PRELIMINARY DESIGN OF A CONSULTATION KNOWLEDGE-BASED SYSTEM FOR THE MINIMIZATION OF DISTORTION IN WELDED STRUCTURES

by

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ABSTRACT

The problem of distortion due to welding has been the subject of continuous research since the early days of ship construction. The control of distortion in welded structures through preventive and corrective procedures is generally well established. However, as with most engineering problems, there are "rules–of–thumb" knowledge, or heuristics, which streamline the design process and enhance the performance of the final product. Those rules–of–thumb are usually known to a few experts who, through their own personal involvement and experience over the years, have accumulated considerable knowledge in their field.

This thesis proposes to demonstrate the feasibility of implementing such knowledge in a knowledge–based environment. The preliminary design of such a system for the minimization of distortion in welded structures is presented through its development phases. The specific areas of "out–of–plane" and "buckling" distortions are considered. The report consists of three major parts.

- Part I describes the distortion problem, the selected tools for its analysis and the current procedures for its prevention and correction;
- Part II introduces the concepts inherent in knowledge–based systems and their applications in the fields of structural design and welding; and
- Part III presents the preliminary design of DISCON (for DIStortion CONtrol) which includes the derivation of functional specifications as well as a suitable architecture for implementation.

ACKNOWLEDGEMENTS

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To my parents who are always with me in spite of the distances.

To God, whose light can be seen by all who dare to look up and receive without precondition, and for his inestimable Love.

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CHAPTER 1. INTRODUCTION

1.1 Background

An important technical problem associated with welding fabrication is that related to distortion. The intense heat produced during welding causes transient thermal stresses in regions near the heat source. When welding is complete, residual stresses remain and various types of distortion are produced. These stresses and distortions translate into defects which then require corrective action or rework. Within the context of shipyard operations, increased productivity would result subsequent to resolution of this problem.

From the viewpoint of structural designers and welding engineers, control of these imperfections is a major concern because of the adverse effects they have on the load–carrying capacity of welded structures. There appears to be, however, little evidence of distortion analysis in the design stage of structural component fabrication. Moreover, as indicated by numerous investigations into shipyard operations, distortion is usually considered "after the fact" when welding is complete and corrective measures are required. It is often the case that shipyard production shop personnel will avoid the time consuming task of applying post–weld correction techniques and select the option of welding a new structure instead. It would seem reasonable to focus our strategy on preventive techniques rather than rely on a purely corrective approach which, from a cost standpoint, is unacceptable. In this context, it is suggested that an integration of the welding distortion problem be implemented early in the structural design stage.

Knowledge about distortion is largely restricted to the research and academic

institutions and is rarely considered by designers and fabrication specialists for that reason. The problem of distortion is not amenable to simple accuracy–control techniques; it is known to be determined by material selection, heat distribution and residual stress distribution. It is therefore somewhat predictable or deterministic. If an extensive effort could be made to codify heat distortion prediction and minimization so that it can readily be used as a design and production tool, then shipyards would witness significant reduction in rework–type costs.

Considerable information on the topic of distortion has been accumulated over the years in relation to welded structures. Professor K. Masubuchi's book entitled Analysis of Welded Structures [30] is the most detailed and comprehensive document covering the issues of residual stresses, distortions and their consequences. Although much of the knowledge on this subject is expressed in algorithmic form (analytical models, finite element programs, etc.), knowledge is also available as experimental data (empirical knowledge) in the form of tables and graphs. Additionally, much of the information on distortion falls in the realm of experience, skills or "know–how;" this heuristic knowledge is generally unavailable to the public and is stored in the minds of "experts" in the field.

During the last decade, considerable progress has been made in the development of systems which capture the knowledge of such experts. These Expert Systems, or Knowledge–Based Systems[1], differ from the usual computer programming techniques in their ability to "reason" the solution to problems, and their capacity to handle incomplete knowledge. Most problems currently solved by computers have a purely algorithmic solution; the method of solving is well known and can be specified easily in a conventional programming language. Some problems, however, cannot be solved so easily. Many can be solved only by using heuristics, or rules of thumb. An

[1]These two terms are used interchangeably.

example might be the integral of a complex equation for which the solution is not known. There is no well defined algorithm to determine which method to apply. Instead, the integration is performed using trial and error guided by the experience gained in doing previous integrations. It is this important characteristic of expert systems, that of including heuristics in the problem solving strategy, which results in their increased popularity.

1.2 Thesis Outline

The objective of this thesis is to demonstrate the feasibility of implanting knowledge about distortion in a knowledge–based system environment. The preliminary design of a consultation expert system for the minimization of distortion in welded structures is presented. DISCON, for Distortion Control, is a knowledge–based expert system which is intended to provide consultation services to design and fabrication engineers in the manufacture of welded structures with minimal distortion results. The system is designed to operate in two primary modes:

- As a Design consultant, it advises designers on the optimum relationship between a panel structure's geometry and its distortion result;
- As a Fabrication consultant, given the optimum geometry selected, it advises of the pre–weld and post–weld techniques for reducing distortion.

Because of their impact on both the shipbuilding and aircraft industries, the research focuses on the out–of–plane and buckling type distortions. Also, panel structures with longitudinal and/or transverse stiffeners are selected because of their widespread applications.

The report consists of seven chapters.

- Chapter one is the introduction.

- Chapter two describes the distortion problem; the areas of out–of–plane and buckling distortions, with their analysis tools and preventive and corrective techniques, are presented.
- Chapter three describes the nature of the distortion knowledge, its characteristics and sources from which it is derived.
- Chapter four discusses the need for knowledge–based systems as a viable environment for dealing with the issues of availability, systematization and prevention of distortion knowledge.
- Chapter five consists of a general description of expert systems and their particular applications in the fields of structural design and welding.
- Chapter six presents the preliminary design of DISCON, a knowledge–based system for the minimization of distortion. The design is carried through its development phases. Emphasis is placed on the derivation of the desired functional specifications, consultation logic and system architecture.
- Chapter seven is the conclusion and recommendations for future research.

CHAPTER 2. THE DISTORTION PROBLEM

The purpose of this chapter is to describe the distortion problem, its qualitative and quantitative characteristics. Its two most common forms, angular and buckling distortions, are presented in the context of both the design and fabrication of stiffened panel structures. The available analysis tools as well as the preventive and corrective procedures are delineated.

2.1 Distortion and Residual Stresses

The problem of distortion is related to the phenomenon of residual stress: the local nonuniform heating and cooling during welding creates complex thermal stresses and strains, leading eventually to residual stresses and distortion. These two phenomena are interrelated; a system of residual stresses may be modified or relaxed by permanent deformation or distortion [30]. On the other hand, any mechanical restraint imposed on free deformation of a welded joint affects the final state of residual stresses as well as the distortion. Residual stresses may be of yield point magnitude and when in service stresses are superimposed on residual stresses, local plastic flow and a small amount of permanent deformation will occur. If this condition is unacceptable within the finished tolerances of the structure, then corrective measures such as post–weld heat treatment will be needed to minimize the possible dimensional changes in service. In complex structures such as a ship, control of distortion during fabrication is important since major rework is normally needed to correct dimensions. The actual distortion is generally a combination of simple dimensional distortions such as angular, transverse, longitudinal and in many cases

buckling distortion. Consequently, any subsequent effort to minimize distortion is a difficult task at best and leads to excessive fabrication cost. Another problem area is the effect of distortion on the service performance and integrity of a welded structure. For instance, high residual tensile stresses in the region near the weld might induce brittle fracture, reduce the fatigue strength or accelerate stress corrosion cracking. Ironically, any repair work directed toward the elimination of weld defects often contribute to the distortion problem.

As a general rule, there are three fundamental dimensional changes that occur during the welding process to cause distortion [30,36]:

- angular distortion, characterized by rotation around the weld line;
- transverse shrinkage, perpendicular to the weld line; and
- longitudinal shrinkage, parallel to the weld line.

It is the above dimensional changes which produce the various types of distortion encountered in the manufacturing world. There are, however, two types which are most frequently observed, both in the aircraft manufacturing and shipbuilding industries: these are angular (out–of–plane) distortion and buckling distortion. The latter is observed when fabricating thin plate structures of less than 8 mm thickness [5], where the induced welding residual stresses cause the plate to buckle. When welding thick plate structures, the welding stresses cause angular distortion around the weld. Preventive measures can be applied to the structure prior to welding by presetting the joint either through elastic prestraining or plastic prebending techniques [30].

These two forms of welding distortions are analyzed in greater detail in the following section.

2.2 Out–of–Plane Distortion

Distortions are attributed to the plastic flow phenomena which take place when a material is heated nonuniformly. Out–of–plane distortion is caused by angular changes about the weld line. As discussed in reference [30], panel structures with fillet–welded longitudinal and transverse stiffeners often exhibit this type of distortion.

2.2.1 Influential parameters

Figure 2.1 shows the panel deflection, δ, which occurs when a typical panel structure is fillet–welded.

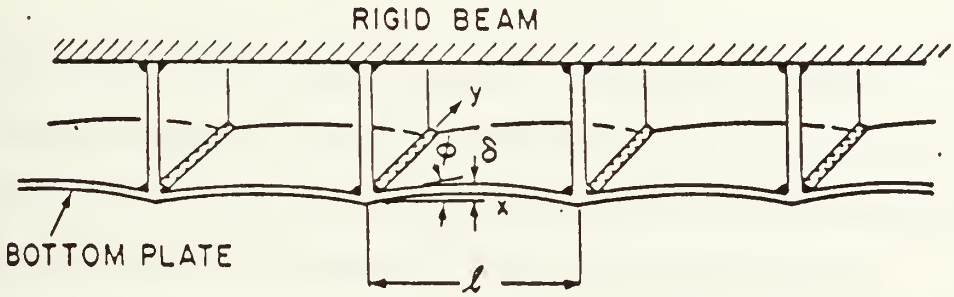

Figure 2.1: Distortion Due to Fillet Welds [30].

The amount of distortion observed is generally determined from the resulting interactions of the following parameters:

(1) The heat input associated with the welding process: the greater the heat input, the greater the likelihood of distortion.

(2) The degree of restraint in a structure: the amount of angular change in a restrained structure is smaller than that found in a free joint.

(3) The plate thickness: this factor is related to the plate's rigidity and Figure 2.2 describes, for a particular set of welding conditions, the

relationship between plate thickness and distortion in a steel structure.

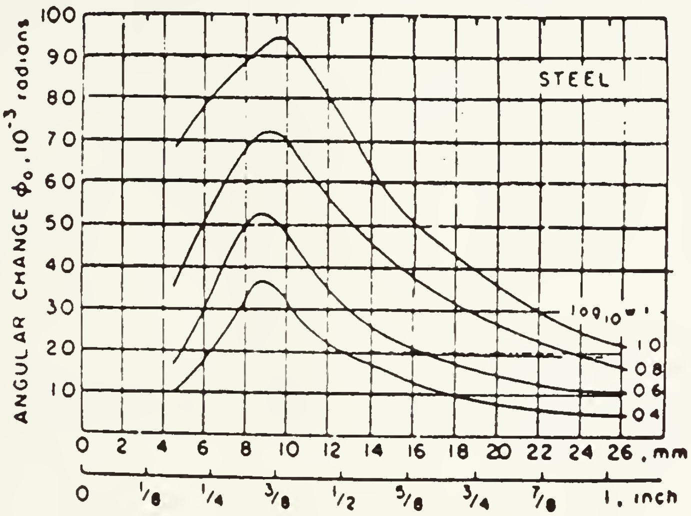

Figure 2.2: Angular Change of a Free Fillet Weld in Steel Versus Plate Thickness [30].

Above a critical value of plate thickness (approximately 3/8 inch), for which distortion reaches a maximum, the angular change decreases as the rigidity of the plate increases. Below this critical thickness the angular change decreases because of the smaller temperature differential between the top and bottom surfaces [36].

(4) The plate free span between stiffeners: as the free span increases, the value of distortion tends to increase.

(5) The size of fillet weld: reducing the size of fillet welds generally decreases the amount of distortion. Too little weld material, however, could affect in–service performance of the structure. Too much weld material could also significantly increase the overall structural weight to unacceptable levels (ship construction).

Experimental results [36] indicate the greatest impact on out–of–plane distortion of a panel structure to be caused by plate thickness, stiffener spacing and fillet weld size; this tripartite relationship is illustrated in Figure 2.3.

Additionally, out–of–plane distortion tends to reduce the buckling strength of

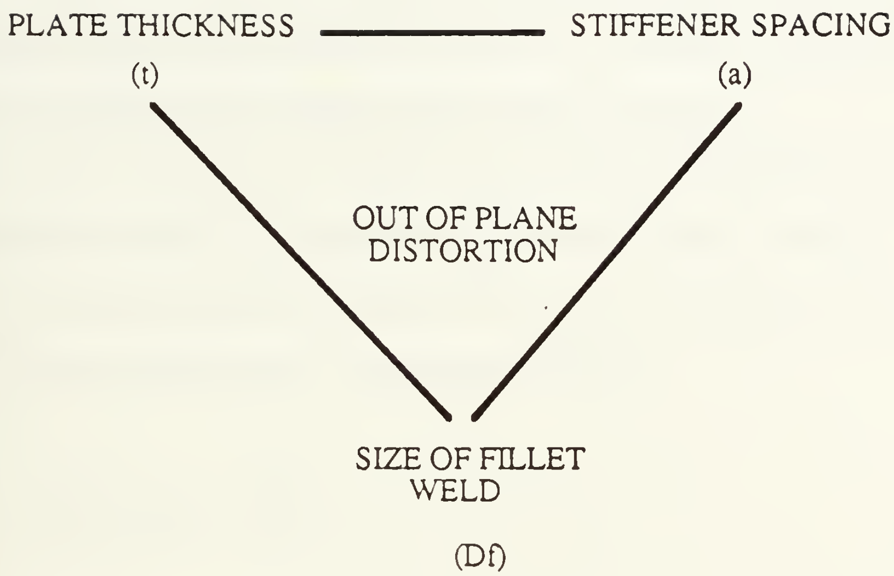

Figure 2.3 : Out Of Plane Distortion Tripartite Relationship

a panel; this condition could potentially affect the results of structural analysis performed prior to fabrication (i.e., in the design phase). It would appear reasonable, therefore, to include distortion analysis as early in the design process as possible.

2.2.2 Analytical formulations

It should be noted at this point that the interactions between these parameters are still not well understood. Analytical models developed at MIT [36] and elsewhere represent valuable tools for the evaluation of distortion. However, there still does not exist an accurate model which integrates these complex interactions.

Still in use today are the relationships developed by Masubuchi et al. [30] which simplify the analysis by assuming a rigid–frame stress condition. If the distortion of all spans are assumed equal and the size of all welds are the same, the distortion, δ, in the x–direction may be expressed as follows:

$$\frac{\delta}{a} = \left[\frac{1}{4} - \left[x/a - \frac{1}{2}\right]^2\right] \cdot \phi$$

where ϕ = angular change at a fillet weld, (radians)

a = length of span between stiffeners.

The maximum distortion is observed at mid–span and has a value δ_0 such that,

$$\delta_0 = \frac{1}{4}\phi\, a$$

Introducing the value of angular change observed in a free joint (Figure 2.4), ϕ_0, and the plastic rigidity factor, D:

$$\phi = \frac{\phi_o}{1 + (2D/a)(1/C)} \quad ,\text{(radians)}$$

where C is the coefficient of rigidity for angular change and is determined by welding conditions and plate thickness.

Furthermore, the fillet size, D_f, is related to the weight of electrode consumed per weld length, w (g/cm), as follows:

$$w = \left[D^2_f/2\right]\left[\rho/\eta_d\right] \cdot 10^{-2}$$

where ρ = weld metal density

η_d = electrode deposition efficiency.

D_f, the fillet size, is commonly used in design work, while w is determined experimentally.

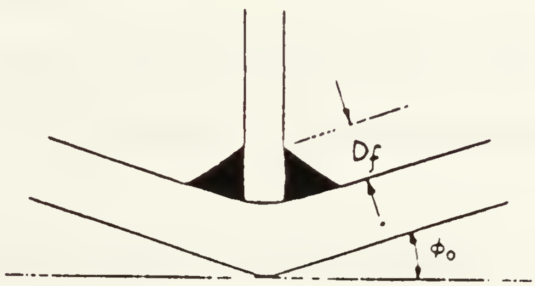

Figure 2.4: Angular Change of Free Fillet Weld [30].

The values of out–of–plane distortion as a function of plate thickness, span length and fillet weld size are shown in Figure 2.5 for both steel and aluminum

experiments.

It should be pointed out that two–dimensional models for the analysis of out–of–plane distortion exist. These models use finite element methods and have been refined over the years providing better correlation with experimental results; Professor Masubuchi's book details the use of these models and should be referred to for further study[1].

2.2.3 Distortion reduction techniques

Several techniques are used in reducing out–of–plane distortion. They include:

(1) Clamping of panels, particularly near the free edges. This is a type of external restraint often used in fabrication. The joint is usually welded under restraint and then the restraint is relaxed after welding is complete. Elastic prestraining and plastic prebending are two general restraining procedures used to reduce distortion.

(2) Preheating. Preheating the back of the plate has been shown to be more effective than preheating the front of the plate. The "differential heating technique" is discussed in Masubuchi's book.

(3) Optimize the structure's geometry with respect to plate thickness, stiffeners spacing and the fillet weld size. The relationship between these parameters was discussed earlier.

(4) Select welding processes with less heat input. This can be done by controlling welding current and/or the travel speed. High travel speeds associated with the electron beam and laser welding techniques reduce distortion appreciably. Finer electrodes are preferred for lower travel speeds because of the smaller weld pool and the inherently lower heat input. Similarly, larger diameter electrodes should be

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[1]As will be seen in the design of DISCON's consultation logic, the selection of the appropriate analysis model for the specific task is most important.

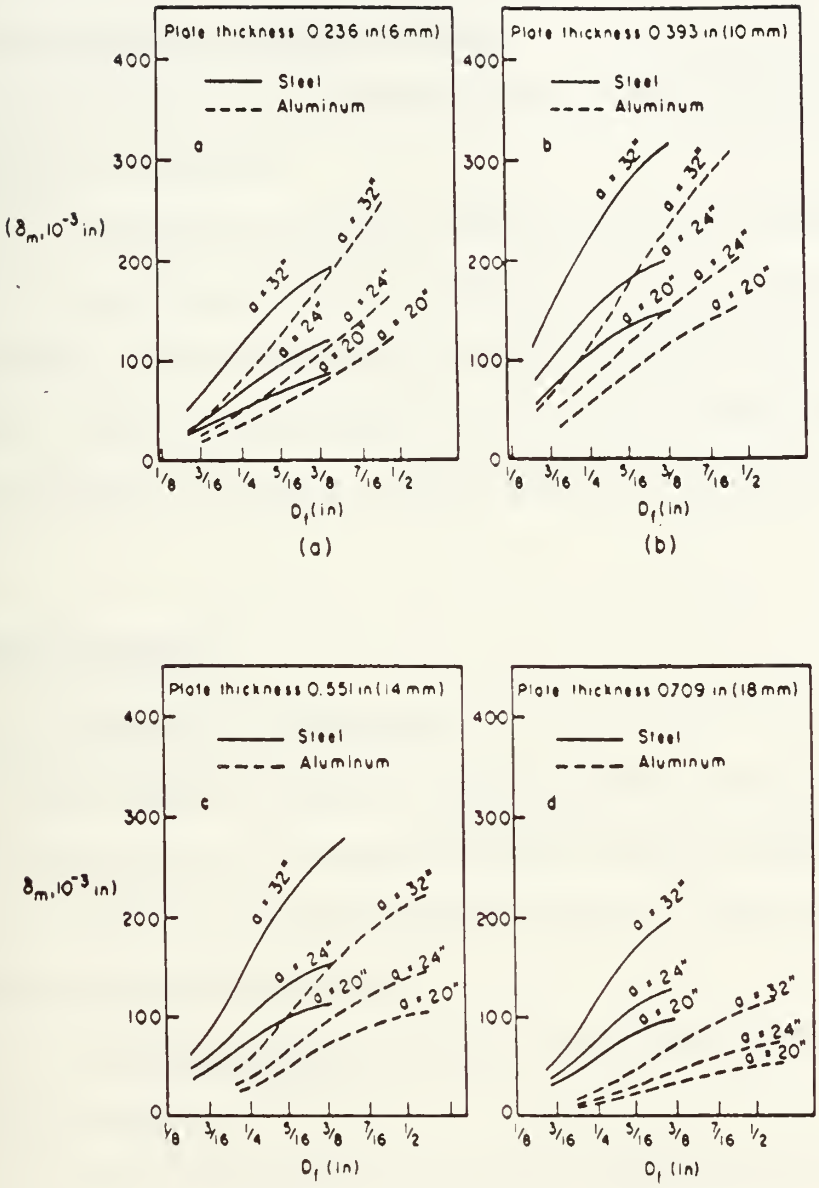

Figure 2.5: Out–of–Plane Distortion, δ_0, As a Function of Plate Thickness, t, Span Length, a, and the Size of the Fillet Weld, D_f, for Steel and Aluminum [30].

used with high travel speeds to provide the weld material required. Also, electrode extension effects can be used to reduce the welding heat input [5].

2.2.4 Distortion correction techniques

Again Masubuchi's book describes several techniques for removal of distortion after welding has taken place:

(1) Straightening techniques. The Plate is heated at selected points (spot heating) or along designated lines (line heating), and then is water–cooled. Other techniques such as pine–needle heating, cross–direction heating are also used.

(2) Stress relieving techniques and the use of an electromagnetic hammer are also used extensively. Discussion of these techniques is available in reference [30] for details.

2.3 Buckling Distortion

2.3.1 Effects of key parameters

When welding thin plates, the residual stresses resulting from the process can cause the plate to buckle. This occurs under three circumstances [30]:

(1) The actual welding heat input exceeds a critical value determined by plate thickness and free span length.

(2) The plate thickness is below a critical value determined by heat input and length of free span.

(3) The length of free span exceeds a limit determined by heat input and plate thickness.

Figure 2.6 shows the tripartite relationship just discussed. A similarity between influential parameters can be made between out–of–plane and buckling distortion. However, the critical parameter in the buckling distortion analysis is the heat input; residual stresses are equally important and are related to it. But because

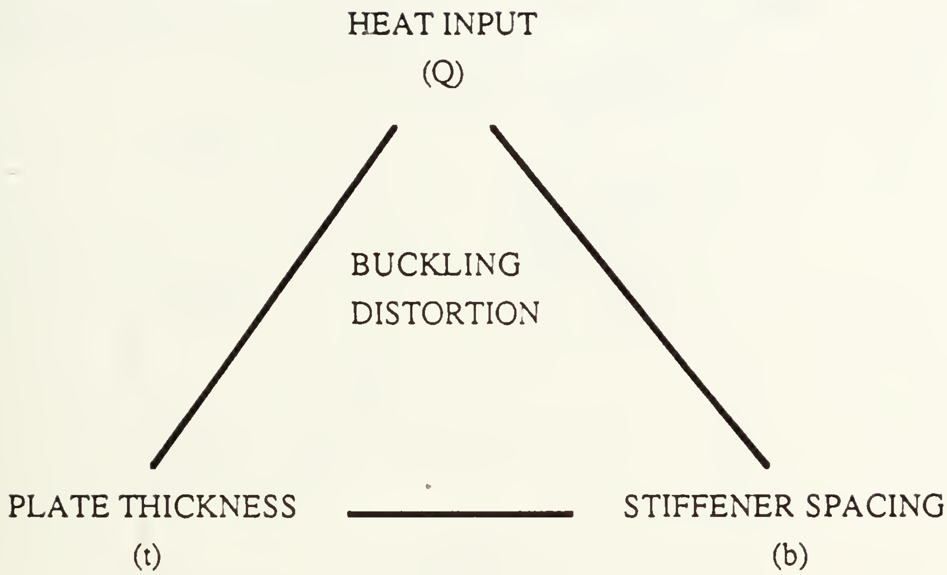

Figure 2.6 : Buckling Distortion Tripartite Relationship

heat input is a welding process parameter, its effect on buckling of thin plates is easier to observe and measure experimentally.

