Hybrid expert system for qualitative and quantitative analysis of mechanical structures

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Abstract

The so-called *hybrid expert systems* for analysis of physical systems (e.g., mechanical) integrate modelling and simulation methods, including classical *numerical* (*quantitative*) methods as well as recently developed *qualitative analysis* methods, using the expert-system *rule-based* techniques. The *diagrammatic representation* methods also turn out to be important elements of knowledge representation (especially the qualitative knowledge) and user interface in such systems. In the paper, problems of construction of such systems are discussed, using an example of the experimental hybrid system for analysis of planar truss structures (currently under implementation).

Introduction

The so-called *hybrid expert systems* are recently proposed as a promising approach to build practically useful computer systems for analysis of complex physical systems (e.g., mechanical) [3]. The expert-system technique, based on the *rule-based knowledge representation*, is used in them to integrate various modelling and simulation methods, appropriate to the particular problem area. In this way, the advantages of both declarative, *shallow-knowledge* approach (characteristic of expert systems) and *deep-knowledge* representation (characteristic of modelling and simulation methods) can be successfully combined [1, 3, 7]. The modelling methods should include both classical ***numerical (quantitative)*** methods [3] and recently developed *qualitative analysis* methods [2, 3, 4]. The recently developed *diagrammatic representation* methods should also be used in such systems, especially for representing the qualitative knowledge and facilitating the interface with the user [3, 5, 8, 10].

In the paper, problems of construction of such systems are discussed, using an example of the experimental hybrid system for analysis of planar truss structures currently being developed and implemented by the authors. The general structure of the system and functional principles of its basic subsystems are described in some detail.

General approach

Hybrid expert systems

One of the basic advantages of *expert systems* is the possibility of formulating knowledge about the analysed system in *declarative* form, comparatively easy to formulate and modify by a human user. It is especially evident when one compares it with problems of *algorithmic* (procedural) formulation of the same knowledge, e.g., in the form of a computer program for numerical analysis of the problem [3].

However, classical rule-based representation of knowledge allows for easy formulation of only the *shallow knowledge*, representing external, phenomenological associations between parameters of the system, in contrast to the *deep knowledge*, describing underlying laws and internal relations governing the functioning of the system [1, 7]. One of the early solutions to this problem was the introduction of so-called *procedural knowledge*, usually by insertion of calls to external procedures calculating algorithmically the required model dependencies.

The more general approach to representation of deep knowledge in expert systems is provided by *hybrid systems* [3]. In them, proper integration of different representations and reasoning types, including choice of appropriate analysis methods to different subproblems, controlling their interaction, "intelligent" integration of partial results, etc., becomes an important issue. Knowledge required to perform these tasks has usually the form of various heuristics, best expressed in logical, rule-based terms, thus the classical expert system formulation is well suited for this purpose. However, a proper implementation of deep knowledge representation requires the use of algorithmic methods, basically of two general types:

- *Quantitative (numerical)*: when the accurate quantitative model of the system as well as the full and exact information about its parameters are known, and the results are also required with full possible precision.
- *Qualitative*: when the exact quantitative model is unknown or incomplete, information about system parameters is incomplete or imprecise, or the numerically accurate results are not needed.

Qualitative analysis

Qualitative analysis constitutes an important element of the deep knowledge representation level. It models a common-sense, mostly non-numerical reasoning people use to estimate possible solutions to real-world problems, especially in the case of inexact or incomplete data. It also promises to avoid unnecessary number crunching in those cases, like conceptual design, when exact knowledge of all numerical results is not required. However, standard qualitative techniques [2, 4] have certain drawbacks, like *over-abstraction*, i.e., giving answers too general or imprecise, or *"intractable branching"*, i.e., producing a great number of uninteresting or impossible qualitative behaviours. One of the proposed remedies is the use of hybrid approaches, in particular combining qualitative and quantitative analysis with rule-based control [3, 11].

Diagrammatic representation

The field of *diagrammatic representation* and *reasoning* has recently become one of the most rapidly growing areas of research in artificial intelligence and related fields. It investigates possibilities and methods of using visual representations of various information and knowledge for their description, storage and processing (reasoning with them), both by humans and computers [5]. Human problem solvers use diagrams constantly to formulate and communicate problems and as, often indispensable, aids to solve them. The problem is how to transfer this ability to computers.

