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Designer-fabricator interpreter :

Marcello Barone
Lehigh University

Designer-Fabricator Interpreter: A Step Towards Computer Integrated Construction

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Marcello Barone

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Advisor *John L. Wilson* Date *April 10, 1990*

Dr. John L. Wilson

Chairman *[signature]* Date *April 12, 1990*

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Abstract

The Designer-Fabricator Interpreter (DFI) is a knowledge-based system that aids the design of beam-to-column connections. The system, as a step toward computer integrated construction (CIC), attempts to bridge the information gap between designers and fabricators of structural steel systems. This research is directed towards the eventual development of integrative tools which encompass constructability issues during preliminary design. DFI intelligently guides structural engineers to a feasible connection configuration by incorporating general fabrication and erection knowledge. The system incorporates issues, such as cost, strength, constructability, and safety of the proposed connection. By making general fabrication and erection knowledge available to structural engineers at the pre-bid stage of the design process, DFI will help designers make more "intelligent" initial design decisions and possibly avoid major problems in the fabrication and erection of proposed beam-to-column connection configurations.

The major potential for integrated design and construction systems is in the support of the development, management and sharing of information and knowledge among participants at all stages of the construction processes. These systems can act as a catalyst to improve ways of planning, organizing and coordinating activities throughout the life cycle of a project. Allowing different groups to collaborate more effectively in the overall activities could help reduce overall project costs while delivering a high quality, on time structure.

A detailed decomposition of the information each participant considers important in the satisfactory execution of their role in the design and construction process is developed. A method of relating unique viewpoints and fostering cooperative solutions between the participants of the design and construction process is also discussed. Case studies are presented which illustrate how DFI evaluates and selects alternative connection designs.

1. Introduction

The Designer-Fabricator Interpreter (DFI) project is part of a comprehensive research effort intended to provide an environment which fosters communication between the various participants or agents (i.e., owner, architect, designer, fabricator and erector) involved in a construction project. DFI, as a step towards computer-integrated construction (CIC), attempts to bridge the information interface gap between design engineers and fabricators of structural steel systems. By making general fabrication and erection knowledge available at the pre-bid stage of the design process, structural engineers will be able to make more intelligent initial design decisions and possibly avoid any major problems with the fabrication and erection of their proposed beam-to-column connection configurations.

This chapter is organized in the following manner. First, the research objectives are formulated. A brief discussion is also included on how these objectives are related to problems facing the U.S. construction industry. Some common practices of the industry are described to illustrate the lack of communication, interaction and integration between the field construction site and the design office. Next, a brief discussion of the need for systems to integrate design and construction will be presented. To illustrate this need, a simplified information flow diagram of the building design process is presented along with typical problem areas. The potential usefulness of integrated systems is also discussed with a description of their current application in manufacturing. Next, four knowledge-based systems related to structural design are described along with a description of the approach taken in developing DFI. This chapter is concluded by a brief section on the organization of the remainder of this thesis.

1.1 Objectives of the Research

The overall objective of this research project is to provide a tool which can incorporate construction knowledge into the preliminary design stage. Connections were chosen as a focus because they are the "hotspots" for problems in structures. The Hyatt Regency skywalk collapse, a devastating failure in recent history, can be viewed as an extreme case for the need of systems like DFI to point out potential downstream (i.e., construction) problems with a design.

The research was performed in two distinct phases. The objective of the first phase was the rapid development of a pre-prototype system to critique the geometric fit-up of beam-to-column connections. This phase involved performing the following three tasks:

1. Developing a hierarchy of objects to describe a building decomposition focused on connections.
2. Identifying common mistakes or *"goofs"* in connection designs and representing them in a knowledge base.
3. Developing and implementing a pre-prototype system which critiques connection configurations and provides explanations and suggestions of common fabrication and erection errors [Barone et. al. 89].

The first phase of the research had dual purposes. Primarily, the DFI researchers were interested in showing a demonstration-of-concept or working system. In addition, the pre-prototype served as a testbed for knowledge and data acquisition.

The objective of the second phase was to build a prototype for preliminary connection design. This prototype system addresses the lack of communication between designers, fabricators and erectors during the design and construction stages. The initial pre-prototype was rewritten to include a cooperative problem-solving scheme so agents were capable of suggesting alternative connection configurations while taking into account other viewpoints. The tasks involved in the second phase of development were:

1. Restructuring the phase one knowledge base into a set of constraint tables.
2. Developing a database of connection configurations using input from design, fabrication and erection viewpoints.
3. Building models of the information each agent considers important in the satisfactory execution of their role in the design and construction process.
4. Defining a relational network for a cooperative problem-solving model.
5. Developing and implementing a system that provides a cooperative means of generating alternative Type 1 connection configurations from three unique viewpoints (design, fabrication and erection).

The second phase of development permitted the researchers to explore different areas of applied artificial intelligence, specifically negotiation and concurrent design, while expanding and refining the civil engineering domain knowledge and databases of the pre-prototype from phase one.

1.2 Present Practice

Fragmentation in the U.S. construction industry has caused a decline in its ability to compete successfully on a global scale [Moavenzadeh 89]. This dispersed industry is made up of companies with their own distinct construction procedures and information flow practices. Due to the industry's fragmented nature, the most current engineering information is seldom used in the field. Typically, as problems arise in the field, the contractors make notes on their drawings. These field notes are used by the contractors to point out any potential construction problems with the design. At times, the drawings considered current in the field are as many as three revisions behind the engineer's most current drawings. The principal reason for this is that the contractors do not want to lose their handwritten notes made on the original field drawings. Integrated construction systems, such as DFI, could be used by designers, prior to construction, to asses the potential problems, make any necessary changes and provide engineering solutions, in part, to the contractor's field problems. This approach would reduce field rework and cost overruns due to miscommunication between the needs of the designer and the ability of the contractor to meet those needs.

1.3 Need For Computer-Integrated Construction

The need for Computer Integrated Construction (CIC) will be illustrated by presenting a highly simplified description of the design and construction process shown symbolically in Figure 1.1. The process begins with an owner's concept, needs and method of financing the project. Next, the participants associated with the professional services and construction contracts for the project are identified. The professional services provided include the architectural layout, structural design and field inspection. Once the architectural and structural designs are completed, the construction contracts are awarded to a general

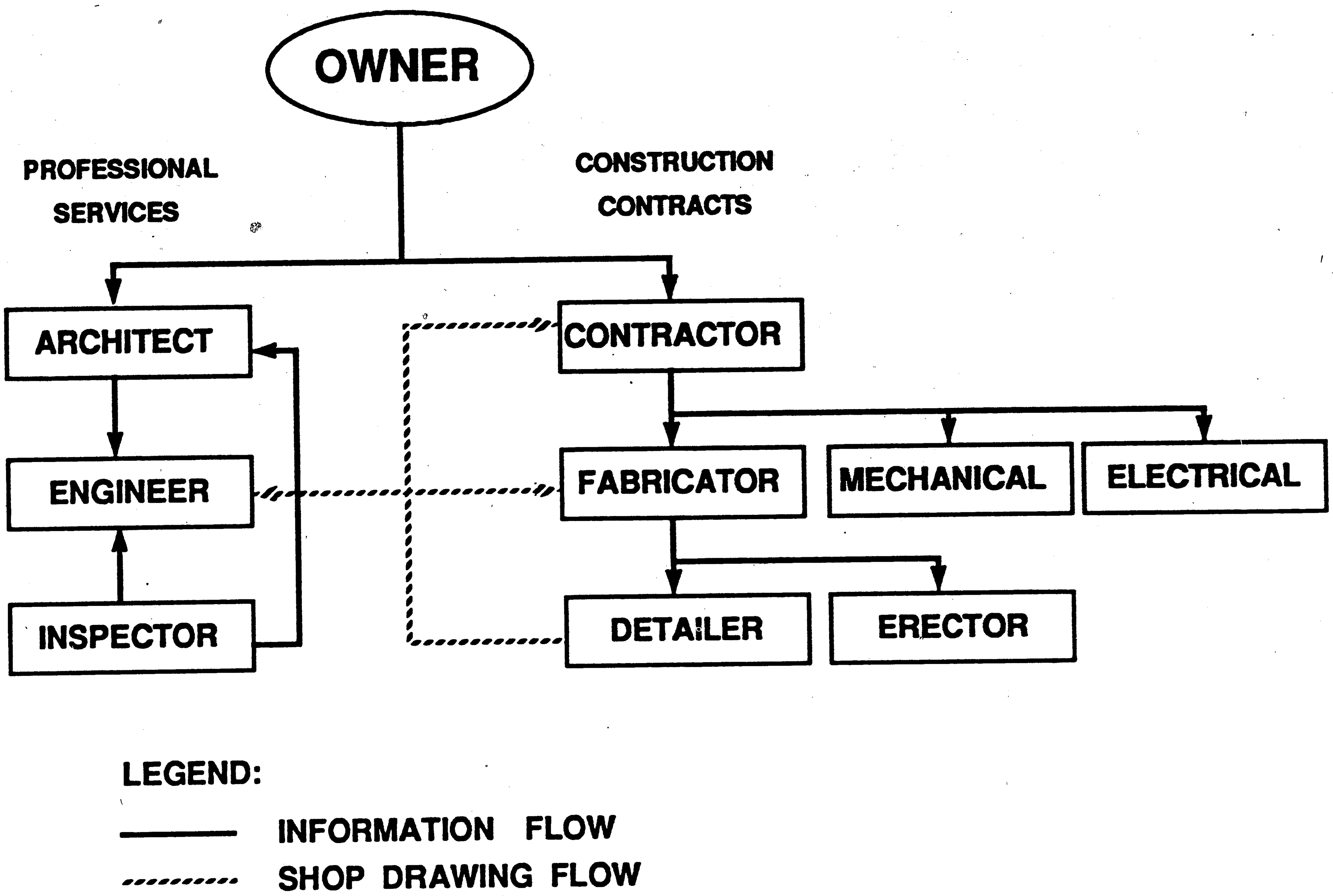

Figure 1.1 Information Flow Among Participants* [Becker 89]

contractor who then selects various subcontractors such as fabricators, mechanical and electrical.

To illustrate typical problems with connection designs, the frequent lack of interaction between designers and fabricators should be considered. When bidding a job, fabricators are usually unaware of many design details (such as connection details). This often occurs because structural design firms may leave the connection design to the fabricator. The fabricator employs a detailer to generate the necessary shop drawings to assemble the structure, and an erector to assemble the structure. Prior to construction, the shop drawings are reviewed and approved by the engineer. At times, engineering firms may not be fully qualified to approve the shop drawings because they are unfamiliar with specific

* This figure attempts to show the dispersed nature of the construction industry. This is not always the case since design/build firms exist in the industry. A much different information flow diagram would be shown for those firms.

construction practices. This situation causes problems for both the engineer and fabricator since neither may be sure what the other has done to develop their respective designs for the structure. These uncertainties often lead to downstream fabrication and field erection problems.

An example which illustrates a possible downstream fabrication problem is whether or not the designer has made most efficient use of material for the basic structural frame, e.g., the lightest-weight column and beam sections. When the fabricator begins the connection design and finds that the column webs or flanges must be stiffened, which may not have been considered in the original bid, he must take the financial burden of the additional material and labor costs.

Implementation of CIC is intended, at a minimum, to alleviate basic information flow problems and highlight any potential downstream problems [Wilson 87], [Sanvido 89]. In the previous example, if the designer were made aware of a potential connection problem, a larger column section could be used to simplify the connection design [Becker 88a]. To implement the concept of CIC, one would need a database of project information, accessible to all agents involved, that would include all aspects of building design such as mechanical, electrical, structural. Thus, when design changes occur, they could be posted quickly to the common database and affected agents could be notified. For example, if the depth of a beam were changed, this might affect mechanical (ducts, plumbing) as well as fabrication (materials ordered) work. As the affected agents are made aware of the change, they could suggest alternatives to the initial change to reduce the amount of field rework.

Thus, the implementation of CIC will provide an environment that will allow agents to post information to a common database as well as to interpret posted information. In reality, the common database might consist of a group of distributed databases located at the different construction agent's locations. The interpretation of information will be assisted by knowledge-based systems which will act as intelligent interfaces between different agents in the construction process. These knowledge-based systems will share common information as well as posses unique information for each end user. These systems are intended to allow architects, designers, fabricators, and others to work cooperatively while responding to posted changes with alternative suggestions beneficial both to themselves and other agents.

DFI addresses this need, in part, by providing designers with a tool for evaluating their preliminary connection designs from the viewpoints of standard fabrication and erection practices. The system is also capable of generating alternative connection configurations based on a set of issues considered important from the perspectives of design, fabrication and erection. A detailed description of DFI's capabilities is presented in Chapter 2.

1.4 The Potential of Integration

Integrated design and construction systems can act as a catalyst to improve ways of planning, organizing and coordinating activities throughout the life cycle of a project. These systems have proven especially useful in the manufacturing industry in handling critical information flow between different activities [Turksen 88]. Each activity can be characterized by a distinct knowledge base. Relieving the *bottleneck of information flow* at each different activity (or interface) can lead to the integrated engineering or manufacturing of large systems. For example, an effective design considers not only the functional aspects of a structure, but also the labor, time and resources required for fabrication, construction and operation.