2.3.2 Critical heat input estimation

Experimental results clearly indicate the existence of a critical buckling heat input for a given test condition. Figure 2.7 indicates that the critical buckling heat input decreases as plate thickness decreases and the free span increases.

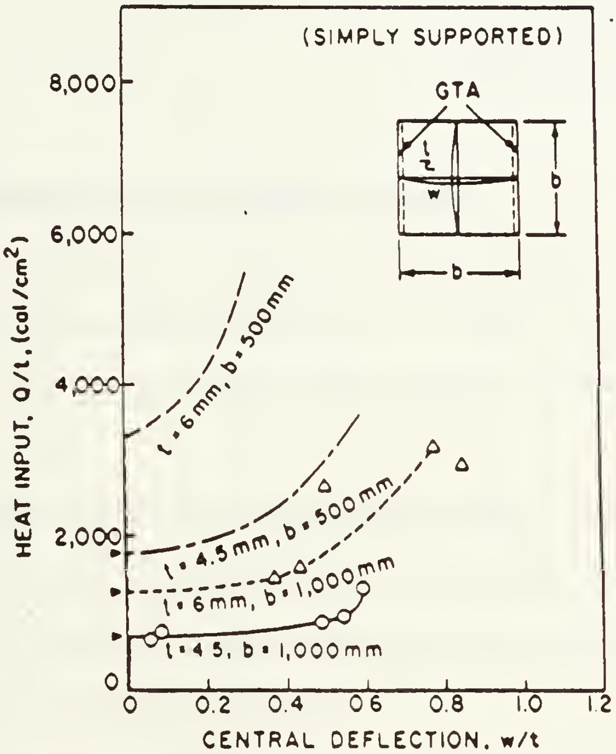

Figure 2.7: Relationship Between Heat Input and Deflection [30].

Experimental results obtained at Kawasaki Heavy Industries, Japan, for specimens tested under various conditions [29] provide a conditional relationship for the occurrence of buckling distortion:

$$H_{cr} = \frac{Q_{cr}}{t^3}(a) \geq \text{Approximately } 4 \times 10^5 \text{ cal/cm}^3$$

where H_{cr} is called the critical heat input index and a is the span length, t the plate thickness. Q_{cr} is the critical heat input for welding and is matched against the anticipated heat input to be used for welding. The heat input is calculated by using the simple relation:

$$Q = \frac{V \cdot I}{v}$$

,where V = voltage

I = amperage

v = arc travel speed.

2.3.3 Buckling distortion reduction techniques

For a given structure, there exists a critical buckling load which is normally identified in the structural analysis portion of the design. The key for reducing this type of distortion is to keep welding stresses below this level. Several options are available:

(1) Minimize residual stresses formed during welding by controlling the in–process parameters, specifically heat input. This is done by welding less, applying less heat, controlling the travel speed or removing the heat produced by using backing plates, chill bars or water cooling techniques.

(2) Use well documented stretching and heating techniques, such as those developed at Kawasaki Heavy Industries and described in Masubuchi's book:

(i) SS method – straightening by stretching

(ii) SH method – straightening by heating

(iii) SSH method – straightening by stretching and heating.

This chapter was intended to familiarize the reader with the problem of distortion through the examples of out–of–plane and buckling distortions. This

introduction is necessary, if anything, to point out the following:

- Distortion is a complex problem, not easily modeled with current techniques of analysis;
- This complexity issue requires us to narrow the domain of analysis to the study of specific types of distortion (i.e., out–of–plane and buckling) for which considerable experimental–type knowledge is available;
- There is a clear relationship, in the case of panel structures, between a structure's geometry (e.g., plate thickness, stiffeners spacing), the conditions under which it is welded and their effects on distortion.

CHAPTER 3. THE NATURE OF DISTORTION KNOWLEDGE

The types of knowledge which characterize the distortion domain need to be identified before a knowledge representation formalism can be selected. Perhaps this process can best be highlighted by describing a scenario in which the various components of that knowledge are articulated; the scenario is that of the design and fabrication of a panel structure which includes distortion in its analysis.

3.1 Scenario

The design begins by considering the particular loading conditions the structure is likely to encounter; these are determined from either previous similar designs or the requirements of a particular operating environment. These loads may be independent or combined. The materials to be used are selected on the basis of their metallurgical and physical properties such as ductility, yield without fracture characteristics, etc. The knowledge of the failure mechanisms is established and analyzed. An initial structural configuration is chosen and accompanied by its preliminary sizing. The tools for structural analysis such as numerical analysis techniques, finite element programs, stress–strain curves and analytical models are selected and tailored to the problem. Also, the constraints imposed through codes and regulations (e.g., ABS rules, etc.) are included in the analysis. For example:

> The stiffness on a plate subjected to combined loading shall be designed to resist a destabilizing axial load defined by:
>
> $$N_x = J_x (A + St) + C_{tst}$$
>
> where Q = d–.2, but not less than 0 and not greater than 1.0 [10].

Then, the stress and strength analysis are performed on the preliminary structure using the available tools. Given a set geometry, in itself an output of the structural analysis described above, a distortion analysis is made with assumptions about welding processes anticipated in the fabrication stage. Based on empirical and analytical knowledge, approximate values of distortion are derived and matched against standards of allowable deformation. If acceptable, the geometry is fixed and a fabrication methodology is invoked. In this fabrication stage a welding procedure is written which includes specifications of the welding method, welding process, etc. To reduce the possibility of out–of–plane distortion, a clamping technique is used because the angular distortion of a fillet weld decreases as the degree of restraint increases, and the induced distortion is reduced. This is true because of the following relationship.

$$\phi = \frac{\phi_0}{1 + (2D/a)(1/C)}$$

where D is the plate rigidity and ϕ is the angular change of a fillet weld. ϕ_0 is its value in a "constrained–free" condition.

The welding parameters specified in the welding procedure have causal effects on distortion. Because a lower heat input generally translates into a weld with less distortion, processes such as electron beam and laser welding should be considered. Also, in the selection of electrodes, those with a large diameter generally results in less shrinkage.

Welding takes place by attempting to control those welding parameters which affect distortion and weld quality; these are amperage and travel speed, all related to heat input. When welding and cool–down take place, the structure is inspected for defects. If distortion is detected and found to be unacceptable, then various correction

techniques, discussed in Sections 2.2 and 2.3, are applied as necessary to avoid rework.

Although procedural by design, the above scenario illustrates how different types of knowledge are put together to design and fabricate a particular structure. A more detailed breakdown is necessary.

3.2 Types of Distortion Knowledge

3.2.1 Declarative knowledge

This category is also referred to as factual knowledge and contains the following:

- facts about objects, such as a description of the elements which make up a stiffened panel structure: "*A stiffened panel structure is composed of a base plate, transverse and longitudinal stiffeners.*"
- facts about events, such as those derived from a particular experiment: "*The results obtained during the experiment conducted by the MIT welding research group indicated that serious distortion problems were encountered during welding fabrication of aluminum structures using plates thinner than 8 mm.*"
- facts about situations, such as the following statement about the reasoning behind the process of stiffening a plate: "*The designer stiffens thin plate structures in order to impart structural stability and rigidity and in order to avoid global buckling collapse.*"

3.2.2 Procedural knowledge

This type of knowledge is common and most prevalent in the techniques used in reducing and correcting distortion. As an example: "*In the prestraining method of clamping, the clamps hold only the bottom plate tips to the table. The round bar is then placed under the plate along the longitudinal centerline (weld line) to induce a reverse curvature counteracting the out-of-plane distortion caused by welding.*"

Procedural knowledge is also included in the methodology used in designing DISCON: "*Before a knowledge representation scheme can be selected, it is necessary to first break down the distortion problem into smaller components and identify the types of knowledge which characterize distortion.*"

3.2.3 Causal knowledge

It establishes the cause and effect relationship between the relevant parameters. The effect of heat input on buckling distortion can be expressed as follows: "*Increasing heat input beyond a critical value will cause buckling distortion to occur in thin plate structures.*" or "*When welding thick plate structures, the welding residual stresses cause 'angular' or 'winging' distortion around the weld.*"

3.2.4 Quantitative knowledge

This type of knowledge is found in the many mathematical expressions used in evaluating distortion, such as the calculation of angular change in a weld:

$$\phi = \frac{\phi_0}{1 + (2D/a)(1/C)} \quad \text{, radians.}$$

where ϕ_0 is the value of angular change in a restraint–free condition.

3.2.5 Qualitative knowledge

The application or usefulness of this form of knowledge may be found in the design consultant[1] mode where an optimization of the structure's geometry is desirable following unsatisfactory distortion analysis results: "*An increase in either heat input or free span will increase the tendency for a given plate thickness to buckle during welding.*" or "*The out–of–plane distortion result is inversely related to stiffener spacing in a typical stiffened panel structure.*"

---

[1]Also called DECON, it is one of two primary modules used in DISCON. Refer to Chapter 6 for more details.

3.2.6 Heuristic knowledge

It is also referred to as "rule–of–thumb" knowledge and plays a vital role in the development of any expert system; its primary role lies in narrowing down the search process in the solution space. The distortion domain offers several examples of heuristic knowledge.

On welding under restraint: "*It is generally true that a good way to reduce distortion and residual stresses is to weld under restraint and then remove the restraint after welding is complete.*" On the clamping method: "*Although the clamping method is widely used in industry, it does not guarantee reduction of residual distortion.*" With respect to buckling distortion: "*In welding thin plate structures of less than 8 mm thickness, buckling distortion is likely to occur.*" With respect to distortion analysis of panel structures: "*It is generally agreed upon that the 1D analysis of angular change in a fillet weld of a restrained panel structure provides more accurate results than the existing 2D model.*"

3.2.7 Constraints Knowledge

These are largely contained in the rules and regulations applicable to distortion.[2] In this design, constraints are imposed as allowable deformation values (NAVY standards). As an example: "*The shrinkage allowance for plates 1/4 to 3/8 inch thickness is 1/32 inch per stiffener (Mild Steel).*" [35]. Figure 3.1 illustrates the various components which make up the distortion knowledge domain.

For reasons which will become obvious to the reader (see Chapter 6), there exists a hierarchical refinement in the structure of knowledge which further breaks it down into smaller components. These are:

(1) Objects, such as: structure, welding process, pre–weld method;

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[2]The structural analysis portion of the overall design also includes constraints. These are not discussed in this thesis.

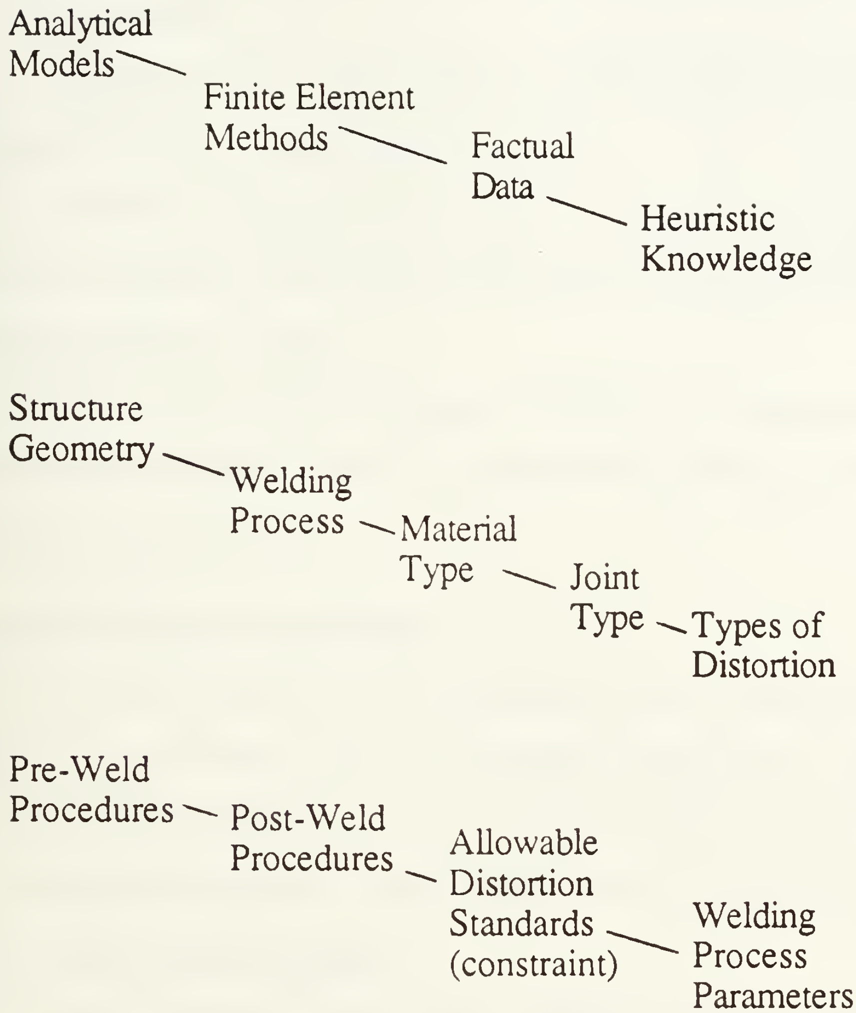

Figure 3.1 : Distortion Knowledge Breakdown

(2) Attributes which describe the objects, such as: a panel structure is composed of stiffeners and a bottom plate;

(3) Values, attributes may have certain possible values such as: small, thick, wide, strong, appropriate;

(4) Predicate which is the means by which values are related to the attributes, such as: is, is not, greater than, less than.

The section on knowledge representation will discuss this aspect in greater detail. There are several other knowledge representation schemes presently available and these will be presented as well.

A necessary step in the development of DISCON is the identification of the various sources of knowledge from which knowledge about distortion is derived. Those are described in the next section.

3.3 Sources of the Distortion Knowledge

We have three main sources of knowledge: literature, experts and examples. And there are three different bases of knowledge: scientific laws, experience and models. In general, knowledge for our purpose is any information which helps us solve problems in the distortion domain. These sources consist of the following.

3.3.1 Empirical/factual results

In the case of distortion, this category represents a large portion of our current knowledge. Experiments have been conducted over many years under different conditions and with different variants. Data on these experiments is almost exclusively in the form of tables and graphs.

Although other sources were consulted [13,36,42], most results were extracted from Prof. K. Masubuchi's book on Analysis of Welded Structures [30]. There are several reasons for selecting this document as a primary source of reference.

- First, it is generally accepted as the most extensive investigative work on

this topic.

- A single reference brings consistency in the knowledge acquisition process, and avoids the potential for conflicting knowledge which results when consulting with multiple expert sources. "Conflict resolution" in expert systems is presently the focus of considerable research.
- Finally, there is considerable advantage in using a document written by an expert who is readily available and willing to participate in the development efforts.

3.3.2 Analytical formulations

These are at the core of any engineering problem solving environment and constitute a primary means of analysis. Although numerous attempts have been made to devise comprehensive models for distortion analysis, most have not shown satisfactory agreement with experimental results and have consequently not been used in DISCON.

(1) Out-of-plane distortion. Here, the model developed by Masubuchi et al. is used because of its simplicity and fair correlation with experimental results on stiffened panel structures. Section 2.2.2 presents the elements of that analysis.

(2) Buckling distortion. As discussed in Section 2.3, a panel structure's sensitivity to buckling distortion involves the consideration of the following key parameters: plate thickness, free span between stiffeners and heat input. The conditional relationship involving the critical heat input index is used to determine the likely occurrence of buckling distortion. This critical heat input is a non-process specific heat input and is compared with the actual heat input value to determine the occurrence of buckling distortion.

3.3.3 Heuristics

This is an important feature of expert systems. Experts do not simply follow

a set of rules. They have insight into problems and use their professional judgement. The use of heuristics involves the ability to choose a best path from various possibilities, using the best stimuli from several available. In the distortion domain, these are derived from years of experience in the field by the expert.

3.3.4 Rules and regulations

This source of knowledge imposes constraints on the design and distortion minimization process. Because this study is largely focused on the application of DISCON in the Naval Shipyard environment, the standards used are the NAVY standards of allowable deformation. These allowable standards are almost exclusively presented in curve form: a sample curve for steel is shown in Figure 3.2.

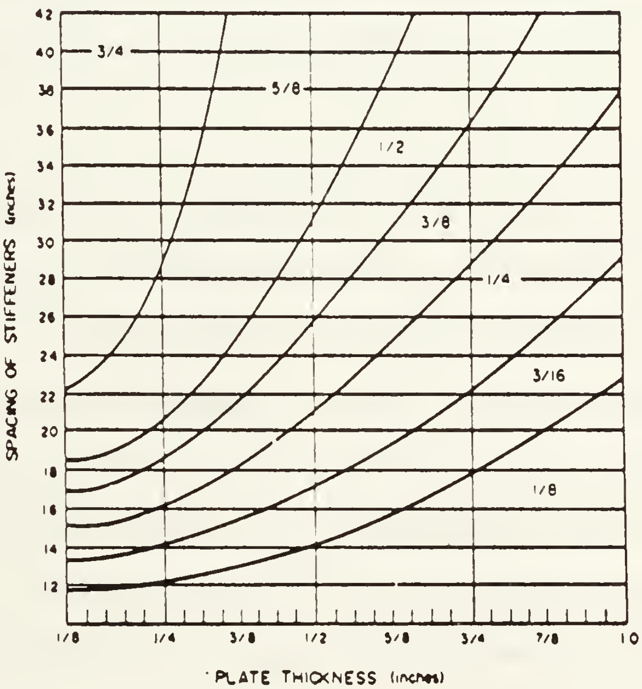

Figure 3.2: Permissible Unfairness in Steel Structures
Specified by the Navy (from NAVSHIPS 0900.060.4010).

CHAPTER 4. STATEMENT OF NEED

The previous sections described the distortion problem, the available tools for it analysis and the source from which the knowledge is derived. The introduction also pointed to the observation that although distortion is a readily known and identifiable phenomenon, its understanding by designers and fabrication engineers is limited and contributes to distortion–related defects. Furthermore, the expertise in this file lies in the minds of a few experts and is generally not easily available to the public.

Consequently, there is a need for improvement which the author feels should be focused in the following areas: how to make the knowledge on distortion more available, integration of this knowledge in the design phase of fabrication, and the systematization and preservation of that knowledge.

4.1 Availability

Experts acquire their expertise over the course of many years. The practitioners learn from their experience gained in dealing with different cases, and learning patterns and principles which are heuristics or guidelines. These are seldom documented. Declarative knowledge (or facts) is relatively easy to acquire; the procedural knowledge, or how to use those facts, is far more complex. If the expert's knowledge could be encoded, then many "blueprints" of that knowledge could be made available in a short period of time and to a wide range of users (duplication of expertise). This process would be similar to the increasing availability of computer software over the past ten years.

4.2 Integration of Distortion in Design

It is clear that integration of knowledge on distortion early in the design phase

of manufacturing is a desirable feature. The designer must consider the "fabrication friendliness" of a proposed design in addition to its structural analysis [6]. Ideally, the proposed structure would be "tested" for distortion prior to fabrication with the intent of resolving potentially inadequate fabrication issues early on.

An optimum design must take into account structural integrity, welding fabrication, structural weight, as well as fabrication cost. As mentioned in Chapter 2, the effects of welding distortion on the buckling strength of panel structures are often underestimated and can lead to serious defects in the course of a structure's life cycle. the areas of structural analysis and welding engineering are rarely integrated within the framework of the overall structural design process. The distortion problem should be included in the stress analysis phase of design as well as during the identification of failure mechanisms. It is the author's opinion that the current practice of omission leads to an inadequate assessment of the strength capabilities of a welded structure.

4.3 Systematization and Preservation of Distortion Knowledge

One of the primary objectives of DISCON will be to systematize and preserve the expertise of specialists in this field. Years of experience are required for specialization which, if preserved by implementing this knowledge in a knowledge–based environment, would allow not only the training of untrained personnel to be facilitated, but also the growth of our understanding of distortion to expand quickly as new results and analysis tools become available with time (a refinement of the stored expertise). Preservation of "Corporate Knowledge" is an important issue in any industrial activity or research environment and must be facilitated.

As is shown in the next chapter, expert systems provide a solution to our problem and are discussed next.

CHAPTER 5. EXPERT SYSTEMS IN STRUCTURAL DESIGN AND WELDING

This chapter introduces the essential concepts of a "new programming methodology"[1] known as knowledge based expert systems.[2] Their unique characteristics as well as their basic structure are first presented. This is followed by a brief discussion of the knowledge acquisition and representation issues which are fundamental to the creation of KBES. Finally, a literature survey of their applications in the fields of structural design and welding is reviewed.

5.1 Introduction

Expert Systems, or KBES, are computer programs using AI techniques to assist in solving problems involving knowledge (rather than pure data), heuristics and decision–making. These systems produce "intelligent" behavior by operating on the knowledge of a human expert in a well defined application domain. KBES have been expanding at an accelerated pace in many areas of applications ranging from medical diagnosis to engineering design. There are several reasons for this growing interest in knowledge–based techniques:

- The potential expansion of human knowledge by making explicit the experiential and judgmental knowledge known to a few "experts" in a field;
- The increasing viability of new areas of computer applications, and the

---

[1]This terminology is borrowed from a conversation with J. Connor, Professor in the Civil Engineering Department, MIT.

[2]The abbreviation KBES will be used from now on.

increasing power of symbolic inferencing techniques; and

- The demonstrated potential for enormous cost savings in computation and instrumentation by using these methods.

One of the most common tasks which KBES undertake is that of giving advice, or acting as a consultant. This has been particularly so in the case of large scale systems such as PROSPECTOR [22], for advising on mineral exploration, MYCIN [7], for diagnosing blood diseases, and XCON [47], for advising on the configuration of computer systems.

5.2 Characteristics of KBES

KBES are useful in handling problems which are ill–structured[3] and can only be solved by one's judgement and experience, rather than by purely algorithmic means. The particular knowledge is usually highly specialized and focused on problem solving skills in a narrowly defined subject area.

There are many features of expert systems which distinguish them from other programming environments:

- They are knowledge–intensive programs and, within their field, can demonstrate human expertise;
- They use heuristic, or rule–of–thumb approaches that suggest a procedure to solve a problem, acquired through one's personal experience and "know how;"
- They are programmed in a declarative style rather than procedurally constructed as conventional computer programs usually are;
- The knowledge base of such systems is executable, unlike databases

[3]"Ill–structured problems" denote problems without clearly defined algorithmic solutions.

which are not; the execution is performed by the inference engine[4] which reads statements in the knowledge base and executes them through search controlled reasoning mechanisms;

- The knowledge base is often modular and separate from the control mechanism [17], facilitating the additions or deletions to and from the knowledge base without the risk of affecting overall performance and integrity;
- The ability to handle uncertainty, although somewhat limited in its degree of sophistication, is inherited from the fact that there always exists a degree of uncertainty in knowledge. KBES can draw inferences based on incomplete or uncertain information. Uncertainty of fact or rules are traditionally represented by probabilistic judgement such as that provided by the Baysian theory or the Dempster–Shafter theory of evidence [4]. As an example, MYCIN and PROSPECTOR state not only their conclusions to a particular problem, but also the degree of confidence that they attach to these conclusions;
- Finally, and most important in the performance of consultation functions, KBES provide the ability to give explanations, allowing the user to challenge and examine the reasoning process underlying the system's answers.

