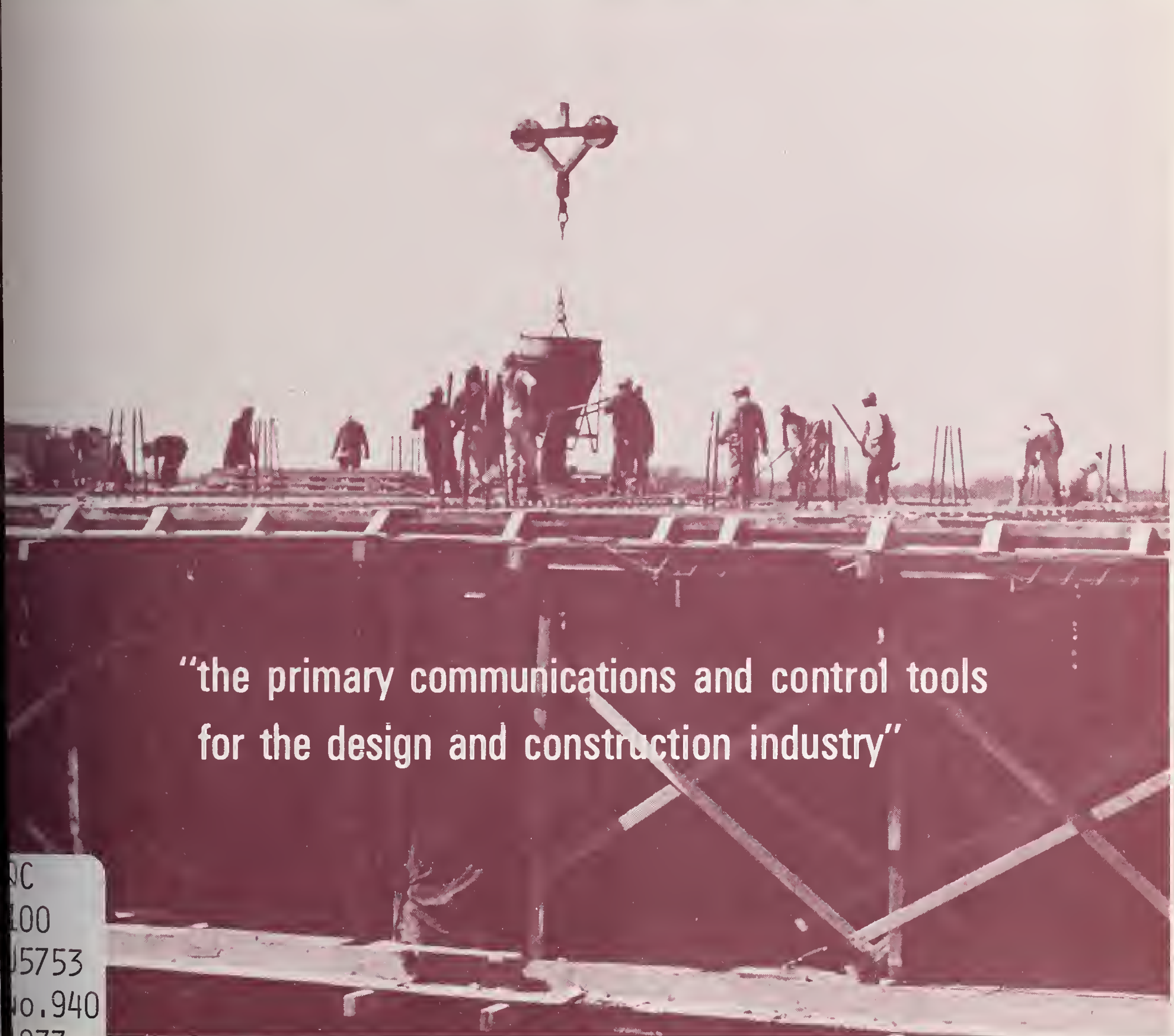
NBS TECHNICAL NOTE 940

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

The Representation and Use of Design Specifications



"the primary communications and control tools for the design and construction industry"

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The Representation and Use of Design Specifications

t. Technical Note no. 940

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THE REPRESENTATION AND USE OF DESIGN SPECIFICATIONS *

by

S. J. Fenves and R. N. Wright

Abstract

Design specifications are presented as the primary communication and control tool for the design and construction industry. Requisite properties of completeness, uniqueness and correctness are identified, and the role of performance and limit state concepts in specifying intent of the specifications are emphasized. Formal representational methods are presented at three levels: decision tables for specification provisions, an information network for related provisions, and argument trees for organizing and outlining. An idealized process for specification development is presented, and the use of the representational tools for checking specifications and providing strategies for textual expression is described and illustrated. Development of computer aids for specification processing in design and conformance checking is described.

Key words: Building codes; computer programming; decision tables; graph theory; performance specifications; standards.

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1. INTRODUCTION

We use the term design specifications to encompass all types of formal documents used for the evaluation of engineering or architectural design. These include:

- legal building codes;
- model building codes;
- consensus standards such as the ACI Building Code Requirements for Reinforced Concrete (2);[1/]
- proprietary or trade association specifications such as the AISC Specification for the Design, Fabrication and Erection of Structural Steel for Buildings (20); and
- specifications of agencies or owners, such as the U.S. Department of Housing and Urban Development Minimum Property Standards for Federal Housing Administration mortgages (10).

Our discussion specifically excludes project specifications and other specifications used in contractual relationships, and product specifications describing existing products or systems.

Design specifications are the primary communication tools and control mechanisms for the design and construction industry. They provide for effective expression of intent between owners, designers, public authorities, builders, and users of buildings. The quality of the built

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[1/] Numerals in parentheses refer to entries in the Reference.

environment, including its functionality and safety, is directly dependent on the quality of the specifications controlling its design. Ventre (21) has argued that because of the "diverse, dispersed, detached, and discontinuous" nature of the building industry, specifications, and especially their legal embodiments in building codes, represent essentially the only "collective memory" of the industry.

Design specifications represent the culmination of a broad professional concern. Generally, design specifications intend to assure the functionality of a building or system and to protect the public health, safety and welfare during construction and use. Designers and building regulatory officials use design specifications to achieve a common understanding in order to effectively control designs. Specification writers translate knowledge of the environment, structural behavior, and requirements for functionality and safety into usable requirements or practices in specification form. Most civil engineering researchers aim to improve design and construction practices; much of the output of this research is implemented through new or revised specifications. Siess (19) has described the mutual interaction and reinforcement between research, practice and specifications.

While most researchers are concerned with improving the content of specifications by basing them on more rational models of material and structural behavior, our concern is primarily with the format of specifications. It will be shown that the two aspects of content and format are closely interrelated, and that methods designed to improve their format can also yield better content.

At the present, there are no recognized formal methods for generating or reviewing proposed new specifications or modifications of existing ones. Notwithstanding the importance of design specifications to the building industry and the cost of producing them, there is no methodology, beyond informal peer review and occasional test comparisons with previous specifications, for making any quantitative evaluation of proposed specifications. Furthermore, while an increasing fraction of processing of design information against specifications is performed by computer programs, the entire responsibility for the correctness of these programs, including the selection of provisions to be included and the detailed interpretation of these provisions, rests with the computer program developers. Neither the users of these programs nor building officials required to pass judgment on their output have any ready means to ascertain that programs perform in all cases as intended by the specification writers.

