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Autor: Cauvin, Aldo / Stagnitto, Giuseppe

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General Purpose Expert System for Preliminary Structural Design

Structure générale d'un système expert pour l'avant-projet de structures

Struktur eines Expertensystems für die Vorbemessung von Tragwerken

Aldo Cauvin
Prof. of Structural Eng.
University of Pavia
Pavia, Italy

Aldo Cauvin earned his Dr of Eng. degree from Politecnico Milan, where he has been Professor since 1986. Author of papers on nonlinear analysis of reinforced and prestressed structures and on application of expert systems to structural design.

Giuseppe Stagnitto
Research Eng.
University of Pavia
Pavia, Italy

Giuseppe Stagnitto earned his Dr Eng. degree from the Univ. of Pavia and joined the Dept of Struct. Mechanics there. Author of papers on expert systems applied to structural design and structural restoration and strength assessment of Historical Buildings.

SUMMARY
An expert system for the preliminary design of structures is presented. Structural types are classified for a rational organisation of data and knowledge bases. Knowledge is organised in "models" establishing a relationship between structural types and behaviours. A simple "abductive" inference mechanism leads from given boundary conditions to non-univocal reasonable solutions, among which the designer can choose the most suitable one. The process is divided in a series of logical stages which lead to a "prototype" design, permitting an adequate evaluation of quantities and costs.

RÉSUMÉ
Un système expert est proposé pour l'avant-projet de structures. Les types de structures sont classés en vue d'une organisation rationnelle des données. La connaissance est organisée en "modèles" établissant une relation entre types de structure et leurs comportements. Un mécanisme inférentiel simple de type "abductif" conduit, à partir des conditions-limites à des solutions raisonnables et non univoques, et l'ingénieur peut choisir la mieux indiquée. La procédure est divisée en suite logique, conduisant à un projet-type, permettant une évaluation adéquate des quantités et des coûts.

ZUSAMMENFASSUNG
Vorgestellt wird ein Expertensystem für den Vorentwurf von Tragwerken. Die Klassifikation von Bautypen dient als Grundlage für die Datenorganisation. Das Wissen wird in "Modellen" organisiert, die die Bautypen und ihr Verhalten verbinden. Mit einem einfachen ableitenden Schlussverfahren werden aus geltenden Randbedingungen mögliche Lösungen entwickelt, aus denen der Ingenieur die geeignetsten auswählen kann. Der Prozess ist in logische Phasen gegliedert, die zu der Komposition eines "Prototypen" führen, für den hinreichend Massen und Kosten ermittelt werden können.

1.INTRODUCTION

The potential importance of Knowledge Based Systems in the preliminary phase of structural design in which qualitative choices of shapes and materials rather than quantitative evaluations based on repeated structural analyses prevail, was soon recognised[1] [2] especially for those structures,such as bridges and tall buildings ,which are both important and thus require a careful evaluation and selection of types ,and can be classified using limited and well defined structural schemes and components.
These projects ,in analogy with KBES prepared for other fields,and often using "general purpose" shells,use inference mechanisms based on deductive processes(forward and backward chaining).
In the approach which will be presented here a different approach was adopted,in which knowledge is described in the form of "models" and an abductive inference mechanism is used[10].
The resulting expert system,named EXSTRUCT, is described in the following paragraphs.
A particular version of it,devoted to the preliminary design of bridges and named EXBRIDGE2 is described in some detail in [8]

2.GENERAL CLASSIFICATION OF STRUCTURES

The first step in the preparation of an expert system for structural design is the definition of structural types among which a selection must be made in the preliminary stages of the design process.This definition is an uneasy task and,given the enormous variety of structural shapes and layouts which can be used in practice,could never be complete and entirely satisfying.
For some categories of structures this task can be made easier by the fact that in most cases the structural types are well defined and limited in number.Such is the case of bridge structures and tall buildings[1][2][3][4][5].
All this considered,it seems useful to determine a broad classification of structural types which can include most of those structures whose design requires a careful attention,especially in the initial stages,when critical decisions concerning selection of construction materials and structural types need be made.These structures,excluding some very specialized kinds such as dams,reservoirs,retaining walls and so on can be classified in three broad categories(see fig.1):
1)Structures whose most important elements lie essentially in a vertical plane;this is the case of bridges:the main structural elements to be designed are decks(horizontal layout) and piers(vertical layout)
2)Structures whose most important elements lie essentially in an horizontal plane or whose dimensions in the two horizontal directions prevail on the vertical one.This is the case of long span low rise buildings,such as industrial buildings,multistoreys parking lots,assembly and sports halls.The main structural elements in this case are floors ,roofs and theirs supporting beams(all horizontal or sub horizontal elements)
3)Structures whose elements must constitute a system capable of resisting strong horizontal actions.
This system is composed of frames,shear walls,tube elements,braced frames connected by floors and is contained in a 3d space.This is the case of tall buildings and seismic structures.
Of course there are some cases which lie somewhere between situation 2 and 3.
Collection of data pertaining to these categories is now under way as a part of this research project.

