about the total structure. These cause the engineer to particularize his analysis goals and insure that his problem falls within the consultant's ken.

It is then followed by the interchange involved while the analyst described the loadings and three load components to be considered for each of the two substructures of the total structure.

The last paragraph shows the interchange as the consultation is completed. The exchange is terminated when the analyst indicates all substructures have been treated. The answering remarks define the analysis classification and special analysis tactics that should be used.

<SCP>TYPESCRIPT.511   Fri 10-Mar-78 7:34AM

March 10, 1978 7:31AM in <SCP>MARC.SAV:9
Loading <SCP>STRUCTURE.511...

10-Mar-78 07:31:36
Enter date and time of consultation (CR for today's date):
**

--------STRUCTURE-5--------

1) What is the name of STRUCTURE-5?

** AIRPLANE WING

2) Assuming that your characterization of airplane wing in terms of its geometry, material characteristics, and boundary conditions are accurate, how much error (in percent) is tolerable for the analysis?

** 10

3) Do you want to examine the responses of airplane wing, to evaluate its unstability, or both?

**EXAMINE-RESPONSES

4) Does airplane wing have any time dependent terms in its equations of equilibrium?

**NO

5) Is heating or cooling of interest in determining structure responses?

**NO

6) Have you decomposed airplane wing into a number of potential substructures which are relevant to this analysis?

**YES

--------SUBSTRUCTURE-1--------

7) What is the name of SUBSTRUCTURE-1?

** WING TIP

8) What is the material composing most of wing tip

(SUBSTRUCTURE-1)?

** HIGH-STRENGTH-ALUMINIUM

9) Enter the average longest dimension of wing tip (SUBSTRUCTURE-1) in inches (or <number> CMS):

** 40

10) Enter the average thickness of wing tip (SUBSTRUCTURE-1) in inches (or <number> CMS):

** 5

11) Enter the weight of wing tip (SUBSTRUCTURE-1) in pounds (or <numbers> KGS):

** 83

12) Would you describe the construction of wing tip (SUBSTRUCTURE-1) to be truss and/or frame elements (NETWORK), sheets and/or blocks of material (CONTINUUM), or a combination of both?

** CONTINUUM NETWORK

13) What is the configuration of support for wing tip (SUBSTRUCTURE-1)?

** ONE-SIDE

14) Can wing tip (SUBSTRUCTURE-1) be modelled as a one, two, or three dimensional system?

** 2

15) Is the overall geometry of wing tip (SUBSTRUCTURE-1) curved or planar?

** CURVED

The first loading applied to wing tip (SUBSTRUCTURE-1) will be called:

--------LOADING-1--------

16) What is the name of LOADING-1?

** AIR PRESSURE

17) Enter the number of loading cycles to be applied:

** 1

The first load component associated with LOADING-1 will be called:

--------LOAD-COMPONENT-1--------

18) Would you describe LOAD-COMPONENT-1 as being DISTRIBUTED over most of the substructure or as acting at a POINT of the substructure?

** DISTRIBUTED

19) Which surface of the substructure does LOAD-COMPONENT-1 act NORMAL to? (If more than one surface, you should consider the loading as two more component loadings)

** WIDTH-LENGTH

20) Enter the magnitude of the distributed load (in pounds):

** 1

21) Are there any other load components associated with LOADING-1?

** YES

--------LOAD-COMPONENT-2--------

22) Would you describe LOAD-COMPONENT-2 as being DISTRIBUTED over most of the substructure or as acting at a POINT of the substructure?

** DISTRIBUTED

23) Which surface of the SUBSTRUCTURE does LOAD-COMPONENT-2 act NORMAL to? (If more than one surface, you should consider the loading as two or more component loadings)

** WIDTH-LENGTH

24) Enter the magnitude of the distributed load (in pounds):

** .5

25) Are there any other load components associated with LOADING-1?

** NO

26) Are there any other loading conditions associated with wing tip (SUBSTRUCTURE-1)?

** YES

--------LOADING-2--------

27) What is the name of LOADING-2?