We will show here that rigorous mathematical foundations exist on which efficient, formalized procedures for developing and using specifications may be built. These methods apply to three distinct processes:

- <u>formulation</u>, the development of the information content of the specification;
- <u>expression</u>, the exposition of the information content in both conventional textual form and in forms adaptable for computer processing; and
- <u>use</u>, the interpretation and application of the specification to the evaluation of designs in both manual and computer-aided processes.

Our objective is to improve engineering practices through better specifications and better methods for their use. We present the bases for a systematic approach to the formulation, expression, and use of specifications which assure three requisite properties:

- completeness, that the specification explicitly applies in any possible situation;
- uniqueness, that the specification yields one and only one result in any possible situation; and
- correctness, that the result is that intended by the specification writers.

The methods presented are suitable for both manual and computer-aided applications by specification writers, designers, and reviewers for building regulatory authorities. With slight modifications, the methods are equally applicable to three types of design specifications:

- performance specifications, which state the required attributes in a scheme-independent manner, such as the Guide Criteria for Operation BREAKTHROUGH (9);
- procedural specifications, which state required attributes and procedures for their evaluation in a scheme-dependent manner, such as the ACI and AISC specifications; and
- prescriptive specifications, which state required dimensions or properties in a manner completely defining the acceptable configurations or procedures in a scheme-dependent manner, such as the One and Two Family Dwelling Code (6).

2. BACKGROUND

The investigation of the properties of completeness and uniqueness of specification provisions is closely related to the aspect of linguistics called syntax, dealing with language organization. Correctness, on the other hand, deals with meaning and intent, and is therefore related to semantics. The formalization of the semantic aspect of specifications is aided by two powerful concepts.

First, the performance concept involves stating the attribute satisfying the needs of the users without prescribing the materials, components, or systems to be employed. J.R. Wright (22) describes the evolution of the performance concept from its apparent beginnings at the Building Research Station in the United Kingdom in the 1930's. As will be shown, performance is important for all specifications, not only performance specifications, since it gives explicit attention to the attributes the designer intends to provide.

The limit state concept is a second formalism appropriate to the semantics of specifications. As described by Allen (1), limit states describe those conditions for which systems or elements would no longer fit their intended purposes. A limit state is not synonymous with a performance attribute, since the condition may deal with a response related to the intended performance, such as cracking, but not occurring in all possible solution schemes.

Neither the performance attributes of interest nor the limit states of concern are explicitly expressed in most existing specifications. This lack of clarity has made it difficult to improve specifications through research, as there can be no certainty that a specification provision is improved if neither the response of concern nor the desired performance attribute is clearly defined.

The proper syntax or organization of the information in specifications is also vital to the transmittal of intent from writers to the users. Frequent complaints of practitioners and students alike indicate that specifications are "too complex" and "hard to follow." It will be shown that many of these valid complaints can be removed by the use of formal methods to assure that the intent of the specification writers is maintained in the textual expression.

The methods here are primarily based on the writers' cooperative efforts over a long period. In 1966, Fenves (5) identified the applicability of decision tables, a then-recent program development tool, to the representation of provisions of procedural design specifications. With Gaylord and Goel, he presented in decision table form the AISC Specification (7). Decision table formulations of other design specifications have been developed by Seeberg (18) and Noland (12).

The AISC study (7) also revealed that the information content of the specification is topologically related in a hierarchical network; this observation led to a prototype computer program for the review of designs (8). Wright, Boyer and Melin (23) recognized that the topological relationship of data provided a key to the efficient formulation and processing of constraints in computer-aided design programs. The implication of these studies on computer-aided design was summarized by Fenves (7). Fenves and Wright investigated the application of the concepts developed to the restructuring of the textual expression of the AISC Specification (24, 15). Based on this work, Nyman and Fenves (14) explored algorithms and computer aids for organizing the information content of specifications and its textual expression. The methodology has been advanced substantially in work continuing at Carnegie-Mellon University, the National Bureau of Standards, and the University of Illinois. This paper summarizes the technologies and presents the recent advances.

3. ANALYSIS OF SPECIFICATIONS

The concepts outlined in the preceding sections are best illustrated by applying them to the analysis of selected portions of the AISC Specification (20). The AISC Specification, as most specifications in use today, is an outgrowth of a long historical development started decades before the concepts of performance and limit states were introduced. Thus, a part of the analysis is to locate and identify these qualities.

3.1 DEVELOPMENT

In performance terminology, the AISC Specification deals with the entity "structure" or "structural system" and the two major attribute categories of "safety" and "serviceability." Within "safety," the environment of concern is the effect of external loads, while for "serviceability," the concern is with fitness for erection and use. To achieve these performance attributes, the design must guard against applicable limit states.

The entity "structure" must be further subdivided. A major category is that of "member," which is readily distinguished from other categories, such as "connection" and "connector," dealt with in the Specification. The entity "member," however, is still too general, in that specific limit states cannot be directly associated with it. Since limit states are related to response, it is convenient to introduce a subdivision of members by stress type, such as "tension," "compression," etc. It is to be noted that stress type is not a strict subdivision of members (at different stages of the design process, a member may be investigated for different stress types or combinations), but a common property of members which acts as a selector to associate members with the applicable limit states.

For the subdivision of "tension members," the applicable limit states under "safety" are "yielding" and "rupture," whereas under "serviceability," the AISC Commentary specifically mentions "undesirable lateral movement ("slapping" or vibration)" (4).

Finally, it is necessary to prescribe a measure which will insure satisfactory performance. In dealing with members, the AISC Specification handles the safety attribute by specifying a maximum allowable stress, and satisfies the serviceability attribute by limiting the slenderness ratio.

Thus we arrive at the two provisions of the AISC Specification dealing with tension members, reproduced verbatim from reference (3):

"1.5.1.1 Tension

On the net section, except at pin holes:

$$F_t = 0.60F_y$$

but not more than 0.5 times the minimum tensile strength of the steel.

On the net section at pin holes in eyebars, pin-connected plates or built-up members:

$$F_t = 0.45F_y."$$

"1.8.4 Maximum Ratios

The slenderness ratio, $K\ell/r$, of compression members shall not exceed 200.

The slenderness ratio, $K\ell/r$, of tension members, other than rods, preferably should not exceed:

For main members 240

For bracing and other secondary members . . . . 300."

3.2 REPRESENTATION

In this section we deal with the formal representation of specification provisions and their relations, using as examples the provisions identified above. Three representational tools are used, corresponding to three levels of abstraction of specification.

Provision Level

At the level of single provision, the technique of decision logic tables, or decision tables for short, is used. The decision table representation of Section 1.5.1 is:

Table 1. Allowable Tension Stress

At pinhole	N	Y
F_t = min. $(0.60F_y, 0.50F_{ts})$	Y	
$F_t = 0.45F_y$		Y

As can be seen, the table is divided into four sections. The upper left section, called condition stub, is a list of all Boolean conditions (in this case, the single condition "at pinhole?"). The lower left section, called action stub, is a list of all applicable actions. The upper right section, called condition entry, contains entries of Y (yes) or N (no) corresponding to the conditions, organized into vertical columns called rules. A particular rule governs if the given data (values of the Boolean conditions) match the values given in that rule of the condition entry. Finally, the lower right section, called action entry, contains entries of Y and blank indicating that the corresponding action is or is not to be executed in a given rule. The table is to be read by proceeding down within a rule and across for each succeeding rule as follows: "If not at pinhole, then F_t = min. ($0.6F_y$, $0.5F_{ts}$); if at pinhole, then $F_t = 0.45F_y$." For tables with more than one condition, it is understood that the conditions are related by the logical operator and.