5.3 Basic Structure

KBES, to be defined as such, require the following necessary conditions:

- They must have knowledge;
- They require a means of handling that knowledge; and

[4]These terms are defined in the following pages.

- They must be capable of communicating/interfacing with the user.

A model of the basic elements of such KBES is shown in Figure 5.1, and it can be seen to be comprised of:

5.3.1. Knowledge base

A knowledge base, which contains a representation of the knowledge that is pertinent to the particular domain. It generally consists of facts and heuristic knowledge. The most common formalisms used in knowledge representation are rules, frames and semantic networks. It is also desirable, in such applications as designs, to have the knowledge base divided into knowledge levels[5] in order to help organize the problem solving activities.

5.3.2. Inference Mechanism

The inference mechanism, which is the control mechanisms or means by which this knowledge is handled and processed.

	User		
	User Interface		
EXPLANATION	Knowledge Base	ACQUISITION	CONTEXT
	• Rules • Heuristics		
	• Facts • Meta–Rules		
	Inference Engine		

Figure 5.1: Basic Structure of a KBES

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[5]DESTINY, a KBES for design of structures is an example of such hierarchial representation of knowledge.

It uses the knowledge contained in the knowledge base to solve a specific problem. In AI terminology, a solution is reached by searching from a search space (the set of all possible solutions); this search space can be large or small, structured or unstructured.[6] Large search spaces present a problem in that the "search time" may be too long and the problem solving strategy may lack focus. In expert systems, search and focusing problems are handled by the inference engine. Some of the more common inference mechanisms used today are: Forward–chaining, Backward–chaining, Generate/test, Recognize/act, Constraint–directed, Heuristic search and Meta rules.[7] Of those mentioned, only Forward–chaining, Backward–chaining and Meta rules will be briefly explained because of their popularity in existing systems, and their employment in DISCON.

(a) In Forward–chaining the reasoning proceeds from data or symptoms to hypotheses. In other words, the system begins with the evidence and then tries to see which "goals" or possible solutions it can prove. It is a goal seeking mechanism, whose objective is to reason forward from existing rules and facts to derive additional facts that must hold. In the case of the simple network shown in Figure 5.2, the system would begin by asking questions 1, 2 and 3, for which, depending upon the answers, it might be able to prove goal 1 or goal 2. If not, it would ask question 4 and try to prove goal 3 [49].

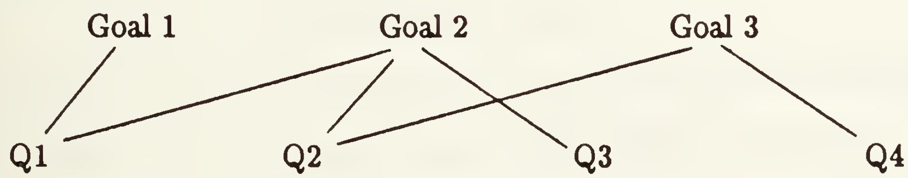


Figure 5.2: Simple Inference Network [49].

[6]Refer to Expert Systems, April 1986, Vol. 3, No. 2 for more details.

[7]These mechanisms are specific to the various KBES shells available commercially.

(b) In Backward–chaining, a set of possible conclusions are evaluated to see whether the evidence supports them. It is a data driven mode, whose objective is to reason backward from a given goal, searching the knowledge base for rules and facts supporting that goal and declaring them true. Again, using Figure 5.2., the system would begin with the first possible solution (goal 1) and try to prove it, asking questions 1 and 3. If unsuccessful, it would move on to goal 2, for which it would then need to ask question 2, and so on. Backward–chaining is the most widely used problem solving technique in consultation–type expert systems being developed.

(c) Meta rules are a form of control which allows for greater efficiency in a system's search for a solution by reducing the search space. They express strategies for using other knowledge in rules, frames, or other source in the knowledge base, to invoke subsequent rules in a situation. Given a particular problem to be solved by either a forward–chaining search through rules first or a tree search through a frame structure first, a meta rule could indicate which approach to take, based on the characteristics of the problem and other specifications of the desired solution. An example of such a rule is found below.

A SAMPLE META RULE

IF: 1. You are interested in calculating the amount of out–of–plane distortion

AND: 2. The structure is a panel structure with stiffeners

AND: 3. The material is made of Steel or Aluminum

AND: 4. There are rules which describe empirical data

AND: 5. There are rules which describe analytical formulations,

THEN: The rules for empirical data should be checked first for a possible match and those for analytical formulations checked second.

5.3.3 The context

The context, also referred to as the working memory of the system, is where all of the data elements used or created during a problem solving activity are stored. It is in the context that the solution is being formulated during a particular consultation session, and this solution results from the interactions of the user, the knowledge base and the inference mechanism.

5.3.4 User interface

A user interface is an essential element of any computer system. It is the link between user and the system and should be designed simply and with a built–in versatility and instinctiveness which creates a friendly environment for the user.

Figure 5.1 indicates additional features of the basic KBES structure which are desirable. These are an explanation facility as well as an acquisition facility through which programming–type functions are performed.

5.4 Knowledge Acquisition

Knowledge acquisition is the "process" of extracting knowledge from an expert and differs from knowledge representation which is the "procedure" of encoding the knowledge in a program. Knowledge acquisition presupposes the availability of suitable techniques for knowledge representation.

Knowledge may be available in instructions, books, regulations and may be stored in part or as a whole in the brain of human experts. Knowledge acquisition requires a precise understanding of the particular subject matter and knowledge acquisition techniques have proved very useful in this respect. An example of such a technique is modeling whereby the needed information is contained and structured in a "conceptual model" [30].

The field of research involved with developing knowledge acquisition

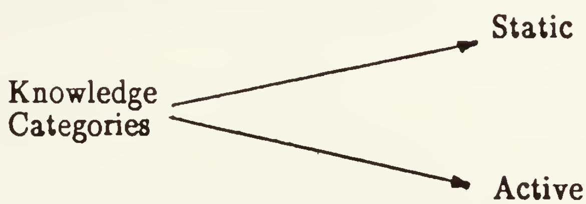
techniques is quickly expanding, primarily because of the need to enhance the quality of the acquisition process in light of the increasingly complex problem domains being investigated.

5.5 Knowledge Representation

The effective knowledge representation of a particular problem domain (such as Distortion) is considered to be the keystone to the success of AI programs. Expertise generally draws on many different kinds of knowledge. The role of KBES is to coherently integrate these various types of knowledge in a knowledge base and provide the reasoning facilities to handle their dynamics. Figure 5.3 shows some of the possible elements of that knowledge to be represented.

Knowledge may be classified into two broad categories:

- Static knowledge, also referred to as knowledge about objects, such as that which involves the description of a welded structure and its components;
- Active knowledge, or knowledge about actions, such as that contained in goals or procedures.



There are several symbolic representation formalisms currently in use [37]:

- Production rules;

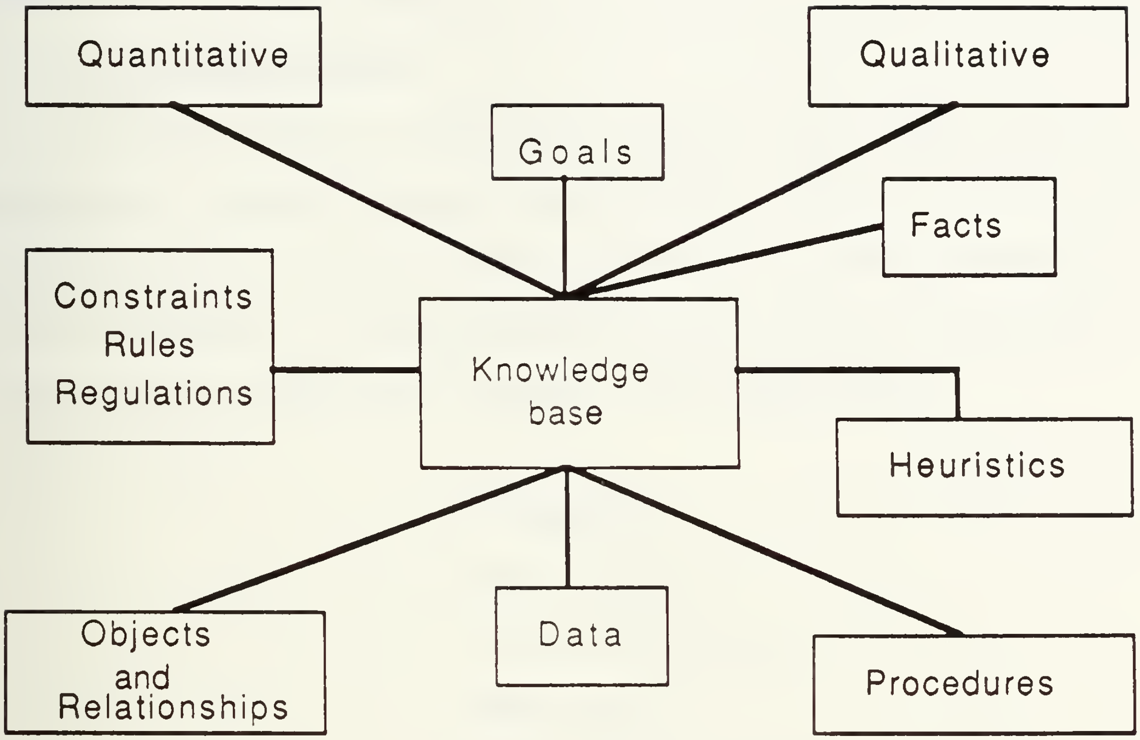


Figure 5.3: Domain Knowledge

- Frames or objects;
- Semantic networks;
- Logic

These are briefly described below.

5.5.1 Production rules

Production rules (or simply rules) are the most widely used form of representation technique in the expert systems industry. This is so because they are simple to construct and easiest to understand and use. They offer the advantages of simplicity, modularity and describe procedural as well as descriptive knowledge. A rule is conditional statement [50] expressed in an ⟨IF–THEN⟩ format:

IF Condition 1

AND Condition 2

THEN Action 1

AND Action 2

Conditions can be combined with AND or OR as can be seen above. They can also contain a degree of uncertainty in the action/conclusion part of the rule (the THEN portion):

IF:	A thin plate is to be fillet–welded
AND:	Heat input is greater than the critical value
AND:	The plate thickness is less than 8 mm
AND:	The material used is Aluminum,
THEN:	Buckling distortion is likely to occur (0.9).

Here, a certainty factor is used to express the degree of certainty (or uncertainty) with which the statement about the likelihood of buckling distortion is made. The specific range of uncertainty used is from (0) for most uncertain to (+1) for certainty.

Also, meta rules (or meta level rules) may be used for more efficient processing of rules, or groups of rules; they serve to direct the problem solver to the appropriate rule category. An example of such a rule is shown below:

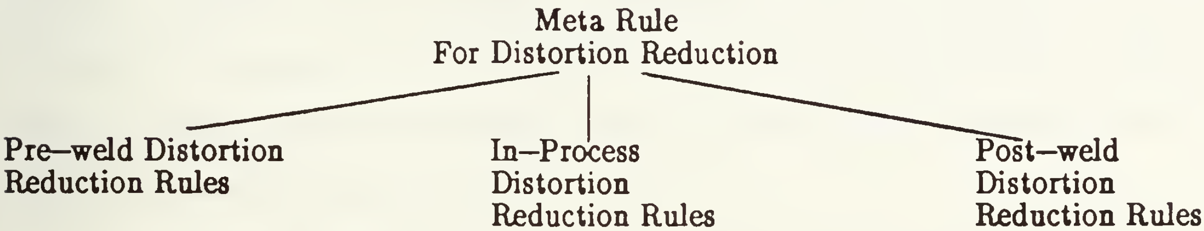


Figure 5.4: Example of Rule Structure

Generally, rules are useful in expressing knowledge which has been acquired as a result of experience. However, their format is inadequate and inconvenient to represent knowledge about facts (steel is a type of material), system structures (component description), or causal relationships (excessive heat input will cause distortion).

5.5.2 Frames/objects

The major inadequacies of production rules are in areas which can be effectively handled by frames.

"*A Frame is a data–structure for representing a stereotyped*

situation like being in a certain kind of living room...Attached to each frame are several kinds of information. Some is about how to use the frame. Some is about what one can expect to happen next. Some is about what to do if these expectations are not confirmed."

Marvin Minsky, 1974

A frame provides a structured representation of an object or a class of objects (Figure 5.5). Frames incorporate sets of attributes called slots; these are used to represent declarative–type knowledge. Specialized slots are available, such as "if–added," "if–removed," slots to represent procedural–type knowledge. Slots in frames can also contain rules, questions to ask users, explanations, hypotheses about a situation or even other frames [32].

Additionally, frames can be linked to other frames and "inherit"[8] data or information from them. This is possible because of the existing hierarchy between frames (higher to lower level frames) and the taxonomic nature of their relationships.

Another powerful feature of frame based representation is its contribution to KBES's ability to reason and provide strategies for controlling the system's reasoning.[9]

Perhaps one of the more promising attempts at representing knowledge has been in integrating both frame and production rule languages to form "hybrid" facilities, thereby offering the advantages of both rules and frame representations (e.g., KEE and LOOPS trademarks of Xerox Corporation and IntelliCorp, respectively).

5.5.3 Semantic networks

Semantic networks were introduced in the late sixties as a means of capturing

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[8]Inheritance refers to the ability of a frame to inherit characteristics or properties of other frames (parental frames); a means of transferring knowledge is thereby established.

[9]Refer to Communications of the ACM, Sept. 1985, Vol. 28, No. 9, for an in depth presentation of this topic.

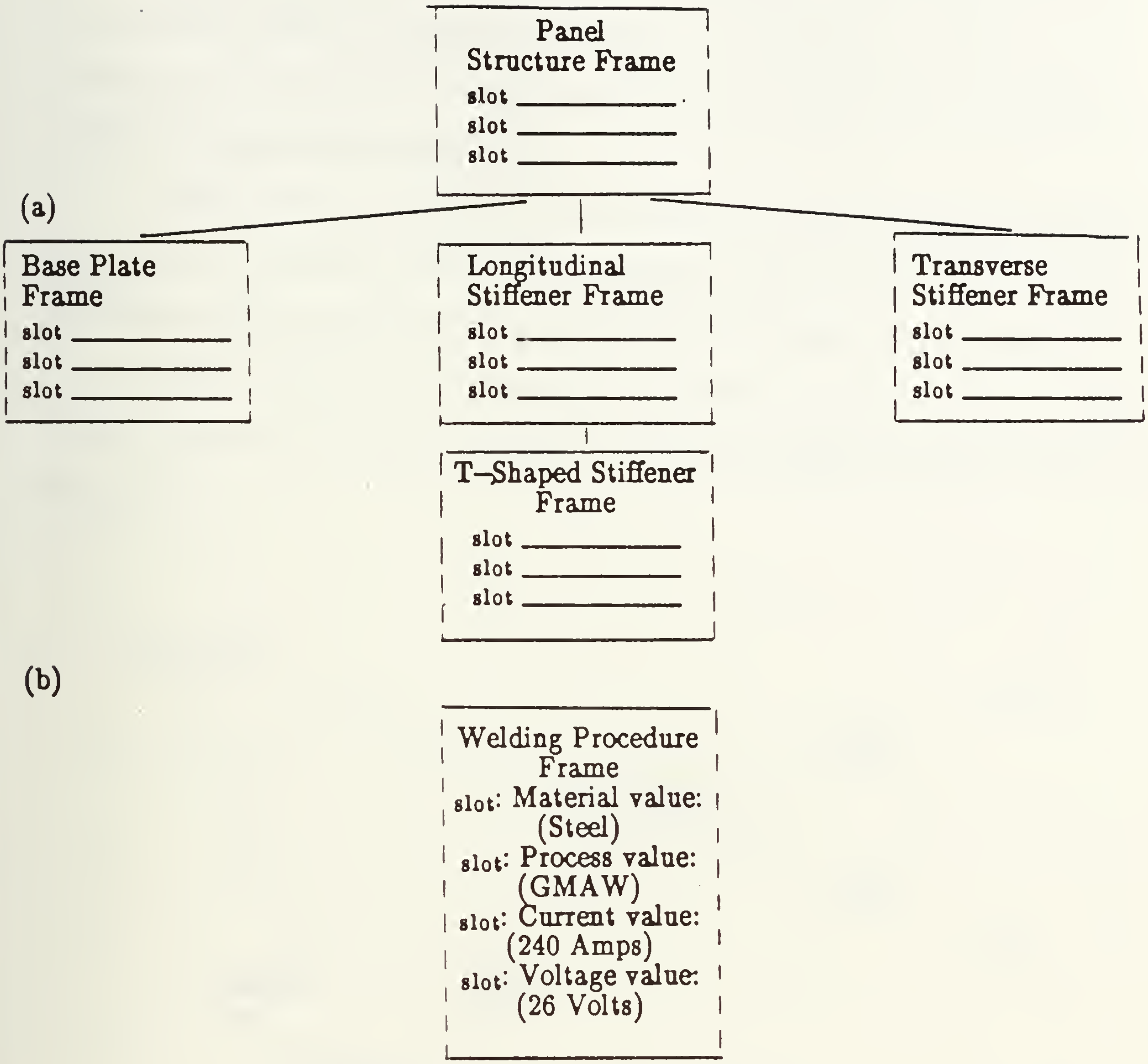

Figure 5.5: Sample Frame Structure

(a) Sample Frame Hierarchy for Panel Structure

(b) Sample Frame for Welding Procedure

the meaning of words; the idea of nodes and links was used. The meaning of words is incorporated in semantic networks via the concept of inheritance.[10] A set of nodes are connected to each other, in a network form, by links (or arcs); these links establish or describe the relationship between nodes.

Nodes are of two types: individual nodes, and generic nodes, which define a class of similar individual nodes. There are different types of links used in semantic networks and these affect the grouping of these nodes and defines their relationships.

Usually, concepts are represented as nodes as well as property values. Property types are contained in the links. A sample semantic network is shown in Figure 5.6.

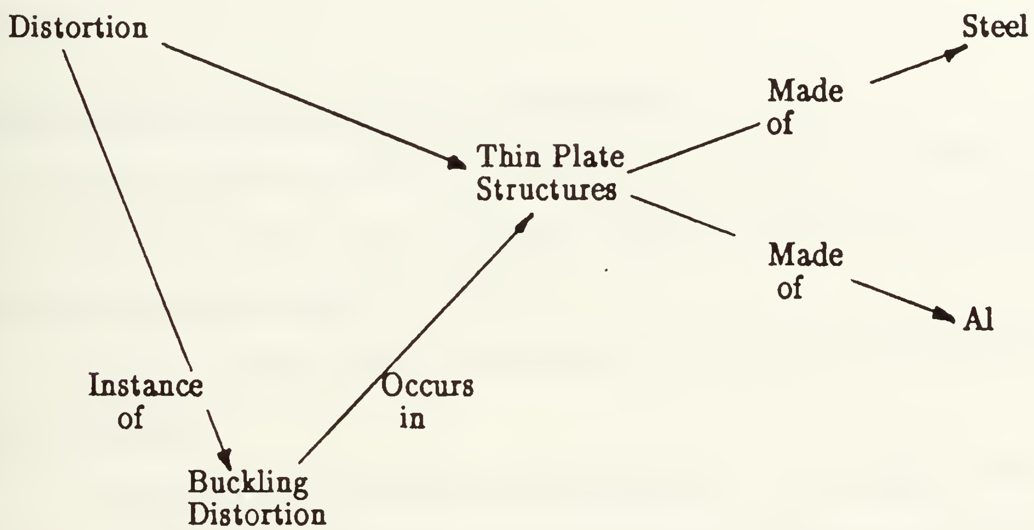

Figure 5.6: Sample Semantic Network

[10]Inheritance is the ability of a node to inherit characteristics of other nodes that are linked to it.

5.5.4 Logic Representation

The representation of knowledge in logic form is gaining increasing acceptance in the field of AI because of its precise mathematical expression of knowledge. Two types of logic languages are currently in use:

- propositional calculus, which use proportional variables, and
- predicate calculus, in which logic expressions consist of predicates and values to represent facts.

Predicates are statements concerning an object, such as:

Material (base plate, steel), representing the statement: "the base plate material is steel."

A more formal and detailed treatment of logic based representation can be found in reference [50].

5.6 Expert Systems in Structural Design and Engineering

The field of engineering design, and especially that of structural design, is the subject of increased scrutiny from knowledge engineers because of its enormous potential as an application domain for KBES.

The structural design process is conducive to a knowledge based approach for the following reasons:

- A majority of the knowledge applicable to the design process is structured in the form of codes and standards. Consequently, there is a need to provide a means of searching through those rules and sorting out the ones which may apply to the particular design;
- The design process is a complex decision making activity. Many aspects must be considered and these are usually in complex relationships with each other. There is often no one suitable alternative (there are likely to

be several to choose from) and therefore a decision must be made as to which alternative is best among possible alternatives;

- They can assist in the control of the design process by performing evaluative tasks and assuming information processing–type functions;[11]
- They can be used in the integration of the various elements of human expertise in design problems: problem solving tools, technical references, design standards, design level scheduling, design process scheduling, working sheets, design agendas and design drawing utilities (CAD).
- Many structural design problems require experience and intuition from the designer, particularly in the preliminary design stage; for example, the selection of optimum structural systems obtained implicitly through the designer's expertise, preference and existing documents.

In searching through the AI literature, it became clear to the author that a majority of KBES in structural design and engineering are not fully implemented, but are still in prototype status. Also, the distinction between those "in service" and those in "experimental" status is not always made clear. This distinction, therefore, will not be made in the KBES presented below.

⟨SACON⟩

The bulkiness of FEM packages, the difficulty to use them, the need to interface them intelligently with design programs were among the motivations to apply KBES to build analysis assistants. SACON [1] is an expert system which provides guidance to the user on the appropriate use of the MARC finite element program for structural analysis. It was implemented using the EMYCIN model and consists of

[11]The problem of control in the design process is discussed in a paper entitled "Management of the Design Process," P. Derrington, Carnegie–Mellon University, Pittsburg, PA.

production rules and consultation parameters such as load components, type of materials and loading conditions. It uses backward–chaining as an inference mechanism. The structural mechanics knowledge base of SACON consists of:

(1) Rules for determining the appropriate analysis package to be performed (i.e., an analysis strategy) and the analysis recommendations;

(2) Rules for inferring the dominant stress, deflections and non–linear behaviors;

(3) Mathematical models, used to determine a range of values for stress and deflections.

SACON has been operational for approximately ten years. Other similar packages developed are FACS, FEASA and CARTER [1].

⟨HI–RISE⟩

HI–RISE [1] was developed at Carnegie–Mellon University for the preliminary design of high–rise buildings more than ten stories high. It produces rough designs of buildings and attempts to select the best design according to the criterion of the linear evaluation function. HI–RISE uses weighing factors in a linear evaluation factor to evaluate the merits of the different structural systems. It selects two functional systems (i.e., lateral load and gravity load resisting systems). Inputs to the program are: the number of stories desired and the inter–column spacing.