** LANDING

28) Enter the number of loading cycles to be applied:

** 300

The first load component associated with LOADING-2 will be called:

--------LOAD-COMPONENT-3--------

29) Would you describe LOAD-COMPONENT-3 as being DISTRIBUTED over most of the substructure or as acting at a POINT of the substructure?

** DISTRIBUTED

30) Which surface of the substructure does LOAD-COMPONENT-3 act normal to? (If more than one surface, you should consider the loading as two or more component loadings)

** WIDTH-LENGTH

31) Enter the magnitude of the distributed load (in pounds):

** 5

32) Are there any other load components associated with LOADING-2?

** NO

33) Are there any other loading conditions associated with wing tip (SUBSTRUCTURE-1)?

** NO

34) Are there any other substructures of airplane wing relevant to this analysis?

** YES

--------SUBSTRUCTURE-2--------

35) What is the name of SUBSTRUCTURE-2?

** ROOT

36) What is the material composing most of root (SUBSTRUCTURE-2)?

** HIGH-STRENGTH-ALUMINIUM

37) Enter the average longest dimension of root (SUBSTRUCTURE-2) in inches (or <number> CMS):

** 54

38) Enter the average thickness of root (SUBSTRUCTURE-2) in inches (<number> CMS):

** 8

39) Enter the weight of root (SUBSTRUCTURE-2) in pounds (or <numbers> KGS):

** 180

40) Would you describe the construction of root (SUBSTRUCTURE-2) to be truss and/or frame elements (NETWORK), sheets and/or blocks of material (CONTINUUM), or a combination of both?

** CONTINUUM NETWORK

41) What is the configuration of support for root (SUBSTRUCTURE-2)?

** ONE-SIDE

42) Can root (SUBSTRUCTURE-2) be modelled as a one, two, or three dimensional system?

** 3

43) Is the overall geometry of root (SUBSTRUCTURE-2) curved or planar?

** CURVED

The first loading applied to root (SUBSTRUCTURE-2) will be called:

--------LOADING-3--------

44) What is the name of LOADING-3?

** LANDING

45) Enter the number of loading cycles to be applied:

** 300

The first load component associated with LOADING-3 will be called:

** 250000

--------LOAD-COMPONENT-4--------

46) Would you describe LOAD-COMPONENT-4 as being DISTRIBUTED over most of the substructure or as acting at a POINT of the substructure?

** POINT

47) Which surface of the substructure does LOAD-COMPONENT-4 act NORMAL to? (If more than one surface, you should consider the loading as two or more component loadings)

** WIDTH-LENGTH

48) Describe where on the substructure LOAD-COMPONENT-4 is applied:

** NEAR-FREE-EDGE

49) Enter the magnitude of the point load (in psi):

** 250000

50) Are there any other load components associated with LOADING-3?

** YES

--------LOAD-COMPONENT-5--------

51) Would you describe LOAD-COMPONENT-5 as being DISTRIBUTED over most of the substructure or as acting at a POINT of the substructure?

** POINT

52) Which surface of the substructure does LOAD-COMPONENT-5 act NORMAL to? (If more than one surface, you should consider the loading as two or more component loadings)

** WIDTH-LENGTH

53) Describe where on the substructure LOAD-COMPONENT-5 is applied:

** NEAR-FREE-EDGE

54) Enter the magnitude of the point load (in psi):

** 1000

55) Are there any other load components associated with LOADING-3?

** NO

56) Are there any other loading conditions associated with root (SUBSTRUCTURE-2)?

** NO

57) Are there any other substructures of airplane wing relevant to this analysis?

** NO

58) Do the supports of airplane wing involve Coulumb friction, nonlinear springs, and/or gapping?

** NO

GC: lists
4021, 20405 FREE CELLS

The following analysis classes are relevant to the analysis of your structure:

1) General-inelastic

Logic to scan deflections, calculate relative values, and compare with code limits should be called upon.

Logic to scan stresses, smooth, and compare with allowable stresses (with appropriate safety factors) should be used.

Activate incremental stress - incremental strain analysis.

Model nonlinear stress-strain relation of the material.