3.ADOPTED "MODEL ORIENTED" APPROACH TO EXPERT SYSTEMS IMPLEMENTATION

According to the definition given by Faltings[10] a model is a rule where the premise contains the cause and the conclusion the consequence of that cause(fig.2).In the case of design the cause represents the choice of a given structural component,layout or structural type,the consequence one of the predicted behaviours of that choice .
The relationships among causes and consequences can be represented in a given design space by a graph(fig.2) in which the joints Ci represent the choices to be made,the joints Rj the predicted behaviours,the arrows the models connecting choices and behaviours.
Therefore the knowledge base can be graphically represented by a network of joints and arrows as the one represented again in fig.2.
It is easy to observe that,while, given a choice,all the behaviours corresponding to that choice do occur ,given a behaviour,there are in general more than one choice which can alone produce it.

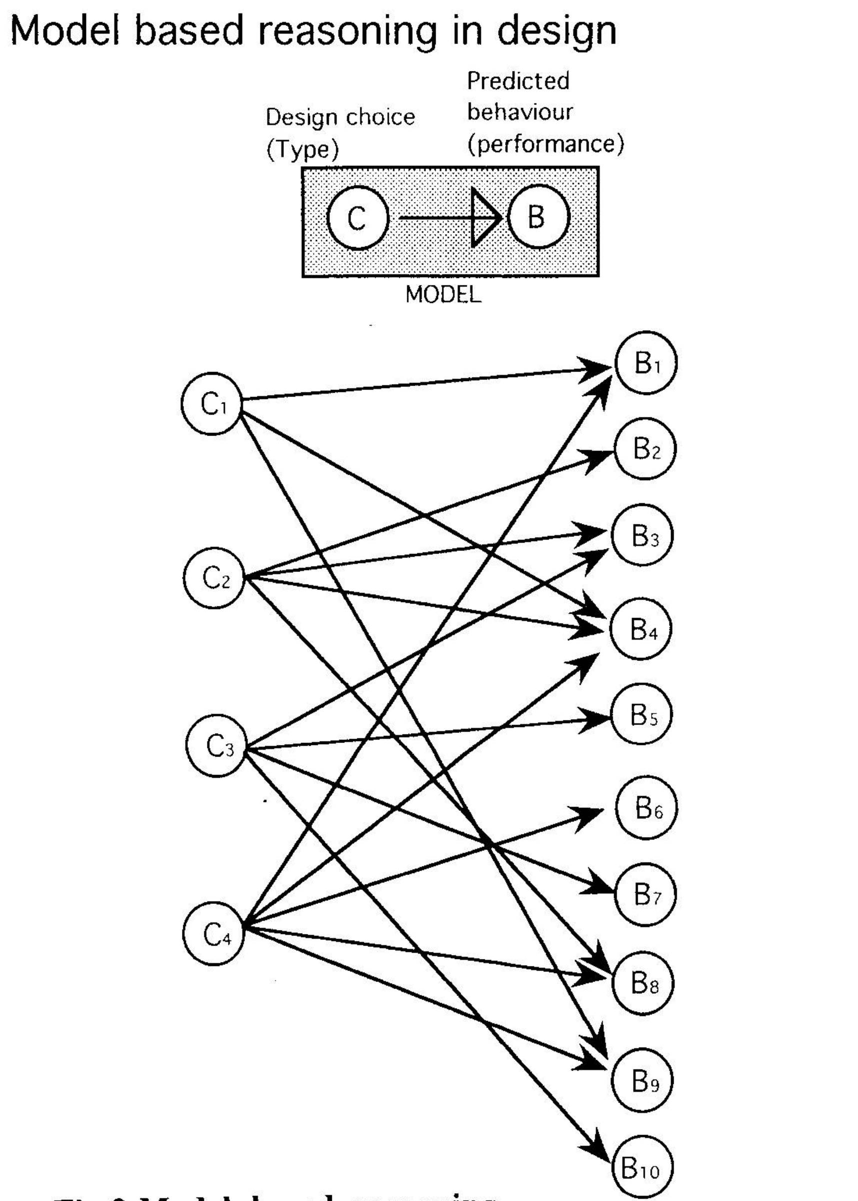

Fig.2-Model based reasoning

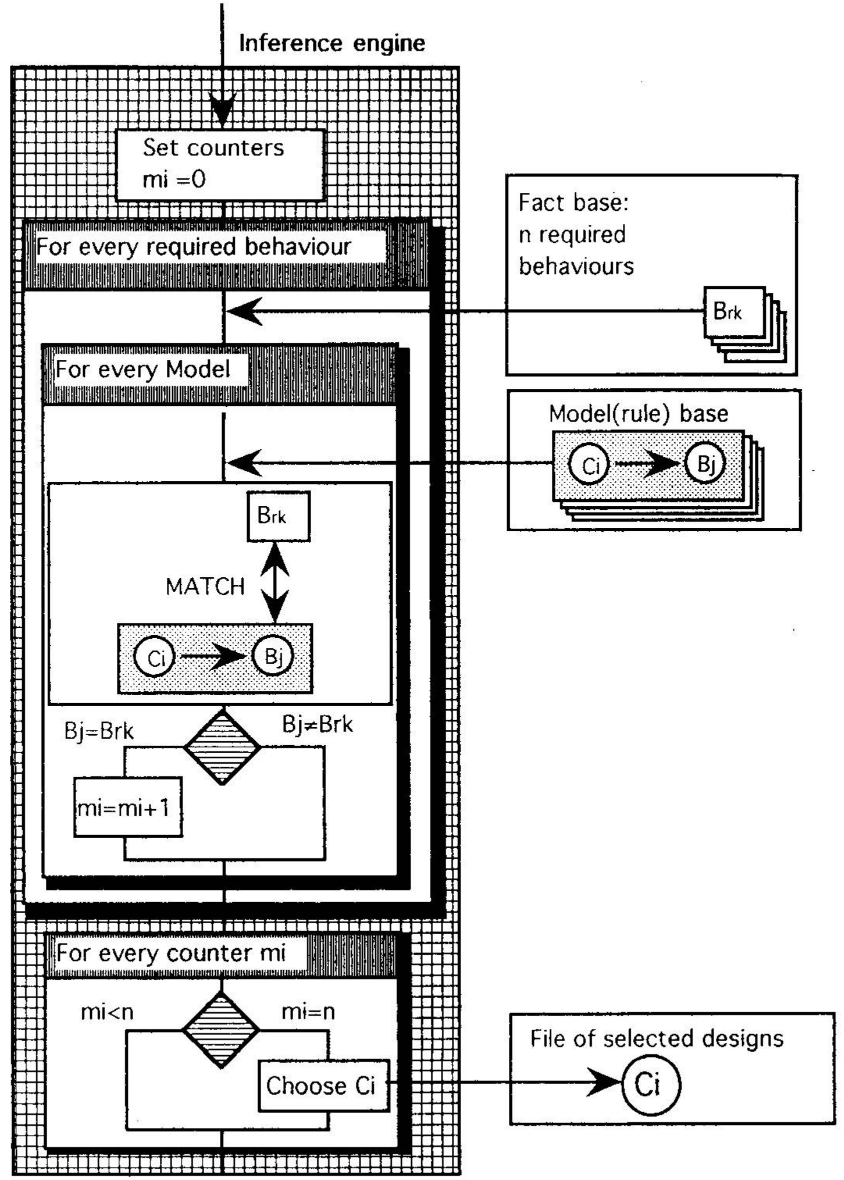

Fig.3-Abductive inference mechanism

The heuristic abductive problem which needs to be solved in the case of design is the following:
-Given a set of known required behaviours(performances)(F1,F2,.....Fk) derived by given boundary conditions ,and the corresponding functions to be fulfilled,determine the set of choices (C1,C2,...Cj) whose predicted behaviours match all the required behaviours and therefore permit to fulfill all the needed functions.
For what has just been said,the choices are not unique and therefore the non univocal,ambiguous nature of design is correctly simulated.
It is at this point up to the designer to choose,somewhat arbitrarily,one of the selected solutions,which are all reasonable as they comply to the boundary conditions.
The inference procedure,which is schematically represented in fig.3 can be briefly described as follows:
-Models are extracted from the knowledge base one by one.
-For each model predicted behaviours(conclusions) are matched against required behaviours(derived from boundary conditions)
-If the predicted behaviour of the model under consideration matches one of the required behaviours,a counter corresponding to the choice(premise of the model)is incremented by one.
-At the end of the process,all the choices whose predicted behaviours match all the required performances(that is whose counter matches the number of required preformances),are considered possible and reasonable designs among which the final selection can be made.
This procedure can be refined according to the procedure illustrated in[8] .
The design space is theoretically unlimited, being unlimited the number of possible structural types,components and layouts[1*] .
However,in the field under consideration, it is quite reasonable to reduce the possible choices to a limited number of well defined types,whose association,composition and sizing can generate a "prototype" design.
In this way the space to explore is limited and the type of design can be considered as a "routine" design according to the classification given by Gero[5] in the sense that both functions and possible types are well defined (It is not certainly however a routine design in the common sense of the word!).
The design space can be furtherly reduced by the fact the design process of a complex "artifact" such as a civil structure can be considered as an assemblage of well defined modules and must be executed in different steps which are,to some extent,independent from one another.
We can therefore divide the generic design space in a number of "specialized" design spaces according to a procedure which can be defined as"top down refinement plus constraint propagation"[11]as it will be explained in the next paragraph.