The manufacturing industry has been able to implement computer-integrated manufacturing (CIM) systems [Rembold 86] because the entire process of manufacturing a product usually takes place in one central location and focuses on producing many of the same items (i.e., assembly line).

The major differences between the manufacturing and the construction industries are fragmentation [Sanvido 89] and the product being made. Construction involves the production of a *single, distinct* product, such as, a building, bridge, or power plant. As described previously, the process of designing and building a structure involves many agents performing specific tasks in very different environments. Integrated design and construction systems will link processes by allowing multiple agents to interactively utilize data and knowledge from their perspectives, without requiring that the activities take place in one single location. Specialization has made it impractical to suggest a return to the *"good old* *days"* of construction where a single company was *able and willing* to design, detail and build a structure. Rather, CIC can act as a vehicle to integrate specialized activities in a cooperative environment of compromise to build more economical structures from various viewpoints.

The major potential of integrated design and construction systems is in the support of the development, management, and sharing of information and knowledge among participants at all stages of the construction processes. This allows the different groups to collaborate more effectively in the overall activities.

By attempting to bridge the information gap between designers and fabricators of structural steel systems, DFI is providing a testbed for the incorporation of construction knowledge in the preliminary design stage.

1.5 Review of Related Work

Recently there has been a large amount of attention focused on developing systems to automate, integrate and eventually streamline the design and construction process. Much of the work has focused on the development of tools to automate the design of structures. This type of research is important but does not address the needs of the constructors. Focusing on the optimization of one aspect in the total process can cause problems downstream during construction, and, as mentioned, cause significant field rework. Many of these automated design tools do not consider how the design will eventually be built.

Other researchers [Baker and Fenves 89], [Maher 89], [Sause and Powell 89], [Sriram et. al. 89], [Talukdar and Fenves 89], [Tenenbaum 89] have also focused their attention on the development of models for the integration of design and construction. Many models describing design as a multi-level process which can be hierarchically decomposed have been developed. Few of these conceptual models have been implemented because the level complexity often is too great for a prototype system.

The approach taken in the DFI research has fallen somewhere between the two approaches mentioned above. Extensive industry interaction has helped formulate the focus of the system so that DFI serves as a "standby advisor," leaving the actual design to the user.

This section is intended to show how DFI fits into the overall picture of other research initiatives as well as to point out its uniqueness. Four systems will be described in this section to illustrate some past, present and future directions for knowledge-based systems. The discussion will focus on the type of system being developed and the intended use of the system. The systems are HI-RISE, IBDE, DICE and CONXPRT.

HI-RISE is a well-known knowledge-based system that performs preliminary design of a three-dimensional building grid. IBDE (Integrated Building Design Environment), is an attempt at "vertically integrating" or linking several knowledge-based systems from planning to construction scheduling. DICE describes an environment for cooperative engineering which attempts to consider all aspects of design. CONXPRT, a knowledge-based system to design connections, provides a different approach than DFI to handling the problems associated with designing connections.

1.5.1 HI-RISE

HI-RISE is "an expert system that configures and evaluates several alternative structural systems for a given three-dimensional grid" [Maher et. al. 84]. The expertise in HI-RISE is primarily from the book, Structural Concepts and Systems for Architects and Engineers by T.Y. Lin and S.D. Stotesbury.

HI-RISE uses the topology of a three-dimensional building grid which is defined by the number of stories, the number of bays in each direction, the minimum required clearance for a typical story and the location of vertical service shafts or internal spaces. The intended occupancy of the building, and wind and live loads are also required. HI-RISE uses this information to perform the preliminary structural design. The system first determines possible configurations for the lateral load resisting system, and then designs feasible gravity load resisting systems. The design of one system is not done until the previous system is completed. HI-RISE uses a task-subtask decomposition to design alternative functional structural systems.

HI-RISE graphically presents structurally feasible systems ranked by an evaluation function which considers aspects of economics, efficiency and structural integrity. The user is free to choose the recommended "best" design or any of the other structurally feasible design alternatives.

HI-RISE and DFI share some common ideas. Both deal with preliminary design, have a hierarchal decomposition of building data, and both present multiple results graphically. The differences lie in their respective focus. HI-RISE is a design system while DFI is primarily an evaluation system for connection designs. DFI uses multiple viewpoints to perform an evaluation while HI-RISE is only concerned with design and does not consider constructability issues.

1.5.2 IBDE

IBDE (Integrated Building Design Environment) is "an integrated software environment for building design and construction" [Fenves et. al. 88]. The system vertically integrates the processes of architectural, structural, and foundation design with construction planning using seven knowledge-based systems [Talukdar and Fenves 89]:

1. An architectural planner (ARCHPLAN).
2. A building core layout designer (CORE).
3. A structural system selector (STRYPES).
4. A structural component selector (STANLAY).
5. A structural component designer (SPEX).
6. A foundation designer (FOOTER).
7. A construction planner (CONSTRUCTION PLANEX).

The seven systems share global information which is hierarchically organized in an object-oriented programming language. A blackboard architecture is used to coordinate communication between the systems.

IBDE is the first attempt at integrating all of the above processes. The main drawback with this approach is that "there is one and only one path" [Talukdar and Fenves 89] through the system. Actual design and construction processes, however, are iterative and require feed-forward and feed-back loops to identify potential problems. DFI, on a much smaller scale, attempts to integrate the processes of preliminary and detailed design of connections.

1.5.3 DICE

DICE (Distributed and Integrated environment for Computer-aided Engineering) is "an object-oriented programming environment for cooperative engineering design" [Sriram et. al. 89]. This initiative is a proposed framework to consider all aspects of design from the conceptual layout and planning to the manufacturing and construction of a *"design artifact."*

DICE consists of three main types of components: the control mechanism, the blackboard, and the knowledge module. The control mechanism is defined by the "communication, coordination, and data transfer." It could also be viewed as an inference mechanism. Communication takes place through the blackboard which is divided into three partitions: coordination, solution, and negotiation. Each blackboard partition contains specific information which relates, traces or coordinates the knowledge modules to a specific task. The knowledge modules are grouped into four categories: strategy, specialist, critic and qualitative. Each of the knowledge modules can be viewed as either knowledge-based expert systems, CAD tools, specific databases, analytical programs, human users, or combinations of the above.

DICE is intended to provide an environment where multiple designers in separate disciplines can coordinate their respective activities while resolving any conflicts among the disciplines. The current status of this initiative is a prototype for the automatic generation of construction schedules from architectural drawings. Utilities for updating and modifying the blackboard information have also been developed. A simulation program to show the possible potential of DICE has been produced using the Hyatt Regency skywalk collapse as a case study.

The engineering environments that DICE and DFI intend to provide are similar in that each proposes the use of multiple viewpoints to resolve conflicts. The major difference is the approach taken in developing the systems. DICE is being developed top down, attempting to model all interactions prior to implementing the system. A middle out approach has been taken in DFI. By taking representative yet manageable segments of the design/construct process, the DFI researchers have been able to formulate connection evaluation procedures and agent interaction schemes to build a working prototype.

At this point, comparisons cannot be made on the negotiation scheme used in each system, since one has not yet been implemented in DICE. The blackboard facilities developed for DICE, however, are more extensive than those implemented in DFI.

1.5.4 CONXPRT

CONXPRT (CONnection eXPeRT) is "a knowledge-based system for the design of connections in steel framed buildings" [Elhouar and Murray 88]. This system contains design knowledge for three types of simple framing connections: framing angles, a shear end plate, and a shear plate. These connections were chosen for their frequent use in steel framed buildings, for their versatility (each can either be used as a beam-to-column or beam-to-girder connection), and for the large amount of information that exists in the literature.

CONXPRT uses the beam and column AISC (American Institute of Steel Construction) shape, span length, end reactions, and connection type to design and detail a particular framing connection. The system provides a graphical representation of the connection as well as a textual report detailing the design parameters.

The report facilities of CONXPRT also point out any potential design problems with the connection. CONXPRT may or may not suggest how to correct an encountered problem - this is left to the user. The process of changing and re-evaluating the connection parameters is lengthy but straightforward. Very little information regarding the constructability of the connection is presented to the user. This is not very important, however, when dealing only with simple connections.

DFI and CONXPRT could complement each other quite nicely. As a back end to DFI, CONXPRT could be used to design and detail the suggested connection from a DFI evaluation. DFI would point out constructability problems with a connection prior to being detailed by CONXPRT. A combined system of DFI and CONXPRT could improve significantly the current design tools used in industry.

1.6 The DFI Approach

DFI encompasses aspects of the four systems described above. The current research involves the development of a connection design environment which attempts to integrate the stages of preliminary and detailed design by addressing, in part, the information gap between designers, fabricators and erectors of steel framed buildings.

The environment allows design engineers (the intended end users) to have their preliminary connection designs critiqued from downstream fabrication and erection viewpoints. The critiquing capabilities of DFI are also capable of generating alternative connection configurations which match aspects, or satisfy pre-established constraints, of the user's initial connection. The key aspect of this research is the development of a multiagent cooperative problem-solving platform through which necessary agents can communicate and negotiate the outcome of a connection evaluation [Werkman et. al. 90]. The evaluation and suggestion of alternate connections is based on issues or concepts such as strength, constructability and safety. Information models of the agents (designer, fabricator and erector) have been developed which decompose agent issues to build a network of concepts (i.e., strength, stiffness and safety). Relationships between the concepts have been developed to link the agents' shared knowledge, identify unique agent knowledge, and allow communication and coordination of the agents' activities during the evaluation process.

During the critiquing process, agents will comment on connection characteristics based on their unique knowledge and suggest alternative connection configurations. Also, a preliminary control scheme has been developed to provide a framework for negotiation between agents when a conflict is encountered. A central arbitration agent is used to aid in communication between agents and system control [Werkman et. al. 90]. A detailed description of the DFI System is presented in Chapter 2.

1.7 Thesis Synopsis

The remainder of this thesis is organized in the following manner. Chapter 2 provides a description of the pre-prototype DFI system (Phase 1) and current DFI prototype system (Phase 2). The stages in the design and construction process are described in Chapter 3. A description of the agents, their concerns and responsibilities, their respective issues, and preliminary information models, is also presented in Chapter 3. Chapter 4 further refines the agent information models, formulates relationships between the agents, and provides an illustrative scenario to demonstrate the application of these models. A description of the implemented system, a test case, and a critical review and evaluation of the DFI system are presented in Chapter 5. A summary of the work, conclusions and observations are discussed in Chapter 6. Chapter 7 provides a set of suggestions for extending the current system to incorporate more detailed connection information and to solve more global problems (i.e., a complete building evaluation). Appendix A describes the connection information forms used in DFI to build a working connection database. Appendix B lists the relationships implemented in the DFI system that exist between the agents and their issues. A decomposition of subissues which are discussed in Chapter 4 is presented in Appendix C.

2. The DFI System

As mentioned in Chapter 1, the first phase involved developing a pre-prototype system that would critique preliminary connection designs from the viewpoints of fabrication and erection. The second phase focused on developing a system that generates alternative connection configurations from initial user input and other applied system constraints.

This chapter is organized in the following manner. First, research undertaken in phase 1 is described. The system components including the data and rule structure, frame hierarchy and user interface are presented along with a description of how the pre-prototype system works. Then, the connection database, information flow, relational network, agent communication scheme, and the evaluation procedure are then discussed for the phase 2 system. Finally, a comparison between the two development phases is presented.

2.1 Phase 1: A Critiquing System

The first phase of research developed a system that provides, a user (structural designer), a critique of a proposed connection configuration from the viewpoint of practical and economical fabrication and erection. To accomplish this, the pre-prototype DFI incorporated fabrication and erection heuristics in the form of rules in an object-oriented frame-based knowledge representation which models building elements.

The components of phase 1, the critiquing system, include the knowledge and data representation, the rule structure and inference mechanism, and the user interface. Following the description of these components, a discussion of how the system works will be presented.

2.1.1 System Components - Phase 1

Figure 2.1 shows various software modules, including a representation scheme for a building, a graphical and menu-based user interface, and a backward-chaining inferencing mechanism utilizing object-oriented goal-based rules. The DFI pre-prototype is implemented in Quintus Prolog™ using Quintus ProWindows™ for its graphical interface. The system was developed to run under the Sunview™ windowing environment on Sun™ workstations.