It uses a language called PSRL, a frame based production system language developed at Carnegie–Mellon University. The knowledge base consists of declarative knowledge represented in lists, and the procedural knowledge is represented by production rules and LISP functions. The latter is organized into several knowledge modules representing both the two functional systems described above and the synthesis, analysis, parameter selection, evaluation and system selection functions of the design.

⟨SPECON⟩

SPECON [44], for SPEcifications CONsultant, is a small KBES which checks structural steel members for compliance with AISC specification. The incorporation of specification constraints mandated by codes and regulations into computer aided design programs expedites the detailed design of structural components governed by these constraints. The organization of the system is similar to that of SACON. It includes a knowledge base consisting of production rules to identify applicable constraints and the specific design constraints. The context keeps track of the various facts generated during the consultation. The inference mechanism is similar to MYCIN's backward–chaining strategy. SPECON has an explanation module to answer questions such as (1) how a hypothesis is deduced, and (2) why a particular questions was asked by the system.

⟨SSPG⟩

SSPG [1] is an expert system for design of stiffened steel plate girders (SSPG). It was designed primarily because of the following observations:

– The optimization of stiffened plate girders is not amenable to conventional programming techniques, due to the highly non–linear and implicit nature of the design constraints, as well as the existence of discontinuities;

– The design does not involve a lot of common sense–type knowledge; and

– Some experiential knowledge is generally required in the preliminary design of these structures (e.g., estimating loading conditions).

An interactive BASIC program for the design of stiffened steel plate girders is first used to determine an optimum depth of web–to–length of span ratio. This information is fed into SSPG to design the web plate, flange plates, bearing and intermediate stiffeners using steel plates of varying thicknesses.

SSPG is implemented in ELISP language and consists of approximately 300 production rules.

⟨OE–DESTINY⟩

OE–DESTINY [9] is a knowledge–based approach for the design and analysis of offshore structures. It is also unique in that it represents a methodology for integrating the various sources of knowledge required in the design and analysis of complex structures.[12] The system consists of a knowledge base containing several knowledge modules organized into a hierarchy of three levels: strategy, specialist and resource levels. Each of these knowledge modules represents a specific discipline in the design process, and all communicate through a Blackboard (or a global database) by means of a control mechanism implemented in the object–oriented programming style.[13] The blackboard itself consists of several levels, each defining the abstraction of objects used in the design.

What makes the type of architecture used in OE–DESTINY attractive is its potential for application in any design and analysis–type of problem requiring integration of many sources and components of knowledge.

<u>Summary</u>

The above overview of KBES indicates the considerable effort made to include knowledge–based system technology in structural design and engineering. Adaptation of these designs to the derivation of welded structure KBES designs appears feasible and should be investigated.

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[12]OE–DESTINY is still in the implementation phase.

[13]Object–oriented programming involves the use of objects and messages which perform all actions.

5.7 Expert Systems in Welding

The complexities associated with the welding environment often limit the trustworthiness of modeling techniques and cause welding engineers to rely on expertise and knowledge accumulated over years of experience. This expertise is essential during all phases of the welding process and is distributed in the following areas:

- The selection of weld design and processes;
- The derivation of suitable welding procedures;
- The control of the welding process;
- The post–weld analysis;
- The planning and management of welding operations.

Computer encoding of this knowledge in a knowledge base expert system methodology has demonstrated enormous potential in a few systems.

As in the investigation of structural KBES, a majority of the systems presented in the literature are in a prototype stage; very few are commercially available.

The Welding Institute is focusing an important part of its efforts [49] on the development of diagnostic expert systems in such applications as the diagnosis of weld defects and welding equipment faults. The role of expert systems technology in the field of welding is expected to produce considerable benefits as intelligent consultants to engineers and non–experts alike.

The following is a review and description of welding expert systems currently in use or under development.

⟨WELCON⟩

WELCON was developed by FUKUDA of the Welding Research Institute,

OSAKA University [3], and is designed to provide the appropriate welding condition to prevent weld crack initiation.

Production rules are used to represent the rules and heuristics associated with chemical composition and crack sensitivity, the estimation of material structures and toughness, the determination of preheating temperature as well as the common sense knowledge used by welding engineers.

The flexibility of the system is found in the control mechanism which allows different responses to different user requirements; the least–commit policy allows the user the option of conversing with the system without necessarily following its lines of reasoning (i.e., a level of reasoning exists for each user's area of expertise or background). Both forward– and backward–chaining are used during the consultation process. WELCON may be employed in the future as an integration tool by regrouping in a single environment multiple expertise.

⟨WELDEX⟩

WELDEX [3] is an expert system which provides expert advice in the selection of arc welding processes as well as joint design and process parameter recommendations. It also provides information on defects associated with welding and their causes. The system is modularized into several applications modules and submodules:

– The expert system module consists of three submodules; the knowledge base, which contains the rules for selecting arc welding processes: these rules are framed from 50 conditional database clauses. The inference engine operates in a forward–chaining mode (goal seeking) by searching from the desired conditions and rules until a solution is reached. A user interface allows, by pull–down menus, access to the various modules and submodules;

– A database system module (DBSM), consisting of these major submodules called process parameter module, updating module, and joint design module;

– A defect analyses module, which provides information regarding welding defects and their causes.

A graphics package is also available and can display a recommended joint design with the desirable geometry.

This system is still believed to be in the development stage.

⟨WELDA⟩

WELDA [18] is a system conceived to provide advice on a variety of fabrication processes of a product in limited production quantity. The welding method as well as the cutting and bonding methods are recommended in this program based upon the function, size and geometry of a particular structure.

WELDA is implemented using the rule based paradigm. The OPS 83 language is used. Knowledge of the manufacturing process is contained in fourteen different groups of rules concerned with material selection, material characteristics, structural requirements, distortion, welding method, cutting and bending methods, and post–processing requirements. The processing of these rules is performed by four different types of control–rules (or meta rules). The working memory is broken down into element class and their attributes. For example, the class "material characteristics" consists of the attributes of weldability, Young's modulus, thermal conductivity, etc.

An evaluation of distortion is possible by linking to Fortran subroutines.

The consultation begins with the user providing inputs about the structure, and it advises on the selection of a material to be used. Then, a number of welding

methods are considered for the particular problem and the user selects the method of his choice. The same logic is applied to the selection of a cutting and bonding method.

⟨NEWCS⟩

NEWCS [38] (for Naval Expert Welding Control System) is a generic expert system designed to meet the demands of small–batch arc welding operations which exist in the Naval shipyard environment. The difficulties of applying welding automation in these operations are associated with machine, workpiece and metallurgical variables particular to the arc welding process used. NEWCS provides the mechanism for intelligent decision–making by allowing it to be used in conjunction with sensor fusion data available during weld execution. Other components of the expert welding control system are the weld planner, post–weld analysis, quality analysis inspection and fault diagnosis and a conventional welding control subsystem (i.e., power supply, wire feeder, torch manipulator and parts positioner).

Prior to welding, the NEWCS receives input data concerning the weld from the weld planner, such as part geometry and weld parameters.

During welding, data is received from multiple sources including welding sensors and the welding control subsystem. Based on this information, NEWCS evaluates the adequacy of current process parameters and modifies them as necessary.

After welding, statistical–type analysis is performed and stored in the system from the collected data. An important characteristic of the NEWCS is its autonomous feature.

The rule based representation formalism is used to represent the knowledge. Control is exercised through three phases called matching, conflict resolution and action. Conflict resolution among rules is made from first–come, first–served rule priority and rule regency–type strategies. An important characteristic of NEWCS is

the management of multiple goal situations. Here, goal resolution techniques are used which reduce the multiple goal situation to a single goal by designating one goal as optimized and the remaining goals as constraining.

⟨WELDSELECTOR⟩

This system is developed by the American Welding Institute [49] for the selection of welding electrodes. The system is built on the Personal Consultant expert system shell and uses over 100 rules. The selection is limited to the Gas Metal arc, Shielded Metal arc and Flux cored welding electrodes. The system interfaces to a very large database which contains the various material data and properties.

⟨WISP⟩

WISP is a prototype consultation system for automated weld inspection used in a vision–aided robotic welding environment [3]. This system is intended to be used in conjunction with a robot–mounted sensor which provides a 3–D model of the weld surface and the existence of possible surface defects. WISP operates using the following flow of control:

– First, it interfaces with the user to determine the existence of surface defects;

– It establishes the significance of these defects and suggests the possible causes for these defects;

– The system then establishes the likely causes by resolving any conflicts between the possible causes;

– It determines corrective actions and required repairs based on the knowledge provided.

WISP is implemented in the YASP building tool, supporting both rule–based and object–oriented programming.

Summary

Several KBES in the field of welding were presented. All of them represent applications in a narrow welding domain (e.g., welding procedure generation) with varying levels of complexity. The use of expert system technology in welding has caught on in the industry and many systems are expected to be developed in the near future.

Although many areas of the welding domain should be researched for possible KBES implementation, such as distortion, an important accomplishment would be the development of an integrated tool which encapsulates knowledge from several welding domains. In this regard, structural design KBES such as OE–DESTINY represent significant advances in the application of this new technology. Their architectures are well suited to an integration approach.

The goal of integrating welded structural design and fabrication knowledge seems possible in light of recent advances.

CHAPTER 6. DISCON: A KNOWLEDGE BASED TOOL FOR THE MINIMIZATION OF DISTORTION IN WELDED STRUCTURES

This chapter outlines the preliminary design of DISCON, a consultation knowledge–based system for the minimization of distortion in welded structures. The design is presented throughout its development phases. Emphasis is placed on the derivation of the system's specifications and of an architecture suitable for implementation. The elements and strategy of the consultation process (flow of consultation) are defined.

6.1 Introduction

DISCON, for DIStortion CONtrol, is a knowledge–based system intended to provide consultation services for structural designers and fabrication engineers in the area of distortion. The system is designed to operate in two primary modes called consultants.

- As a design consultant (DECON), it accepts key parameters from structural analysis results[1], as inputs, and evaluates distortion by accessing to external programs and suggests methods to optimize the structure's geometry to achieve minimal distortion results.
- As a fabrication consultant (FABCON), it advises the user of distortion reduction and correction techniques.
- Independent of the particular mode selected, DISCON is intended to be used as a knowledge bank, providing information to supplement the

[1]These parameters are particular to the structure. For a panel structure these consist of plate thickness, stiffener spacing, welding process, material properties and fillet weld size.

usual sources such as books, journals and databases.

Distortion minimization raises a number of issues as an A.I. problem. First, distortion is a complex phenomenon – it revolves around the mutual interaction of three major sets of parameters (Figure 6.1):

- Structural parameters, such as structure configuration, plate thickness, joint type, etc;
- Material parameters, such as base plate material and filler material properties;
- Fabrication parameters, such as welding methods, process and assembly parameters.

The distortion analysis itself proceeds along the following procedural logic [30]:

- The dimensional changes in the weld must be determined by performing a heat flow analysis, evaluating the magnitude of thermal stresses during welding as well as the dimensional changes induced by incompatible strains (causing transverse shrinkage, longitudinal shrinkage and angular changes);
- The amount of distortion induced by these dimensional changes is evaluated, usually by adopting elastic or plastic theory principles;
- Finally, the total magnitude of distortion is determined by combining all dimensional changes and induced distortions.

The analysis results depend on the major parameters described earlier and their combinations. There is no universal model for distortion analysis which can represent this combinatorially complex phenomenon. As a result, several analysis tools were developed each focusing on a specific and narrow problem domain, for example, the analysis of out–of–plane distortion of a stiffened panel structure. The knowledge available to guide the search is primarily procedural and heuristic, coupled with

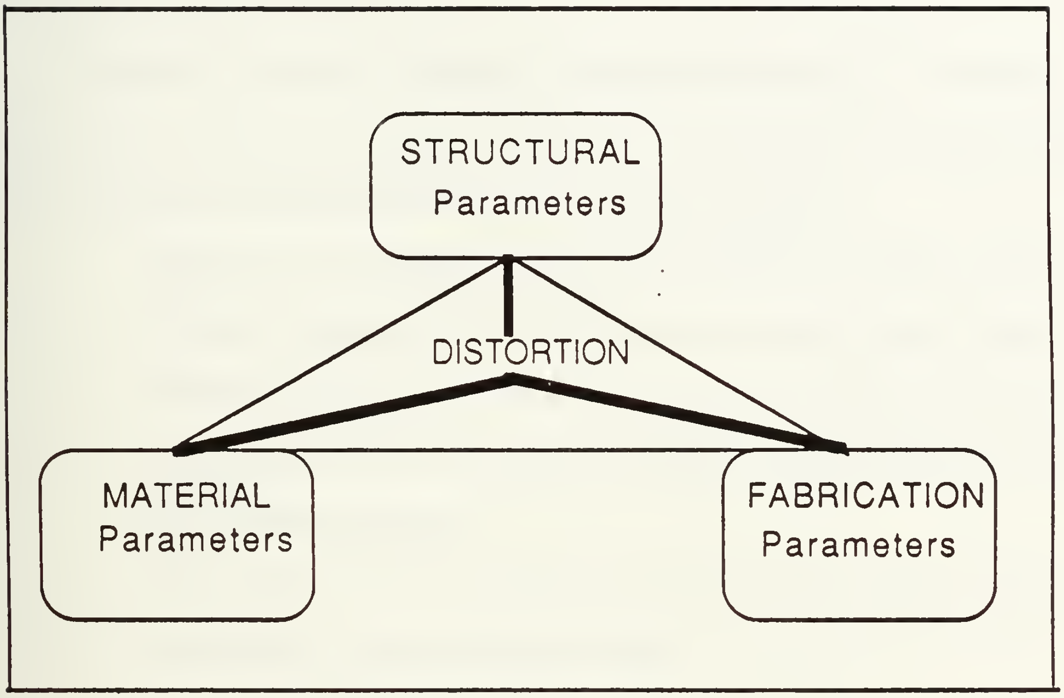

Figure 6.1: Spaces Of Domain Knowledge

empirical and analytical tools gained over years of experimentation.

A second issue in the design of DISCON deals with the logic of the consultation process itself: what is the order of consultation, what is the selection of criteria used for deciding which analysis tool to use for a specific problem, and how does the system respond to user queries? DISCON proposes to use strategy rules (meta rules) to resolve this issue.

Finally, a third issue concerns knowledge representation. Knowledge of the elements which compose a structure is descriptive in nature and not easily represented by rules. Several representation formalisms are used in DISCON:

- Descriptive knowledge of structural elements, welding methods and processes, materials and their properties are represented by frames;
- Procedural knowledge contained in the various reduction and correction techniques, as well as heuristic knowledge, are represented in rule form (IF–THEN statements);
- The strategic knowledge (meta rules) involved in the control of the consultation is also contained in rules.

The architecture selected in DISCON is that of a structured production system, with several knowledge modules, each specializing in a specific area of the distortion domain.

Finally, the domain knowledge is limited to the study of both out–of–plane and buckling distortions in stiffened panel structures which are fillet welded. The modular structure of the knowledge base allows for future expansion of the system's "expertise" by including other distortion analysis tools and a variety of other types of structures[2] as they become available.

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[2]The preliminary design is intended to indicate the <u>feasibility</u> of implementing distortion knowledge in a KBES; there is enough information in the areas selected to make a positive step in that direction.

6.2 DISCON Organization

6.2.1 Design objectives

The proposed knowledge–based system is designed to provide consultation services to designers and fabrication engineers of welded structures by meeting the following objectives.

(1) Given a panel structure to be welded, minimize distortion by approaching the problem on two fronts:

- optimize the structure's geometry in the design stage by including a distortion analysis as an integral part of the structural analysis, and advising of configuration options;
- provide expert advice in the fabrication stage of the design by presenting those preventive and corrective distortion control techniques which contribute to minimize distortion.

(2) The system should be designed with the flexibility to support expansion of the knowledge base, as our understanding of the distortion problem is enriched.

(3) The design specifications should be so formulated so as to permit interfacing with other expert system tools available commercially.

6.2.2 Design methodology

This section discusses the methodology employed in the design of DISCON. It is typical of any system development and its logic is modeled after the discussion contained in Building Expert Systems by Hayes–Roth, Waterman and Lemat [22].

Figure 6.2 summarizes the principal elements of the development cycle. These are:

1. Identification – This stage includes the definition of the problem domain, characterization of the distortion knowledge, evaluation of the suitability of

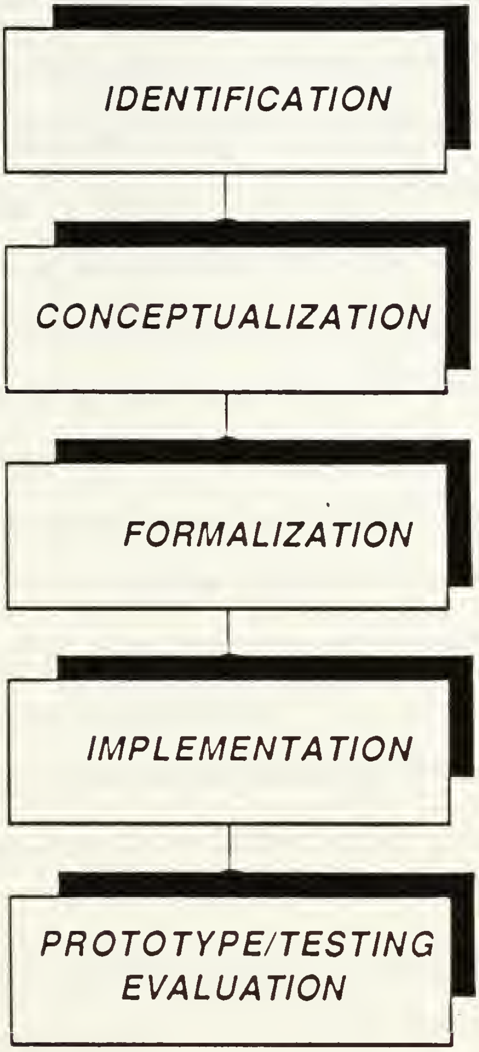

Figure 6.2 : < DISCON> Development Phases

the expert system tool in solving the problem of interest. The expert is identified as well as the resources needed for the task. In the preliminary design stage of system development an effort is made to narrow the problem domain. Hence, DISCON is currently conceived to only consider out–of–plane and buckling distortions.

2. Conceptualization – Here, the concepts and sub–tasks as well as the strategies are defined. The functional specifications of the design are delineated (i.e., input, output, user interface) and the system architecture is detailed. The information flow which characterizes the consultation process is defined. This phase is most important since it is the articulation of these concepts which will contribute to the successful completion of the formalization and implementation phases.

3. Formalization – A knowledge representation formalism is selected to describe the knowledge base (i.e., rules, frames, logic or combination of these). The knowledge base is organized in a suitable manner.

4. Implementation – This step essentially involves encoding the particular knowledge into the knowledge base (i.e., writing rules or implementing the knowledge into frames).

5. Validation – The preliminary design is tested against selected problems. Typically, the prototype would be built and a sample session would verify both the accuracy of the knowledge base and the control structure of the system. Further research is expected to produce a workable prototype which will be subjected to a more rigorous testing/validation cycle.

It should be noted that the term preliminary design involves sequencing through the five steps described above. The design process, in general, is iterative in nature and proceeds in a spiral–like fashion (see Figure 6.3); each iteration provides a new level in the refinement of the design.

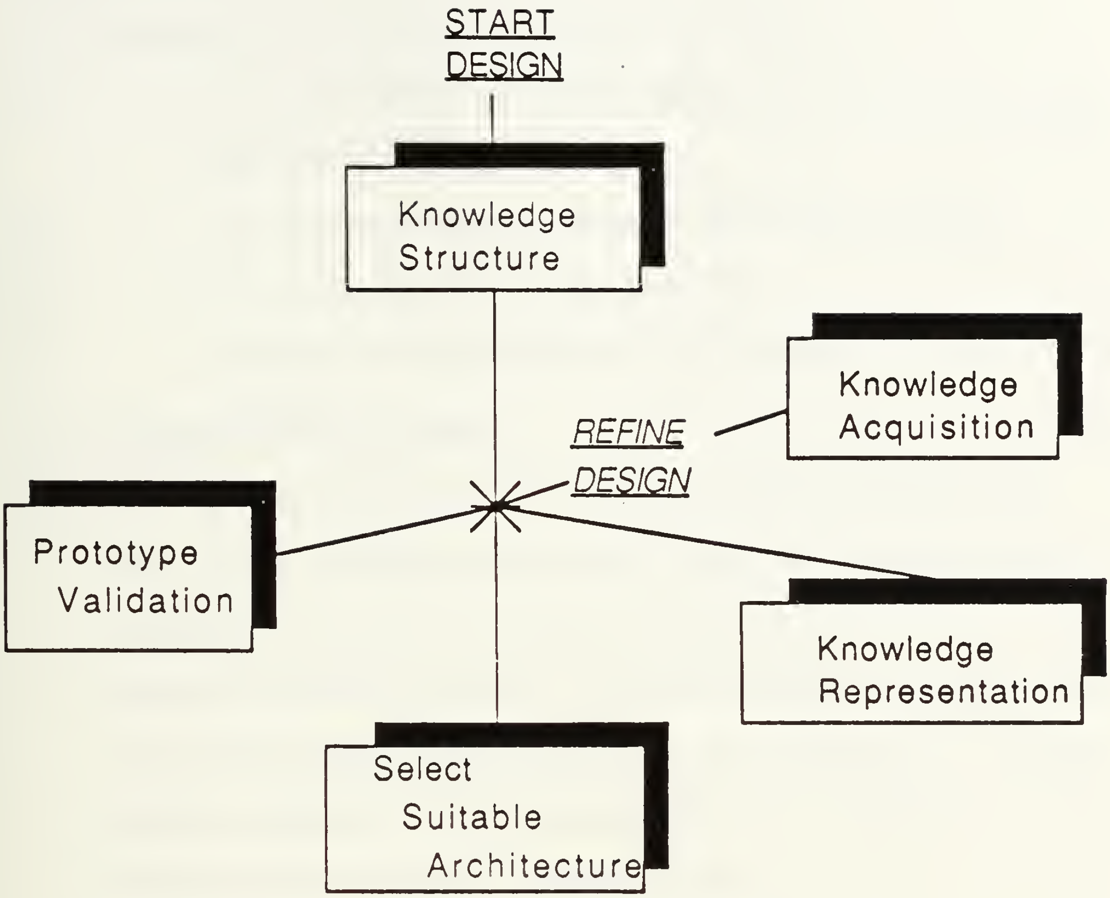

Figure 6.3: Preliminary Design Spiral

6.3 Identification Phase

This phase essentially establishes the following conditions:

(i) The use of expert systems technology will meet the proposed design objectives;

(ii) The distortion problem is a suitable expert system domain;

(iii) The problem domain is clearly identified;

(iv) The problem is decomposable into sub–problems.

6.3.1 Suitability of expert systems

Expert systems are particularly well suited because of their inherent traits:

- They process knowledge rather than data and include reasoning strategies well suited for consultation–type functions;
- They allow symbolic inferencing. The use of symbolic inferencing is one of the most original accomplishments in data processing. It makes reasoning possible in terms understandable by specialists and goes beyond the mere computation of numerical data;
- The discrimination between the knowledge base and the control structure makes modification of the various pieces of knowledge easier;
- The modularity of the knowledge base allows for local and partial corrections of imputed knowledge;
- Expert systems often provide explanation facilities, a desirable feature for a consultation–type system. Ultimately, these facilities are useful in making adjustments to the knowledge base by systematically validating the performance of the system through question–answer dialogue;
- Expert systems can easily be linked to other problem solving environments. For instance, the data handling package can perform its sophisticated procedures while the expert system concentrates on

reasoning tasks, the two making a powerful combination.