4.MODULAR NATURE OF STRUCTURAL DESIGN

The process of preliminary structural design can be divided in the following phases:
-Definition of basic boundary conditions
-Definition of general required behaviours(specifications)
-Definition of basic layout
-Definition of shapes
-Preliminary Sizing
-Preliminary quantities and costs evaluation.
The first two phases constitute the formulation of the problem and require the use of deductive processes.
The following three phases constitute the design part of the process and can in turn be divided in a number of "levels" as specified in fig.4
Each level can be processed in an independent way,with its own design space,proceding from top levels down to the lower ones(that is from more general design choices to increasingly more detailed designs)provided that specifications directly deriving from choices performed at the preceding

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*collectively called "structures" in ref.[5].We won't however use this term to avoid confusion with the term structure,intended in the proper sense.We use the term "choice" or "type"instead.

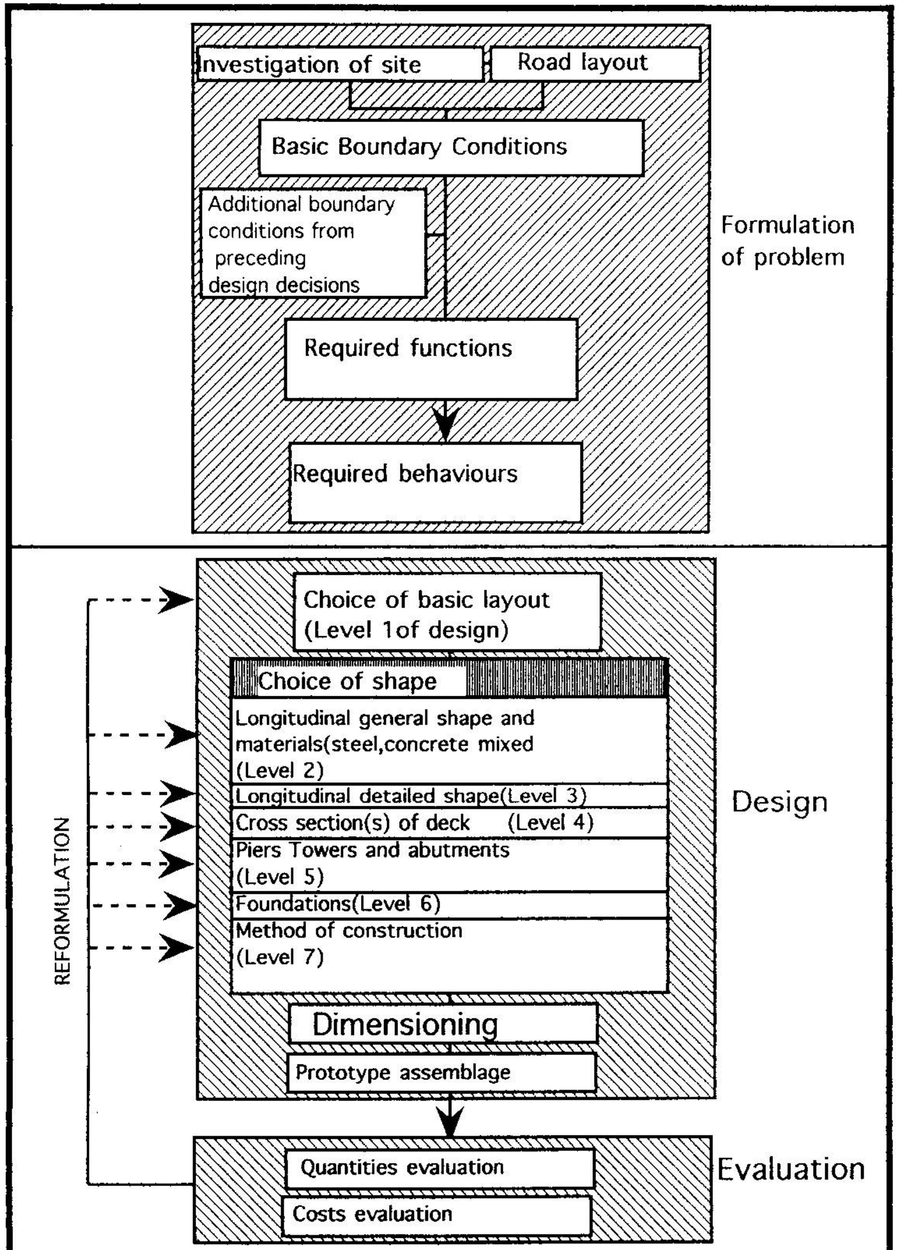

Fig.4-Levels of design in the case of bridges

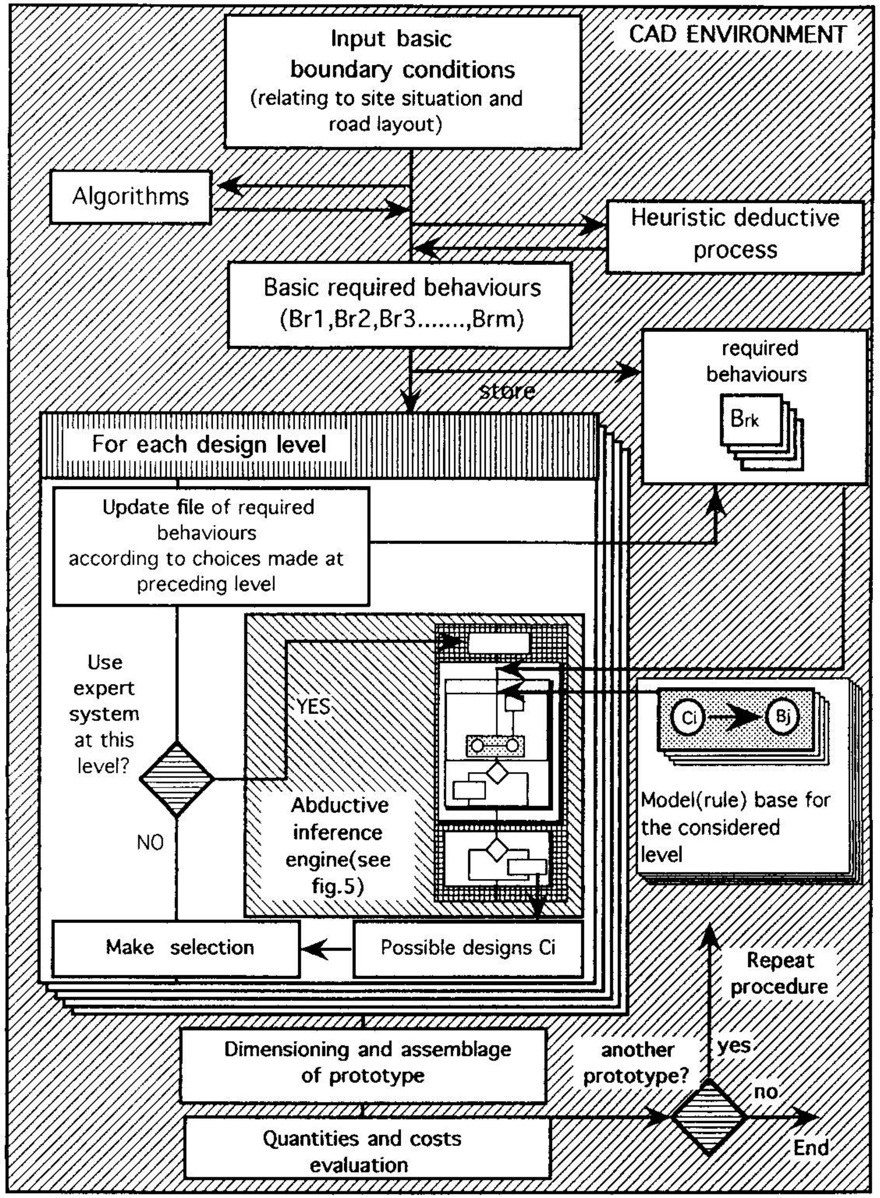

Fig.5-Macro flow-chart of the system

levels are added to the general specifications of the problem to be processed (by an abductive inference engine) at the level under consideration.
The preliminary sizing phase does not utilize procedures of Artificial Intelligence but rather statistical data transformed into suitable diagrams,and logical considerations related to the shape and compatibility of the chosen parts of the design,and also "rules of thumb" derived by common design sizing practice.
Once the various parts of the design are dimensioned they can be assembled in a "prototype" design which ,although generical,stereotypical and not detailed,should contain enough information for the evaluation process of the chosen structural type which must follow.