Section 1.8.4 is represented by the following table:

Table 2. Slenderness Ratio Criterion

Compression member	Y	Y	N	N	N	N	N	N	E
Member a rod	I	I	Y	N	N	N	N	N	
Check for max. ratio desired	Y	Y	I	N	Y	Y	Y	Y	
Main member	I	I	I	I	Y	Y	N	N	
$K\ell/r \leq 200$	Y	N	I	I	I	I	I	N*	
$K\ell/r \leq 240$	Y*	I	I	I	Y	N	I	N*	
$K\ell/r \leq 300$	Y*	I	I	I	Y*	I	Y	N	
Section 1.8.4 satisfied	Y		Y	Y	Y		Y		
Section 1.8.4 not satisfied		Y				Y		Y	
Else action									Y

Several new symbols may be noted in the condition entry. First, a number of conditions is immaterial (I) in certain rules (e.g., the question "main member?" is immaterial for compression members). Second the symbols Y* and N* are introduced to denote implicit entries, that is, entries known to be yes or no from other conditions (e.g., if "$K\ell/r \leq 200$" is true, it implies that "$K\ell/r \leq 240$" and "$K\ell/r \leq 300$" are also true). Finally, the last column, denoted E for <u>else</u>, covers all possible combinations not matched by the other rules; the corresponding action, designated <u>else action</u>, indicates that there are combinations of conditions not covered in the provision.

The decision table corresponding to Section 1.5.3--Compressive stress is shown below:

Table 3. Allowable Compressive Stress

Main member	Y	Y	N*	N*	N*	N*	N*	N*
Bracing or secondary members	N*	N*	Y	Y	Y	Y	N*	N*
Plate girder stiffener	N*	N*	N*	N*	N*	N*	Y	N*
Web of rolled shape	N*	N*	N*	N*	N*	N*	N*	Y
$K\ell/r \leq C_c$	Y	N	Y	N	Y	N	I	I
$\ell/r \leq 120$	I	I	Y	Y	N	N	I	I
F_a by Eq. 1.5-1	Y		Y					
F_a by Eq. 1.5-2		Y		Y				
F_{as} by Eqs. 1.5-1, 1.5-3					Y			
F_{as} by Eqs. 1.5-2, 1.5-3						Y		
$F_a = 0.60F_y$							Y	
$F_a = 0.75F_y$								Y

The first four conditions are mutually exclusive, that is, a compression member can only be one of the four types covered in the provision; thus, in every rule, only one of the first four entries is yes, the other three being implicit no's.

Each table generates only one item of data, which can be a numeric value, such as F_t, or a Boolean datum, such as "Section 1.5.1 satisfied." This restriction to a single output, absent from our early work (7), is necessary for the proper interaction with the information network to be discussed. The result generated in one table can be used in conditions of other, higher-level tables:

Table 4. Stress Criterion for Tension Member

$f_t \leq F_t$	Y	N
Section 1.5.1.1 satisfied	Y	
Section 1.5.1.1 not satisfied		Y

Here, a single value of F_t is used, regardless of which rule of Table 1 generated it. Finally, all provisions for a tension member can be combined in one table.

Table 5. Conformance Criteria for Tension Member

Section 1.5.1.1 satisfied and Section 1.8.4 satisfied	Y	N
Tension member conforms	Y	
Tension member does not conform		Y

In this table, a compound condition is used to indicate that both the stress and maximum slenderness ratio criteria must be satisfied for the member to be acceptable.

Information Network

At the next level of representation, we are concerned with the information flow between related provisions, specifically, the manner in which data generated or defined in one provision are used in other provisions in order to represent the hierarchical sequences of definitions, computations and tests comprising the specification.

The logical relations between items of data are described by two relationships, that of ingredience and dependence. The ingredients of an item are all data items needed to evaluate that item. Referring to Table 1, the ingredients of F_t are: F_y, F_{ts} and the Boolean variable "at pinhole." Conversely, the dependents of an item are all data items which are a function of the data item in question.

A convenient representational tool for these interrelations is a directed graph or information network, obtained by assigning a node to each data item and assigning a directed branch from the data node to each of its dependents. Since, as discussed earlier, each decision table produces only one data item, it is not necessary to distinguish in the graph between nodes generated by a formula or by a decision table.

A somewhat condensed information network for the three provisions discussed above is shown in figure 1. More detailed networks, which include the intermediate computations and tests within a provision, are given in (13). Larger networks, including the global network of an entire specification, can be built up from subnetworks, or, more precisely, from the ingredients or dependents of the individual data items. As an illustration, the network for tension and compression member criteria is sketched in figure 2. The sketch is intended to illustrate that the effective length factor, K, taken as a simple ingredient in figure 1, is in fact, the terminal node of a subnetwork, and that the evaluation of the members also requires computation of the actual stresses f_t and f_a, involving definitions of net and gross areas, and the like, and checking of Section 1.9 for limiting proportions of column elements. The subnetworks indicated by dashed lines intersect the network shown in figure 1., i.e., share some of their ingredients.

Organizational Level

Finally, at the topmost level of representation, our concern is with identifying keywords or arguments which concisely describe the scope or range of applicability of a provision, and their interrelationships, which may be used to organize or outline the entire specification. These arguments can be represented as hierarchically structured argument trees. Figure 3a represents the segment of the attribute tree for the physical component descriptions encountered in the AISC Specification provisions discussed above. It is to be noted that a member may have only one attribute at any one level (e.g., a member is either "main" or "secondary"), but it may have attributes from several levels.

3.3 ANALYSIS

Analysis for the three requisites of uniqueness, correctness and completeness can be carried out at each of the three levels discussed above. Furthermore, the analysis deals both with syntax, that is, "how to do it?", and with semantics, that is, the "why?" for each provision, group of provisions, or the entire specification.

Provision Level

Decision tables lend themselves directly to syntactic analysis for uniqueness and completeness. Because the condition entry is a matrix of Boolean variables, formal tests for uniqueness (lack of redundancy or contradiction) and completeness are available (17). For example, analysis of Table 2 shows that it is incomplete, in that it contains no rules for which condition 1 ("compression member") is yes and condition 3 ("check for maximum ratio desired") is no. However, a review of the Specification and Commentary indicates that the table is functionally complete since the limitation of $K\ell/r \leq 200$ is mandatory, and not optional as for tension members.

From a semantic standpoint, a major shortcoming of the present AISC Specification is, as discussed before, the absence of explicit reference to performance attributes and applicable limit states. Provisions for tension members could, for example, be restructured according to the decision table shown below, with appropriate measures identified for the controlling limit states:

Table 6. Conformance Criteria for Tension Member (modified)

Stress concentration present	N	N	Y	Y
Yield criterion_1 satisfied and Rupture criterion satisfied and Slenderness criterion satisfied	Y	N	I	I
Yield criterion_2 satisfied	I	I	Y	N
Tension member conforms	Y		Y	
Tension member does not conform		Y		Y

Information Network

At the information network level, the directed graph can again be used for syntactic analysis. In particular, for completeness and uniqueness, the graph must be:

- connected, that is, there can be no data items which are not ingredients or dependents of other items; and
- acyclic, that is, there can be no closed directed paths in the network, as this would imply either circular definitions or iterative computations.

These two properties can be ascertained by standard network traversal algorithms. The information network cannot be formally analyzed for correctness and semantics. As will be shown in Section 5.2, a major source of incorrect interpretation arises from the textual expression of the network.