Advantages of diagrammatic representations come partially from the fact that they permit explicit representation and direct retrieval of that information which can be represented only implicitly in other types of representations and then has to be computed (or inferred), sometimes at great cost, to make it explicit for use. They also permit effective control of the reasoning process, facilitating search both in data and solution spaces, as the search can be guided by explicit proximity or adjacency relations between elements of the representation.

Diagrammatic reasoning seems especially useful for qualitative analysis because, being qualitative by its very nature, it can be nevertheless developed into a completely precise and formal method of reasoning [5]. It is particularly suitable for problems involving spatial relationships, like kinematics or analysis of beam structures [3, 10].

The diagrammatic encoding of information, its transformations during reasoning, and the reasoning results, are often more natural and understandable to human users, especially in applications where already the use of drawings and diagrams is essential and widely practised. Thus, the diagrammatic representation field can be considered as an extension of the field of *graphical man-machine interfacing*, especially (automatic) *graphical data presentation* [5, 8].

Experimental truss analysis system

To investigate the problems of construction of hybrid expert systems as introduced above, an experimental system for analysis of planar truss structures is being developed. It is implemented using the Smalltalk-80 object-oriented language whose advantages for tasks of this kind have been presented in [8]. The system structure is shown in Fig. 1. It can be divided into the following, partially overlapping subsystems:

- *Representation of the truss*: its geometry, parameters of elements, and current state of the analysis.
- *Quantitative numerical analysis* of the truss, using the classical method involving a system of linear equations.
- *Qualitative-numerical analysis* of the truss, based on qualitative solving of the linear equation system using interval arithmetic.
- *Qualitative analysis* of the truss, using qualitative simulation of local load propagation.
- *Rule-based* subsystem, used for overall control and integration of the hybrid analysis process.
- *Diagrammatic data representation* and *user interface*.

Representation of the truss structure

It comprises the following elements:

- *Geometry* of the truss, in diagrammatic form. Currently it is assumed that the geometry of