At last the quantities evaluation,obtained by using a spreadsheet associated with each part of prototype design which automatically update itself as dimensions are changed,provides an analytical mean of computing expected costs.A more syntetical mean would be provided by manipulation of parametric statistical data concerning costs extracted by a number of similar executed designs.
The choice and sizing of structural types and components,as well as their manipulation and assemblage in prototype designs is greatly facilitated if the system is programmed within a CAD system which can provide an enormous amount of graphic functions and facilities.This is made possible by the use of programmable CAD environments such as AUTOCAD™ and MINICAD™.
Let us at this point consider with some detail the nature and the tasks to be performed at each level,illustrating the process with an hypotetical design example.

5.DEFINITION OF BASIC LAYOUT

The first level of design concerns the determination of basic layout of the structure. In the case of bridges five types of basic layouts have been determined,in which most of the possible cases can be included.
The determination of the layout type and the values of spans can be determined taking as input data the basic required behaviours deduced from site situations and the road or railway layout.
In the given example,concerning the preliminary design of a cable-stayed bridge and schematically illustrated in fig.6, the inference procedure leads to the choice of two layouts between which the layout consisting of a large central span with two lateral smaller ones was selected.

6.DEFINITION OF SHAPE

The complete individuation of the bridge shape is accomplished in the next six levels:
The second level concerns the determination of the general longitudinal shape(structural scheme) ,which is associated closely with the choice of the construction material.
A simplified set of rules for this level is represented on fig.7,whose only purpose is to illustrate the logics of the process without any pretension of being complete.
To make these choices the specifications deriving from the preceding level are added to the basic specifications .
This procedure will be repeated in the following levels,every time a given choice increases the number of boundary conditions to be accounted for.