Organizational Level

At the organizational level, the directed tree of arguments is again well suited for analyzing completeness and uniqueness, which require that at each level the arguments be:

- exhaustive, that is, cover all possibilities[2/]; and
- mutually exclusive, that is, a given element should match only one argument.

In order to properly address the semantics of the specification, the argument tree of physical component descriptions must be complemented by a second, independent argument tree of performance attribute and limit state descriptors, as shown in figure 3b. Each of the criteria can then be uniquely identified by the applicable entries from the two argument trees, as illustrated in Table 7.

[2/] In figure 3, dashed horizontal branches are used to indicate that the arguments shown do not constitute an exhaustive set.

Table 7. Classification of AISC Criteria

	PHYSICAL ENTITY											PERFORMANCE ATTRIBUTE/LIMIT STATE										
CRITERION	Tension	Compression	Main	Secondary	Rod	Eyebar	Pinhole	Plate Girder	Stiffners	Rolled Edge	Web	Safety	Rupture	Yield	Stress Concentration	Instability	Inelastic	Elastic	Local	Serviceability	Vibration	MEASURE
1.	✓													✓								$f_t \leq 0.6F_y$
2.	✓												✓									$f_t \leq 0.5F_{ts}$
3.	✓		✓																		✓	$K\ell/r \leq 240$
4.	✓			✓																	✓	$K\ell/r \leq 300$
5.	✓				✓																✓	no requirement
6.	✓						✓							✓								$f_t \leq 0.45F_y$
7.		✓	✓														✓					$f_a \leq$ by Eq. 1.5-1
8.		✓	✓															✓				$f_a \leq$ by Eq. 1.5-2
9.		✓		✓													✓					$f_a \leq$ by Eqs. 1.5-1, 1.5-3
10.		✓		✓														✓				$f_a \leq$ by Eqs. 1.5-2, 1.5-3
11.		✓																	✓			limitations of Section 1.9
12.		✓																			✓	$K\ell/r \leq 200$
13.		✓							✓								✓					$f_a \leq 0.75F_y$
14.		✓									✓						✓					$f_a \leq 0.75F_y$

4. NETWORK REPRESENTATION OF SPECIFICATIONS

In this section, the representational tools discussed in Section 3.2 in connection with a segment of a specific specification are formally summarized.

Provision Level

The logical content of a specification provision is represented by a decision table. The decision table, in turn, can be converted to a decision tree, which is a graph having the following properties:

- there is a single entry node with one exit branch;
- all intermediate nodes have one entering branch and two exit branches, corresponding to the two outcomes (yes or no) of the condition represented by the node; and
- terminal nodes have one entering branch and no exit branches, and correspond to the rules of the decision table.

Each decision table produces one data item, the rules only identifying alternate methods or formulae for deriving the item. A degenerate decision table is a function, containing no conditions and represented by a single node. A decision tree representation of Table 2 is shown in figure 4. As discussed in Section 3.3, there is a terminal node corresponding to the else rule. As can be seen from the figure, the decision tree resembles a conventional flow diagram, and is thus familiar to programmers. On the other hand, a decision tree always implies a specific sequence of testing the conditions, whereas the table is independent of sequence. The use of alternate sequences for different textual expressions is discussed in Section 5.2.

Information Network

The hierarchical interrelationship among data items appearing in a specification can be represented by two sets of compact lists, the ingredience and dependence lists. Formally, for each data item d_i, the ingredience list:

$$I(d_i) = \{d_k, d_l, \ldots, d_m\}$$

is the list of data items directly entering into the determination of d_i. Conversely, the dependence list:

$$D(d_i) = \{d_p, d_q, \ldots, d_r\}$$

is the list of data items which directly depend on d_i, i.e., for which d_i is an ingredient. These lists can be represented in graph or network form by assigning a node to each datum and a branch from each datum to all elements of its dependence lists. Global dependents of a datum can be traced out by traversing the network from the datum in question to all nodes reachable in the direction of the branches. Global ingredients of a datum can be similarly located by traversing the network in the direction opposite to that of the branches. Data items having no ingredients are basic parameters which must be independently defined for the written expression of the specification or input directly for computer processing. Data items having no dependents are the criteria which must be evaluated to ascertain conformance with the specification.

Organizational Level

Finally, for organizing, outlining, and indexing purposes, a number of descriptors or arguments is associated with each criterion. The arguments form argument trees, representing the logical subdivisions of the organizational bases. In every specification, there are at least two disjoint argument trees, corresponding to the subdivisions of the physical entities addressed and the performance attributes sought, respectively, as illustrated in figure 3. Additional argument trees may be introduced where provisions deal with certain common properties which do not strictly correspond to physical subdivisions or performance attributes. Formally, for each criterion, the argument list:

$$A(d_i) = \{a_k, a_l, \ldots, a_m\}$$

is the list of all arguments applicable to the criterion. The list contains only the terminal argument from each attribute tree applicable to the criterion; the path to that argument from the root of the tree is uniquely determined by the requirement that arguments have unique names. Conversely, for each argument, a_k, the scope list:

$$S(a_k) = \{d_i, d_j, \ldots, d_o\}$$

is the list of all criteria for which the argument appears. Table 7, read row-wise, represents the argument sets of the 14 criteria shown; read columnwise, it represents the scope list of each terminal argument.

5. SYNTHESIS OF SPECIFICATIONS

In synthesizing or developing a new design specification, many concurrent activities of groups of professionals occur. Generally, it is not possible to completely separate the contents of the proposed specification from its format, nor can one clearly distinguish the activities of generating the information base of the specification and of writing the text expressing this information. The development process is frequently iterative, where new concepts, even the need for new research, emerge as portions of the specification are developed. Nevertheless, it is useful to postulate a simplified, linearized model of the synthesis process, the first stage, formulation, dealing with the development of the information content and the generation of its formal representation, and the second stage, expression, dealing with the formatting of that representation.

5.1 FORMULATION

A linearized model of the formulation process consists of five successive activities. All specifications deal, explicitly or implicitly, with performance objectives. Thus, as a first step, the performance attributes to be achieved must be defined. Design specifications and building codes have traditionally dealt with the overall objectives of maintaining health and life safety; more recently, additional attributes, such as energy conservation or operability after natural disasters, have been introduced as requisites. An attribute such as "maintenance of life safety" is too broad a concept for developing specification provisions. Therefore, the environments or factors within each attribute have to be further isolated and identified. For example, "safety" may be subdivided into "internal effects," such as explosions and other potential causes of progressive collapse, and "external effects," such as wind, earthquake, and the like. This leads to the identification of the anticipated response of the system to the adverse environment, and to the definition of the limit states, that is, the conditions under which the anticipated response renders the structure or system unfit for its intended purpose.

As the second step, it becomes necessary to identify the physical entities which are susceptible to failure or disfunction corresponding to the limit states considered. As mentioned earlier, it is advantageous at this stage to introduce common abstract properties, such as, "tension stress" for certain ultimate limit states or "horizontal surfaces" for the limit state of ponding, rather than attemption to exhaustively enumerate all possible components or configurations susceptible to a given limit state. The intersection of limit states, common properties and physical elements identifies the criteria that have to be met.

The third step involves the definition of measures quantifying each criterion, from simple statements that a certain device or item shall be provided to limits or ranges on critical parameters. As a fourth step in the formulation process, evaluation procedures must be developed to ascertain each of the measures defined previously. In performance specifications, these procedures are treated separately from the criteria, whereas procedural specifications consist largely of the detailed exposition of such procedures.