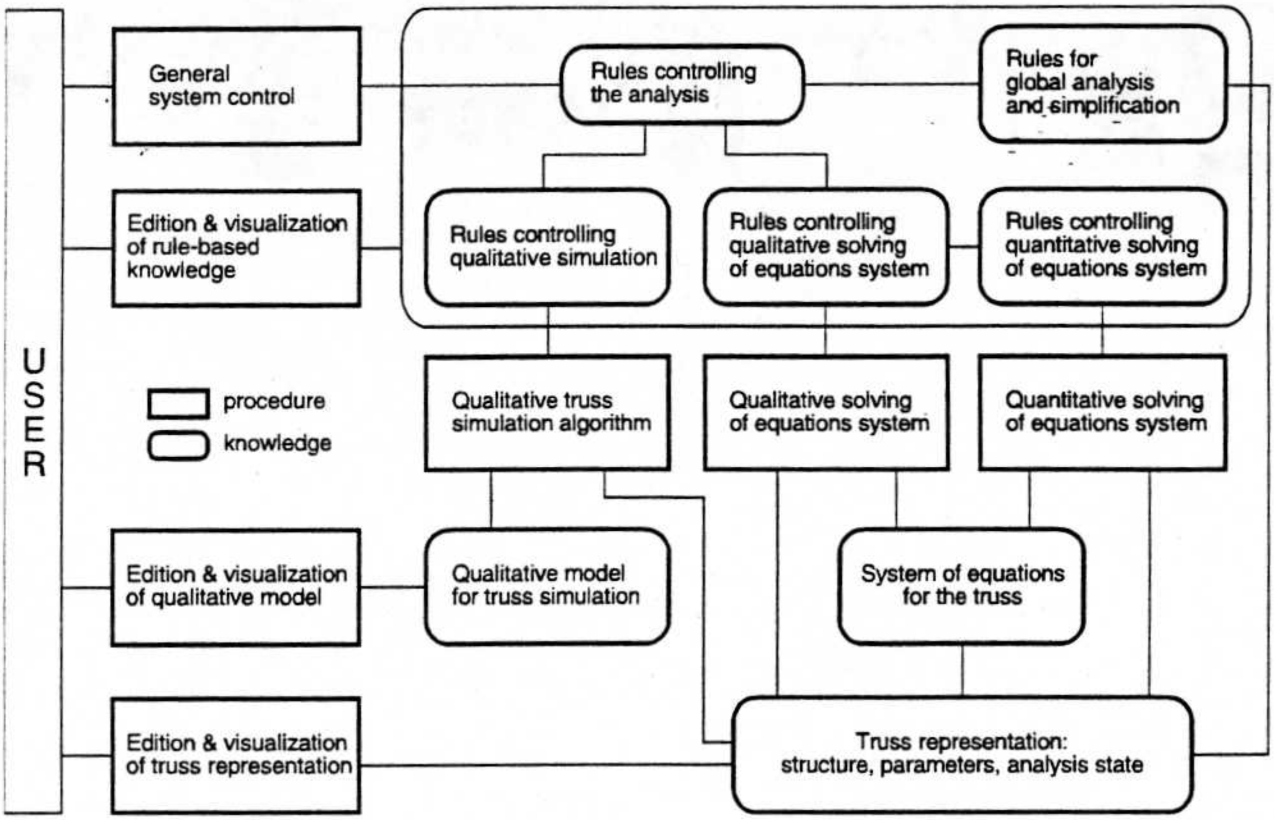

Fig. 1. General scheme of the hybrid system for analysis of truss structures.

the truss is known accurately. Most of the possible imprecision of the geometry can be adequately represented as imprecision of truss parameters, like the tolerance of bar lengths.

- *Parameters of elements*: material properties, lengths and cross-sectional areas of the bars (or directly — their stiffnesses), external and internal loads. They can be also specified in imprecise (qualitative) terms, e.g. some parameters can be given as intervals (instead of exact values), as signs (e.g., of the axial forces in the bars), or comparatively (some bars are more stiff than others).
- *Current state of the analysis*, including analysis method, (possibly partial) analysis results (axial forces in bars, node displacements), currently analysed node (for load propagation method), etc.

Quantitative analysis

This module uses the classical method of solving a system of linear equations describing the force equilibrium conditions in the truss. The system of equations (for node displacements as unknowns) is constructed from the representation of the truss and then solved numerically, using the standard Gauss-Jordan method. The method can be applied only when numerical parameters of the truss are known exactly. In other cases the module serves an accessory role, e.g. in finding interval estimates (see the next Section). It can also be used to conduct "case studies" for the truss, i.e., sampling the solution space for selected special cases from the range of possible values of qualitatively specified parameters.

In accordance with the experimental character of the system, no attempt to optimise the numerical calculations has been made. The straightforward Smalltalk implementation of the Gauss-Jordan method has produced quite satisfactory performance for the example trusses analysed, some of them quite large.

Qualitative-numerical analysis

When the truss parameters are not exactly known, the analysis method must necessarily use elements of qualitative analysis. One of the simplest ways of representation of the inexact or incomplete data, as used in qualitative analysis, is based on interval arithmetic [2, 6, 9]. In this module, the classical linear equation system approach is also used, but now it uses interval arithmetic to allow for range specification of parameters. The resulting linear system of equations with interval coefficients can be solved with