The third level concerns the refinement of the longitudinal shape .In the given example,this refinement consists in the choice of arrangement of the stay cables.
From this stage downwards the choices are being made among well defined components of the design which can be parametrized.
The fourth level concerns the choice of the type of deck cross section
The fifth level concerns the choice of vertical supports(towers,piers and abutments).
The sixth level concerns the choice of foundation types.
At last the seventh level concerns the choice of construction method
In the scheme of fig.6 the path which was followed for the given example,as well as the possible alternatives which could have been reasonably chosen are illustrated.

7.SIZING AND PROTOTYPE ASSEMBLAGE

At this point the general shape of the bridge and of its main components is clearly defined.

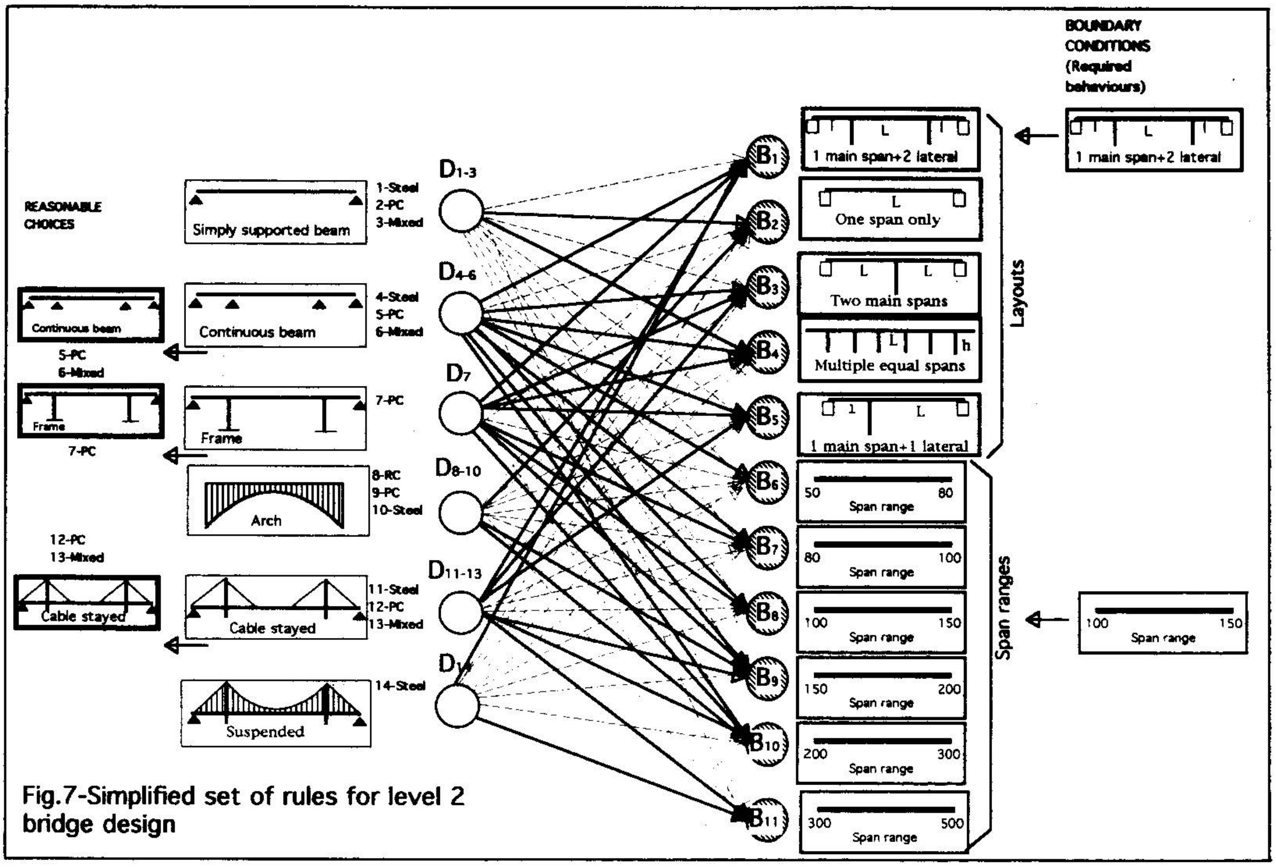

Fig.7-Simplified set of rules for level 2 bridge design

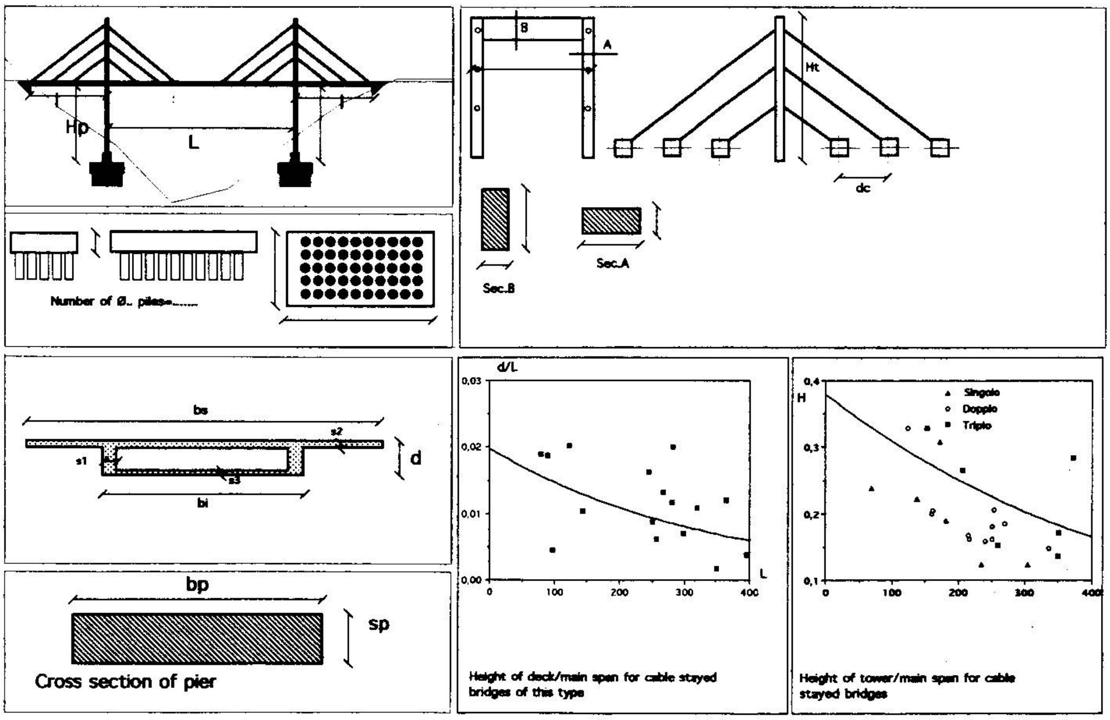

Fig.8-Preliminary dimensioning

To evaluate the obtained design and,in case,to perform preliminary structural analyses on it,it is needed to complete the definition of dimensions.
The sizes needed to univocally determine the project can be divided into four categories:
-Sizes which are defined from the beginning(for example the deck width) or as a consequence of the basic layout choice(the length of the spans,the height of piers)
-Sizes which can be defined statistically by comparison with designs of about the same shapes and span length.
-Sizes which can be determined using empirical "rule of thumb" rules in function of the already determined shapes.For example the depth of th web in a beam can be established in function of its height.
-Sizes which are established to insure compatibility between connected parametrized parts of the design.
Using these criteria the parts of the bridge are completely defined and can be assembled in a "prototype" on which the design evaluation can be performed .
The "sizing" process is schematically represented on fig.8

8.MACRO FLOW-CHART OF SYSTEM

The self explanatory macro flow chart of the system is represented on fig.5.
It can be divided into three parts according to the functions to be performed:formulation ,design and evaluation.
It is interesting to notice that,at each design level the use of the inference engine is not mandatory,but the design choice can be made directly in those cases where the knowledge base is not considered sufficient,reliable or it lacks completely;it is thus possible to use the procedure even when the collection of knowledge is far from complete.