Throughout the formulation process outlined, the growing information base of the specification being developed can be directly incorporated into the formal representation. Specifically, the first step involves the development of the attribute argument tree, such as the one given in figure 3b. The second step consists essentially of the development of the physical entity argument tree, the definition of criteria, and then the establishment of the argument and scope lists. The third and fourth steps involve the development of the information network among the related criteria, measures and evaluation procedures and the generation of the decision tables for the individual provisions.

The final step in the formulation process consists of the application of the analysis tools described to the representation, in order to ascertain the requisite properties of completeness, uniqueness and correctness. At the risk of repetitiousness, we emphasize that such analyses will inevitably reveal violations of the above properties and require additional iterations on the formulation process.

5.2 EXPRESSION

We call expression the process of converting the abstract representation into usable forms for a readable textual format and for the generation of computer aids. This latter topic will be discussed in the next chapter after some additional topics are introduced.

The difficulties of achieving a usable, readable text arise because the text must follow a linear sequence, whereas the information it contains is highly non-sequential, consisting of disjoint argument trees terminating in criteria, which in turn depend on an information network with many multiple connections, the nodes of which themselves may consist of substantial decision trees. Expression is, therefore, the task of unraveling this complex structure into a linear format that is easy and convenient to use, that gives confidence to the designers that they are following the specification writers' intent, and that similarly gives assurance to the specification writers that the provisions are correctly interpreted and executed.

We are convinced that many of the complaints concerning present specifications, and often the resistance to the introduction of new ones, are the result of poor textual expression, as evidenced by awkward outlines and uninformative provision headings, lack of proper cross-referencing among related provisions, procedural sequences poorly related to the design process, and badly composed provisions which are hard to interpret and follow.

We are not in a position to propose universally applicable methods for expression, but we have developed strategies which may be explored by specification writers in order to achieve better textual expression, and computer aids which allow exploring alternatives without the danger of losing the intended coverage and meaning. These strategies are essentially means for transforming the complex representation into different linear sequences.

Provision Level

Here, the problem is that of converting a decision table into a decision tree, which can then be expressed as one or more sentences containing conditional clauses. The literature on decision table processing discusses two basic strategies, called immediate decision, where the objective is to isolate rules as quickly as possible, and delayed decision, where the objective is to reduce the number of possible rules roughly in half with each test (17) (the numerical analyst will recognize the analogy of the two strategies to searching by iteration and searching by interval halving, respectively). These two strategies can be directly applied to the expression of provisions: in the immediate decision method, the simplest rules (containing the largest number of immaterials), unique rules (differing in one condition from all other rules), or the most common rules could be listed prior to the other rules; in contrast, by following the delayed decision method, provisions could by systematically broken into shorter subprovisions of roughly equal scope.

Information Network

At the intermediate level, the problem is that of representing the graph of the information network by a suitable spanning tree (i.e., a subgraph which contains all the nodes of the original graph but only as many branches as necessary to provide a single path from any node to any other node), and then to display the nodes of the tree in a linear sequence. By the nature of the information network, all branches not in the spanning tree become cross-references among the data items. Two strategies for generating such a spanning tree are available, involving a simple graph traversal algorithm. Assume that a fictitious "end" node is made a dependent of all terminal (criterion) nodes, a fictitious "start" node is made an ingredient of all input (basic parameter) nodes, and that all branches are of "length" one. If the nodes are ordered by increasing longest path from the "start" node, one obtains a sequence, which we call direct execution, in which every term, formula, test, etc. is defined just before it is first used, yielding concise, specific sequential instructions, with all cross-references pointing to terms previously defined. The strategy can, however, become lengthy and tedious for an experienced user thoroughly familiar with the specification. By contrast, if the nodes are ordered by increasing longest path from the "end" node, one obtains a sequence, which we call conditional execution, where the criterion to be checked is given first, followed by its ingredient subcriteria, and so on, until finally the basic data elements are defined. Such a strategy permits an experienced user to read only as far down as necessary to locate the controlling provision or test; however, if necessary, by reading further he can refresh his memory on more detailed provisions. Variants of these two strategies are further discussed in (15).

Organizational Level

In generating the outline and overall organization of the specification, it is necessary to linearly sequence criteria which are indexed and only partially ordered by the nodes of disjoint attribute trees, as illustrated in Table 7. We have not yet developed general strategies for this phase of expression. It is to be noted, however, that here syntax and semantics interact very strongly: a sequencing which orders first on attributes and limit states, with the physical classification in a secondary rule, is likely to be more appealing to the researcher and theoretically inclined designer, whereas the opposite strategy is likely to be more familiar and convenient to the average designer.

The three sets of strategies discussed should be taken as boundary values on a continuum of possible expressions, rather than as absolute alternates. Any given specification is likely to contain a mixture of all the above strategies. It is also possible that eventually frequently used specifications may be expressed in one form for a specific use, say, for designers, and that alternate forms may be provided for alternate uses, say, one for students and another one for building regulatory officials, with full confidence that the contents and meaning will be preserved.

6. USE OF SPECIFICATIONS

In the Introduction, we refer to use as the application of specifications to the evaluation of designs in both manual and computer-aided processes. It is to be hoped that manual processing can be improved by the application of the formulation and expression strategies discussed. Computer-aided processing can also benefit significantly from the methods discussed, as will be demonstrated in this section.

In computer-aided processing, one deals with constraints, rather than criteria. A constraint is a particular application of a design criterion. It is particular in the sense that it is a criterion applied to a particular entity or point for a particular loading or environmental condition. Usually, each design criterion results in many constraints.

Systematic approaches can be provided for the computer-aided development of programs for constraint processing. These aids are significant because manual programming is extremely expensive and subject to mistakes in the interpretation of the intent of specifications. The cost of preparation of new computer aids for constraint processing appears to become a major impediment to the implementation of research knowledge in improved specifications.

6.1 EXTENSIONS OF REPRESENTATION

In order to accommodate constraint processing, the representation presented in Section 4 has to be extended in three ways.

First, in representing criteria, we treated a particular datum (e.g, member length, ℓ, stress, F_a, etc.) as an individual item. In actual design use, these quantities would be subscripted variables (e.g., the length of the ith member, the stress at station k of member i in loading condition 1, etc.). All such subscripted variables are stored in some data structure which is accessed by the design and analysis routines as well as the constraint processor. The logical data of the specification must be related to the subscripted data of the files for computer-aided data processing. This relationship cannot be a fixed property of the specification, since it should be possible to use the specification with a variety of project data structures. Therefore, we have presented elsewhere generalized procedures for generating constraint processors compatible with rational, but essentially arbitrary, file structures (23, 24). The significant feature of these procedures is that additional ingredients, called pointer vectors, are appended to the ingredient lists. A typical pointer vector would, for example, relate stations along the member to the member designation. The extended representation only shows that a pointer vector is needed to access the stations where the stress constraint is to be checked; the actual form and content of the vector would depend entirely on the data file structure for the particular project.

Second, the ingredience and dependence relationships themselves must be extended to account for the subscripted nature of the actual design data. In the work cited (23, 24), we have developed a calculus of subscript calculations, so that the subscripts of the dependents can be automatically obtained from the subscripts of the ingredients, and vice-versa. This approach can significantly decrease the cost of developing computer aids for constraint processing.