6.3.2 Distortion as a suitable problem domain

The distortion problem is a suitable problem domain for the following reasons:

- The distortion problem cannot be solved simply via algorithmic methods;
- Heuristic knowledge is available and will grow as our understanding of the distortion field increases;
- The problem boundaries are clearly defined. The domain is narrowed to the study of out–of–plane and buckling distortions;
- The problem domain is decomposable, meaning it can be subdivided into smaller areas, and each can be manipulated separately. For example, each procedure for post–weld control of distortion can be defined by a series of specific steps;
- The task domain has well established experts;
- There is a deep need for conservation of expertise in this area. This expertise needs to be standardized and readily available to designers and fabrication engineers in a usable form;.
- It represents a step forward in the implementation of flexible automation concepts in shipyards.

6.3.3 Knowledge breakdown

A breakdown of the distortion knowledge was presented in Chapter 3. Furthermore, it is possible to represent this knowledge using representation formalisms available in the Artificial Intelligence field. The sources from which the knowledge is derived were identified in Chapter 3.

6.3.4 Identifying causal relations

In order to derive an appropriate design for the minimization of distortion, it is necessary to identify the causing factors and their respective interactions. These problem components interact in complex ways and there are likely disagreements between experts regarding these cause and effect relationships. Nevertheless, it is generally agreed upon that the following factors contribute to the distortion analysis:

- Material type
- Plate thickness
- Structure geometry/type
- Welding method
- Welding material
- Welding process parameters
- Degree of restraint
- Joint type
- Joint characteristics
- Type of distortion
- Distortion standards
- Distortion evaluation
- Distortion prevention/correction techniques.

Figure 6.4 illustrates, in nodal form, the above listed components and their interactions[3].

Table 6.1 details the characteristics, or attributes, of some of these components or objects. Each will become elements of the knowledge base.

6.4 Conceptualization

This second phase of the preliminary design articulates the concepts needed to

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[3]The format of this figure is taken from [18].

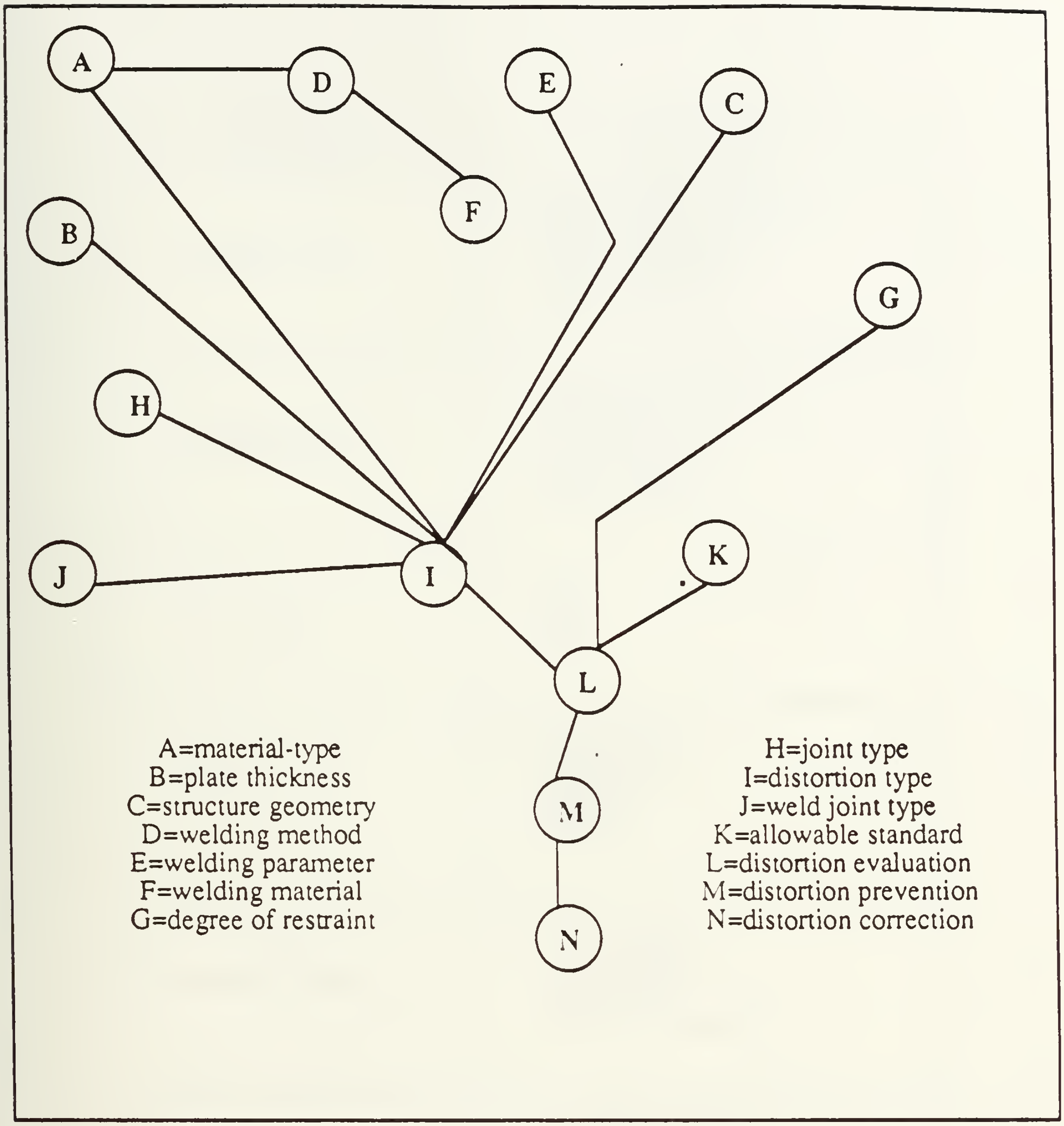

Figure 6.4: Causal Relationships

OBJECTS	ATTRIBUTES
Material- type	Carbon, Low Alloy Steels High Strenght Steels Aluminum Alloys Stainless Steels
Welding Process	Shielded Metal Arc Gas Metal Arc Gas Tungsten Arc Electron Beam
Joint -type	Butt Lap Fillet
Distortion-type	Longitudinal Transverse Angular Buckling
Joint Characteristic	Root Opening Groove Shape Joint Width Weld Cross Section
Structure Geometry	Base Plate Thickness Stiffener Thickness Longitudinal Spacing Transverse Spacing

Table 6.1 : List of Objects and Attributes

produce the desired objectives. It addresses the following issues:

(i) System functional specifications

(ii) System architecture

(iii) Consultation strategy.

The system specifications detail what we expect the system to accomplish. The system architecture defines the elements of the design (i.e., inference mechanism, knowledge base, context, etc.) and their interfaces. The consultation strategy indicates how the user and the system interface with each other in the course of a session.

This phase of the design provides the framework for the remaining stages and will eventually determine the quality of our product.

The elements of the conceptualization phase are depicted in Figure 6.5.

6.4.1 Functional Specifications

The functional specifications define the functions we desire the system to perform. They are a precise statement of the requirements to be satisfied. The following areas are specified:

(i) System inputs

(ii) System outputs

(iii) User interface.

6.4.1.1 Input Specifications

Inputs provide the system with the necessary information to initiate the consultation process. They are required to be interactive, presenting the user with a set of familiar questions asked until sufficient information is provided for both the distortion analysis (design) and expert consultation (Design and Fabrication) to occur.

Knowledge of the structure geometry and dimensions, as well as the welding process variables, are necessary to evaluate distortion. Consequently, two types of

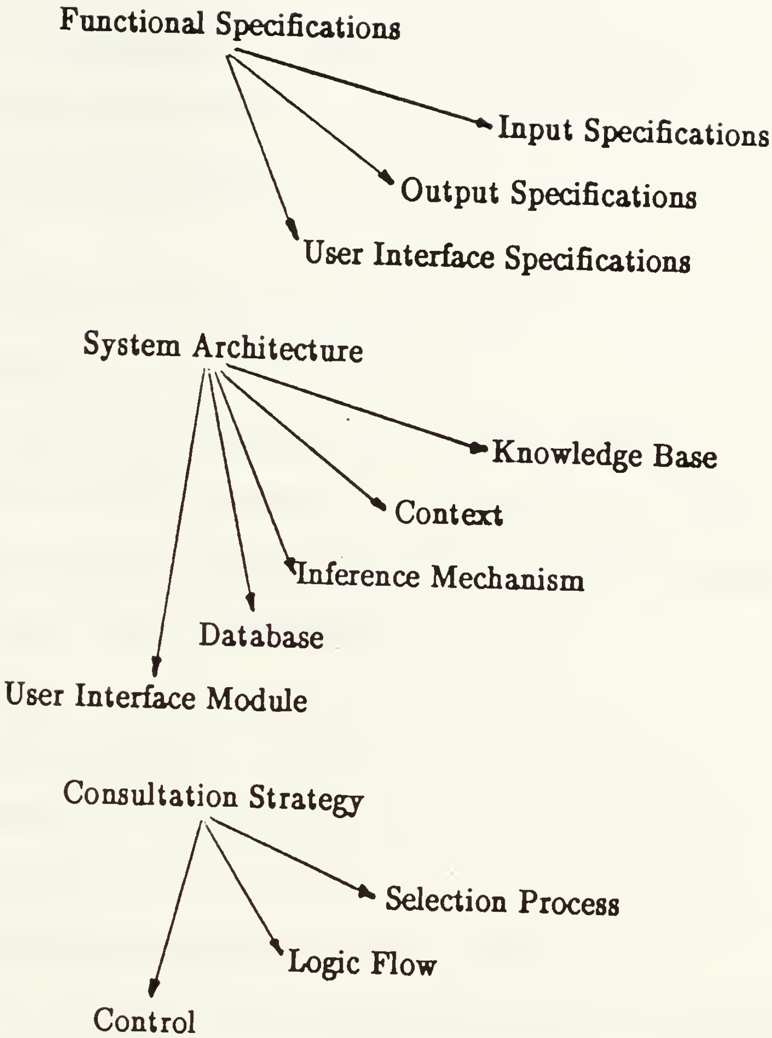

Figure 6.5: Elements of Conceptualization Phase

inputs are requested:

- Inputs about the structure
- Inputs about welding.

Inputs about the structure are derived from a previously performed structural analysis[4]. The results of that analysis consist of:

- Structure preliminary dimensions;
- Material type;
- Maximum allowable strength of members;
- Weld size required.

Several analysis program exist which perform these calculations. It is envisioned that they would be accessed externally from DISCON using customized interface programs, or simply the results acquired separately and entered manually in DISCON. Inputs about welding consist of the following:

- Welding method;
- Welding process parameters;
- Degree of restraint;
- Joint characteristics.

Figure 6.6 describes the input flow of a possible consultation with DISCON.

It is recognized that knowledge of the welding parameters may not be known with certainty during the design stage. However, the designer may be made aware of the well established welding practices of the industrial activity designated for product manufacturing. In the fabrication mode, that knowledge is expected to be more readily available (the user may be an employee within the manufacturing activity).

It is also possible to acquire this information from the results of a session with

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[4]Several computer programs are available for calculating stress and strains resulting from external loading on a given structure: ASSSA1 performs axially symmetric shell stress analysis (NAVSEA software).

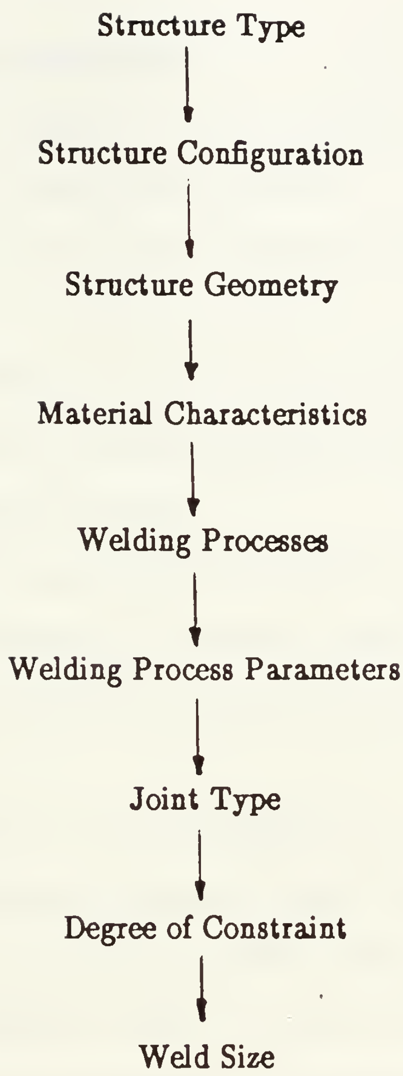

Figure 6.6: Input Flow Logic

an expert tool such as WELDEX which specializes in the selection of welding methods for specific applications.[5]

6.4.1.2 Output specifications

DISCON essentially produces two types of outputs:

(i) Output of the distortion analysis;

(ii) Advice–type outputs in response to user's queries found during the consultation process.

Outputs of the distortion analysis are found when operating in the Design Consultant (DECON) module. This module addresses structural design related issues and the user is provided with the following:

- The value of estimated distortion from the analytical model as well as the value of permissible deformation derived from allowable standards. The results for both out–of–plane and buckling distortion analysis are presented;
- A determination of the acceptability of the distortion results. The acceptance/rejection criteria is presented in equation form (i.e., $\frac{\delta M}{\delta A} \geq 1$). If $\frac{\delta M}{\delta A} \geq 1$, i.e., if the analytical model results in greater than the allowable standard, DISCON advises the user of design options When modifications are implemented, a reevaluation of the structural analysis results is suggested;
- DISCON advises the user of the geometry optimization options; specifically parameters such as fillet weld size, base plate thickness or span length of stiffeners (panel structures). For example, in the case where out–of–plane distortion results are unsatisfactory, the system will show these options:

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[5]WELDEX is briefly described in Chapter 5.

→ Recommend these options (prioritized).

(1. Decrease fillet weld size

2. Reduce span length of stiffeners

3. Increase plate thickness)

→ Select option desired.

The idea is to provide the user with recommendations of a qualitative nature. The user ultimately makes the final decision on the direction in which to proceed;

- Graphical displays are available in this mode. These include:
  - Angular change versus plate thickness
  - Angular change versus stiffener spacing
  - Heat input versus buckling distortion.

Figure 6.7 shows a sample output of the distortion analysis.

Because DISCON is a consultation system, an output may also be viewed as the results of the system's interaction with the user. For instance, in the fabrication module, the system provides the user with the available preventive and corrective distortion reduction techniques. These are listed during the session, but are also available in printed output form at the end of the consultation session.

6.4.1.3 User interface specifications

The primary function of DISCON is to provide consultation services to the end user. Therefore, the success of its design depends on the quality of interactions between system and user. The following attributes are desirable:

- Flexibility;
- Simplicity (friendliness);
- Instinctiveness;
- Modularity.

OUTPUT

<OUT–OF–PLANE DISTORTION>

- Calculated, δ_M = in
- Allowed, δ_A = in

Out–of–Plane Distortion

SAT

UNSAT

<BUCKLING DISTORTION>

- Critical Heat Input, Q_{crit} = J/in
- Designed Heat Input, Q = J/in

Buckling Distortion

SAT

UNSAT

Given above results, please select from the following options.

(1. Geometry optimization advice
2. Distortion reduction advice
3. Distortion correction advice
4. Graphical displays
5. Quit)

Figure 6.7: Distortion Analysis Output

Flexibility allows the system to present a range of options from session start to finish. These should range from permitting the selection of a well suited distortion reduction technique to explaining the system's inference process.

Simplicity is closely related to user friendliness and includes built–in execution mechanisms such as pull–down menus for module selection. Also, multiple choice–type answers from which to select is a display option with which the user readily identifies.

Instinctiveness is that characteristic which models the user's thought process by anticipating events; for example, asking the right kind of question at the right time.

Modularity permits individual functions to be performed without degradation of the remainder of the system (e.g., addition and deletion of rules). The modules are components of the system which can be revised over and over.

Modes of operation

The user interface allows the operator to access the system via two primary modules.

- DECON (DEsign CONsultant): Results of the structural analysis are used to evaluate distortion. Qualitative advice is provided to the user about the structure's geometry in an effort to minimize the distortion results.
- FABCON (FABrication CONsultant): In this module, expertise is given regarding pre–weld distortion controls (PRECON) and post–weld distortion control techniques (POSTCON).

Available submodules within DECON and FABCON are represented in Figure 6.8 and can be accessed directly from the screen.

The user interface includes two vital elements:

(i) Explanation facilities;

(ii) Help facilities.

Explanation facilities

DISCON must be capable of explaining its reasoning process; it must be capable of showing HOW the rules were used and HOW it provided the information to the user. Specifically, the following capabilities are required.

- The facility should give both a priori (WHY a certain fact is requested) and a posteriori (HOW a given conclusion was reached) information.
- It should be capable of justifying its chain of reasoning to the user.
- It should explain WHY it did not use a certain piece of information.
- It should explain WHAT the system is presently doing.
- It should support the user by providing domain explanations (WHAT IS A).

In DISCON, as in most rule–based systems, explanations are generated by collecting the rules that are "fired." The explanations are invoked by the user input and directed by the user's queries. Hence, the explanation strategy should be an implicit mechanism.

The DISCON explanation facility provides responses to two different kinds of questions:

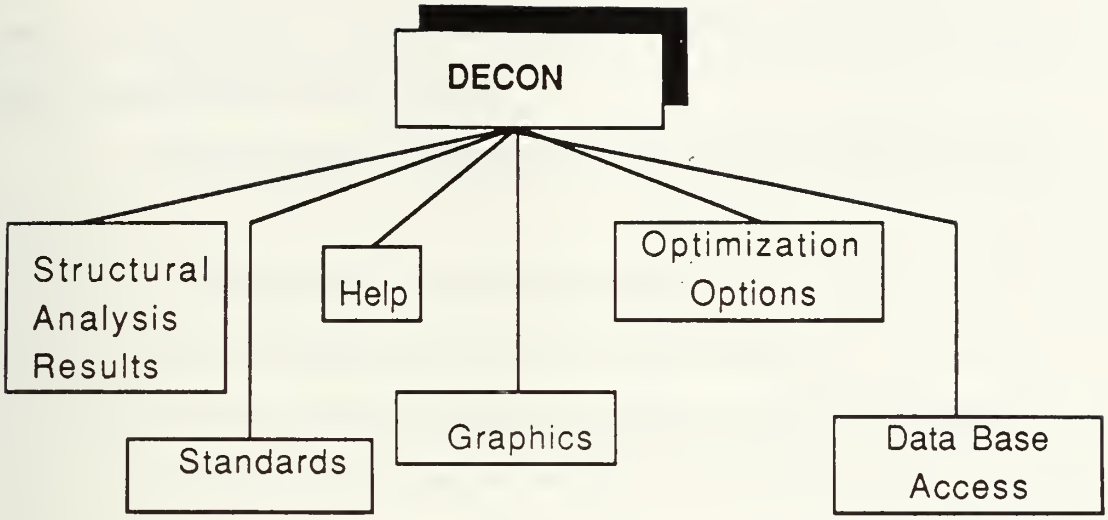
- Questions about domain knowledge – these are questions which can be answered independently of the ongoing consultation session. Such questions may be of the type:

  "*What are the assumptions made in the 1–D distortion analysis?*"

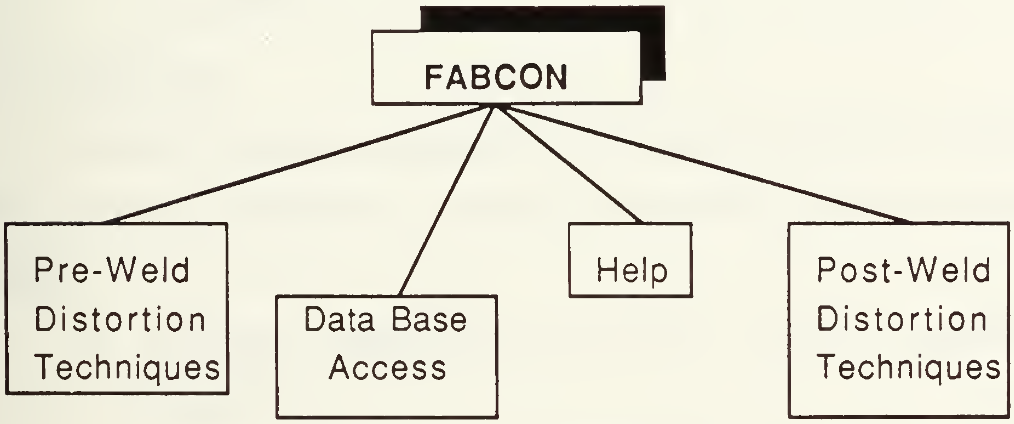
  or

  "*How is the knowledge–based organized?*"

  These questions produce static–type answers.
- Questions about problem solving knowledge – these questions relate the



(a) < DECON menu >



(b) < FABCON menu >

Figure 6.8 : DISCON's Modular Structure

dynamics of the problem at hand and require an understanding of the behavior of the system. Such questions are of the type:

"*Why was this procedure recommended instead of the other one?*"

or

"*What mode are we presently operating in?*"

These questions produce dynamic–type answers.

The execution of these explanations is made through two techniques:

- Canned texts – these are similar to traditional program comments, and they comment on the rule at the time the canned text was written;
- Rule expansion – rules in the knowledge base can be retranslated into a telegraph style Abbreviated Rule Language such as that done in MYCIN [7]. In this way the explanations always effect the current contents of the knowledge base and even the current state of a dynamically changing consultation.

Help facility

The HELP facility is accessed when operating in either one of the primary modules (DECON, FABCON). The facility is designed to provide the user with the following:

- A general description of DISCON's structure, organization and capabilities;
- A listing of its current problem solving domains – in this case, out–of–plane and buckling distortions only. This is needed as more types of distortion problems could be handled in the future;
- Definition of terms;
- On screen displays of the analytical formulations used, their assumptions and constraints; and

- Listing of all sources of knowledge and data used (references, experts, etc.).

User–system interaction logic

The overall flow of interaction is illustrated in Figure 6.9. There are two additional features which should be included in this discussion. First, because of possible external constraints imposed outside of the system's current state of knowledge (e.g., loading frequency), the system should be prepared to investigate another solution (than that already provided) if the user has reasonable grounds for rejecting the options listed. Also, the user should be given the flexibility of reselecting another option after a selection has been "processed" by the system.

It is important to note that in consultation/advisory systems the user is the final authority with regard to selection processes.

Execution mechanisms

The following mechanisms for executing user interface functions discussed above are:

- Pull–down menus;
- Graphical displays.

These are sufficiently adequate to perform the required tasks.