9.CONCLUSIONS:ADVANTAGES OF CHOSEN APPROACH

The advantages of the chosen"top down refinement plus constraints propagation" approach can be summarized as follows:
-The division of design and therefore of the knowlege base in different stages both simplifies the formulation of rules and reduces the number of operations to be performed by the inference engine at each stage.
This approach also has drawbacks in the sense that the exploration of different and to some extent independent design spaces can lead to disregard some connections among the different stages;however the fact that design proceeds hierarchically"top down" that is,from general to more particular problems permits to conclude that the design spaces at the lower levels are in some way included in those at the upper ones (and therefore their rules do not normally contradict those at the upper levels).In other words it is assumed that "strategic" choices do influence more particular ones while it seldom happens that a particular decision can invalidate a strategic choice.Also the procedure is usually an iterative one,in the sense that it is repeated several time to get a number of possible design among which economical comparisons can be made.During this process possible contradictions can be detected and eliminated.
-The abductive approach to models elaborations does not eliminate artificially the inherent ambiguity of the design process and permits to obtain not a single but a range of possible designs.In this way the creativity of the designer is ,even at this stage, inhibited only to the extent that absurd or irrational choices can be avoided.
.The final decision stems from the comparison of these designs,which can be obtained quickly,with a sufficient degree of detailing to make these comparisons highly meaningful and reasonably objective.
-The inclusion of the process in a CAD environment which can be performed easily ,given the availability of programmable CAD systems,permits to interact graphically with the system in a very intuitive and clear way,avoiding lengthy and ambiguous descriptions of results.
-The modular nature of the process permits to skip some of the stages by directly making the decision at those stages.
In this way the system can be usefully exploited even if the model base is far from complete.
We could conclude saying that this framework works both for general purpose and for specialized Expert Systems devoted to design.