Finally, in design, data also have a temporal character. In our early work, we made use of the concept of <u>status</u> (8). The status of a datum is <u>valid</u> if it has been calculated in accord with the current values of all the data in its global ingredients. The status of a datum is <u>void</u> if it has not yet been calculated, or if changes have been made in one or more of the items of data in its global ingredience since the datum was computed. More recently we have introduced the concept of <u>permanence levels</u> to distinguish between levels of definition of data (25). For instance: data being used by a number of different groups of the design team, such as the architects, structural engineers, and mechanical engineers, might be given a permanence level 1, data used in a more transient fashion by one of these disciplines designated level 2. A trial structural design might be conducted at level 3, the gradient calculations used to determine whether an improvement in the design is possible might be conducted at permanence level 4, and when the trial design is determined to have converged its data might be relabeled to level 2, when the structural design is deemed consistent with the current work of the architects and mechanical engineers, it could be relabeled at permanence level 1.

6.2. COMPUTER AIDS FOR CONSTRAINT PROCESSING

The computer aids available for efficient constraint processing can again be discussed at the three levels used previously.

Provision Level

Two direct uses can be made of the decision table representation of specification provisions. First, decision tables can be used directly as a programming language; efficient preprocessors exist which convert decision tables to procedural language statements using the strategies discussed in Section 5.2, thereby significantly reducing programming costs (17). Alternatively, the decision tables can be used as data by a general-purpose interpretive program (8), thereby providing great flexibility in experimenting with alternate specification provisions, as only the data would have to be changed.

Second, wherever specification provision deals with several entities, or allows designer choices or alternatives, and a particular organization knows *a priori* which of these entities or choices it intends to use, the application programs can be drastically reduced in size by the systematic elimination of options not wanted. As an example, Table 2, introduced previously, could be systematically reduced to the following programs:

- compression members only (one condition, two rules)
- all tension members (five conditions, six rules)
- tension members with slenderness check (five conditions, five rules)
- tension members without check (table eliminated altogether).

Information Network

The two strategies, direct and conditional execution, discussed in Section 5.2. are directly applicable to constraint processing. Conditional execution begins with the particular constraint to be evaluated, tests whether it can be evaluated directly from its ingredients, and proceeds with the evaluation of ingredient data only when some are unknown. Direct execution begins with the known input quantities, and proceeds to evaluate all higher level data starting with the data directly dependent on the input.

Conditional execution is appropriate when the computer is used to check only a few of the possible constraints where a criterion applies; this is the usual mode of use in design and in review. Direct execution is suitable when substantially all derived properties are needed for the given values of the input data. This may occur in certain large volume, low-level design and detailing applications, and in review for some types of specifications. Systematic approaches to efficient data processing for both strategies are briefly discussed below.

For conditional execution, we have developed a single general operator, called SEEK (23, 6), which uses the information network and the status indicator discussed in the preceding section to recursively computer only the ingredients actually needed and set their status to valid.

Another elemental activity in design is to change the value of a design variable. Use of the information network allows a recursive WARN procedure (23) to set to void the status of each datum which would be affected by the change. It would be possible to reevaluate the affected data immediately. However, if a number of data are to be altered, immediate reevaluation would be wasteful. When data are needed again, SEEK is used to selectively reevaluate only the data affected by the changes.

When the number of criteria to be evaluated can be restricted to a relatively small number defined in advance, it is entirely feasible to develop an efficient constraint processor using direct execution. The order of computation may be generated directly by expressing the global information network of the required portions of the specification in post order (11). Then, using the subscripted ingredience relationships defined above, computations may be carried out systematically to evaluate all dependents, rising in the information network from the input data to the highest level criteria.

Organizational Level

In constraint processing, the organizational level acts as a switching network or directory to lead the process to the execution of the appropriate constraints. In conditional execution, especially in an interactive (time-shared) environment, the user can specify the node(s) of the argument trees where he intends to begin constraint processing. For direct execution, the argument trees are used directly to sequence the computations for efficient processing. As with the other two levels, the application programs can be substantially improved in size and speed by pre-specifying the subtrees comprising the criteria to be incorporated into the programs.

7. SUMMARY AND CONCLUSIONS

We have presented an abstract representational model of design specifications, and have identified the formal properties of completeness, uniqueness, and correctness which every design specification should possess. The formal representation consists of decision tables or derived decision trees for the provisions, an information network for interrelated provisions, definitions and evaluation procedures, and argument trees for organizing and outlining. We have identified methods for formulating specifications, and tools for checking them for the requisite properties. We described a number of strategies for expressing specifications in textual form, and the relative advantages of each. Finally, we have shown the extensions necessary to apply the procedures discussed to the generation of computer aids for processing project design data against the specifications for design and conformance checking.

Our study demonstrates that the concepts of performance and limit states need to be an integral part of specification development to insure that the users know the intent of the specification and can correctly apply its writers' intentions. We have indicated how the formal representation may be used to generate alternate formats for distinct users, say, for experienced designers, students, and building officials. We have shown how computer aids may be used in formulation and expression to reduce the cost and uncertainties in specification developments. While the prime use of these tools is in the synthesis of new specifications, the benefits accrued from the formal representation and purposeful expression may be great enough to warrant review and clarification of existing specifications without major changes in scope or technical content. We have also demonstrated that the generation of computer aids based on the specifications can and should be made an integral part of specification development.

The methods presented have been tested in the analysis of a number of diverse specifications and are considered reliable. There is need, however, for further systematic studies in formulation and expression of specifications, especially in the evaluation of the strategies of expression described.

It is our hope that through the methods presented, specification development can become a much more integral part of the transmission and implementation of research results, and that design specifications will no longer be looked upon by designers as a necessary evil, but as a constructive aid in achieving design objectives.