Solution will be based on a mix of gradient and Newton methods.

End of Consultation.

DISCUSSION AND CONCLUSIONS

This examination of the use of heuristic programming to assist an engineer in selecting an appropriate analysis strategy leads to the following conclusions:

1. The heuristic approach includes all capabilities necessary for rationally selecting solution strategy. In particular, a preliminary analysis model can be imbedded in the rules, the analyst and consultant can address decision making substructure by substructure, and data on material and analysis characteristics can be accessed and manipulated as necessary.

2. The approach can offer valuable assistance to the structural analyst. With the implementation used, the consultant supplies expertise in a readily accessible and usable form. It interfaces with the analyst only on matters pertinent to his structure and analysis. By appropriate addition of logic it can be made to interface with the analyst over a spectrum of details pertinent to the structure, analysis procedure and model. The initial user of the program is prepared to put up with detailed questions in order to ensure that the model is correct. A proficient user will know the parts of the consultation that should be used. This method, therefore, resolves the problem in interactive computing of writing a program that can react to the knowledge level of the user.

3. The ability to query the data base and to obtain documentation on the use of the rules for consultation makes the system an efficient tool for programmed learning.

REFERENCES

[1] Feigenbaum, E. A., Buchanan, B. G. and Lederberg, J.: On Generality and Problem Solving: A Case Study Using the DENDRAL Program, Machine Intelligence, Edinburgh Univ. Press, 1971.

[2] Shortliffe, E.: Computer-based Medical Consultations: MYCIN; New York, Elsevier, 1976.

[3] MARC-CDC User Information Manual, Volumes I-IV; MARC Analysis Research Corporation, Palo Alto, California, 1978.

TABLE 1

STRESS FORMULA

Configuration	Point Load Site: Support	Point Load Site: Centroid	Dist.Load: Free	Dist.Load: Uniform
1 side $\frac{L}{W}$	$\frac{PDL}{8IeW}$	$\frac{PDL}{4IeW}$	$\frac{3PDL}{8\ W}$	$\frac{DpL}{4Ie}$
2 sides opp. $\frac{L}{W}$	$\frac{3PDL}{32IeW}$	$\frac{PDL}{8IeW}$	$\frac{DPL}{8IeW}$	$\frac{DPL}{16Ie}$

RELATIVE DEFLECTION

Configuration	Point Load Site: Support	Point Load Site: Centroid	Dist.Load: Free	Dist.Load: Uniform
1 side $\frac{L}{W}$	$\frac{PL}{48EIeW}$	$\frac{PL}{12EIeW}$	$\frac{3PL}{16EIeW}$	$\frac{pL}{24EIe}$
2 sides opp. $\frac{L}{W}$	$\frac{7PL}{192EIeW}$	$\frac{PL}{24EIeW}$	$\frac{7PL}{192EIeW}$	$\frac{5pL}{192EIe}$

*For plate, shell, and semi-monocoque structures; for multiple member networks.

"Plate" = Continuum, 2D, planar, width-length loading
"Shell" = Continuum, 2D or 3D, curved, any loading
"Semi" = Network and continuum, 2D or 3D, any loading
D = Section depth (in.)
E = Young's modulus (#/in²)

Ie = Effective inertia $-\frac{D}{12}$ for solid section, $\frac{TD}{2}$ for thin walled section (T=wall thickness)

L = Longest distance between or from support lines
P = Point load (#)
p = Distributed load magnitude, (#/in²)

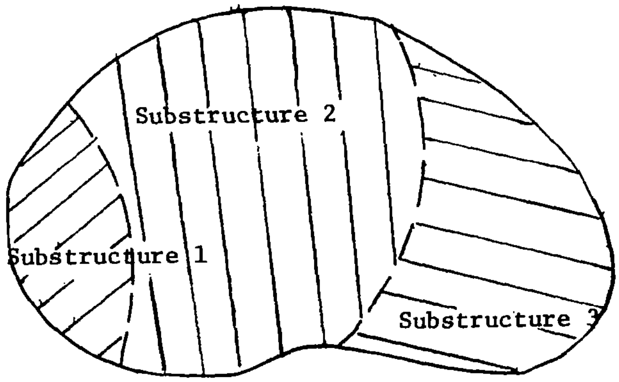
W = $\frac{Wt}{LDe}$ for solid; = $\frac{Wt}{2LTp}$ for thin walled; and WT = weight (#)