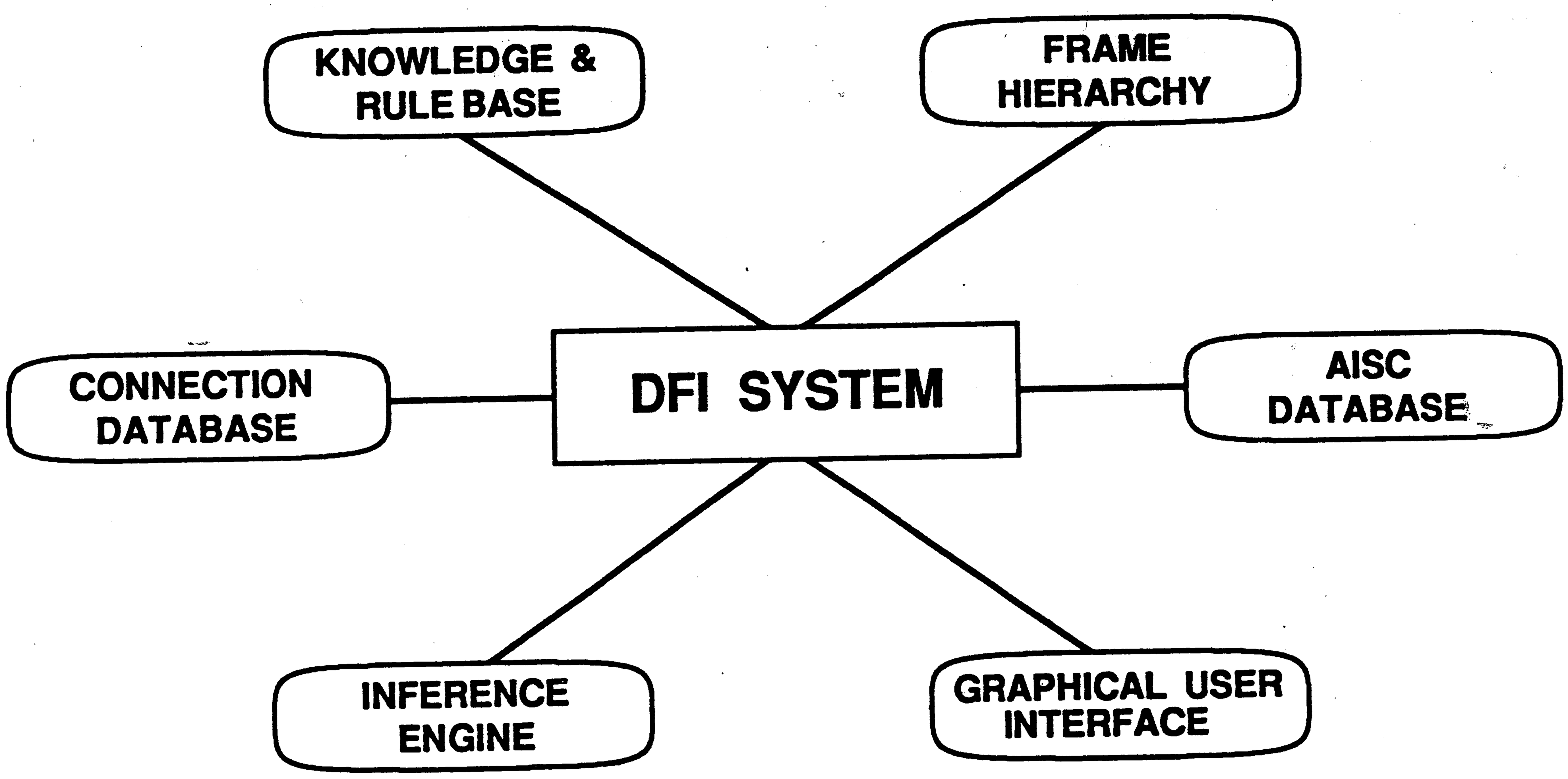

Figure 2.1: Software Modules in DFI

2.1.1.1 DFI Building Decomposition

Figure 2.2 shows a simplified *Beam-to-Column* Connection Hierarchy. This figure depicts the hierarchy used to model a beam-to-column connection and its relation to other objects in a building. The DFI system is centered around a frame-based part, part-of representation [Frenzel 87] of a building which is decomposed into a group of objects (parts) that are ordered hierarchically from a root object (**aBuilding**) terminating at connection fastener objects (**Fastener-Object**).

In DFI, a building is composed of column lines that are made up of individual column members. Floors are composed of beams that intersect the building's column lines. The intersection of a floor with a column line is represented by connection node. Each connection node can have up to four beams framing into the column at 90 degree angles. Each beam framing into a column is represented as a beam-to-column connection. This connection object is further decomposed into a column, beam and connection detail material such as an end plate or flange and web connectors.

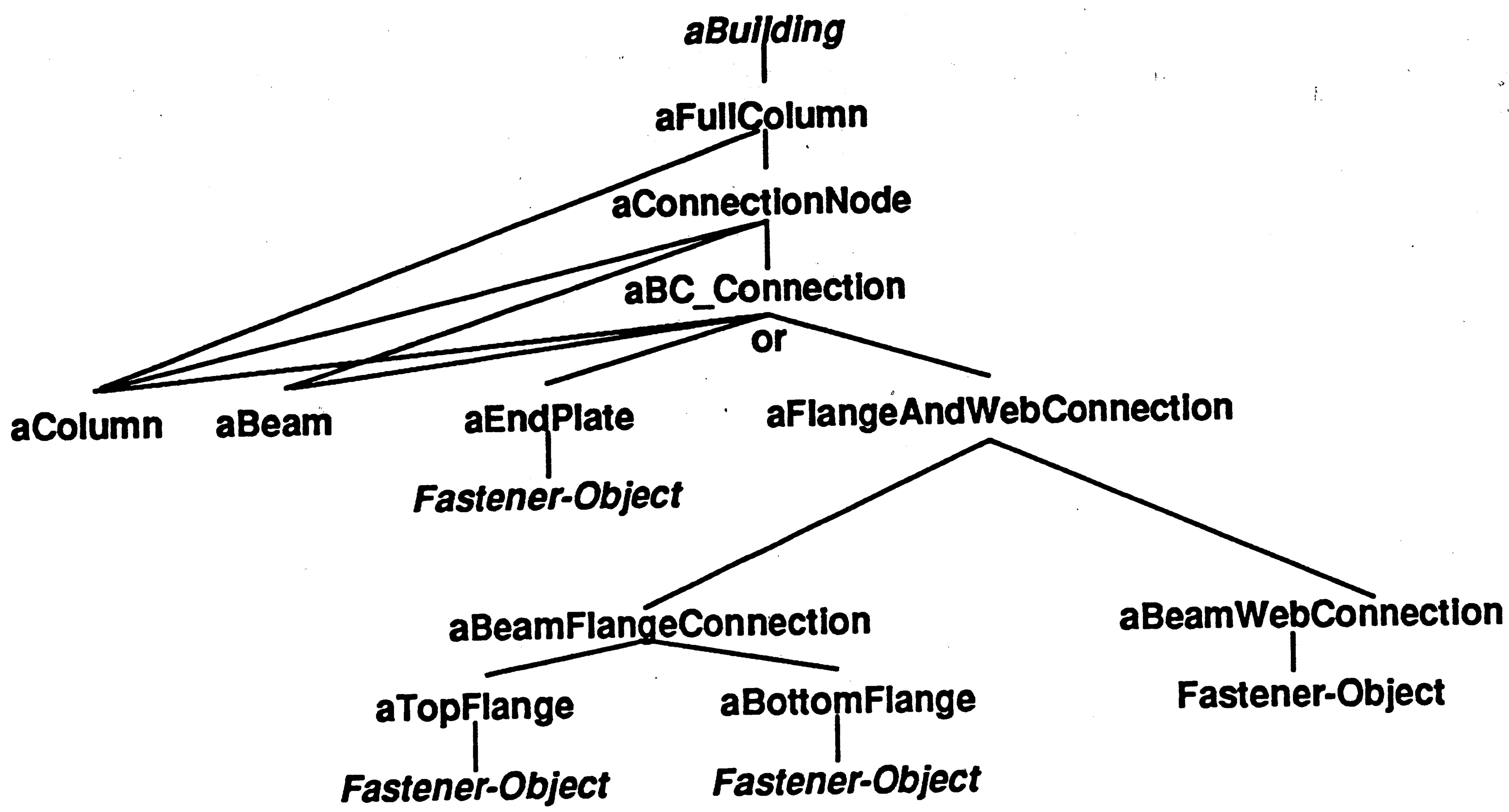

Figure 2.2: DFI Beam-to-Column Connection Hierarchy

2.1.1.2 DFI Building Data

For a system such as DFI to function properly, a consistent building data structure was required. Currently, the standard industry practice is to summarize column information on tabular column schedules [Hooper 88]. The remainder of the building components are shown on the job drawings. This type of building representation is very difficult to model in a computer.

To model a building in a mutually human/computer recognizable way, the tabular column schedules were extended to include tabular beam schedules and framing plans. The typical column schedule information includes a column identification code (ID), yield strength value, AISC shape designation, splice and floor elevations, and loads at each floor. The beam schedule information includes a beam ID, floor location, AISC shape designation, yield strength, camber, end reactions and moments, and number and spacing of shear studs. Finally, the framing plan describes how the column and beam schedules relate to form a building. Information necessary for the framing plan includes the column and beam ID's, floor, and the orientation of the beam attachment to the column*.

2.1.1.3 Rule Structure and Inference Mechanism

Prior to developing a rule set to critique a connection for phase one of DFI, domain specific (i.e., fabrication/erection) knowledge had to be acquired and represented systematically. The process of knowledge acquisition began with a survey of various civil engineering textbooks and manuals on design and detailing connections [AISC 80], [AISC 83], [AISC 84], [Fisher 74], [Blodgett 68].

The next aspect of the knowledge acquisition process involved interviews with industry participants**. For the fabrication domain expertise, interviews were conducted with Mr. Ed Becker who was the chief structural designer at Lehigh Structural Steel and has approximately 30 years experience in the fabrication industry. Mr. Becker has also participated in several ASCE committees and structural task forces. Through these interviews it was possible to obtain the necessary fabrication experience to evaluate partially and fully rigid connections from an economical point of view (i.e., what fabricators view as practical connection design).

After completing the preliminary knowledge acquisition, a set of formal rules for the system were developed. The rule base is sectioned into three rule sets:

1. A column consistency checking set.
2. A beam consistency checking set.
3. A connection evaluation set.

Each rule set is applied to a given context during operation of the system. A rule set consists of a decision tree based on a single goal which is then decomposed into a series of subgoals that are represented as rules and subrules. The rule inferencing process that best suited these goal-based rules was a backward-chaining [Winston 84], fully exhaustive methodology. Thus, rules composed of disjunctive subrules will have all of their "OR" subrules evaluated regardless of the truth of each subrule. This could result in a rule possibly having

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* Data exist for both beam-to-girder and beam-to-column connections - but the pre-prototype only critiques beam-to-column connections. Beam-to-girder connections were omitted because these are usually Simple Type connections and designed solely by the fabricator with little or no input from the structural designer.

** A profile of the design expert is presented in Chapter 5.

several disjunctive subrules supporting it. This form of inferencing is done to assure all impractical conditions (fabrication and erection oversights) are identified and presented to the user for review.

An advantage to a hierarchical rule structure over a flat rule set (i.e., a series of non-interconnected rules) is that the evaluation takes place in a controlled fashion. Also, the rule firing sequence, depth vs breadth [Rolston 88], can be quite easily imposed. DFI uses a combination of depth and breadth searches. First, the rule hierarchy is traversed down to a terminal node (a depth search), then the system recursively backs up and follows the next logical path to another terminal node (a breadth search) until the entire rule tree has been evaluated. In a flat rule set, rules fire sequentially so an initial-fired rule may be replaced by a conflicting rule as the evaluation progresses [Buchanan and Shortliffe 84] - thus causing an invalid or unpredictable evaluation to take place. With a hierarchical rule structure this type of problem can be more easily handled [Rolston 88]. Also, a hierarchically structured rule set tends to allow for more easily written rules since people tend to describe tasks in terms of subtask hierarchies.

2.1.1.4 User Interface

The frame-based interface provides control for generating input menus and output graphics. Menu prompting is provided by procedures which are attached to frame slots. When the value of a slot is requested, the associated slot procedure will return either a menu of choices or a default value. The user either selects a menu item or enters a value. Thus, the type of information entered dynamically determines the sequence of menu prompting. Verification of user input is provided by dynamically generated graphics which display the connection and its component pieces.