6.4.2 Knowledge system architecture

In this section we outline the overall architecture and elements of the system. Several problem solving architectures were investigated such as neural networks, blackboard systems and analogical reasoning systems [22]. These have found useful applications in systems such as HEARSAY–II, OPM and DESTINY. However, they

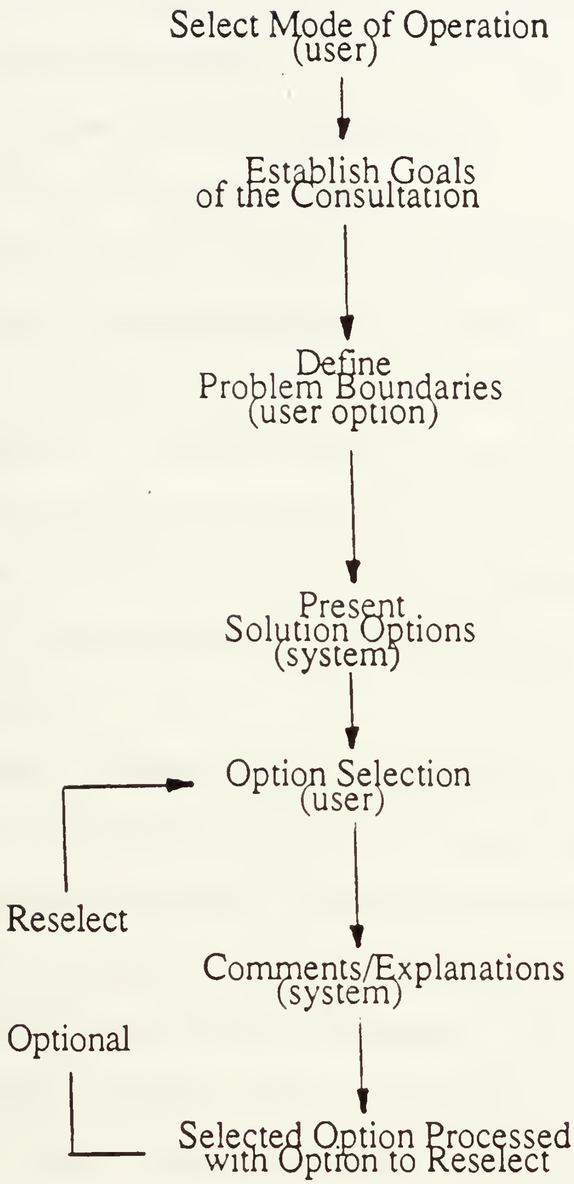


Figure 6.9 : User-System Interface Logic

carry with them a level of sophistication ill–suited for simple consultation tasks, a primary function of DISCON.

Selection methodology

Three basic knowledge–based system architectures were considered:

- Production systems;
- Structured production systems; and
- Distributed reasoning systems.

Production systems are commonly used in welding application because of their simplicity and ease of implementation [49]. A single knowledge base consists of a list of rules called production rules (IF–THEN format), which are executed by a single inference mechanism. A working memory stores the data and goals of the specific problem consultation session. All the rules in the list are checked until the designated result is achieved. This architecture works well for systems consisting of a small number of rules, but is inefficient in moderate to large production systems because of poor execution time.

Distributed reasoning systems are based on the concept of specialized knowledge bases (KBs) which cooperate in solving a specific inference. These KBs have their own particular structure. The corresponding knowledge bases are organized in a hierarchical structure [37]. A blackboard permits all specialist nodes with a structured common area to access information. This architecture is valuable in potentially complex systems where the particular structure requires extensive communications between several knowledge sources (such as fault detection, test generation and maintenance systems).

Structured production systems (Figure 6.10), from which DISCON was conceived, is more adequate in meeting our objectives. Here, the knowledge base is divided into several knowledge modules, each specializing in a particular area of the

USER

Inference Module

Interface Engine

Knowledge Base

Context/
Working
Memory

<u>Meta Rules</u>

IF < > THEN <GO TO PRECON>

<u>OPTCON Module</u>

IF < > THEN < >

<u>PRECON Module</u>

IF < > THEN < >

<u>POSTCON Module</u>

IF < > THEN < >

Figure 6.10: Structured Production Architecture

problem domain. Meta rules (rules about the use of rules) determined which set of rules (and from which module) should be accessed to solve the particular problem. Since only a selected number of rules are checked for a given set of input data, execution time is considerably reduced and the design is generally more efficient.

DISCON architecture

DISCON is organized around five essential elements (see Figure 6.11). These are:

- A knowledge base;
- A situation base;
- An inference mechanism;
- A user interface;
- A database.

6.4.2.1 The knowledge base

DISCON's knowledge base is modular in structure and consists of three separate knowledge modules called CONSULTANTS.

(i) <OPTCON>, for OPTimization CONsultant, includes the qualitative and heuristic knowledge needed to advise the user of the design options which lead to minimum distortion. An example of such a rule is provided below.

SAMPLE RULE FROM <OPTCON>

IF:	The structure is a panel structure
AND:	It has transverse and longitudinal stiffeners
AND:	Fillet welds are used
AND:	The value of out of place distortion exceeds allowable standards,
THEN:	First reduce the size of the fillet weld.

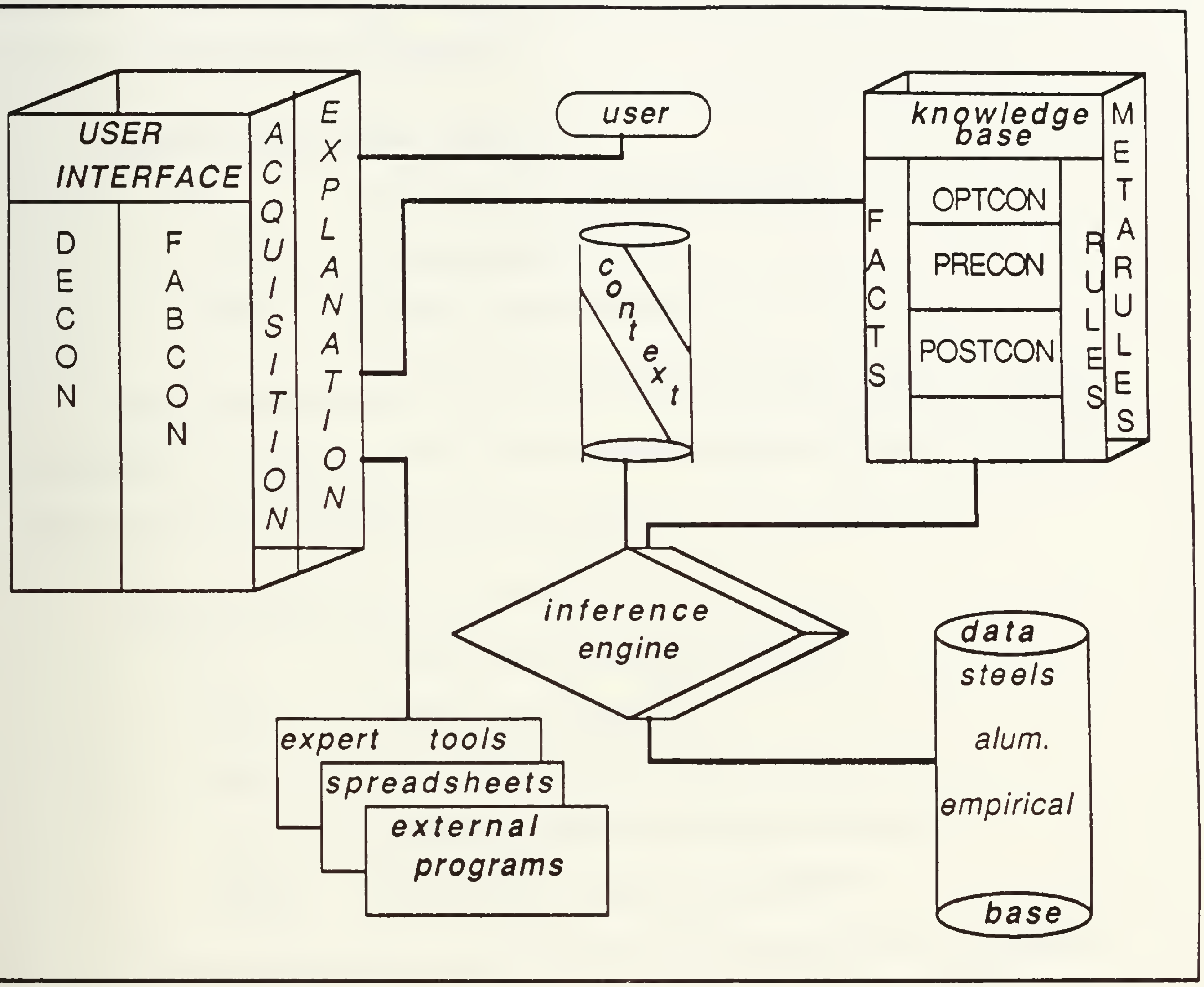


Figure 6.11: DISCON Architecture

(ii)<PRECON>, for PRE–weld CONsultant, regroups the factual, procedural and heuristic knowledge concerned with pre–weld distortion prevention techniques. A sample rule from PRECON is given below.

SAMPLE RULE FROM <PRECON>

IF:	Reduction of out–of–plane distortion
AND:	Stiffened panel structure,
THEN:	Increase degree of restraint.

(iii)<POSTCON>, for POST–weld CONsultant, includes factual, procedural and heuristic knowledge concerned with post–weld correction techniques. A sample rule from POSTCON knowledge base is given below.

SAMPLE RULE FROM <POSTCON>

IF:	Correction of out–of–plane distortion
AND:	Stiffened panel structure
AND:	Fillet welds are used
AND:	Inspection indicates out–of–plane distortion,
THEN:	Consider flame straightening techniques.

The knowledge representation formalism (see Section 6.5) used is a hybrid of production rules and frames; procedural as well as heuristic knowledge are best represented by rule based systems. The rule which follows also indicates the use of certainty factors (included in parentheses) ranging from 0 to +1 to express the level of certainty of the action part (THEN part) of the rule. If a statement is made with certainty, then the certainty factor is omitted.

SAMPLE RULE FROM <OPTCON>

IF: A thin plate structure is to be fillet welded

AND: Welding heat input exceeds the critical value

AND: The critical limit is determined by plate thickness and length of free span,

THEN: Buckling distortion is likely to occur [0.8].

Rules generally consist of a left hand side, stating the condition (IF) and right hand side stating what action follows if those conditions hold true (THEN). The extent to which the action is likely to hold is indicated by the certainty factor (in this case, 80% sure). Frames are used to represent descriptive/factual knowledge. The modular structure of the knowledge base allows the addition/deletion of rule without affecting the performance of the knowledge base.

6.4.2.2 The context

It is the working memory of the system. It is used to store the input information provided by the user during the consultation session, and plays an important role in determining when a rule can be "fired."

6.4.2.3 The inference engine

The inference mechanism is the system's reasoning mechanism. It sequences through the rules of the knowledge base as to appropriate questions of the user, and then offers advice based upon the rules fixed and the user's answers. It is the active component of the system in that it selects rules from the knowledge base which match the contents of the situation base. The principal control strategy employed in DISCON is backward–chaining. Here, the reasoning proceeds from hypothesis to data. The inference engine first selects a hypothesis to be tested and then seeks the data required to test the hypothesis. Backward–chaining inference allows a more focused dialogue (goal oriented) with the user.

6.4.2.4 The user interface

As discussed in a previous section, the user interface allows access to the consultation through two primary modes of operation: DECON and FABCON. During the course of consultation the user is asked pertinent questions and responds via multiple choice–type format. Both explanation and help facilities answer the WHY, HOW and HELP questions. Rules are entered via the acquisition module. An option to link with external expert tools is possible provided customized interface programs or compatible programming languages exist. Also, Fortran subroutines may be accessed from DISCON for the purpose of performing the distortion calculations required (external programs interface). The specifications for the user interface module were discussed in a preceding section.

6.4.2.5 Database

The database is used to store static empirical/factual data which would otherwise saturate the knowledge base; each database record would require corresponding rules, making it unnecessarily large and inefficient to operate. The use of spreadsheet software is included because it offers several built–in features such as:

- Database management, performing the data search and sorting functions;
- Graphics facility, which is called during the consultation when necessary.

The types of information contained in the database spreadsheet element are:

- Permissible standards in tabular form;
- Steel related properties;
- Aluminum related properties.

Rules for specifying database operations, spreadsheet operations are incorporated in the knowledge base for access.

6.4.3 The consultation strategy

DISCON's primary function is consultation. It is therefore essential that the

elements of the consultation be defined. Specifically, the following issues must be addressed:

- What is the logic sequence of consultation?
- How is the consultation process controlled and executed?
- What is the format of consultation?

The elements of the dialogue between user and DISCON are goal–dependent. In the design mode (DECON), the primary emphasis (or goal) is a distortion analysis and the generation of advice based on the qualitative relationship between a structure's geometry and the resulting distortion. In the fabrication mode (FABCON) the emphasis is on providing advice on distortion preventive and corrective techniques. As a result, the structure of the consultation can be seen to include several goals, each directing the program in a particular direction:

- The main goal is the minimization of distortion in a given structure;
- There are sub–goals whose purpose is to achieve the main goal (e.g., optimize geometry, pre–weld reduction techniques, etc.);
- Furthermore, these sub–goals reside in a particular mode (DECON and FABCON).

The idea of a goal–driven consultation is used extensively in existing knowledge–based systems.

6.4.3.1. The logic sequence of consultation

An overview of the logic sequence of consultation in the design mode is shown in Figure 6.12. The user is required to provide specific inputs initially in order to perform the distortion analysis.[6]

A more detailed sequence of this mode is shown in Figure 6.13.

---

[6]For example, in the "out–of–plane distortion analysis," the required inputs are: plate thickness, stiffener spacing, material properties (E,) and fillet weld size.

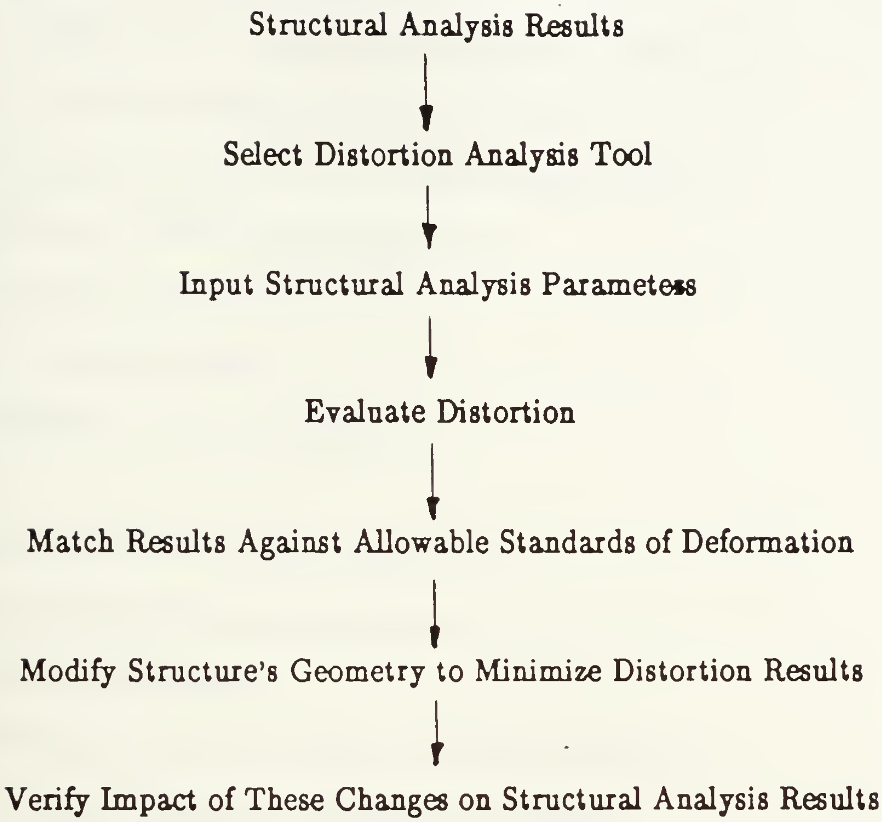


Figure 6.12: Design Mode Consultation–Logic (Overview)

Start

Structure Type <panel, shell, cylinder, etc.>

Structure Configuration <longitudinal, transverse, stiffeners, etc.>

Material <base plate material, component material, etc.>

Structure Geometry <plate thickness, stiffener spacing, etc.>

Welding Process <GMAW, GTAW, EB, etc.>

Process Parameters <heat input, etc.>

Joint Type <butt, lap, fillet>

Degree of Restraint <free, restrained?>

Weld Size

Distortion Analysis <1–D Model, FEM, etc.>

Select Analysis Tool <list available tools>

Discuss Criteria for Selection

Calculate Distortion <access to database, external programs>

Establish Range for Allowable Deformation <access to database>

Compare Results <calculated distortion ≥ allowable distortion?>

Interpret Results <acceptable, unacceptable>

Make Recommendations <change fillet size, modify geometry>

Reevaluate Distortion

Check Impact on Structural Analysis

Finish

Figure 6.13: DECON Enquiry Logic

The flow of consultation in the fabrication mode is structured differently as shown in Figure 6.14.

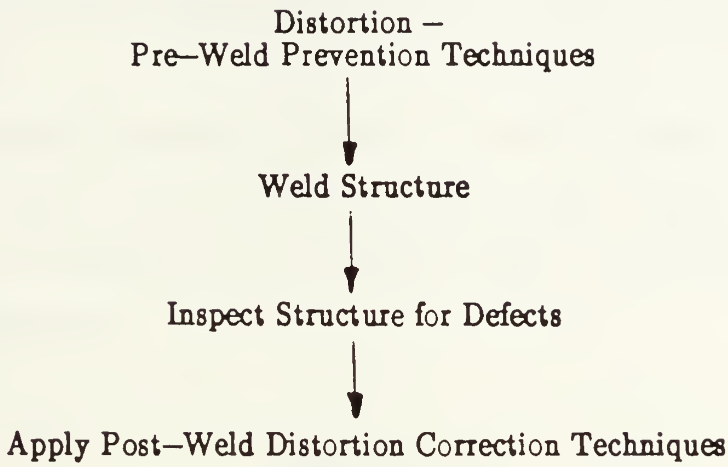


Figure 6.14: Fabrication Mode Consultation Logic (Overview)

Operation in this mode occurs independently of the distortion analysis performed in the design mode. It is not intended to be an analysis oriented consultation, but rather an information based program which makes available to the user a range of options to select from in the areas of preventive and corrective measures.

An advantage of a goal oriented approach is its positive contribution to program execution by allowing the user to proceed directly to the area of interest without sequencing through the entire list of system queries. Search speed within the knowledge base is increased by focusing in a specific area of domain knowledge.

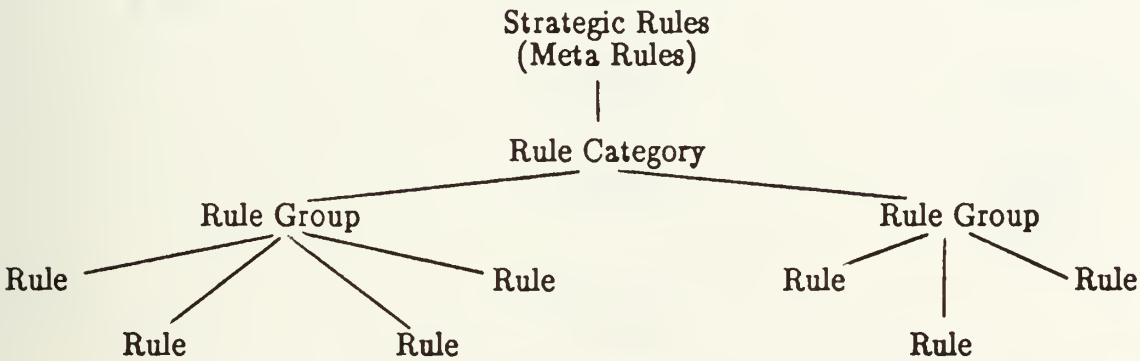
6.4.3.2. Control strategy

This section addresses the issue of control during the consultation process. The importance of an appropriate strategy for control can be shown through an

example.

Consider the distortion analysis portion of the design mode. Given a structure to be examined, an analysis tool must be selected which best models the problem at hand. How does DISCON proceed with the selection? What is the criteria used in the selection process?

The strategy for control in DISCON is contained in rules. These strategic rules direct the course of consultation and participate in the "decision selection" nodes of the program by controlling the processing of rules. The rule structure is best represented schematically:



There are three basic rule categories in DISCON:

- Rules for structural design;
- Rules for manufacturing;
- Strategic rules which control the processing of the above rules.

Each rule category is composed of rule groups. Each rule group consists of individual rules.

A more comprehensive breakdown of these rules is presented in Section 6.5 (i.e., formalization stage).

The employment of strategic rules is illustrated in Figure 6.15 during a

Enter
DISCON

Establish
Consultation Goals

List Rules
and Regulations

Run External
Programs

Distortion
Analysis

Input Required
Parameters

Rules for
Selection

F.E.M.

Select Analysis
Tools

Analytical
Models

Empirical
Formulations

Estimate
Distortion

Rules for
Database
Access

Distortion
Allowed

Interpret
Results

Rules for
Interpretation

Optimize Structure
Geometry

Rules for
Optimization

Continue

Figure 6.15: How Control Rules Are Used

segment of consultation in DECON.

The goal driven feature emphasized in this section is well suited to a backward–chaining search strategy. The particular search strategy (forward, backward, or mixed) is selected by the user at the beginning of the session.

6.4.3.3. Format of consultation

The consultation proceeds with the following format:

- The goals of consultation are defined by the user;
- The system requests inputs from the user sequentially by asking for specific information;
- Explanations are provided at user's request;
- Information–type knowledge is included in the program's logic sequence and appears as text between system queries without user intervention;
- Outputs of a particular session are made available at the end of consultation.

6.5 Formalization

The conceptualization phase of DISCON's development identified the key concepts needed to articulate the elements of the distortion problem. The design specifications were formulated and a workable architecture derived.

Before implementation can take place, a selection of the appropriate formalisms for mapping these concepts is necessary. Specifically, the following issues must be considered:

- How should the domain knowledge be represented?
- How should the knowledge base be organized to support problem solving activities?

6.5.1 Knowledge representation in DISCON

As stated in several parts of this thesis, the goal of the proposed design is the development of a knowledge–based tool which provides consultation services in the area of distortion control. To accomplish this goal, it is necessary to devise a knowledge representation structure which can combine the existing empirical and analytical foundations of the distortion problem with a heuristic knowledge base.

The distortion control domain includes many aspects: a descriptive definition of distortion related terms (e.g., "out–of–plane distortion"), descriptions of individual domain objects and their relationships to each other (e.g., "A panel structure is composed of a base plate and stiffeners."), procedural knowledge of the methods for minimizing distortion (e.g., pre–weld techniques such as clamping), and heuristic knowledge (e.g., a prioritized preference of post–weld correction techniques from an expert's experience developed over many years). Chapter 5 presented an overview of the possible representation schemes used in existing KBES.

The following formalisms are used in DISCON:

1. Production rules are used to represent the procedural, qualitative and heuristic knowledge. These consist of a left hand side which determines the applicability of the rule and a right hand side which describes the actions to be performed if the rule is applied (IF <condition>, THEN <action>). These rules offer the advantage of modularity (i.e., new rules may be added or deleted independently), and they are the simplest of all forms of knowledge representation to understand and use. Moreover, they have dominated as a representation scheme in welding applications and have been used successfully in this area. All rules have the following form:

Rule:	<name>
IF:	<condition>
THEN:	<conclusion>

The condition and the conclusion of a rule consists of one or more facts. Also, whenever all the statements in the condition of the rule are valid, then the conclusion is also valid; it is added to the facts stored in the session context. This is an example of a rule found in the module of the knowledge base called OPTCON (optimization consultant):

Rule:	Panel structure
IF:	Structure has base plate
AND:	Structure has stiffeners,
THEN:	Structure is called panel structure.