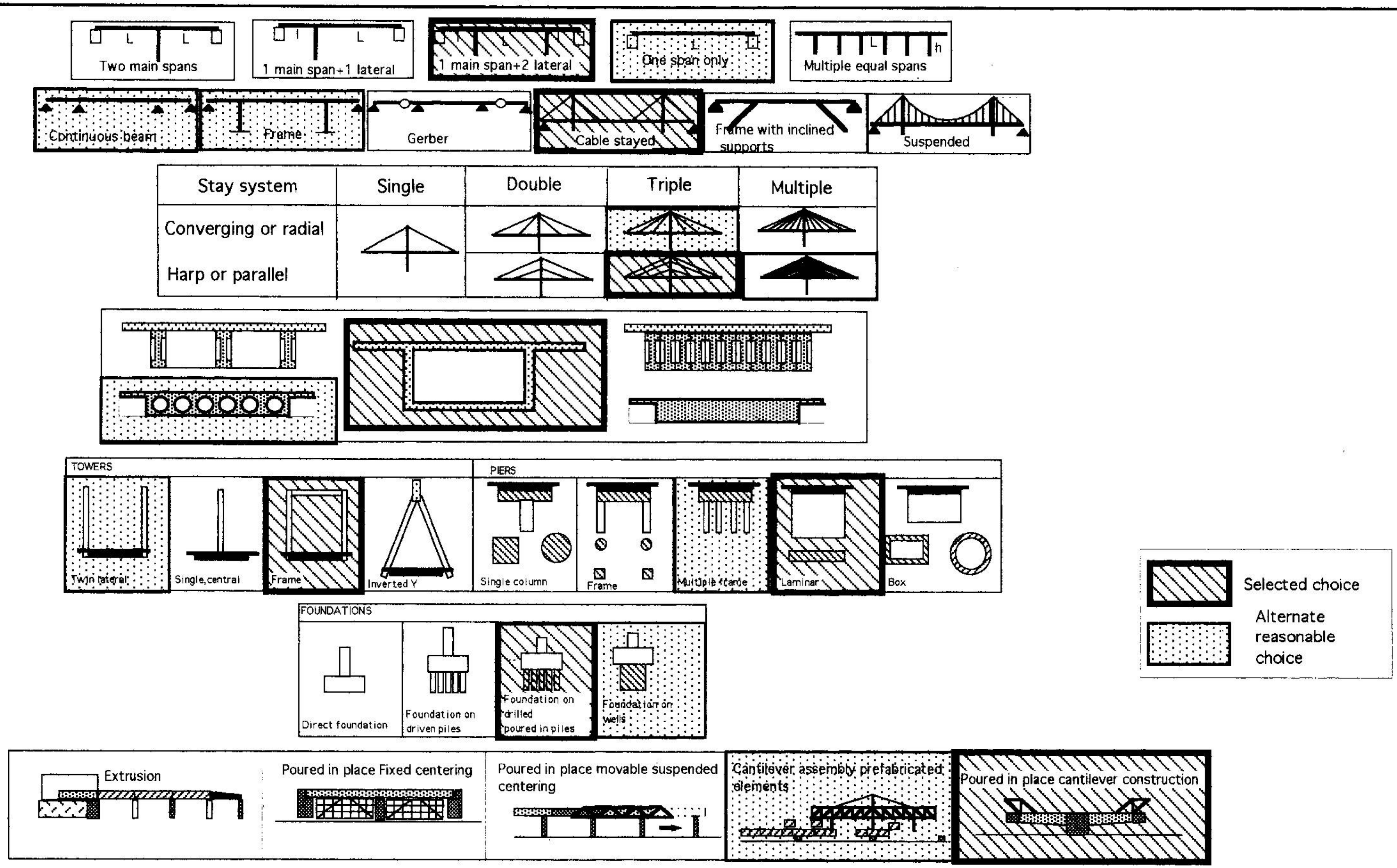

Fig.9-Example of bridge design

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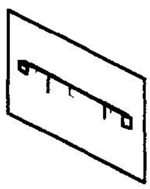
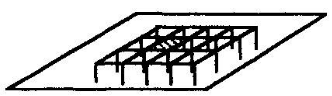
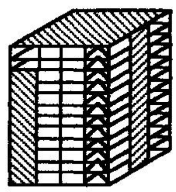
GROUP	MAIN STRUCTURAL ELEMENTS	TYPE OF CONSTRUCTION
 1	DECKS (and their supporting structures such as arches and stays) PIERS	BRIDGES OVERPASSES
 2	FLOORS ROOFS (and their supporting beams)	INDUSTRIAL BUILDINGS ASSEMBLY HALLS SPORTS HALLS MULTISTOREY PARKINGS etc
 3	ALL THE LATERAL FORCES RESISTING 3D SYSTEM	TALL BUILDINGS SEISMIC STRUCTURES

Fig.1-Groups of structures according to given classification