TABLE 2 ANALYSIS STRATEGIES CONSIDERED

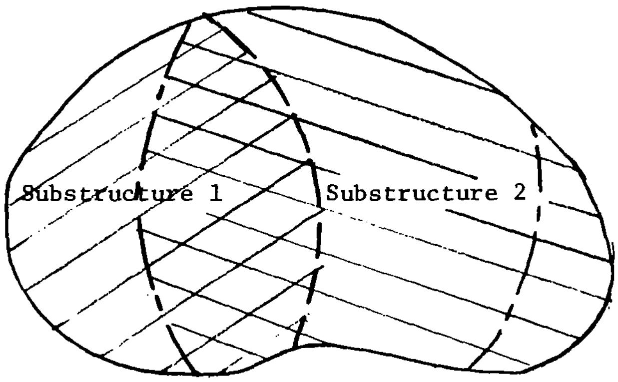
Nonlinear geometry crack growth
Nonlinear geometry stress margin
Nonlinear geometry fatigue
Buckling (extrapolation vs path)
Bifurcation
Nonlinear geometry strength
Nonlinear geometry deflections
Inelastic crack growth
Inelastic stress failure
Material Instability
Inelastic collapse
Inelastic fatigue
Inelastic strain accumulation failure
Elasto-plastic collapse (radial vs incremental)
Inelastic excessive deflection
Inelastic stiffness degradation
Inelastic strength
Inelastic deflection
Nonlinear crack growth
Nonlinear stress margin
Nonlinear material instability
Nonlinear yielding collapse
Nonlinear fatigue
Nonlinear strain accumulation
Nonlinear buckling
Nonlinear bifurcation
Nonlinear excessive deflection
Nonlinear stiffness degradation
Nonlinear strength
Nonlinear deflection
Nonlinear boundary condition
General large displacement analysis
General inelastic analysis
General nonlinear analysis

TABLE 3 PRINCIPAL CONSULTATION PARAMETERS

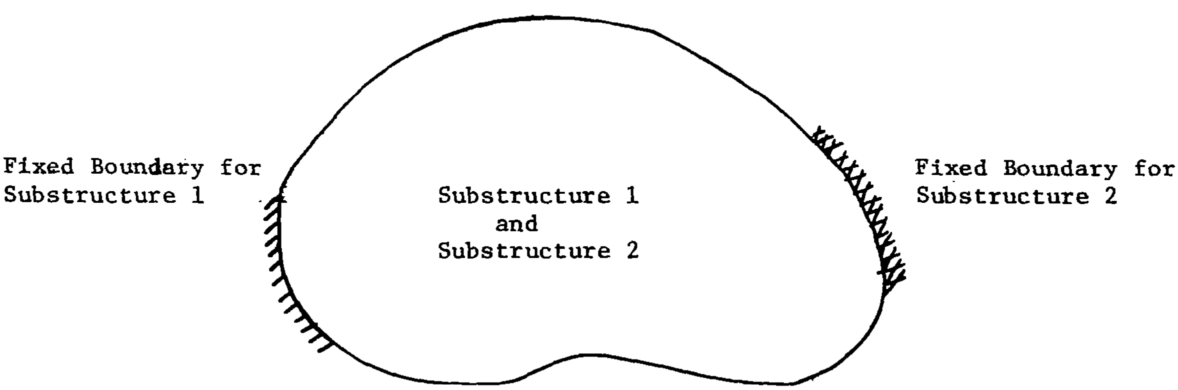
Structure	
o Name	o Maximum deflection
o Type of Nonlinearity	o Maximum stress
o Integrity goal	
o Boundary nonlinearity	
o Analysis	
Substructure	
o Name	o Skin thickness
o Material	o Shape
o Geometry	o Weight
o Construction	o Peak stress
o Support conditions	o Peak deflection
o Length	o Stress criterion
Loading	
o Name	o Stress bound
o Number of cycles	o Deflection bound
Load Component	
o Name	o Stress
o Type	o Deflection
o Direction	
o Magnitude	



(a) Conventional finite element substructures.