One of the problems associated with the rule format is the fact that it is unstructured and does not adequately represent an object or a class of objects. This lack of expressive power may, however, be found in frame–based representation and is discussed next.

2. Frame–based representation is used in DISCON to represent that knowledge needed to describe objects (e.g., structure, welding processes) and their attributes. References [15,32] describe the details and subtleties of using frame–based representation in the area of reasoning. DISCON's use of frames is uniquely limited to structural representation rather than on the control of reasoning[7]. Frames consist of slots describing the attributes of the object or class represented by the frames. For example, a frame representing a panel

---

[7]There is a limit to the level of complexity one should introduce in an initial design. There is enormous potential in using solely frames to represent all knowledge categories in DISCON.

structure might include a description of the structure's components (e.g., stiffeners) as well as the material properties used in each member. An example of such a frame is shown below:

Frame:	Base plate
slot:	Material type
slot:	Dimensions
slot:	Buckling strength
slot:	Location
slot:	Function

Frames can be linked to other frames and can "inherit" information or properties from them. Frame slots can contain questions and explanations for the user, graphics or even other frames. In DISCON, materials and their properties, welding processes and their parameters are examples of object attribute entities that are represented by frames. Within the frame structure lies a hierarchy of "parent frames" and "sibling frames" as indicated in Figure 5.5.

6.5.2 Organization of DISCON's knowledge base

An essential characteristic of DISCON's knowledge base is that it is structured. On a macro–level, the terms "structured" refers to the partitioning of the knowledge base into three modules (OPTCON, PRECON and POSTCON), each representing a particular area of the distortion domain. But on a more refined level knowledge must be viewed in terms of objects and attributes. This process of breaking down the distortion knowledge into these components is vital, in that it brings order and simplicity to the task of implementing this knowledge into rules. But before objects and their attributes are selected, it is useful to identify the relationships

between the primary elements of the distortion problem. This is shown in Figure 6.16[8]. As an example, it is most important to describe in rule form the relationship between welding process parameters and their resulting effect on distortion.

Each object is characterized by a list of attributes. For instance, the object <Structured Parameters> is represented as follows:

$$\text{<Structural Parameters>} \quad \left\{\begin{array}{l} \text{Structure-type} \\ \text{Structure-configuration} \\ \text{Structure-geometry} \\ \text{Material-type} \\ \text{Joint-type} \end{array}\right\}$$

As discussed in Section 6.4, the knowledge base consists of three major rule categories. These are:

- Rules about design;
- Rules about fabrication;
- Meta rules, used in the strategy of selection.

Each of these rule categories comprises several rule groups, themselves consisting of several rules. The elements of Figure 6.16 provide us with the information needed to construct each rule group, by identifying the <condition> and <action> portions of each. Table 6.2 describes the structure of the rule groups associated with the design category. Table 6.3 represents the rule groups concerned with fabrication. Table 6.4 describes the meta rules used for control.

The connections between the body of rules and frames which make up the knowledge base may be constructed as shown in Figure 6.17. This structure of rules and frames repeats itself throughout the knowledge base, and elements of this structure (i.e., rules or frames) may be added or deleted when necessary. As can be seen, the knowledge base can be made to expand by simply attaching new strings of rules and frames.

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[8]This Figure is influenced by [18].

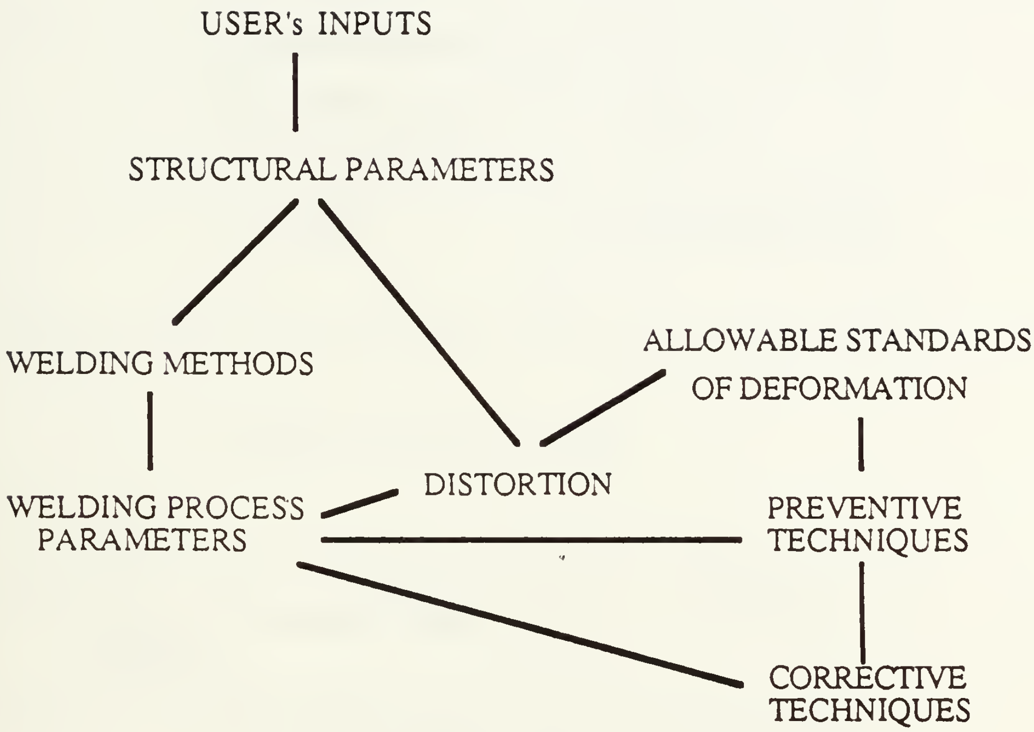

Figure 6.16 : DISCON's Logic Flow

RULE GROUP	< CONDITION >	< ACTION >
1	Structural Parameters	Distortion
2	Structural Parameters	Welding Method
3	Structural Parameters	Process Parameters
4	Allowable Standards	Distortion
5	Distortion	Structural Parameters

Table 6.2 : Design Rule Group

RULE GROUP	< CONDITION >	< ACTION >
1	Welding Method	Process Parameters
2	Distortion	Preventive Techniques
3	Distortion	Corrective Techniques
4	Preventive Techniques	Process Parameters
5	Preventive Techniques	Welding Method
6	Distortion	Welding Method
7	Distortion	Process Parameters
8	Corrective Techniques	Preventive Techniques

Table 6.3 : Fabrication Rule Group

RULE GROUP	DESCRIPTION
1	To Initiate Consultation
2	To Select Distortion Analysis Tool
3	To Select Preventive Techniques
4	To Select Corrective Techniques
5	To Control Flow Of Consultation

Table 6.4 : Control Rule Group

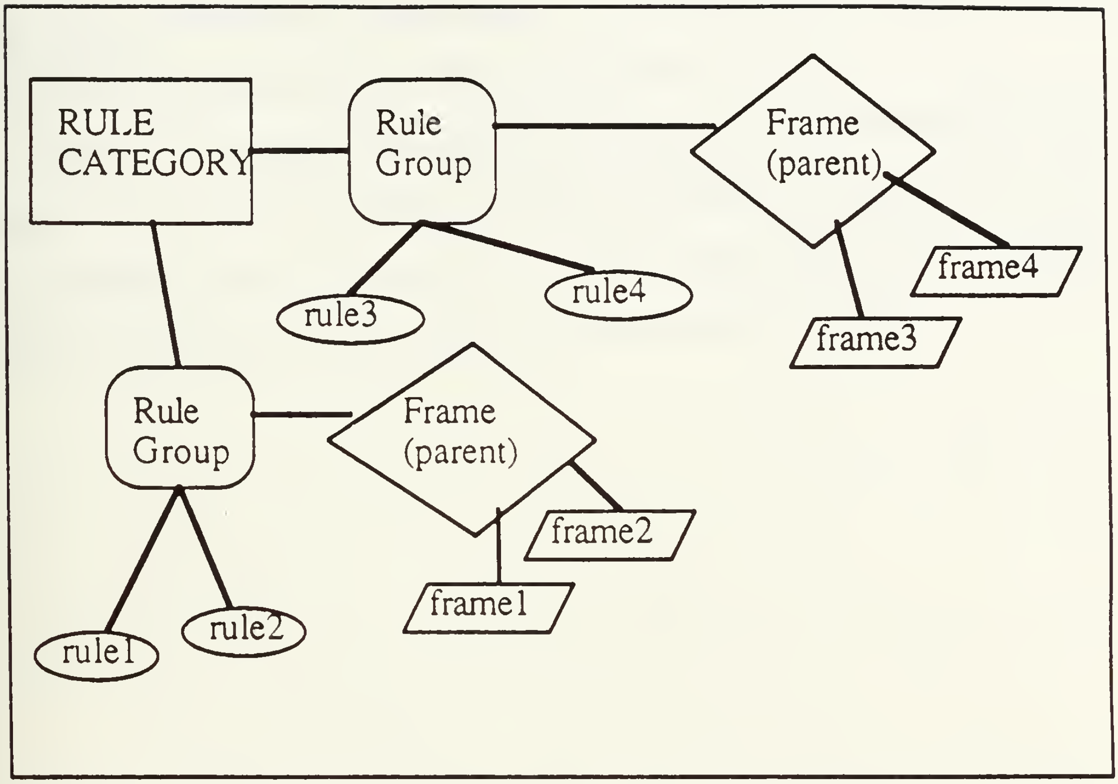

Figure 6.17 : Organization Of DISCON's Knowledge Base

6.6 Implementation and Validation Phases

The implementation and validation phases of DISCON's design will take place with the acquisition of an expert shell capable of performing the functions contained in this chapter. This phase is intended to be pursued in the near future as part of an ongoing research program in the Ocean Engineering Department in the area of Control of Distortion and Residual Stresses in Welded Structures.

However, in an effort to demonstrate the feasibility of implementation of the distortion problem domain in a KBES, the LEVEL–5[9] expert environment was selected as an intermediate step. Appendix A provides the details of the prototype <DISCON> and includes a session output for demonstration purposes.

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[9]LEVEL–5 is a product of Information Builders, Inc., New York, NY 10001.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

The preliminary design of a consultation knowledge–based system for the minimization of distortion in welded structures was introduced. The primary objective was the study of the feasibility of encoding the distortion knowledge in an expert environment, through existing principles of the field of Artificial Intelligence. Specifically, the feasibility entailed the following:

- Breaking down the distortion problem into smaller components in order to identify the types of knowledge and the causal relationships between key parameters;
- Identifying, through the knowledge acquisition process, the sources and means of expressing this knowledge;
- Specifying the functional requirements of our design by considering the input, output and user interface functions to be performed;
- Representing this knowledge using formalisms available in the AI literature; and
- Deriving an architecture which articulates the concepts defined for the design and which is suitable for further implementation and prototyping.

A demonstration of the potential for use in the specific area of out–of–plane distortion was conducted through a simple prototype. The results are significant enough to indicate the need for further exploration. Once a knowledge–based system is built and refined, it is relatively easy to develop tutoring systems which make use of the knowledge contained in the knowledge base.

Furthermore, the practical use of such a system in the manufacturing and repair industry can only enhance the quality of a final product. In the shipbuilding and ship repair industrial environments, where distortion related defects are dominant, considerable gain would result from expert tools specializing in this particular area.

7.2 Recommendations for Future Research

If the feasibility of encoding knowledge of distortion in a knowledge–based system is an acceptable argument, its ultimate usefulness as an expert tool is limited by the following observations:

- There is a need for developing integrated models of distortion which are capable of analyzing many types of distortion. The existing methods for analysis specialize in a particular area of distortion and are largely based on empirical data. The finite element programs could be externally interfaced from the expert tool, but problems associated with long execution times limit their applications in this instance. Current expert systems operating around a "deep causal model" are generally more efficient and successful;
- Existing programs which analyze distortion are written in their own specific program language and currently present interface problems with existing expert systems; a particular interface program is required for each program application. This is an important area of research which needs further emphasis.

The introduction of integrated expert tools in recent years for the purpose of handling complex design–type problems, should encourage research in two possible areas of interest:

1. The development of an "integrated welding expert tool" whose expertise would extend to both consultation and analysis functions. Specifically, it

would be capable of recommending steps for the prevention of multiple defects prior to and during welding (in process control) and provide advice on course of action to correct these defects after welding has taken place. Tailored welding procedures could be produced to optimize the success of the welding operation. Analytical models could predict the magnitude and likely occurrence of these defects;

2. The development of an "integrated ship structural design expert tool" which would provide advice in the following steps of the design process:
   - estimation of the design loads anticipated in service
   - provide an adequate initial structural configuration
   - select appropriate material for use
   - perform structural analysis based on desired optimization criteria
   - perform strength analysis
   - provide a prognosis on the expected failure mechanism to encounter and in which areas of the structure
   - an assessment of the structural integrity of the overall structure.

Finally, it is hoped that the concepts introduced in this thesis might generate with the reader at least a curiosity for this new programming environment.

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APPENDIX A

PROTOTYPE OUTPUT
USING
LEVEL-5 EXPERT ENVIRONMENT

```
TITLE   distortion control consultant    DISPLAY


This knowledge based system determines which specialized
consultant to use.


         * click <Continue> *
GOALSELECT ON
1. desire design related consultation
1.1 select decon
2. desire fabrication related consultation
2.1 select fabcon

RULE for selection of design consultant
IF CHAIN decon
THEN select decon

RULE for selection of fabrication consultant
IF CHAIN fabcon
THEN select fabcon

END
```

```
TITLE design consultant DISPLAY

This knowledge base specializes and provides advice on
 how to optimize a panel structure's qeometry so that
distortion results may be minimized.

    * Click <Continue> *

ATTRIBUTE structure type
AND suspected distortion type
AND welding process
AND material type
AND weld joint type
AND stiffener configuration type
AND distortion result
AND recommendations
AND angular change
AND degree of restraint


NUMERIC plate thickness
AND fillet weld size
AND heat input
AND electrode deposition efficiency
AND electrode material density
AND calculated distortion
AND allowable distortion
AND alowable standard
AND less
AND greater
AND phizero
AND t
AND b
AND u
AND e
AND df
AND d
AND w
AND c
AND phi
AND deltam
AND x
AND density
AND nd


MULTI structure type
AND suspected distortion type
AND welding process
AND material type
AND weld joint type
AND stiffener configuration type

1. try again

RULE for vals asked for
IF ASK t
AND ASK b
AND ASK u
AND ASK e
AND ASK df
AND ASK density
AND ASK nd
THEN vals asked for

RULE for 3/4 in (given in mm)
```

```
IF t< (-44.223+(4.005*b)-(0.106*(b^2))+(0.0009580*(b^3)))
THEN standard is three fourths
AND allowable standard:=19.05


RULE for 5/8 in (given in mm)
IF t<=(-34.224+(3.213*b)-(0.074*(b^2))+(0.0006148*(b^3)))
THEN standard is five eighths
AND allowable standard :=15.875

RULE for 1/2 in (given in mm)
IF t<=(-35.707+(4.041*b)-(0.105*(b^2))+(0.001048*(b^3)))
THEN standard is one half
AND allowable standard :=12.7

RULE for 3/8 in (given in mm)
IF t<=(-92.102+(14.028*b)-(0.604*(b^2))+(0.009147*(b^3)))
THEN standard is three eighths
AND allowable standard :=9.52

RULE for 1/4 in (given in mm)
IF t<=(-135.33+(26.832*b)-(1.574*(b^2))+(0.032*(b^3)))
THEN standard is one fourth
AND allowable standard :=6.35
ELSE allowable standard :=4.76

RULE for log w's range is .4 to .6
IF LOG((df^2/2)*(density/nd)*.01)>.4
AND LOG((df^2/2)*(density/nd)*.01)<.6
THEN range of w is gotten
AND less =.4
AND greater =.6

RULE for log w's range is .6 to .8
IF LOG((df^2/2)*(density/nd)*.01)>.6
AND LOG((df^2/2)*(density/nd)*.01)<.8
THEN range of w is gotten
AND less =.6
AND greater =.8

RULE for log w's range is .8 to 1.0
IF LOG((df^2/2)*(density/nd)*.01)>.8
AND LOG((df^2/2)*(density/nd)*.01)<1.0
THEN range of w is gotten
AND less =.8
AND greater =1.0
ELSE DISPLAY bad vals
AND FORGET ALL
AND CYCLE

RULE for obtaining background info
IF structure type IS shell structure
OR structure type IS panel structure
AND suspected distortion type IS out of plane
OR suspected distortion type IS buckling
AND stiffener configuration type IS longitudinal
OR stiffener configuration type IS transverse
OR stiffener configuration type IS transverse and longitudinal
AND material type IS low carbon steel
OR material type IS aluminum
AND weld joint type IS butt weld
OR weld joint type IS lap weld
OR weld joint type IS fillet weld
AND welding process type IS gmaw
OR welding process type IS gtaw
OR welding process type IS eb
```

```
AND degree of restraint IS free
OR degree of restraint IS restrained
THEN background info is gotten

RULE for allowable standard
IF standard is three fourths
OR standard is five eighths
OR standard is one half
OR standard is three eighths
OR standard is one fourth
THEN allowable standard is calculated

RULE for determining if distortion is calculated
IF  vals asked for
AND range of w is gotten
AND less=.4
AND greater=.6
THEN distortion is calculated
AND d :=e*t^3/12*(1-u^2)
AND w :=(df^2/2)*(density/nd)*.01
AND c :=t^4/(1+w/5)
AND ASK phizero
AND phi :=phizero/(1+(2*d/b)*(1/c))
AND deltam :=(.25*b*phi)


RULE for determining if distortion is calculated
IF vals asked for
AND range of w is gotten
AND less =.6
AND greater =.8
THEN distortion is calculated
AND d :=e*t^3/12*(1-u^2)
AND w :=(df^2/2)*(density/nd)*.01
AND c :=t^4/(1+w/5)
AND ASK phizero
AND phi :=phizero/(1+(2*d/b)*(1/c))
AND deltam :=(.25*b*phi)


RULE for determining if distortion is calculated
IF vals asked for
AND range of w is gotten
AND less=.8
AND greater=1.0
THEN distortion is calculated
AND d :=e*t^3/12*(1-u^2)
AND w :=(df^2/2)*(density/nd)*.01
AND c :=t^4/(1+w/5)
AND ASK phizero
AND phi :=phizero/(1+(2*d/b)*(1/c))
AND deltam :=(.25*b*phi)



RULE for too much distortion
IF background info is gotten
AND distortion is calculated
AND allowable standard is calculated
AND deltam>allowable standard
THEN distortion is too much
AND DISPLAY out of range analysis results
ELSE distortion is ok
AND DISPLAY analysis results are ok
AND CHAIN fabcon
```

```
RULE for recommendations complete
IF distortion is too much
AND weld joint IS fillet weld
AND structure is weight sensitive
AND material type IS low carbon steel
AND NOT material selected a design constraint
THEN recommendations complete
AND DISPLAY aluminum vice steel

RULE for recommendations complete
IF distortion is too much
AND weld joint IS fillet weld
AND structure is weight sensitive
AND material type IS low carbon steel
AND material selected a design constraint
THEN recommendations complete
AND DISPLAY reduce fillet weld size

RULE for recommendations complete
IF distortion is too much
AND weld joint IS fillet weld
AND structure is weight sensitive
AND material type IS low carbon steel
AND plate thickness fixed design parameter
AND material selected a design constraint
AND fillet weld size is minimum value for shear strength
THEN recommendations complete
AND DISPLAY reduce stiffener spacing

RULE for recommendations complete
IF structure type IS shell structure
OR suspected distortion type IS buckling
OR stiffener configuration type IS transverse and longitudinal
OR weld joint type IS lap weld
OR weld joint type IS butt weld
THEN recommendations complete
AND DISPLAY not available

RULE for recommendations complete
IF distortion is too much
AND weld joint type IS fillet weld
AND NOT structure weight sensitive
AND material type IS low carbon steel
AND NOT plate thickness fixed design parameter
AND material selected a design constraint
AND degree of restraint IS free
AND t>9
THEN recommendations complete
AND DISPLAY increase steel plate thickness

RULE for recommendations complete
IF distortion is too much
AND weld joint type IS fillet weld
AND NOT structure weight sensitive
AND material type IS aluminum
AND NOT plate thickness fixed design parameter
AND degree of restraint IS free
AND t>7
THEN recommendations complete
AND DISPLAY increase Al plate thickness
```

```
RULE to determine if should cycle
IF recommendations complete
AND user wishes to do another distortion analysis
THEN try again
AND FORGET ALL
AND cycle
ELSE STOP

DISPLAY aluminum vice steel

     Recommendation is use aluminum vice steel for both base plate and for
stiffener panels. Evaluate impact on structural analysis results.

DISPLAY reduce fillet weld size

     Recommendation is reduce fillet weld size to minimum shear strength
requirements. This will avoid overwelding and produce lowest residual stress
and distortion.Caution: any lower reduction will cause frames to rip from
plating during service.

DISPLAY reduce stiffener spacing

     Recommendation is reduce stiffener spacing.

DISPLAY not available

     Expertise in this area not yet implemented.Go talk to expert.

DISPLAY increase steel plate thickness

     Recommendation is increase plate thickness and reevaluate distortion.Check
impact on overall structure weight.

DISPLAY increase Al plate thickness

     Recommendation is increase plate thickness and reevaluate distortion.

DISPLAY bad vals
     Your values are out of the ranges of this distortion analysis.Try again.

DISPLAY analysis results are ok
     results of distortion analysis are acceptable



DISPLAY out of range analysis results
     The results of the analysis are unsatisfactory from an analysis
     standpoint because calculated distortion > allowable standard:
                    DIScalc [deltam] > DISallowed[allowable standard]

END
```

TITLE fabrication consultant DISPLAY

This knowledge base specializes in the prevention and correction of out of plane distortion which occurs in fillet welded panel structures.