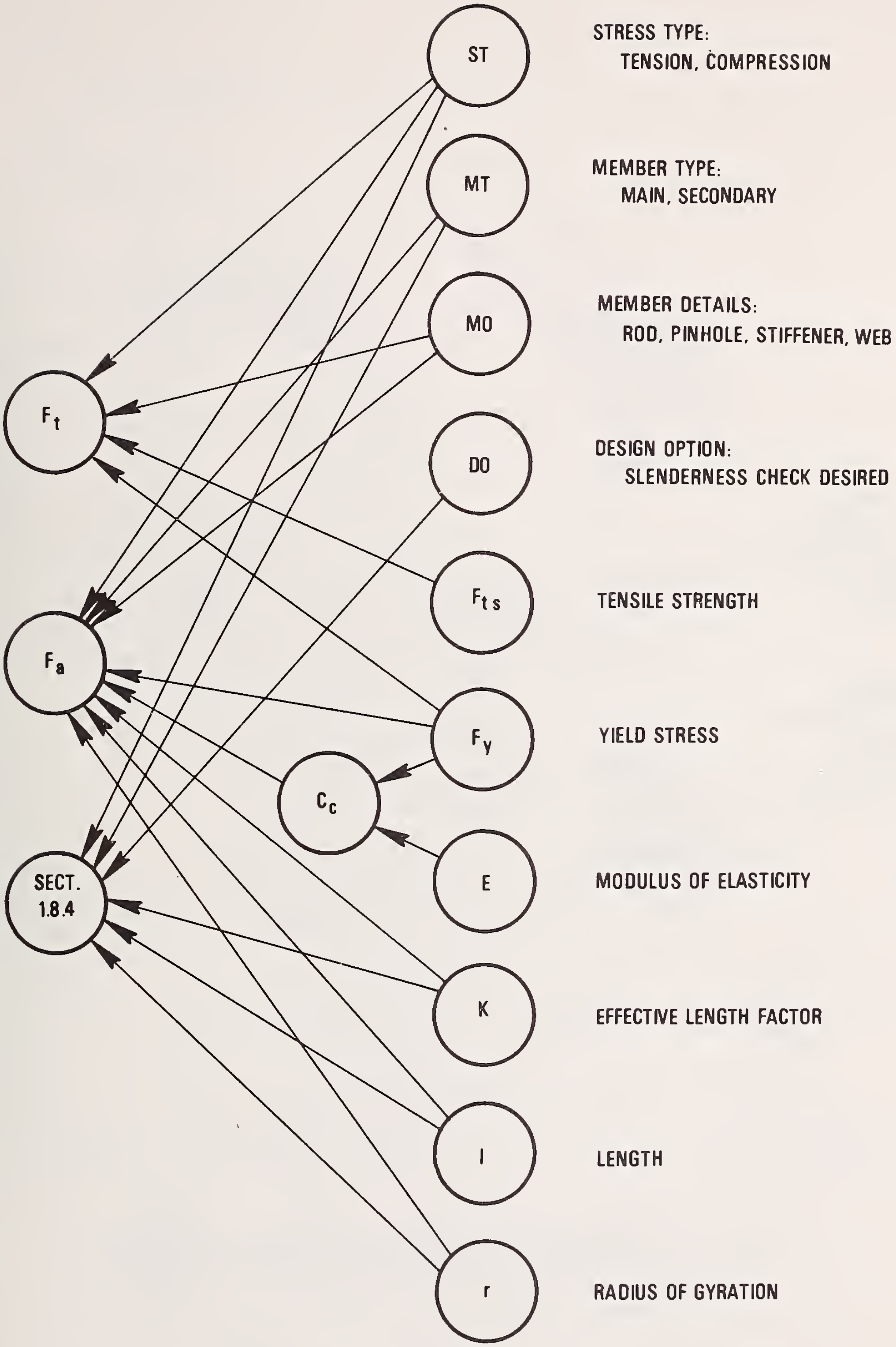


Figure 1. Information Network for Allowable Stress and Slenderness Ratio Criteria

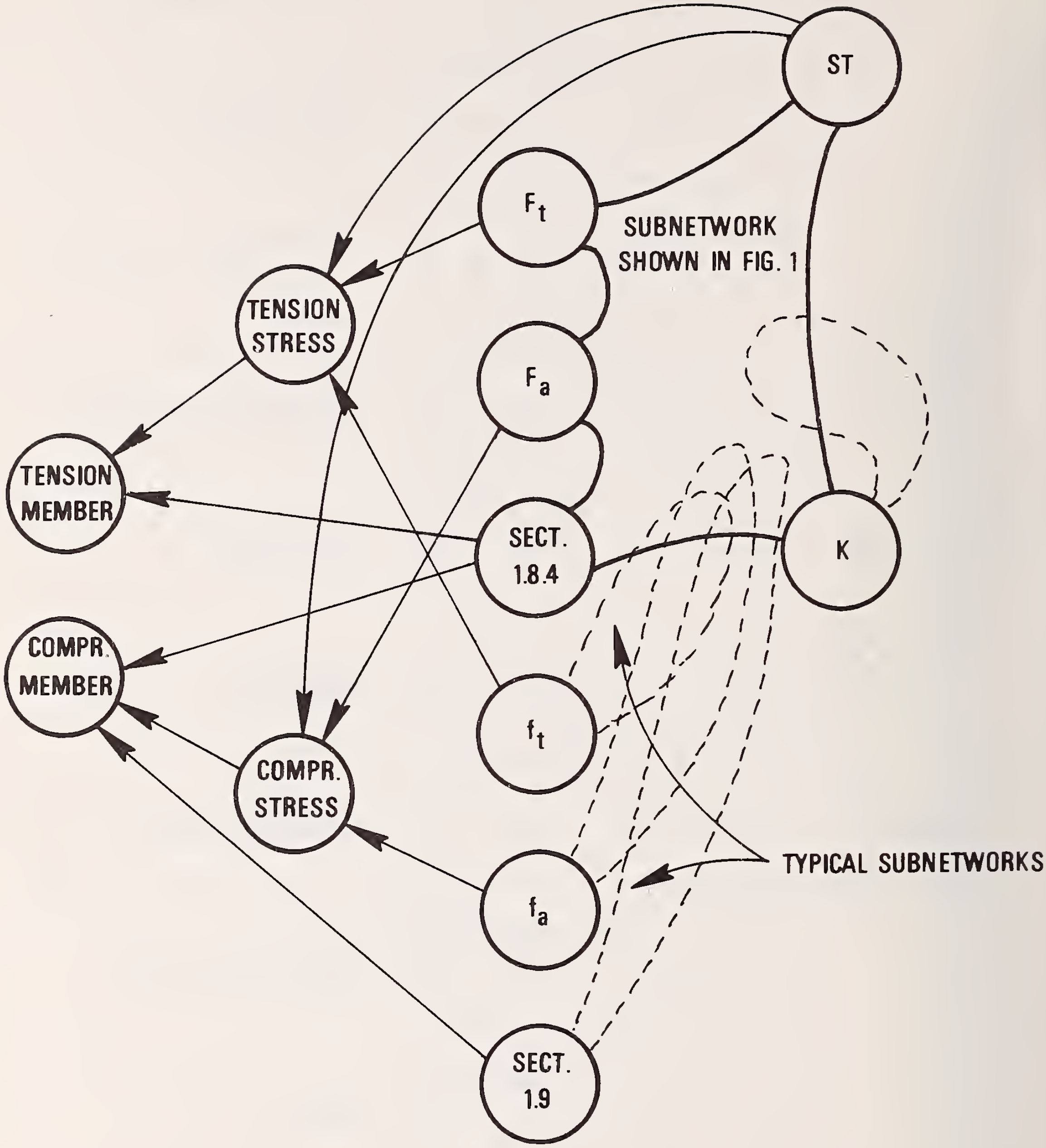
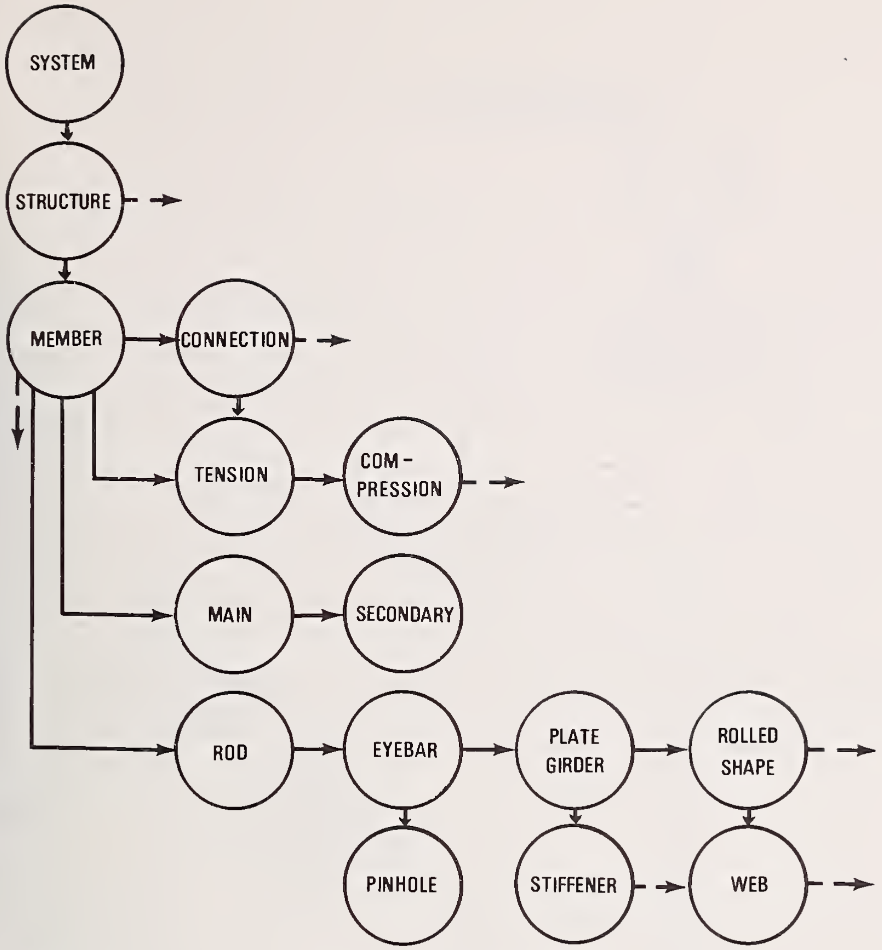
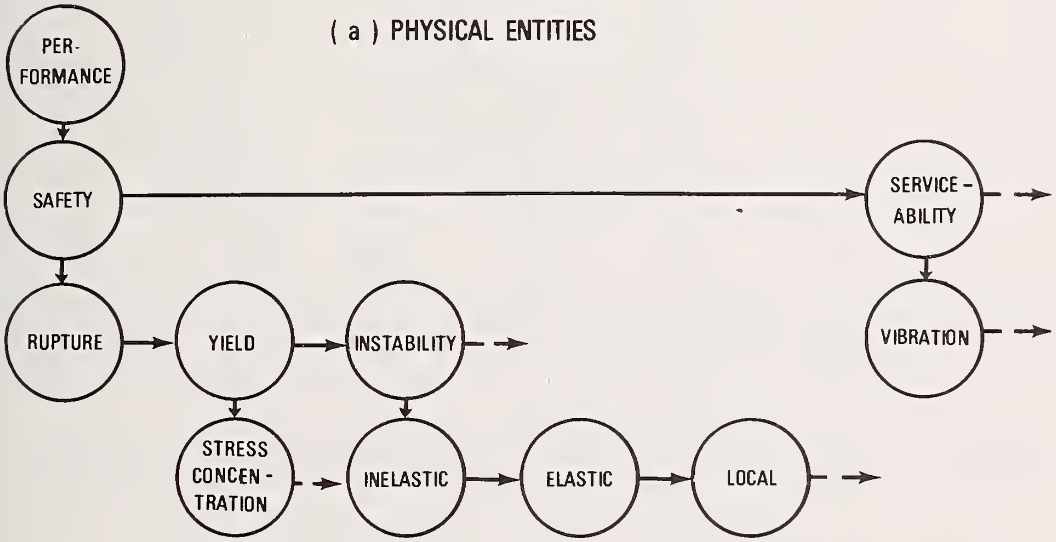