(b) Overlapping substructures.



(c) Dual substructuring.

Figure 1.- Illustrations of substructuring.

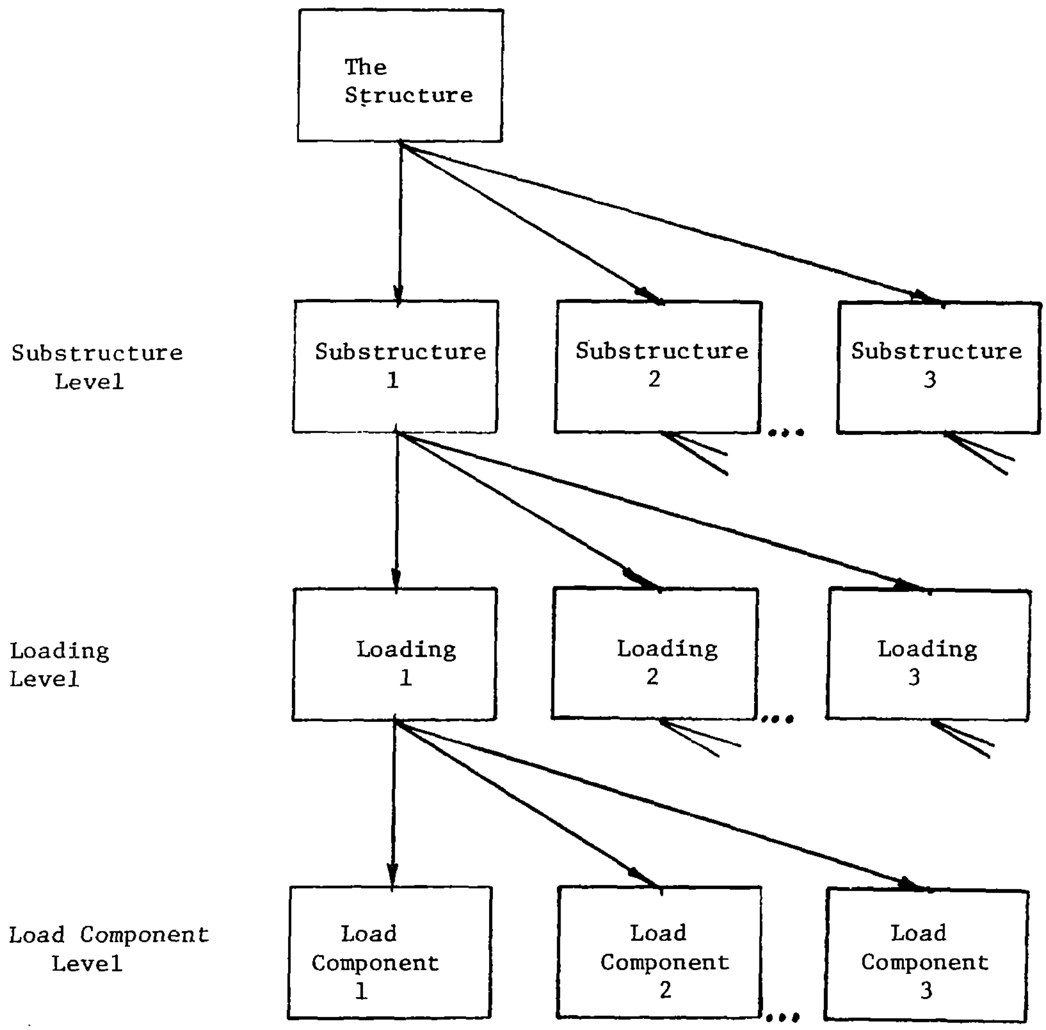


Figure 2.- Context tree.