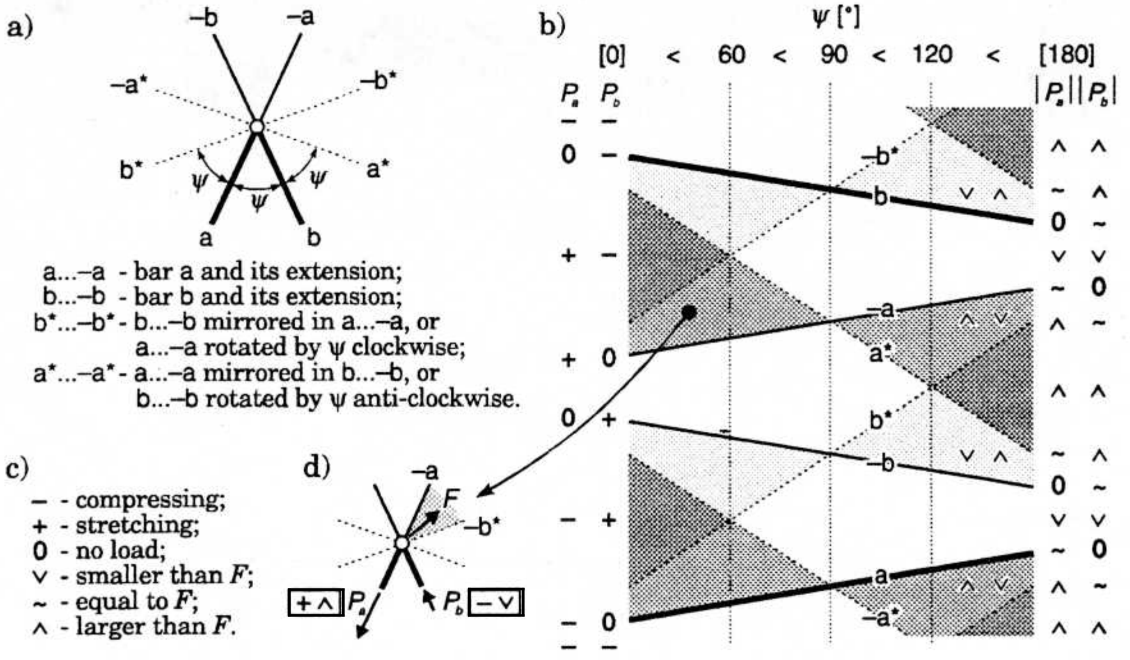

Fig 2. A piece of the qualitative model in diagrammatic form: a simple two-bar configuration with characteristic directions defined (a), signs and comparative magnitudes of axial forces (b), qualitative descriptors (c), and an example situation with qualitative descriptions of resulting axial forces (d).

appropriate method [6] to produce interval estimates of node displacements. Usually it means maximal ranges of displacements, although inner estimates giving minimal possible ranges can also be obtained.

Several algorithms for obtaining such interval estimates were implemented and their performance compared in the system. Preliminary experiments have shown that the estimates are usually too crude to be generally useful, though they can be used in certain cases to disambiguate the alternative qualitative results, pruning out parts of the tree of possible qualitative solutions (see the next Section). This is due in part to certain limitations of interval analysis [6, 9]. Namely, standard interval methods do not take into account that the coefficients in the equations are usually not independent — they are all functions of some (usually few) interval parameters (e.g., stiffnesses of the bars whose unknown exact values are approximated by intervals). This is a problem analogical to the well-known problem in interval arithmetic involving calculation of interval expressions in which some interval variable(s) occur more than once. The research on methods of obtaining interval estimates that take into account that dependency is currently under way.

Qualitative analysis

In this module, a direct qualitative analysis, based on the simulation of local load propagation, is carried on. It constitutes a new approach to qualitative analysis of trusses and is still under development by the authors of the paper.

The distribution of load between bars connected in a single node is determined on the basis of a qualitative model of interaction between neighbour nodes, obtained from analytic solutions of local truss configurations. The qualitative model uses the diagrammatic representation for the local configurations and spatially-related qualitative ranges of the direction and magnitude of the loads (see Fig. 2 and additional explanations in the Section on diagrammatic representation below). At the next step, qualitative estimates of axial forces in the bars, as obtained according to the model, become the loads for the nodes to which these bars are leading. For these nodes the above process is repeated again, propagating the load into subsequent nodes and bars of the truss.

The process usually soon falls into troubles, starting to produce ambiguous results. Due to imprecise knowledge of the truss parameters and intrinsic locality of the analysis, the distribution of load for certain nodes cannot be determined with certainty, even in qualitative terms. This leads to the effect quite familiar to workers in the field of qualitative analysis — the branching of the solution into a tree of possible variants [2, 4]. However, many of the superfluous branches of the tree can be pruned on the basis of additional

Rule 1: *Elimination of noncollinear bar*

if number of bars at node is 3
and support is none
and external load is none
and bars (b_1, b_2) are collinear
and bars (b_1, b_3) are not collinear
then eliminate bar b_3.

Rule 2: *Elimination of two bars at angle*

if number of bars at node is 2
and support is none
and external load is none
and bars (b_1, b_2) are not collinear
then eliminate bars (b_1, b_2)
and eliminate node.