* click <Continue> *

ATTRIBUTE structure type
AND welding process
AND material type
AND stiffener configuration type
AND degree of restraint
AND angular change
AND recommendation
AND likely distortion
AND area of interest
AND distortion analysis
AND welding environment
AND weld joint type

NUMERIC plate thickness
AND fillet weld size
AND heat input
AND calculated distortion
AND allowable distortion
AND stiffener spacing

MULTI structure type
AND likely distortion
AND welding process type
AND material type
AND weld joint type
AND stiffener configuration type
AND area of interest

1. background info is gotten
2. recommendation IS WHAT

RULE buckling possible
IF structure type IS panel structure
AND material type IS low carbon steel
OR material type IS aluminum
AND weld joint type IS fillet weld
AND plate thickness<8
THEN buckling distortion likely
AND DISPLAY buckling distortion

RULE angular distortion
IF structure type IS panel structure
AND material type IS low carbon steel
OR material type IS aluminum
AND weld joint type IS fillet weld
AND plate thickness >8
THEN out of plane distortion likely
AND DISPLAY out of plane distortion

RULE for obtaining background info
IF area of interest IS distortion reduction techniques
OR area of interest IS distortion correction techniques
AND structure type IS shell structure
OR structure type IS panel structure

```
OR structure type IS other
AND stiffener configured
AND material type IS low carbon steel
OR material type IS aluminum
AND welding process IS gmaw
OR welding process IS gtaw
OR welding process IS eb
OR welding process type IS laser
AND welding environment IS dry
OR welding environment IS humid
AND distortion analysis IS performed
OR distortion analysis IS unavailable
AND ASK plate thickness
AND ASK heat input
AND ASK fillet weld size
THEN background info is gotten

RULE welding under restraint
IF background info is gotten
AND out of plane distortion likely
AND material type IS low carbon steel
OR material type IS aluminum
AND weld joint type IS fillet weld
AND area of interest IS distortion reduction techniques
THEN recommendation IS restrain joint
AND DISPLAY weld under restraint

RULE for determining heat input
IF area of interest IS distortion reduction techniques
AND out of plane distortion likely
AND structure type IS panel structure
AND plate thickness<8
AND stiffener spacing<2000
AND background info is gotten
THEN recommendation IS range of heat input
AND DISPLAY range

RULE for welding process selection
IF area of interest IS distortion reduction techniques
AND out of plane distortion likely
AND background info is gotten
AND weld joint type IS fillet weld
AND heat input is unknown
THEN recommendation IS weld with less heat
AND DISPLAY less heat

RULE for distortion correction techniques
IF background info is gotten
AND area of interest IS distortion correction techniques
THEN recommendation IS flame heating
AND DISPLAY flame heating technique


DISPLAY buckling distortion
     buckling distortion is likely to take place when welding thin plate
    structures .This condition occurs for plate thicknesses less than 8mm.

          Click<Continue>

DISPLAY out of plane distortion
     When welding thick plate structures of thicknesses greater than 8mm
   welding residual stresses cause 'angular' distortion around the weld.
           click<continue>

DISPLAY weld under restraint
       There are several methods available for reducing weld distortion:
```

1. apply CLAMPING of the structures (panels if panel structure)
2. stretch and/or heat the plates during welding
3. use intermittent fillet welding if possible
4. use welding processes with less heat input.
5. PREHEAT the plate at selected areas

My recommendation is 1. to apply CLAMPING as a form of restraint
2. PREHEAT the back of the plate rather than the front

Click<continue>

DISPLAY range
The range of heat input varies from 0.2 to 1.0 KJ/mm.These are max design heat inputs values.

Click <Continue>

DISPLAY less heat
Welding processes such as narrow-gap welding, electron beam welding and laser welding are PREFERRED over arc welding processes. The resulting weld is made at lower input implying less distortion.

Click<Continue>

DISPLAY flame heating technique
The flame heating technique includes the following methods:

1.Line heating
2.Side heating
3.Spot heating
4.Triangular heating
5.Pine-needle heating

Recommend side heating technique for limiting residual stress effects resulting from welding

END

Knowledge Base : distortion control consultant

Compiled : 12/16/1988 04:52:49 A.M.

1. desire design related consultation
1.1. select decon
From rule : for selection of design consultant
2. desire fabrication related consultation
2.1. select fabcon
From rule : for selection of fabrication consultant

Knowledge Base : design constultant

Compiled : 12/16/1988 02:26:50 A.M.

1. try again
  From rule : to determine if should cycle
    Uses fact : recommendations complete
      From rule : for recommendations complete
        Uses fact : distortion is too much
          From rule : for too much distortion
            Uses fact : background info is gotten
              From rule : for obtaining background info
                Asks question : structure type shell structure
                Asks question : structure type panel structure
                Asks question : suspected distortion type out of plane
                Asks question : suspected distortion type buckling
                Asks question : stiffener configuration type longitudinal
                Asks question : stiffener configuration type transverse
                Asks question : stiffener configuration type transverse and longitudinal
                Asks question : material type low carbon steel
                Asks question : material type aluminum
                Asks question : weld joint type butt weld
                Asks question : weld joint type lap weld
                Asks question : weld joint type fillet weld
                Asks question : welding process type gmaw
                Asks question : welding process type gtaw
                Asks question : welding process type eb
                Asks question : degree of restraint free
                Asks question : degree of restraint restrained
            Uses fact : distortion is calculated
              From rule : for determining if distortion is calculated
              Uses fact : vals asked for
                From rule : for vals asked for
              Uses fact : range of w is gotten
                From rule : for log w's range is .4 to .6
                  Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
                  Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
                From rule : for log w's range is .6 to .8
                  Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
                  Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
                From rule : for log w's range is .8 to 1.0
                  Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
                  Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
              Evaluates : less=.4
              Evaluates : greater=.6
                From rule : for determining if distortion is calculated
              Uses fact : vals asked for
                From rule : for vals asked for

```
   Uses fact : range of w is gotten
    From rule : for log w's range is .4 to .6
       Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
       Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
    From rule : for log w's range is .6 to .8
       Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
       Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
    From rule : for log w's range is .8 to 1.0
       Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
       Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
  Evaluates : less =.6
  Evaluates : greater =.8
   From rule : for determining if distortion is calculated
  Uses fact : vals asked for
    From rule : for vals asked for
  Uses fact : range of w is gotten
    From rule : for log w's range is .4 to .6
       Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
       Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
    From rule : for log w's range is .6 to .8
       Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
       Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
    From rule : for log w's range is .8 to 1.0
       Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
       Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
  Evaluates : less=.8
  Evaluates : greater=1.0
 Uses fact : allowable standard is calculated
  From rule : for allowable standard
   Uses fact : standard is three fourths
   From rule : for 3
        Evaluates : t< (-44.223+(4.005*b)-(0.106*(b^2))+(0.0009580*(b^3)))
   Uses fact : standard is five eighths
   From rule : for 5
        Evaluates : t<=(-34.224+(3.213*b)-(0.074*(b^2))+(0.0006148*(b^3)))
   Uses fact : standard is one half
   From rule : for 1
        Evaluates : t<=(-35.707+(4.041*b)-(0.105*(b^2))+(0.001048*(b^3)))
   Uses fact : standard is three eighths
   From rule : for 3
        Evaluates : t<=(-92.102+(14.028*b)-(0.604*(b^2))+(0.009147*(b^3)))
   Uses fact : standard is one fourth
   From rule : for 1
        Evaluates : t<=(-135.33+(26.832*b)-(1.574*(b^2))+(0.032*(b^3)))
 Evaluates : deltam>allowable standard
Asks question : weld joint fillet weld
Asks question : structure is weight sensitive
Asks question : material type low carbon steel
```

Asks question : material selected a design constraint
From rule : for recommendations complete
Uses fact : distortion is too much
From rule : for too much distortion
Uses fact : background info is gotten
From rule : for obtaining background info
Asks question : structure type shell structure
Asks question : structure type panel structure
Asks question : suspected distortion type out of plane
Asks question : suspected distortion type buckling
Asks question : stiffener configuration type longitudinal
Asks question : stiffener configuration type transverse
Asks question : stiffener configuration type transverse and longitudinal
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : weld joint type butt weld
Asks question : weld joint type lap weld
Asks question : weld joint type fillet weld
Asks question : welding process type gmaw
Asks question : welding process type gtaw
Asks question : welding process type eb
Asks question : degree of restraint free
Asks question : degree of restraint restrained
Uses fact : distortion is calculated
From rule : for determining if distortion is calculated
Uses fact : vals asked for
From rule : for vals asked for
Uses fact : range of w is gotten
From rule : for log w's range is .4 to .6
Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
From rule : for log w's range is .6 to .8
Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
From rule : for log w's range is .8 to 1.0
Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
Evaluates : less=.4
Evaluates : greater=.6
From rule : for determining if distortion is calculated
Uses fact : vals asked for
From rule : for vals asked for
Uses fact : range of w is gotten
From rule : for log w's range is .4 to .6
Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
From rule : for log w's range is .6 to .8
Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6

```
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
        From rule : for log w's range is .8 to 1.0
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
      Evaluates : less =.6
      Evaluates : greater =.8
       From rule : for determining if distortion is calculated
       Uses fact : vals asked for
        From rule : for vals asked for
        Uses fact : range of w is gotten
        From rule : for log w's range is .4 to .6
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
        From rule : for log w's range is .6 to .8
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
        From rule : for log w's range is .8 to 1.0
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
      Evaluates : less=.8
      Evaluates : greater=1.0
     Uses fact : allowable standard is calculated
      From rule : for allowable standard
       Uses fact : standard is three fourths
       From rule : for 3
           Evaluates : t< (-44.223+(4.005*b)-(0.106*(b^2))+(0.0009580*(b^3)))
       Uses fact : standard is five eighths
       From rule : for 5
           Evaluates : t<=(-34.224+(3.213*b)-(0.074*(b^2))+(0.0006148*(b^3)))
       Uses fact : standard is one half
       From rule : for 1
           Evaluates : t<=(-35.707+(4.041*b)-(0.105*(b^2))+(0.001048*(b^3)))
       Uses fact : standard is three eighths
       From rule : for 3
           Evaluates : t<=(-92.102+(14.028*b)-(0.604*(b^2))+(0.009147*(b^3)))
       Uses fact : standard is one fourth
       From rule : for 1
           Evaluates : t<=(-135.33+(26.832*b)-(1.574*(b^2))+(0.032*(b^3)))
     Evaluates : deltam>allowable standard
   Asks question : weld joint fillet weld
   Asks question : structure is weight sensitive
   Asks question : material type low carbon steel
   Asks question : material selected a design constraint
From rule : for recommendations complete
  Uses fact : distortion is too much
    From rule : for too much distortion
     Uses fact : background info is gotten
      From rule : for obtaining background info
```

```
    Asks question : structure type shell structure
    Asks question : structure type panel structure
    Asks question : suspected distortion type out of plane
    Asks question : suspected distortion type buckling
     Asks question : stiffener configuration type longitudinal
     Asks question : stiffener configuration type transverse
     Asks question : stiffener configuration type transverse and longitudinal
    Asks question : material type low carbon steel
    Asks question : material type aluminum
    Asks question : weld joint type butt weld
    Asks question : weld joint type lap weld
     Asks question : weld joint type fillet weld
    Asks question : welding process type gmaw
    Asks question : welding process type gtaw
    Asks question : welding process type eb
    Asks question : degree of restraint free
    Asks question : degree of restraint restrained
Uses fact : distortion is calculated
    From rule : for determining if distortion is calculated
  Uses fact : vals asked for
    From rule : for vals asked for
  Uses fact : range of w is gotten
    From rule : for log w's range is .4 to .6
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
    From rule : for log w's range is .6 to .8
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
    From rule : for log w's range is .8 to 1.0
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
  Evaluates : less=.4
  Evaluates : greater=.6
    From rule : for determining if distortion is calculated
  Uses fact : vals asked for
    From rule : for vals asked for
  Uses fact : range of w is gotten
    From rule : for log w's range is .4 to .6
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
    From rule : for log w's range is .6 to .8
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
    From rule : for log w's range is .8 to 1.0
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
  Evaluates : less =.6
  Evaluates : greater =.8
```

```
      From rule : for determining if distortion is calculated
     Uses fact : vals asked for
       From rule : for vals asked for
      Uses fact : range of w is gotten
        From rule : for log w's range is .4 to .6
            Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
            Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
        From rule : for log w's range is .6 to .8
            Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
            Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
        From rule : for log w's range is .8 to 1.0
            Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
            Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
     Evaluates : less=.8
     Evaluates : greater=1.0
    Uses fact : allowable standard is calculated
     From rule : for allowable standard
       Uses fact : standard is three fourths
       From rule : for 3
             Evaluates : t< (-44.223+(4.005*b)-(0.106*(b^2))+(0.0009580*(b^3)))
       Uses fact : standard is five eighths
       From rule : for 5
             Evaluates : t<=(-34.224+(3.213*b)-(0.074*(b^2))+(0.0006148*(b^3)))
       Uses fact : standard is one half
       From rule : for 1
             Evaluates : t<=(-35.707+(4.041*b)-(0.105*(b^2))+(0.001048*(b^3)))
       Uses fact : standard is three eighths
       From rule : for 3
             Evaluates : t<=(-92.102+(14.028*b)-(0.604*(b^2))+(0.009147*(b^3)))
       Uses fact : standard is one fourth
       From rule : for 1
             Evaluates : t<=(-135.33+(26.832*b)-(1.574*(b^2))+(0.032*(b^3)))
    Evaluates : deltam>allowable standard
  Asks question : weld joint fillet weld
  Asks question : structure is weight sensitive
  Asks question : material type low carbon steel
  Asks question : plate thickness fixed design parameter
  Asks question : material selected a design constraint
  Asks question : fillet weld size is minimum value for shear strength
From rule : for recommendations complete
  Asks question : structure type shell structure
  Asks question : suspected distortion type buckling
  Asks question : stiffener configuration type transverse and longitudinal
  Asks question : weld joint type lap weld
  Asks question : weld joint type butt weld
From rule : for recommendations complete
  Uses fact : distortion is too much
   From rule : for too much distortion
```

```
Uses fact : background info is gotten
  From rule : for obtaining background info
     Asks question : structure type shell structure
     Asks question : structure type panel structure
     Asks question : suspected distortion type out of plane
     Asks question : suspected distortion type buckling
      Asks question : stiffener configuration type longitudinal
      Asks question : stiffener configuration type transverse
      Asks question : stiffener configuration type transverse and longitudinal
     Asks question : material type low carbon steel
     Asks question : material type aluminum
     Asks question : weld joint type butt weld
     Asks question : weld joint type lap weld
     Asks question : weld joint type fillet weld
    Asks question : welding process type gmaw
    Asks question : welding process type gtaw
    Asks question : welding process type eb
     Asks question : degree of restraint free
     Asks question : degree of restraint restrained
 Uses fact : distortion is calculated
    From rule : for determining if distortion is calculated
   Uses fact : vals asked for
     From rule : for vals asked for
    Uses fact : range of w is gotten
     From rule : for log w's range is .4 to .6
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
     From rule : for log w's range is .6 to .8
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
     From rule : for log w's range is .8 to 1.0
        Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
        Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
   Evaluates : less=.4
   Evaluates : greater=.6
     From rule : for determining if distortion is calculated
    Uses fact : vals asked for
      From rule : for vals asked for
     Uses fact : range of w is gotten
      From rule : for log w's range is .4 to .6
         Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
         Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
      From rule : for log w's range is .6 to .8
         Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
         Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
      From rule : for log w's range is .8 to 1.0
         Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
         Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
```

```
        Evaluates : less =.6
        Evaluates : greater =.8
          From rule : for determining if distortion is calculated
         Uses fact : vals asked for
           From rule : for vals asked for
          Uses fact : range of w is gotten
            From rule : for log w's range is .4 to .6
                Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
                Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
            From rule : for log w's range is .6 to .8
                Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
                Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
            From rule : for log w's range is .8 to 1.0
                Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
                Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
        Evaluates : less=.8
         Evaluates : greater=1.0
       Uses fact : allowable standard is calculated
        From rule : for allowable standard
          Uses fact : standard is three fourths
          From rule : for 3
                 Evaluates : t< (-44.223+(4.005*b)-(0.106*(b^2))+(0.0009580*(b^3)))
          Uses fact : standard is five eighths
          From rule : for 5
                 Evaluates : t<=(-34.224+(3.213*b)-(0.074*(b^2))+(0.0006148*(b^3)))
         Uses fact : standard is one half
          From rule : for 1
                 Evaluates : t<=(-35.707+(4.041*b)-(0.105*(b^2))+(0.001048*(b^3)))
          Uses fact : standard is three eighths
          From rule : for 3
                 Evaluates : t<=(-92.102+(14.028*b)-(0.604*(b^2))+(0.00914 7*(b^3)))
          Uses fact : standard is one fourth
          From rule : for 1
                 Evaluates : t<=(-135.33+(26.832*b)-(1.574*(b^2))+(0.032*(b^3)))
       Evaluates : deltam>allowable standard
     Asks question : weld joint type fillet weld
     Asks question : structure weight sensitive
    Asks question : material type low carbon steel
    Asks question : plate thickness fixed design parameter
    Asks question : material selected a design constraint
    Asks question : degree of restraint free
  Evaluates : t>9
  From rule : for recommendations complete
   Uses fact : distortion is too much
     From rule : for too much distortion
       Uses fact : background info is gotten
         From rule : for obtaining background info
            Asks question : structure type shell structure
```

```
      Asks question : structure type panel structure
      Asks question : suspected distortion type out of plane
      Asks question : suspected distortion type buckling
       Asks question : stiffener configuration type longitudinal
       Asks question : stiffener configuration type transverse
        Asks question : stiffener configuration type transverse and longitudinal
      Asks question : material type low carbon steel
      Asks question : material type aluminum
      Asks question : weld joint type butt weld
      Asks question : weld joint type lap weld
       Asks question : weld joint type fillet weld
      Asks question : welding process type gmaw
      Asks question : welding process type gtaw
      Asks question : welding process type eb
      Asks question : degree of restraint free
      Asks question : degree of restraint restrained
   Uses fact : distortion is calculated
      From rule : for determining if distortion is calculated
    Uses fact : vals asked for
      From rule : for vals asked for
     Uses fact : range of w is gotten
      From rule : for log w's range is .4 to .6
         Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
         Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
      From rule : for log w's range is .6 to .8
         Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
         Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
      From rule : for log w's range is .8 to 1.0
         Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
         Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
    Evaluates : less=.4
    Evaluates : greater=.6
      From rule : for determining if distortion is calculated
     Uses fact : vals asked for
       From rule : for vals asked for
      Uses fact : range of w is gotten
       From rule : for log w's range is .4 to .6
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
       From rule : for log w's range is .6 to .8
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
       From rule : for log w's range is .8 to 1.0
          Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
          Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
    Evaluates : less =.6
    Evaluates : greater =.8
      From rule : for determining if distortion is calculated
```

```
        Uses fact : vals asked for
          From rule : for vals asked for
        Uses fact : range of w is gotten
          From rule : for log w's range is .4 to .6
            Evaluates : LOG((df^2/2)*(density/nd)*.01)>.4
            Evaluates : LOG((df^2/2)*(density/nd)*.01)<.6
          From rule : for log w's range is .6 to .8
            Evaluates : LOG((df^2/2)*(density/nd)*.01)>.6
            Evaluates : LOG((df^2/2)*(density/nd)*.01)<.8
          From rule : for log w's range is .8 to 1.0
            Evaluates : LOG((df^2/2)*(density/nd)*.01)>.8
            Evaluates : LOG((df^2/2)*(density/nd)*.01)<1.0
       Evaluates : less=.8
       Evaluates : greater=1.0
      Uses fact : allowable standard is calculated
       From rule : for allowable standard
         Uses fact : standard is three fourths
         From rule : for 3
             Evaluates : t< (-44.223+(4.005*b)-(0.106*(b^2))+(0.0009580*(b^3)))
         Uses fact : standard is five eighths
         From rule : for 5
             Evaluates : t<=(-34.224+(3.213*b)-(0.074*(b^2))+(0.0006148*(b^3)))
         Uses fact : standard is one half
         From rule : for 1
             Evaluates : t<=(-35.707+(4.041*b)-(0.105*(b^2))+(0.001048*(b^3)))
         Uses fact : standard is three eighths
         From rule : for 3
             Evaluates : t<=(-92.102+(14.028*b)-(0.604*(b^2))+(0.009147*(b^3)))
         Uses fact : standard is one fourth
         From rule : for 1
             Evaluates : t<=(-135.33+(26.832*b)-(1.574*(b^2))+(0.032*(b^3)))
      Evaluates : deltam>allowable standard
    Asks question : weld joint type fillet weld
    Asks question : structure weight sensitive
    Asks question : material type aluminum
    Asks question : plate thickness fixed design parameter
    Asks question : degree of restraint free
  Evaluates : t>7
Asks question : user wishes to do another distortion analysis
```

Knowledge Base : fabrication consultant

Compiled : 12/16/1988 04:54:00 A.M.

1. background info is gotten
   From rule : for obtaining background info
      Asks question : area of interest distortion reduction techniques
      Asks question : area of interest distortion correction techniques
      Asks question : structure type shell structure
      Asks question : structure type panel structure
      Asks question : structure type other
      Asks question : stiffener configured
      Asks question : material type low carbon steel
      Asks question : material type aluminum
      Asks question : welding process gmaw
      Asks question : welding process gtaw
      Asks question : welding process eb
      Asks question : welding process type laser
      Asks question : welding environment dry
      Asks question : welding environment humid
      Asks question : distortion analysis performed
      Asks question : distortion analysis unavailable
2. recommendation
   From rule : welding under restraint
      Uses fact : background info is gotten
         From rule : for obtaining background info
            Asks question : area of interest distortion reduction techniques
            Asks question : area of interest distortion correction techniques
            Asks question : structure type shell structure
            Asks question : structure type panel structure
            Asks question : structure type other
            Asks question : stiffener configured
            Asks question : material type low carbon steel
            Asks question : material type aluminum
            Asks question : welding process gmaw
            Asks question : welding process gtaw
            Asks question : welding process eb
            Asks question : welding process type laser
            Asks question : welding environment dry
            Asks question : welding environment humid
            Asks question : distortion analysis performed
            Asks question : distortion analysis unavailable
      Uses fact : out of plane distortion likely
         From rule : angular distortion
            Asks question : structure type panel structure
            Asks question : material type low carbon steel
            Asks question : material type aluminum
            Asks question : weld joint type fillet weld

Evaluates : plate thickness >8
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : weld joint type fillet weld
Asks question : area of interest distortion reduction techniques
From rule : for determining heat input
Asks question : area of interest distortion reduction techniques
Uses fact : out of plane distortion likely
From rule : angular distortion
Asks question : structure type panel structure
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : weld joint type fillet weld
Evaluates : plate thickness >8
Asks question : structure type panel structure
Evaluates : plate thickness<8
Evaluates : stiffener spacing<2000
Uses fact : background info is gotten
From rule : for obtaining background info
Asks question : area of interest distortion reduction techniques
Asks question : area of interest distortion correction techniques
Asks question : structure type shell structure
Asks question : structure type panel structure
Asks question : structure type other
Asks question : stiffener configured
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : welding process gmaw
Asks question : welding process gtaw
Asks question : welding process eb
Asks question : welding process type laser
Asks question : welding environment dry
Asks question : welding environment humid
Asks question : distortion analysis performed
Asks question : distortion analysis unavailable
From rule : for welding process selection
Asks question : area of interest distortion reduction techniques
Uses fact : out of plane distortion likely
From rule : angular distortion
Asks question : structure type panel structure
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : weld joint type fillet weld
Evaluates : plate thickness >8
Uses fact : background info is gotten
From rule : for obtaining background info
Asks question : area of interest distortion reduction techniques
Asks question : area of interest distortion correction techniques

Asks question : structure type shell structure
Asks question : structure type panel structure
Asks question : structure type other
Asks question : stiffener configured
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : welding process gmaw
Asks question : welding process gtaw
Asks question : welding process eb
Asks question : welding process type laser
Asks question : welding environment dry
Asks question : welding environment humid
Asks question : distortion analysis performed
Asks question : distortion analysis unavailable
Asks question : weld joint type fillet weld
Asks question : heat input is unknown
From rule : for distortion correction techniques
Uses fact : background info is gotten
From rule : for obtaining background info
Asks question : area of interest distortion reduction techniques
Asks question : area of interest distortion correction techniques
Asks question : structure type shell structure
Asks question : structure type panel structure
Asks question : structure type other
Asks question : stiffener configured
Asks question : material type low carbon steel
Asks question : material type aluminum
Asks question : welding process gmaw
Asks question : welding process gtaw
Asks question : welding process eb
Asks question : welding process type laser
Asks question : welding environment dry
Asks question : welding environment humid
Asks question : distortion analysis performed
Asks question : distortion analysis unavailable
Asks question : area of interest distortion correction techniques

Thesis
R2884 Regis
c.1 Preliminary design of a
consultation knowledge-
based system for the
minimization of distor-
tion in welded structures.