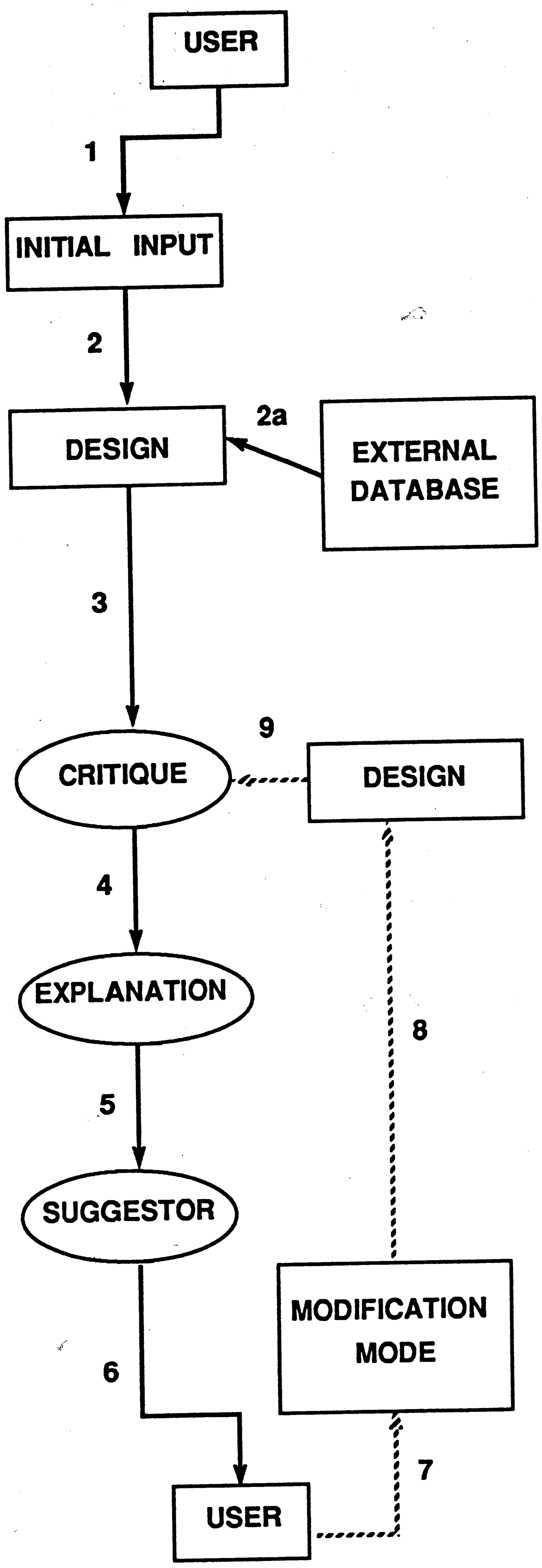
The system dynamically generates graphical output from both user input and internal inferencing. All graphical items are objects associated with the Prolog-based graphical interface. These graphical objects, similar to DFI's frame-based connection objects, are attached as frame slots with the connection component objects which they represent. DFI's graphical output, appearing in several windows, includes a floor plan of the building at specified floors, an elevation view of the specific user selected connection, and a decision tree of the actual rules that fired during the connection evaluation.

2.1.2 How the System Works - Phase 1

The process of how the pre-prototype system works is summarized in the DFI Information Flow Diagram shown in Figure 2.3 where boxes indicate processing states in the system, ovals represent output states, solid lines represent flow of control between states and dashed lines represent enhancements which could be made to the system.

The menu driven DFI system has two stages of operation. The first stage involves user entry of building data (from data files) and system checking of consistency of those data. The data contain a basic description of the building including beam schedule, column schedule, and framing plan. The consistency of these data is then evaluated using required external databases such as American Institute for Steel Construction (AISC) database of shape parameters. If any problems are found, the user is given explanations and suggestions on how to correct the data. For example, the locations of the column splices are checked to ensure that they occur between one and half and two feet above the nearest floor elevation. If this rule fires, the user is provided with a suggestion to change the location of the splice to fit within the standard distance for ease of erection.

The second stage of operation allows the user to interactively enter a connection and then study DFI's critique of that connection. Through a series of brief menus, DFI prompts the user for the location of the beam-to-column connection and all other necessary information such as connection rigidity, connection detail material, e.g., top flange angle, bottom flange plate, and connection fasteners, e.g., shop welded, field bolted. Once the connection input is complete, it is evaluated and critiqued by DFI. The critiquing process utilizes parameters taken from the AISC database to perform calculations to determine if physical fit-up is possible. These calculated results are then used in the fabrication and erection rules. If inconsistencies in entered data are found or impracticalities in fabrication or erection are determined, the user may identify the source of the problem by reviewing the trace of the rule tree. This trace may be examined either from graphical or textual output. The DFI system provides explanations and suggestions of the evaluated rules where appropriate. Detailed case studies are presented in [Glysing-Jensen 89].



Flow Lines	Description of Lines
1.	User inputs the initial design data (beam and column schedules, framing plan and proposed connection detail material).
2.	DFI internally represents the design and produces a graphic display for interactive verification by the user.
3.	The design is critiqued by DFI.
4.	An explanation of the critique is presented.
5.	Suggestions are generated based on the critique.
6.	Suggestions are presented to the user.

At this point, the user chooses the best suggestion for the particular situation. If a modification is necessary, the system must be restarted and the entire process repeated.

	FUTURE CAPABILITIES
7.	User chooses from a menu of suggestions and makes any necessary modifications.
8. & 9.	Modifications are incorporated, and the new design is evaluated

Figure 2.3: DFI Information Flow Diagram - Phase 1

2.2 Phase 2: A Cooperative Problem-Solving System

The second phase of the research developed a prototype environment for the selection of a preliminary connection configuration. This was accomplished by combining user input, fabrication and erection heuristics, and modeling construction agent viewpoints (designer, fabricator and erector) in a cooperative problem-solving environment. A relational network and agent communication scheme was developed to generate alternative connection configurations.

The original system components were basically left intact. That is, the same building decomposition, building data format, inference mechanism, and user interface were used in the development of phase 2 of DFI. Significant changes occurred, however, in the way the rules were used. The old rule structure was replaced with a set of constraint tables represented by a database of connections.

A discussion of the connection database, information flow, relational network, agent communication scheme, and the evaluation process is presented in this section.

2.2.1 DFI Connection Database

To make DFI more suitable for practicing professionals, a connection database was developed by the author using industry input. This database also acts as a constraint table for input so that the user will be systematically guided to a *"complete and correct"* (to the degree of detail that DFI presently uses) connection configuration considered standard in light of common fabrication and erection procedures [AISC 80], [AISC 83], [AISC 84]. The database is composed of a series of "Connection Information Forms" which contain all vital connection data the system needs. Figure 2.4 shows a typical "Connection Information Form." The author developed this modular sheet format divided into five sections:

1. Title Block
2. Connection Detail Table
3. Profile View of the Connection
4. Rating Factors Table
5. Comments.

A complete description of these forms is presented in Appendix A.

1. TITLE BLOCK endplate

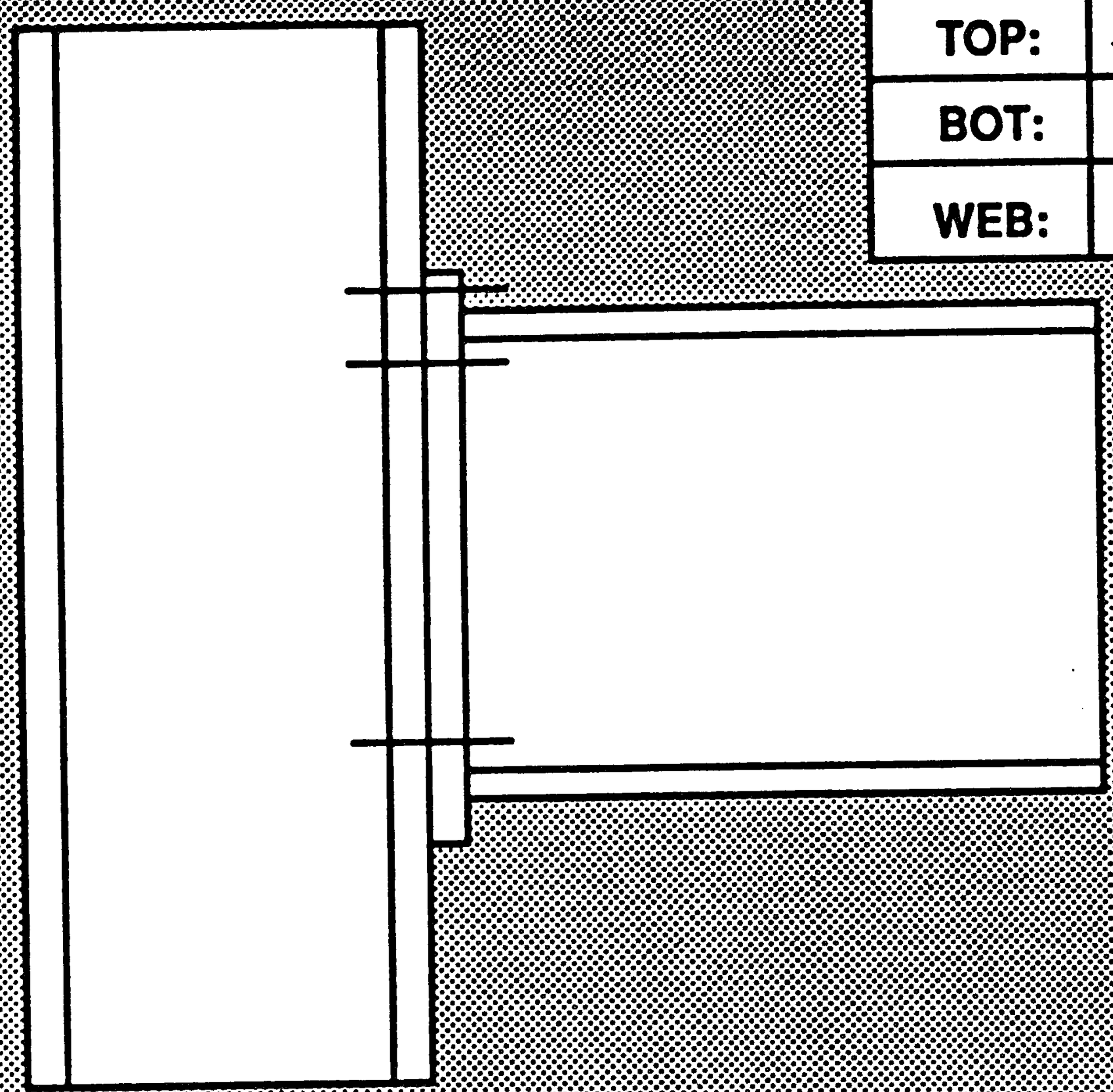
CONNECTION NAME: ***ENDPLATE***

TYPE: ***1*** ORIENTATION: ***FLANGE*** SHEET: 1 of 1

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	ENDPLATE	FIELD BOLT	SHOP WELD
BOT:	ENDPLATE	FIELD BOLT	SHOP WELD
WEB:	ENDPLATE	FIELD BOLT	SHOP WELD

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	3		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		4	
FAB. EASE		3	
MAT. COST		4	
EREC. COST			2
EREC. EASE			2
SAFETY			3

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

D: For fillet weld > 1/2" to attach the endplate, consider using full or partial penetration groove welds with reinforcement.

F: Endplate connections require dimensional control to tight fit-up to column flanges, which is affected by column flange-to-web squareness, beam camber and squareness of the beam end.

F: Shim space may be provided for accommodating mill and fabricating tolerances. Use "finger" shims entered from each side where feasible.

E: Field bolts must be furnished long enough to accommodate any shim allowance.

Figure 2.4: Typical Connection Information Form

2.2.2 DFI Information Flow

The first stage of use involves user entry of building data files and system checking of consistency of data in those files. This is the same procedure as used in phase 1. The information flow, comprised of three stages, is summarized in the DFI Information Flow Diagram shown in Figure 2.5.

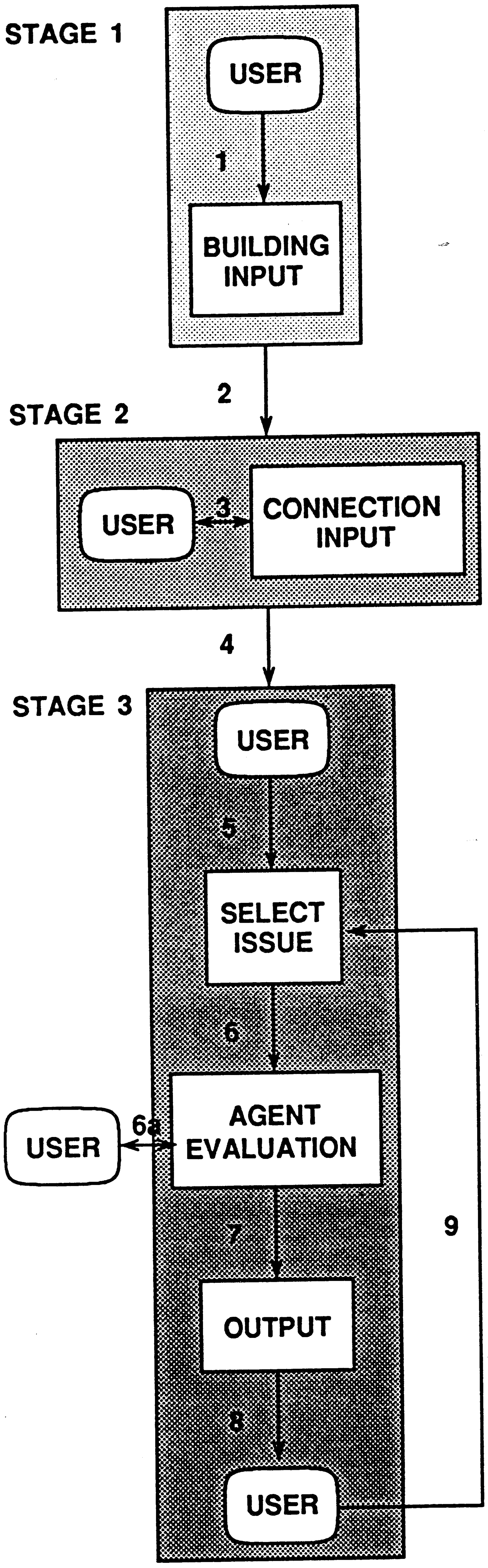
The second stage, in phase 2, allows the user to interactively enter a connection, similar to phase 1 of the DFI system. During input, the system ensures that a standard connection is detailed by applying constraints based on general fabrication and erection knowledge represented in the connection information forms.