Figure 2. Schematic Information Network for Tension and Compression Member Criteria



(a) PHYSICAL ENTITIES



(b) PERFORMANCE ATTRIBUTES AND LIMIT STATES

Figure 3. Argument Trees

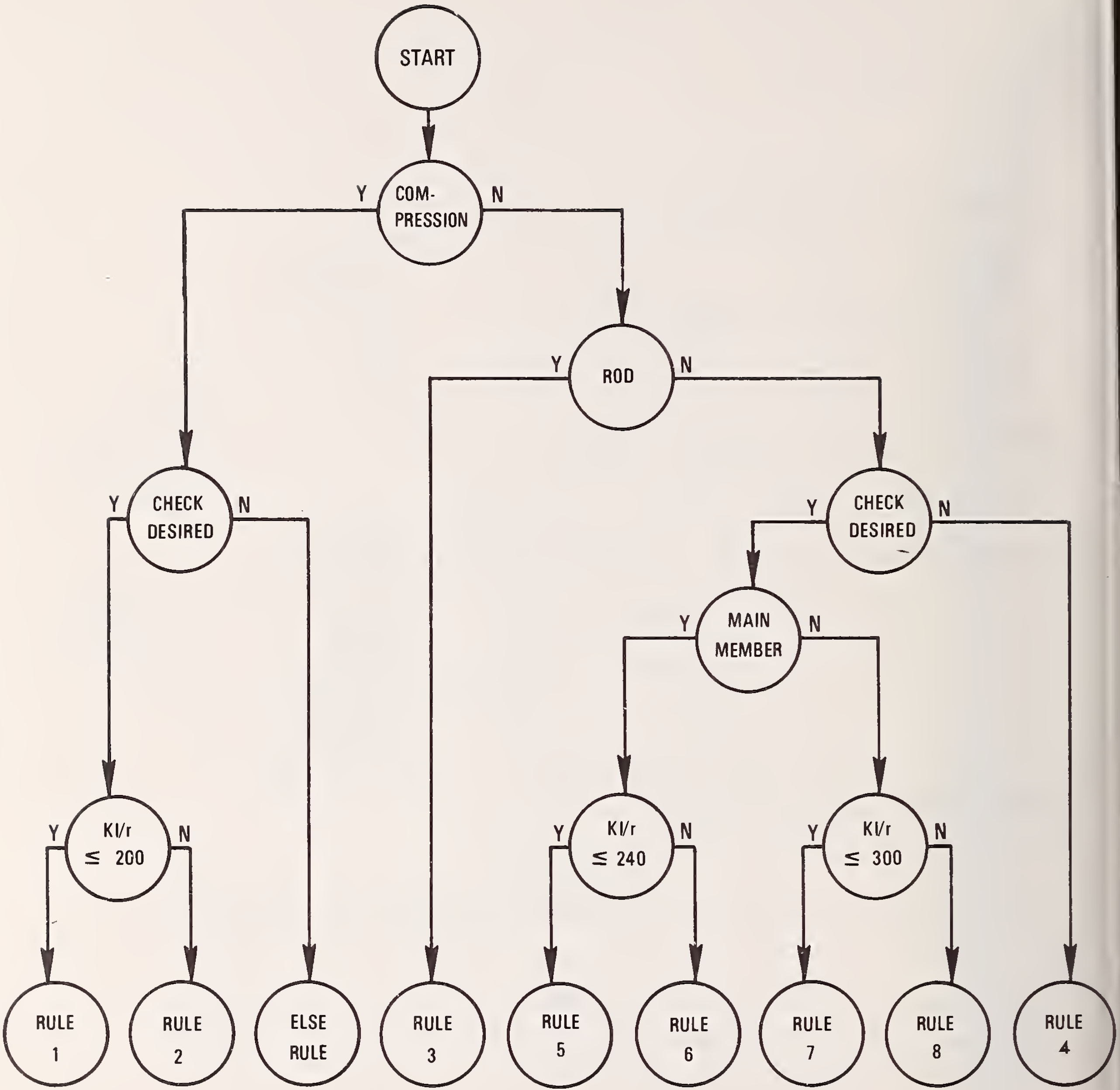


Figure 4. Decision Tree for Maximum Slenderness Ratio Criterion

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Design specifications are presented as the primary communication and control tool for the design and construction industry. Requisite properties of completeness, uniqueness and correctness are identified, and the role of performance and limit state concepts in specifying intent of the specifications are emphasized. Formal representation methods are presented at three levels: decision tables for specification provisions, an information network for related provisions, and argument trees for organizing and outlining. An idealized process for specification development is presented, and the use of the representational tools for checking specifications and providing strategies for textual expression is described and illustrated. Development of computer aids for specification processing in design and conformance checking is described.

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