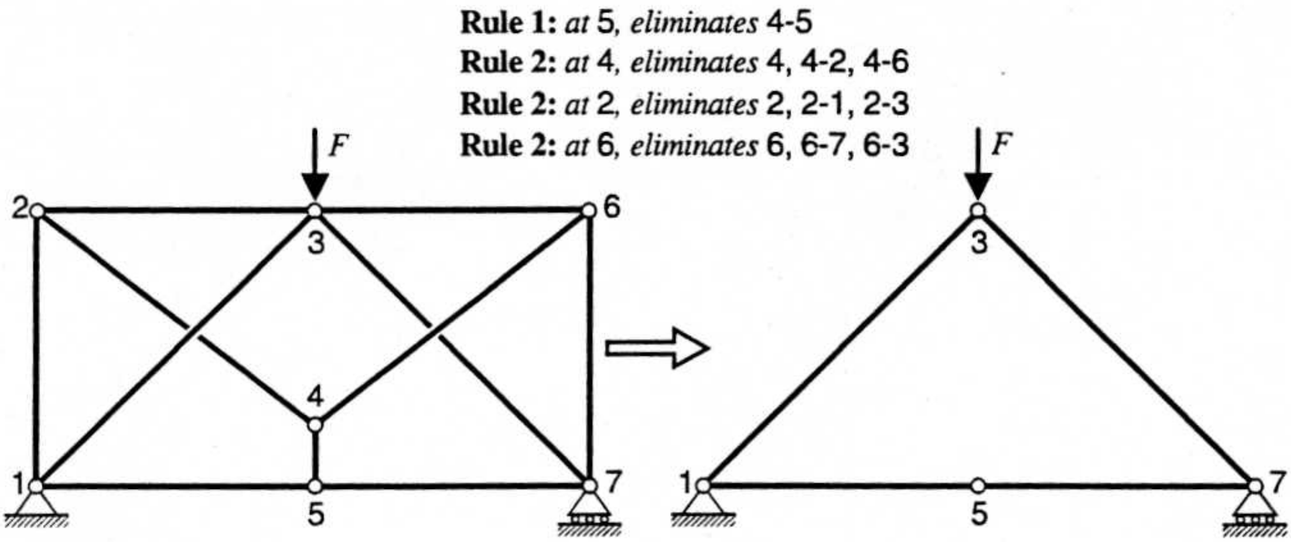

Fig 3. Example of simplification rules and their application to a simple truss (adapted from [3]).

information, including certain heuristic rules depending on the overall structure of the given truss (see the next Section), or results from the interval analysis and sampling of the solution space using the numerical analysis module. More information also becomes available near or at the leaves of the tree, namely for nodes near truss supports. This additional information can be propagated back and used to cut out the unnecessary alternatives.

The process of qualitative load propagation and subsequent pruning of the tree and improving the qualitative estimates (backward analysis) is iterated several times until the solution set ceases to improve.

Proper formulation and organisation of the qualitative analysis approach described above happened to be one of the more difficult problems in the construction of the system. It is mostly due to the particular features of the kind of mechanical systems we chose, i.e. trusses. Namely, the local configurations of the truss are not sufficiently isolated from each other, hence the resulting global dependencies and tight coupling between local models make the standard step-by-step qualitative analysis hard to formulate and adapt to the case.

Rule-based analysis

This subsystem is characterised by the specific knowledge representation and handling used here, namely the logical, rule-based form used in traditional expert systems. Most of the knowledge so represented is used by other modules in the system (as indicated by the arrangement of boxes on Fig. 1). Different groups of rules play the following roles in the system:

- *General control* of the analysis process, including general interaction between several analysis methods used in the system.
- *Global analysis* includes recognition of certain global configurations in the truss (e.g., beam-like trusses) for which there are specific analysis rules, while *simplification rules* attempt to eliminate possible redundant parts of the truss. Fig. 3 shows example rules of this kind in action (adapted from [3]).
- *Controlling the numerical analysis* (quantitative and qualitative), currently rather rudimentary due to relative simplicity of the tasks.
- *Controlling the qualitative simulation* algorithm and providing various heuristics for the qualitative analysis module. As the qualitative

analysis module often uses the information provided by other modules of the system, most of the interaction between several analysis methods is concentrated here too.

No attempt has been made at devising any specific and novel rule-based techniques to use in the system. Standard forward chaining with simple matching of constants and variables is used for organising the execution of rules. Procedural knowledge (used mostly to link the rule-based module with other modules) is implemented with the Smalltalk-80 mechanism of *blocks*: chunks of Smalltalk code (possibly with parameters) that are included directly in the rule (as predicates) and return logical yes/no result as appropriate. The rules are divided into several groups (approximately as shown in Fig. 1) and metarules are used to switch on or off the use of any given group during system execution.