The third and final stage of operation involves the evaluation and rating of the proposed connection. The user selects one of the following design, fabrication or erection issues*:

- **Design Issues:**
  - Strength
  - Stiffness
  - Reliability
  - Versatility
- **Fabrication Issues:**
  - Fabrication Cost
  - Fabrication Ease
  - Material Cost
- **Erection Issues:**
  - Erection Cost
  - Erection Ease
  - Safety.

The selected issue becomes the "key issue" during the evaluation of the connection. The evaluation then takes place with priority placed on the key issue. Each viewpoint, design, fabrication and erection, presents to the user implications or problems associated with the

* Each issue is defined in Chapter 3 with a detailed decomposition into subissues and characteristics being presented in Chapter 4.



Flow Lines	Description of Lines
1.	User inputs the initial building design including beam and column schedules and framing plan.
2.	System provides a consistency check of the initial building data and suggests corrections to errors.
3.	User is guided interactively to a standard connection configuration, this assures a complete, correct connection. Verification graphics are also provided.
4.	Control goes back to the user.
5.	User selects a design, fabrication or erection "key issue."
6.	The connection is evaluated by the system from the viewpoints of design, fabrication and erection.
6a.	User interactively works with the system during the evaluation process to redirect or change the focus of the evaluation.
7. & 8.	Output is generated and provided to the user which includes the following: • Each agent's rule evaluation. • Alternative connections proposed by the agents. • Connection summary sheets.
9.	User may select a different issue to perform another evaluation.

Figure 2.5: DFI Information Flow Diagram - Phase 2

proposed connection and also suggests alternative connection configurations based on an agent viewpoint and the user specified key issue. As the evaluation takes place (see Chapter 5 for a detailed case study), the user is provided with the specific agent's evaluation of the proposed connection, suitable alternative connections based on the agent's evaluation, and summary of each proposed connection. Upon completion of the evaluation, the user may enter a different issue to provide a new rating and evaluation of the initial proposed connection. This interaction, between the user and the system, can take place until all the issues have been investigated or until the user is satisfied with a particular connection configuration.

2.2.3 DFI Relational Network

A relational network was used to model interactions between designers, fabricators and erectors during the connection evaluation process. The network allows the evaluation to proceed in an ordered fashion.

A simplified version of the network is shown in Figure 2.6. The network centers around a connection which is comprised of functional, component and fastener aspects of the connection. The functional aspects deal with the required rigidity and performance of the connection. The component aspects involve the actual parts that make up the connection (i.e., beam, column, and connection detail material), while the fastener aspects involve the operations required to assemble the connection (i.e., shop welding, field bolting).

The agents (designer, fabricator and erector) communicate their important issues to one another by the various links to the connection aspects (functional, component and fastener). Each agent has a particular viewpoint on a specified connection based on their respective issues. For example, the designer's view of a Type 1 (Moment) connection may be only based on the strength and stiffness characteristics of the connection while the fabricator may view the same connection in terms of cost. A Type 1 connection is generally more expensive to fabricate than a Type 2 (Simple) connection because there are usually more parts involved in the production of a Type 1 connection. The erector's view on the same connection may deal with the ease of construction. In the erector's view, a Type 1 connection is more difficult to erect because all the bolts must be fully tightened or alignment problems will occur since the tolerances are quite tight [Becker 88a].

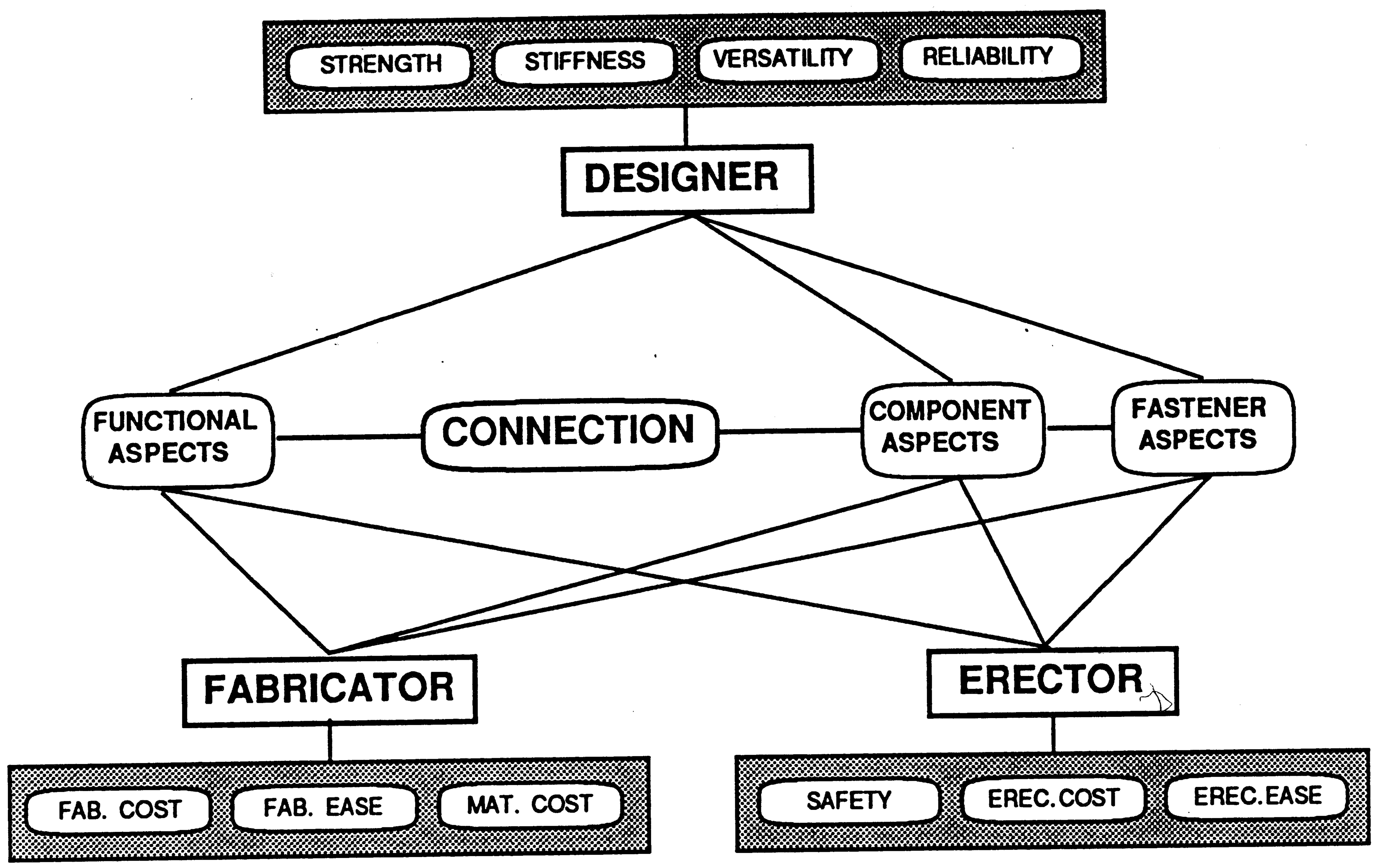


Figure 2.6: DFI Relational Network

Through the use of the network, agents can view the same concept (a CONNECTION) much differently, but are able to communicate with each other through the use of messages linking the connection aspects (FUNCTIONAL, COMPONENT and FASTENER) to a specific agent issue (i.e., STRENGTH, FAB. COST). Therefore, each agent can deal with unique knowledge while communicating with the other agents through the shared connection aspects (FUNCTIONAL, COMPONENT and FASTENER).

2.2.4 Agent Communication Scheme

Along with the relational network, a message or blackboard area was developed for the agents to post their various actions taken while evaluating a connection. In this blackboard area simple messages are posted and viewed by the other agents so that all are aware of the evaluation that is taking place on a particular connection. This information is also provided to the user so there may be direct interaction between the user and the system. When the user is not satisfied with how the evaluation is proceeding, two options are available. The user may select a different key issue or refuse (object to) an agent's proposed connection. These actions post messages to the blackboard so that the evaluation may continue considering any new applied constraints. Thus, the user maintains control of the evaluation and can interact directly with the system.

When conflicts between agents are encountered during the evaluation, an independent arbitrator agent is "invoked." The arbitrator's main function is to monitor the blackboard and intervene when requested by the evaluating agents. The arbitrator uses shared knowledge about the connection to identify conditions which require the evaluating agents to relax their constraints so the selection of alternatives can continue. A more detailed description of the negotiation process and the arbitrator agent may be found in [Werkman 90].

2.2.5 The Evaluation Process

As described previously, DFI requires the user's input of a connection and a "key issue" to focus the evaluation of connection. Once this is done, the arbitrator agent will select the agent (designer, fabricator or erector) worst affected by the user's initial connection. This is done by taking a composite or average score of each agent's issues. The agent with the lowest composite score (i.e., worst affected agent) evaluates the initial connection first.

Table 2.1 shows the Rating Factors Table from the example connection information form previously shown in Figure 2.4. The composite scores computed for each agent are shown at the bottom of Table 2.1. In this table, the Erector would evaluate the connection first with a composite score of 2.33 while the Designer and Fabricator have composite scores of 2.75 and 3.67 respectively.

The evaluating agent selects the worst (lowest value) issue and attempts to improve it by suggesting alternative connection configurations*. Prior to selecting an alternative configuration, the evaluating agent must search the connection database and select all of the connections which have a greater value on the agent's worst issue and also

* For the example Rating Factors Table in Table 2.1, the evaluating agent would be the Erector with the worst issue being Erection Cost. When two issues have the same low value, the first listed one is chosen.

Table 2.1: Example Rating Factors Table

	DESIGNER	FABRICATOR	ERECTOR
STRENGTH	3		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		4	
FAB. EASE		3	
MAT. COST		4	
EREC. COST			2
EREC. EASE			2
SAFETY			3
COMPOSITE SCORE	2.75	3.67	2.33

maintain a minimum value of 3 for the key issues provided by the user. Once this set of connections is determined, the evaluating agent will take the composite score of all the connections in the set and select the configuration with the highest value. This connection is then posted to the blackboard.

The arbitrator then checks the posted connection to determine which agent is worst affected and that agent begins the previously described evaluation process. The arbitrator halts the evaluation when all the agents have had a chance to post an alternative configuration, and two of the agents agree on a connection. If the system does not converge, a default value of six iterations has been imposed to stop the evaluation.

The above is a simplified description of the evaluation process. Specific agent interactions and blackboard messages are presented in Chapter 5. A case study will also be presented in Chapter 5 to describe in detail the evaluation process and show graphically the suggested alternative connections proposed by the agents.

2.3 Comparison of DFI Phases 1 and 2

The first phase of the system was intended to act as a testbed for data and knowledge representation. By building a tool based on a thin-slice of knowledge which could be used to educate inexperienced engineers about beam-to-column connections, the researchers on the project were able to identify information gaps in the design/construct process and determine what issues had to be addressed in later versions of the system. The first phase also acted as a *demonstration-of-concept* and laid a foundation for future work.

Phase 2 of the system was intended to address the needs of the practicing professional by incorporating many of the heuristics during the input phase and eliminating any erroneous type of input. As a step toward computer integrated design and construction, the second phase of development models the interaction of different construction agents for the selection of alternative preliminary connection configurations. The interaction takes place at a composite level of information yet builds an evaluation framework to which more detailed information and more robust agent models can be incorporated.

Detailed models of the design, fabrication and erection agents obtained by issue decomposition are presented in Chapter 3. The stages of the design and construction process and identified information gaps are also discussed in Chapter 3.

3. The Design and Construction Process

When looking at the design and construction process in the U.S. one central theme runs through construction projects, *"An Idea Plus Money."* This can be illustrated by the following quote from [Ayers 75]:

> "In construction, as in most other engineering fields, an entire series of events begins with an idea. Someone has an idea. A government wants a bridge, a sewage disposal unit, or a street lighting system; a corporation wants to improve its plant or an individual wants to place a new product on the market. However, an idea is only an illusion unless it is combined with another ingredient, money."

The intent of this chapter is not to describe a method of implementing a computer model of the entire design and construction process but to focus on the "idea" and determine information that is necessary to go from concept to construction. The issue of "money" will also be touched upon since the *bottom line costs* often determine whether a project will progress any further than the "idea," when in actuality, the *real costs* associated with maintaining the structure throughout its lifecycle often are not considered. Therefore, a structure designed with lifecycle costs in mind may be more "expensive" initially, but more than likely, would have lower rework costs and higher reliability, due to better initial design decisions, thus reducing the overall costs.