Diagrammatic representation and interface

Elements of this module are dispersed within several functional modules as depicted on Fig. 1. The significance of this subsystem comes mostly from the fact that the objects analysed by the system are naturally represented as diagrams.

The first important part of this subsystem concerns the representation and visualisation of the analysed truss. Entering structure and parameters of the truss to the system as well as monitoring progress and results of its analysis is centred on the basic representation of the task, namely the *structural diagram* of the truss (see the example visualisation on Fig. 4). Parameters of the truss can be visualised in many ways (e.g., bar cross-sectional areas — with line thickness), and can be also presented (and edited) in numerical form. The user can at will switch on or off the visualisation of selected parameters and change its form according to currently available possibilities (note the example switches on Fig. 4). The geometrical structure and parameters of the truss are *editable* by the user, either on the diagram itself, or by editing appropriate numerical values (with appropriate dialogue boxes).

The main form of result visualisation is the display of the deformed truss and the values of axial forces in bars (shown by appropriate graphical features of the bars, like colour, or explicitly as stylised vectors), see Fig. 4. Of course, the results are also available in textual form, numerical or descriptive (for qualitative results, cf. Fig 2c). A specific type of visualisation is provided by the display of the *analysis tree*, when several possible variants of the solution exist. The display of the analysis state may also include the rules used and conclusions obtained from them.

Another important part of this subsystem is concerned with diagrammatic representation of the qualitative knowledge about local load propagation — the *qualitative model* of the truss. Fig. 2 shows a fragment of this representation — the distribution of load at a two-bar node. Depending on the direction of the external load vector F relative to the characteristic directions around the node (defined by directions of the bars and the angle ψ between them, Fig. 2a), the signs and relative magnitudes of the axial forces are easily read from the diagram (Fig. 2b), as shown for the example situation (Fig. 2d).

Elements of the diagrammatic representation are also used for editing rules concerned directly with truss configurations, like rules for global analysis and simplification of the truss (see Fig. 3) and rules controlling the algorithm of qualitative truss simulation. There are also procedures (not shown on the scheme of Fig. 1) that search the truss structural diagram for appropriate local configurations needed by the analysis rules and the qualitative simulation algorithm.

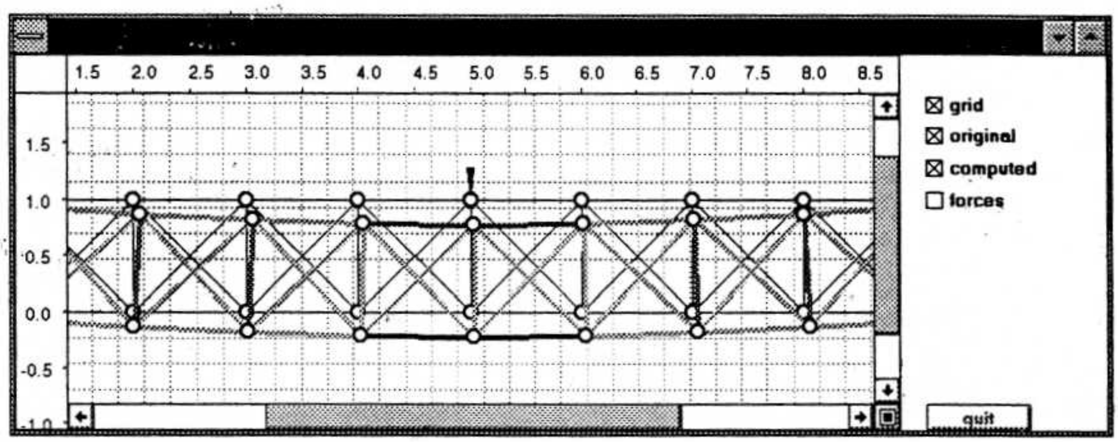

Fig 4. Example visualisation of the truss structure and analysis results (original is in colour).

Conclusions

The experimental hybrid expert system for analysis of mechanical structures in general and truss structures in particular has been described and used to illustrate various problems and principles of construction of such systems. As follows from the research leading to, and experience with the implementation of the system, the most important problems encountered have been the proper formulation and implementation of direct qualitative analysis of the truss (mostly due to the particular features of this kind of mechanical system), and the proper organisation of integration and co-operation of different analysis methods included in the system. It seems that the use of rule-based representation for the control knowledge and elements of diagrammatic representation for the qualitative model and user interface were crucial for the construction of the system.

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