This chapter is organized in the following manner. First, four stages in the design and construction process will be described*. The stages are conceptual design, preliminary design, detailed design, and construction. Next, the gaps in the information flow between Architect-Designer, Designer-Fabricator, and Fabricator-Erector at these stages are discussed. An example of the interactions necessary to correct construction problems due to poor initial designs is presented. Following this is a description of where DFI fits into the design and construction process. Preliminary information models of the Designer**, Fabricator, Erector are developed along with a discussion of their respective concerns and

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* The reader should note this will not be a complete description of the entire design and construction process. The focus of this chapter is on the structural aspects of design. Issues such as the HVAC, electrical, and mechanical design have been omitted from this prototype.

** Structural designers or engineers are simply referred to as "Designers" for the remainder of this thesis.

evaluation issues. Finally, there is a brief description on how other participants could be incorporated into DFI.

3.1 Stages of the Design and Construction Process

Each stage of the design and construction process can be identified by the tasks that take place, the participants involved, the information needed, and the information generated for use by different participants. This section describes four stages in the design and construction process: conceptual design, preliminary design, detailed design, and construction. The required input and anticipated output for each stage is also discussed along with some potential problems that could be encountered. The overlaps between the stages are presented as information gaps (Architect-Designer, Designer-Fabricator, and Fabricator-Erector) that must be "connected" toward an integration of the design and construction processes.

3.1.1 Conceptual Design

The conceptual design stage involves two principal participants: the owner and architect. The owner has an idea for a building and a method of financing the project. The architect is hired to develop a building concept that satisfies the owners' needs. The number of stories, number of bays, typical story height, positioning of stairways and elevators, expected occupancy, floor space requirements, and the site layout of the building are a few of the factors to be considered.

The architect must also satisfy any safety and accessibility requirements of regulatory agencies and any aesthetic requirements of the owner which might exist. This could involve the design of elaborate lobby areas with long clear spans or open atriums. A decision on the type of building shell is also made at this stage, i.e., clear or mirrored glass, marble, or masonry.

Near the completion of conceptualizing the building, a structural designer is brought in to begin the next stage of the process: the preliminary design.

3.1.2 Preliminary Design

This stage begins with structural designer working from the architectural specifications to determine what type of framing system to use. The possibilities include:

a) Rigid frame using all moment connections to carry both the gravity and lateral loads.

b) Braced frame with simple connections to carry the gravity loads and cross braces to carry the lateral loads.

c) Mixed construction with a reinforced concrete core to carry the lateral loads and a steel frame to carry the gravity loads.

Figure 3.1 shows a schematic of each type of bracing system. The designer must know where bracing may be placed (or if it is even allowed) in the building so as not to interfere with the specified architectural features. At this stage, it is highly desirable to identify potentially dangerous features or undesirable consequences in order to protect integrity and ensure good performance of the structure throughout its intended life under loads (i.e., construction, gravity, lateral and seismic).

Once the framing system has been determined and all other necessary discussions relating to the conceptual design have been completed between the architect and the designer; the designer then uses the architect's specifications and local building codes to determine the critical live and dead load combinations, wind loading profile, and any applicable seismic loads. This information is used to perform a structural analysis to size and specify the material strength of the building components (i.e., beams, columns, braces, and shear walls). The designer then begins the preliminary connection design. This may simply be a section in the building specifications stating the type of connection configurations, fasteners, and operations which will be allowed. Often designers consult with fabricators for input in preparing the connection specification [Hooper 88]. This "guarantees" the specification is correct regarding fabrication procedures with which the designer may not be familiar.

At this point, the building design is ready for bid by various fabricators*. The bids are usually based on past experience and total estimated tonnage of steel in the building [Becker 88b]. If the fabricator's estimating department is given a new, innovative design the

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* Some design/build firms exist, notable examples are Bechtel, Flour Daniel, J.A. Jones, Perini and Turner Construction Corp. These types of firms, however, are generally the exception in the fragmented U.S. construction industry.

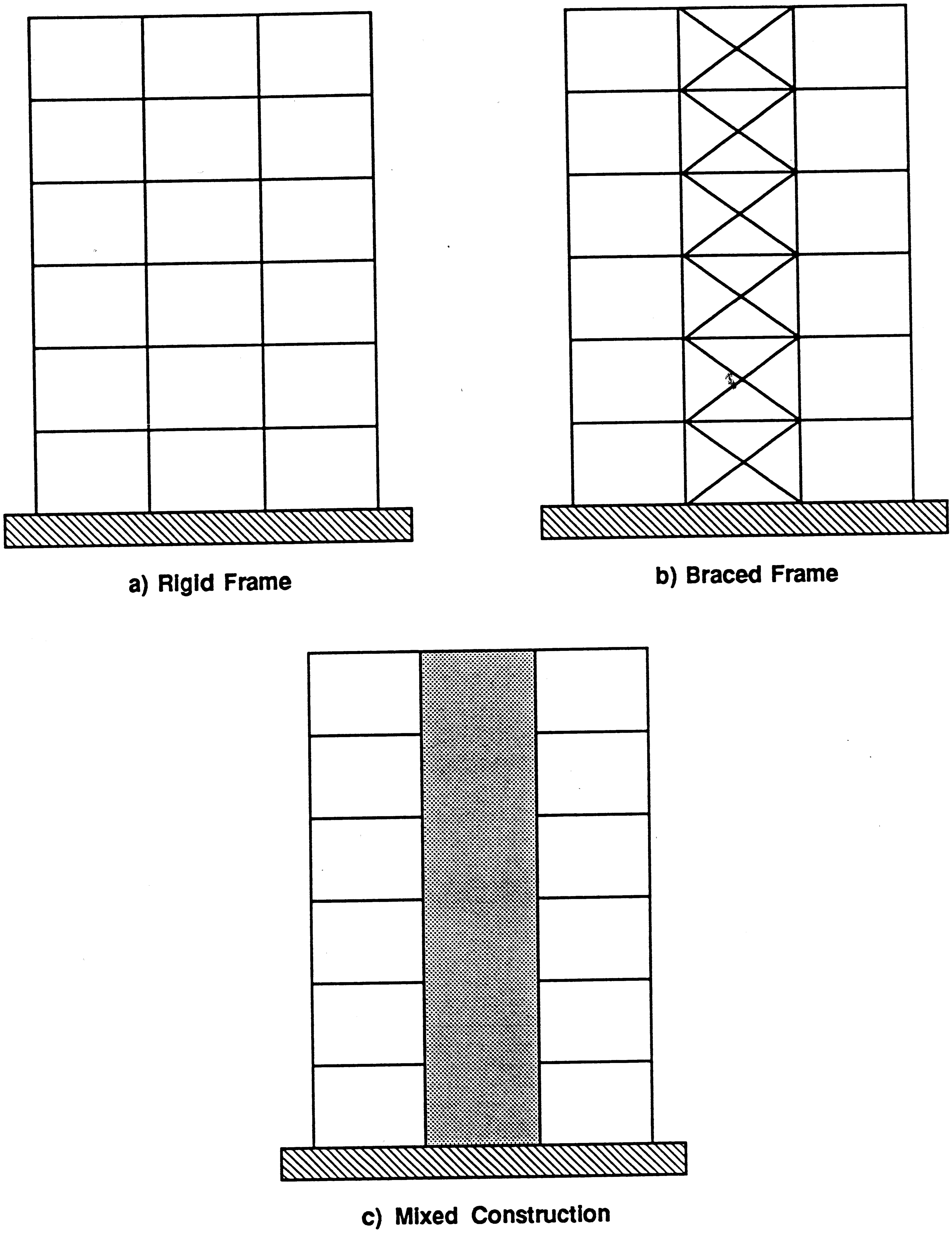


Figure 3.1: Schematics of Possible Framing Configurations

bid may be underestimated because the cost of detailing the connections has been considered a secondary item to the material cost - when, in fact, the details may cost much more than initially expected. This is likely to cause financial difficulties for the fabricator in the next stage of the process: the detailed design.

3.1.3 Detailed Design

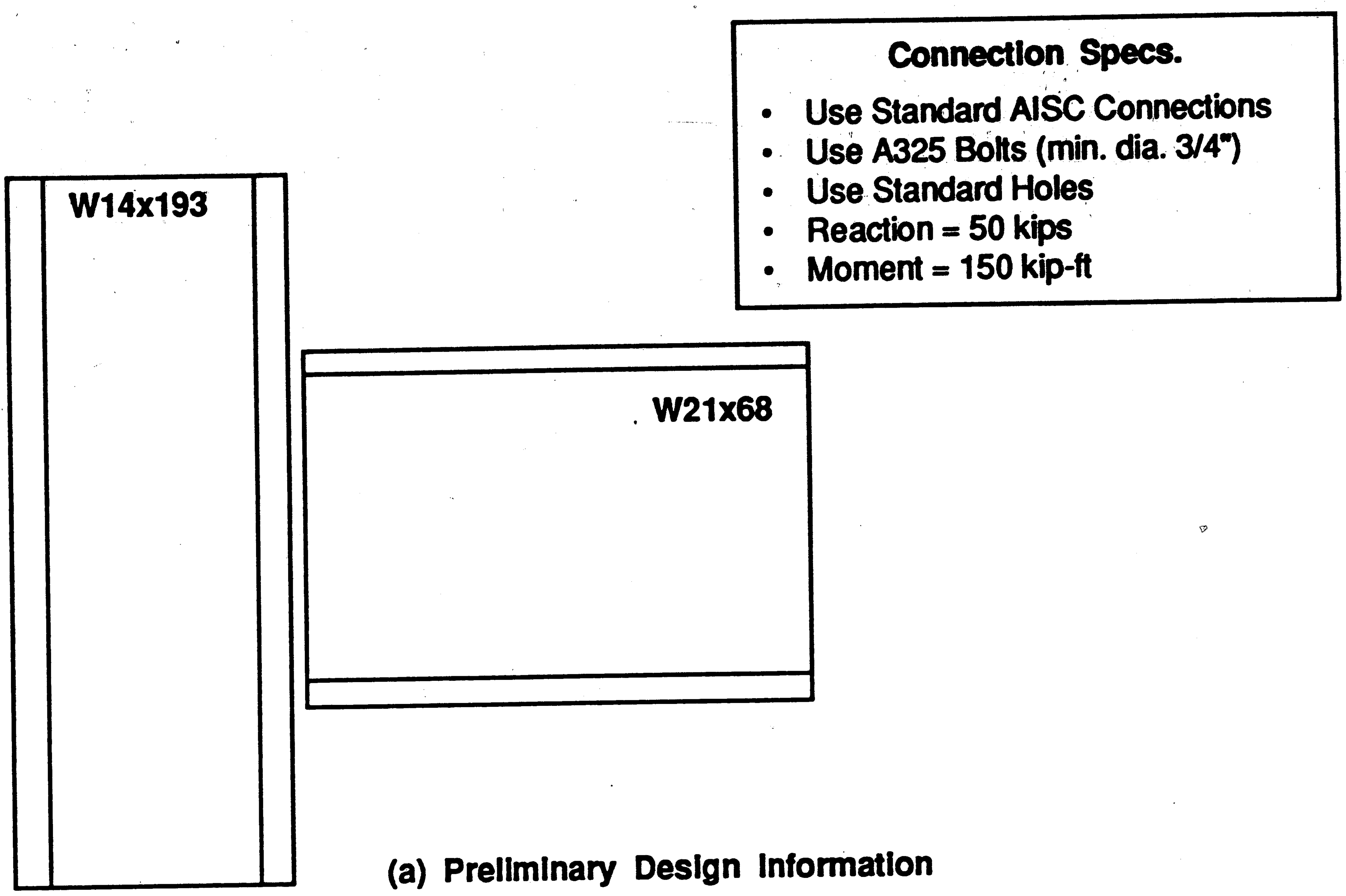
For the remainder of this thesis detailed design will refer to the design and detailing of connections.

The fabricator, upon being awarded the contract for the building, uses the preliminary design information to order the required material from the steel mill. Prior to placing the order, the fabricator must check the adequacy and capacity of the building components in structural connections. As an example of potential problems, it may be found during this check that column webs are insufficient in shear and require doubler plates, or that column flanges are not capable of transferring the required lateral loads and need to be fit with stiffeners [Becker 88b]. Another problem may be that the column web has insufficient depth to make structural connections. Designer's sometimes specify column sections that will carry the given loads but are not deep enough for a connection. This is the case when column sizes smaller than the W10 AISC sections are used [Becker 89].

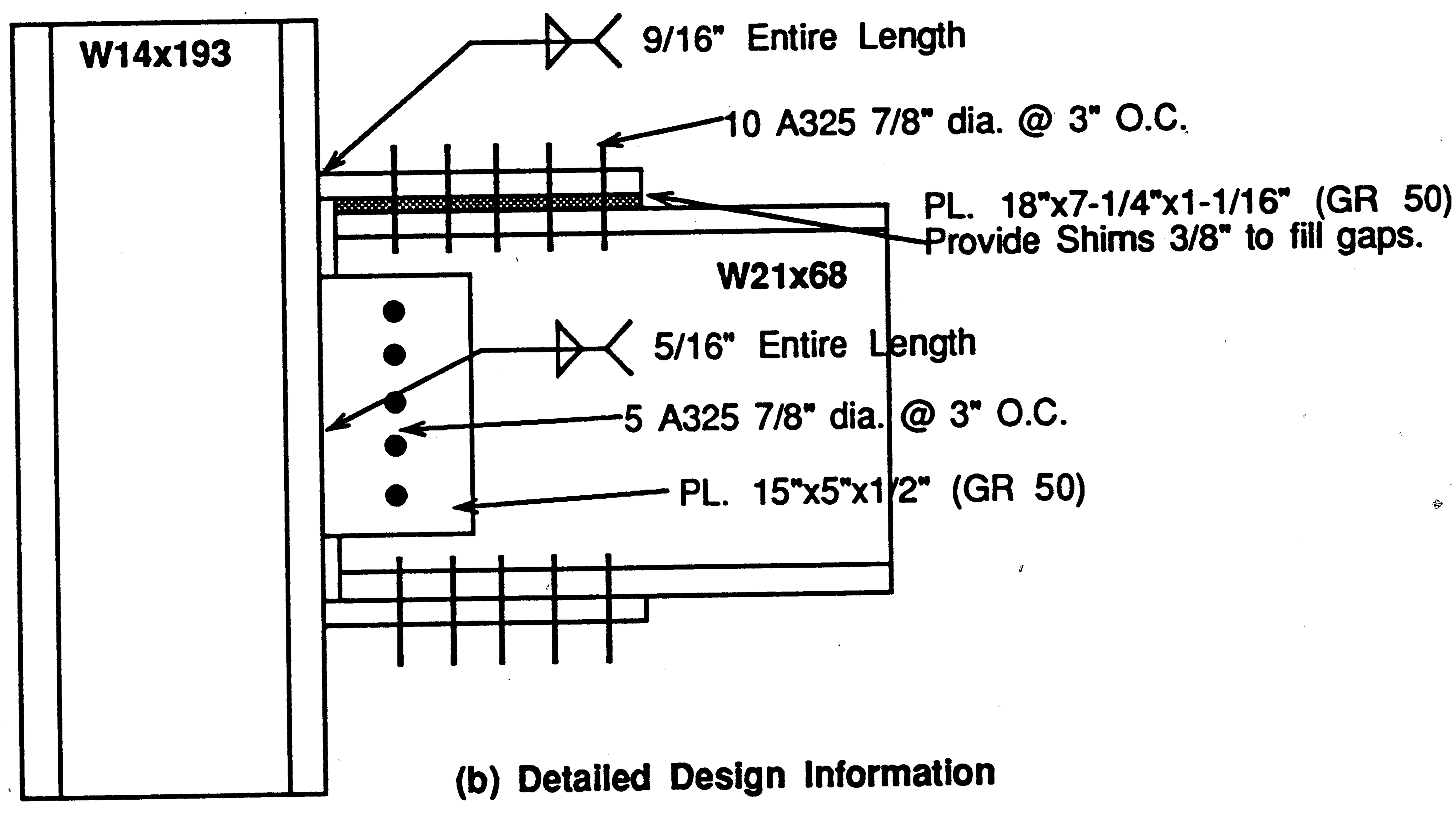
If these or other problems associated with the components of the structural frame are not determined and discussed with the designer, the fabricator must assume the financial responsibility for the additional connection costs. The problems described above could be solved by simply increasing the column member sizes - if the material has not been ordered.

When issues involving the structural frame have been resolved, the fabricator begins the detailed connection design. The connection components, fasteners and operations are determined and shop drawings are prepared. Figure 3.2 shows (a) the preliminary design information, and (b) a possible final detailed design for a given connection [Barone 89].

The fabricator may also be responsible for specifying the construction sequence. This involves designing temporary bracing and falsework. An erector is hired to assist in this task and proceed to the next stage in the process: construction.



(a) Preliminary Design Information



(b) Detailed Design Information

Figure 3.2: Preliminary and Detailed Design Information

3.1.4 Construction

The construction of a building involves the coordination of many interdependent activities. First, the site has to be cleared and the foundation prepared. Next, a survey is done on the completed foundation to check if the elevation and location of the anchors for the steel framing is correct. Problems at this point can lead to impossible fit-up of steel members since the tolerances for steel construction are very tight.

When the erection of the steel begins, other "trades" begin to enter in the construction sequence. A ten step sequence (prior to completion and turn-over) is listed below to show the multiple and varied work taking place simultaneously on a construction site. This basic sequence is suggested as follows*:

1. Columns are set and aligned (two stories in height).
2. Main steel framing is erected to the columns.
3. Secondary steel floor framing is erected.
4. Steel is fireproofed and the floor decking is placed.
5. Steps 2-4 are repeated for the next level of steel framing.
6. Many simultaneous tasks occur as follows:
    a. Steps 1-5 are repeated for higher stories in the building.
    b. Mechanical, electrical, plumbing and HVAC spotting is done on the lower floors.
    c. Concrete floor slabs are poured and finished on the lower floors.
7. Steps 6a-6c are repeated.
8. Exterior work is undertaken.
9. Interior work is undertaken.
10. Landscaping is undertaken.

The ten items listed above serve as an illustration of the complexity of construction projects.

The stages and agents involved in the design and construction process are shown symbolically in Figure 3.3. For example, at the conceptual design stage, the owner and architect are the principal participants. The shading gradually increases in the figure to illustrate how an initial undetected problem can gradually cloud or inhibit the completion of

* The sequence suggested here is a simplified, generalization of typical procedures. Each different project may have a unique construction sequence due to the one-of-a-kind project nature in the construction industry.

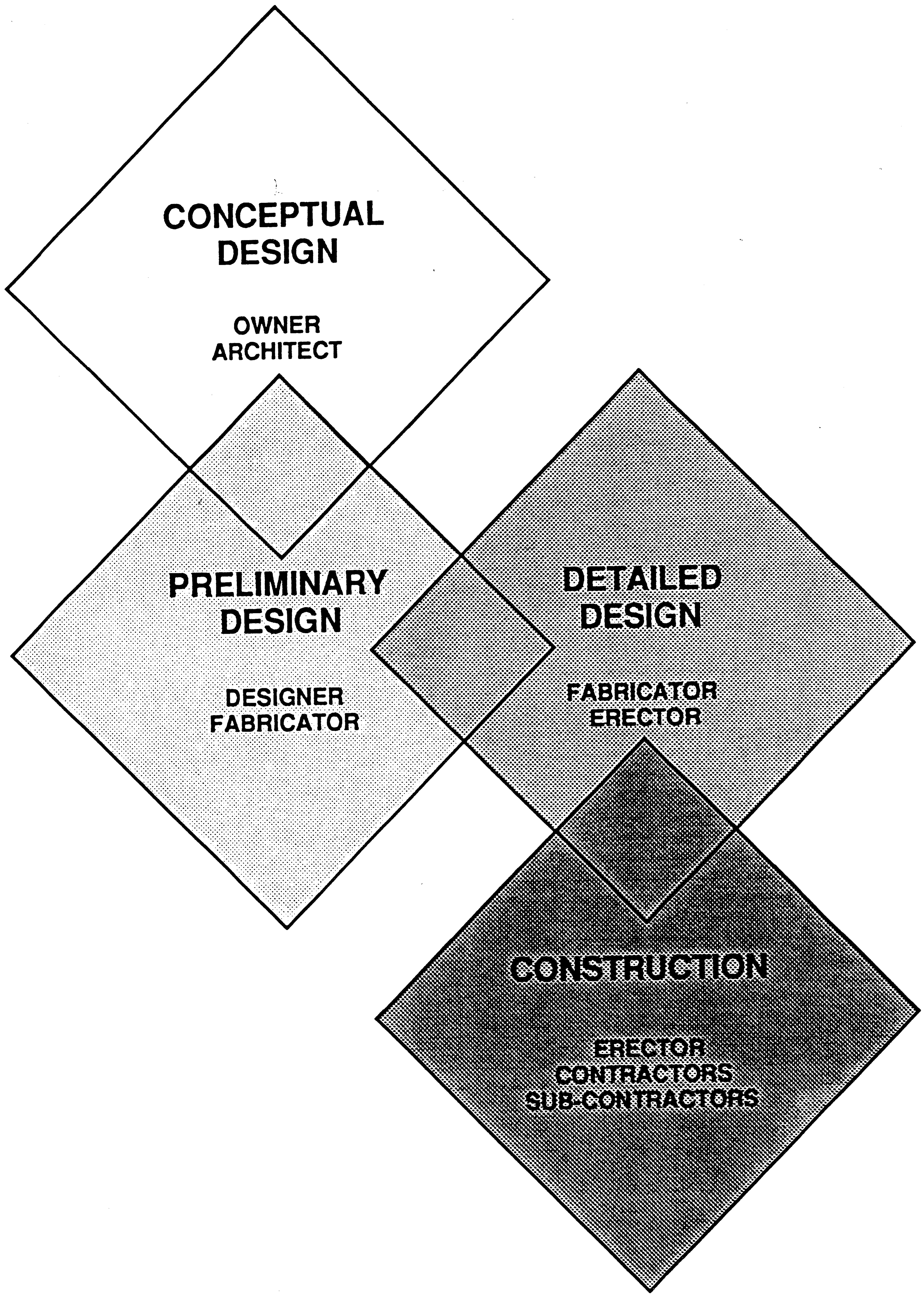


Figure 3.3: Stages of the Design and Construction Process

the later stages. The overlaps in the diagram represent potential gaps of information transfer between the stages and agents. A discussion of these gaps is presented next.

3.1.5 Information Gaps

Each stage in the overall design and construction process involves specialists where the exchange of information among them is highly desirable to coordinate their respective activities. A coordinated effort between specialists earlier in the design and construction process could lead to less field rework and possibly an overall reduction in project costs. The information gaps in the U.S. construction industry have come into existence due to historical trends towards technological specialization. This is quite different from the Renaissance period where one "masterbuilder" dedicated a lifetime to the completion of a single structure from conception to construction.

The information gaps, shown as black diamonds in Figure 3.4 that will be described are: Architect-Designer, Designer-Fabricator, Fabricator-Erector*. The information that should be shared, issues to consider, and what activities should be coordinated between the agents will be discussed along with some example communication problems.

3.1.5.1 Architect-Designer

The information gap between these participants can be illustrated, in part, by a designer's lack of understanding of an architect's concept. On the other hand, an architect may be unaware of whether it is structurally or economically feasible to satisfy the imposed architectural constraints, from the designer's viewpoint. The proposed floor plans, building profile, story heights, and any special architectural features should be discussed jointly and adjusted to facilitate the design and construction. Flexibility is very important here; these agents must consider how their initial decisions will affect the downstream processes, e.g., fabrication and construction, and be willing to compromise to avoid possible construction problems which may be very costly.

* Within each area of specialization, i.e., design or architecture, information gaps also occur. For example, the coordination between the structural and HVAC design has to be considered in a fully integrated scheme. As noted earlier, such interactions are beyond the scope of this thesis.

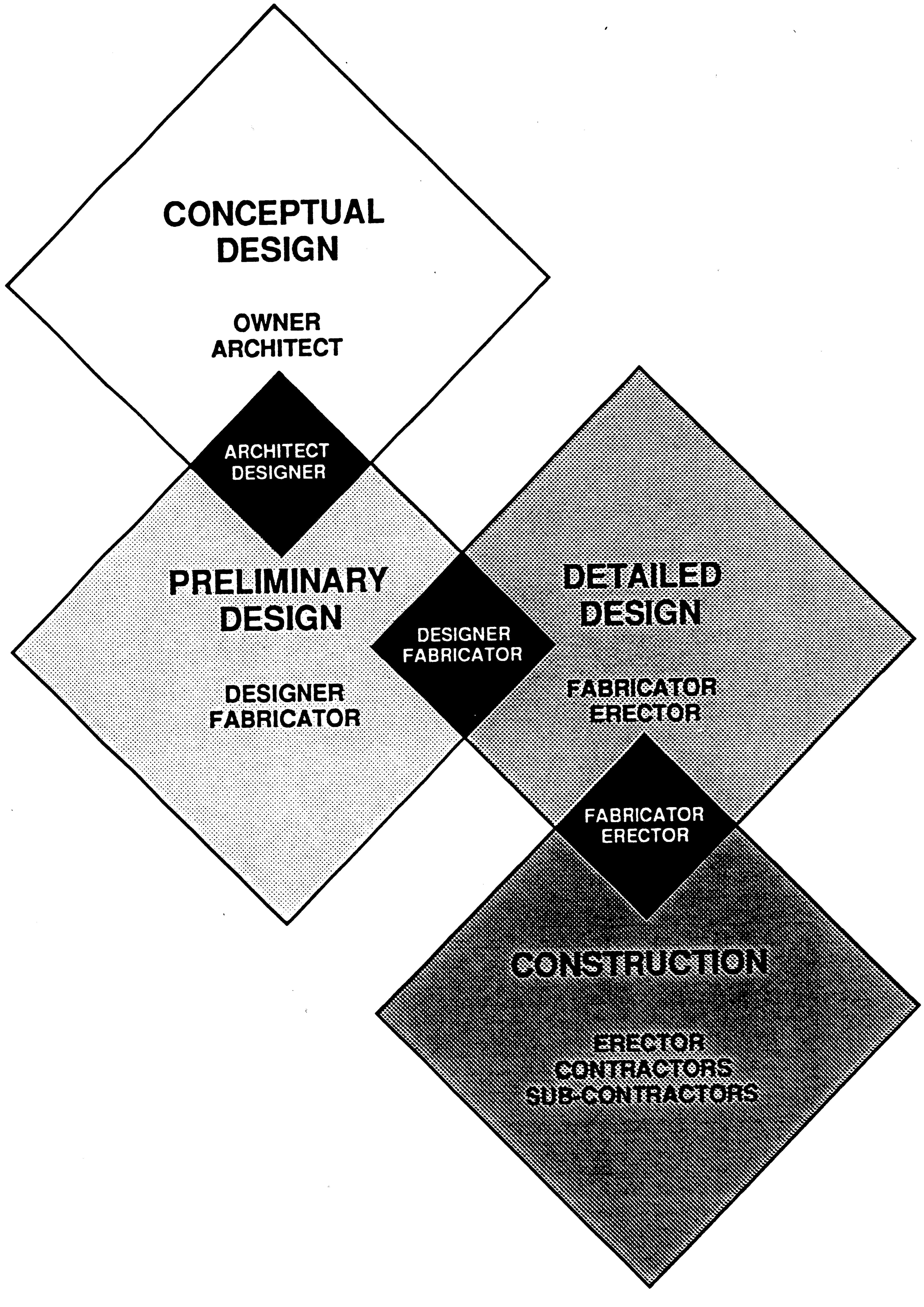


Figure 3.4: Information Gaps in the Design and Construction Process

3.1.5.2 Designer-Fabricator

The information gap between these participants can be illustrated, in part, by the inability of a designer to communicate the requirements so that the built structure behaves similarly to the analyzed structure. For example, the actual connections should be detailed to be consistent with the models used by the structural designer. From a designer's specifications and given applied forces at a node in the building, the fabricator designs and details the connections. Designers seldom provide fabricators with a complete design history listing the critical load cases, and other design assumptions used to perform the structural analysis. This makes the task of designing the connections even more difficult since the fabricator does not know the design intent or expected behavior of the structural system.

Designers and fabricators should strive for consistency between the preliminary component (beams and columns) design and the detailed connection design. The specifics of the connection details must also be agreed upon. The fabricator's economic study of feasible connection details has to agree with the design specifications for allowed connection configurations and components, i.e., top flange plate, bottom flange tee or end plate, material grade, and fastening operations, i.e., shop welding, field bolting. When determining the fastening operations, it is desirable for the designer and fabricator to be aware of the quantity of skilled labor. If a building is specified to have all field welded connections, and there is a shortage of welders in a given region, those financing the project are usually not willing to wait until there is a sufficient labor force to begin construction. The shortage of skilled workers is likely to cause the connection specifications to be rewritten to include field bolted or some other alternative connections which do not require superior skills to construct. Once again, it is desirable to evaluate the upstream design decisions to determine their effect on the downstream fabrication and erection processes.

3.1.5.3 Fabricator-Erector

At this information gap the potential for problems exists because of the need for closer coordination of activities to assemble the structure. Safe, easy and economical assembly is the goal of this interaction between agents. Construction schedules and erection plans are developed, temporary bracing, supports and falsework are designed. Studies are conducted to establish the stability of the incomplete structural frame at various stages of construction. Coordination between material arrival from the fabrication shop to the erection site of the structure has to be established to avoid an excess or shortage of material, which could interfere with the work schedule. An excess of material would force more time to be devoted to the storage as opposed to construction; a shortage would lead to construction delays and unproductive labor time.

Of the three information gaps, this one is the least pronounced because the fabricator and erector generally have a good understanding of what each does. Not too long ago, it was fairly common for the fabricator and erector to be the same company.

3.2 DFI Level of the Process

As described there are information gaps between each of the participants (owner, architect, designer, fabricator and erector). In many cases the flow of critical information is either impeded or is nonexistent. Currently, the design and construction process has little continuity of flow from conceptual design to construction. A system, such as DFI, can provide a mechanism for communicating problems and coordinating solutions among these participants.

Figure 3.5 shows an enlarged view of the stages and participants DFI addresses in the overall design and construction process. DFI is one of the first computer tools that attempts to integrate the upstream design process with the downstream construction procedures by incorporating knowledge from the viewpoints of design, fabrication and erection. As stated in the introduction, "DFI attempts to bridge the information interface gap between design engineers and fabricators of structural steel systems." This interface was chosen because of its importance and the lack of understanding and cooperation that exists between designers and fabricators on their respective tasks. Each is aware of what the other is responsible for, but the specialized nature of the industry has caused a separation of their closely related tasks. This separation is most visible during the connection design process.

This section describes the agents (Designer, Fabricator and Erector) involved in

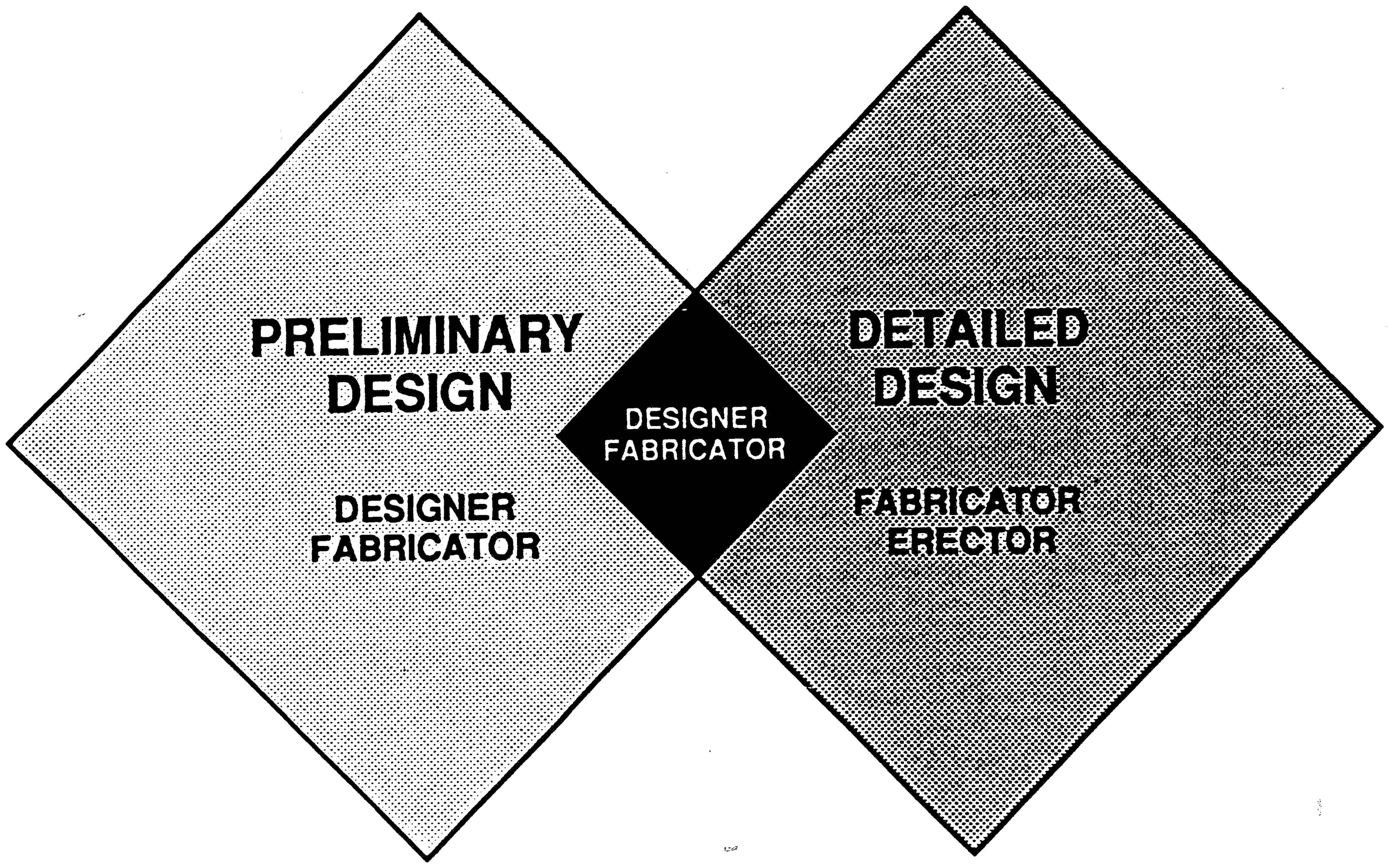


Figure 3.5: DFI Level of Design and Construction Process

the DFI system. Their respective concerns and responsibilities are discussed. The issues each uses during a connection evaluation are defined and presented. Finally, models of each agent are formulated by a decomposition of the issues into lower level subissues that can be used to evaluate a connection.

3.2.1 The Design Agent

This subsection will focus on the designer's concerns and responsibilities at the preliminary design stage. Definitions of the five design issues are developed along with a decomposition of the issues into subissues. The design agent's issues, as represented in DFI, are: Strength, Stiffness, Lifecycle Cost*, Reliability and Versatility. A graphical representation of the agent issue-subissue network is presented later in this section.

* The issue of Lifecycle Cost for the designer was not implemented in the DFI prototype.

3.2.1.1 Concerns and Responsibilities

The designer's main concern is the overall performance of the structure while satisfying the owners and architects needs cost effectively. The structural system designed must be capable of supporting the anticipated loads without experiencing structural or non-structural damage. The responsibilities of the designer include:

a) Developing the structural concept and frame.

b) Sizing and specifying the material grade for the components.

c) Specifying acceptable preliminary connection configurations.

These responsibilities, discussed previously in this chapter, are restated to serve as the basis for the issues and subissues.

3.2.1.2 Issues Used in Evaluation

The design issues as represented in DFI, previously mentioned, are: Strength, Stiffness, Lifecycle Cost, Reliability and Versatility. Figure 3.6 shows the design agent and the first (highest) level of issues. Each issue is considered to be generic so that its definition is applicable to the design procedures associated with a structure, substructure or a component within the structure.

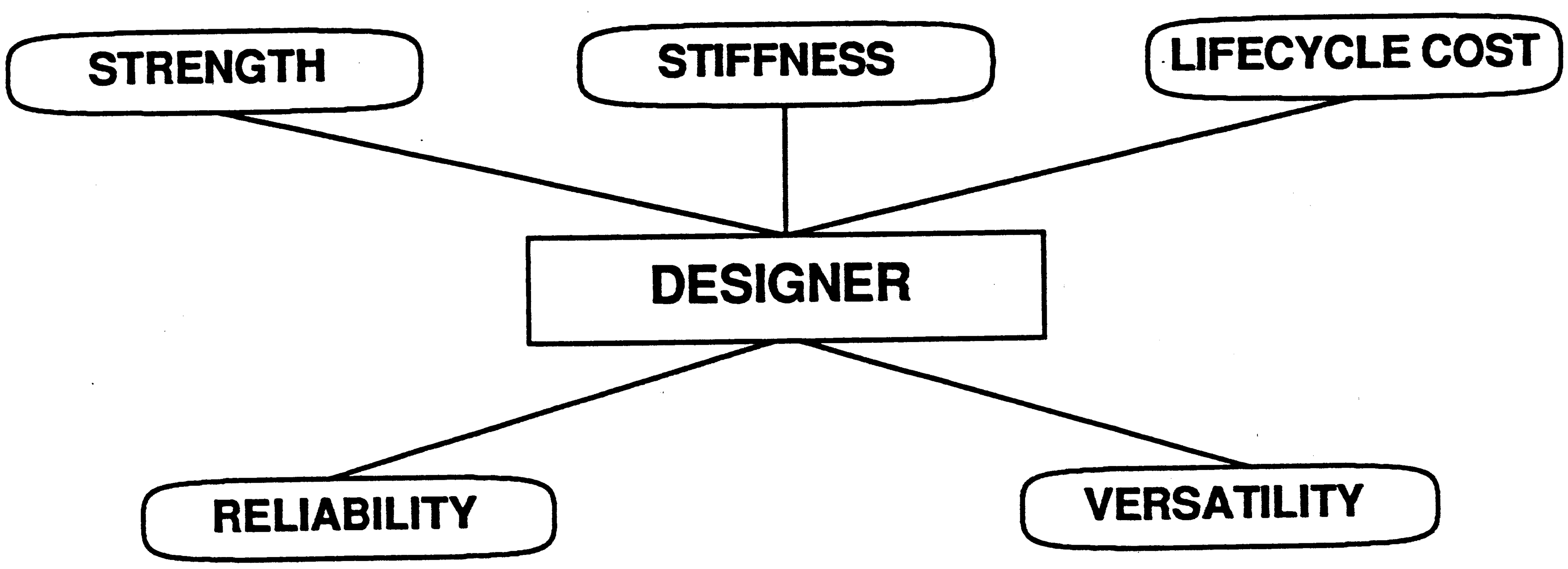


Figure 3.6: Design Agent Issues

The issues are defined below with their respective subissues listed after the definition.

Strength is defined as a structure's ability to support loads throughout its intended lifecycle (construction - maintenance - retirement). Figure 3.7 graphically shows the first layer of subissues for Strength*. These subissues are:

- Structural Concept
- Structural Detailing
- Physical Components
- Material Properties.

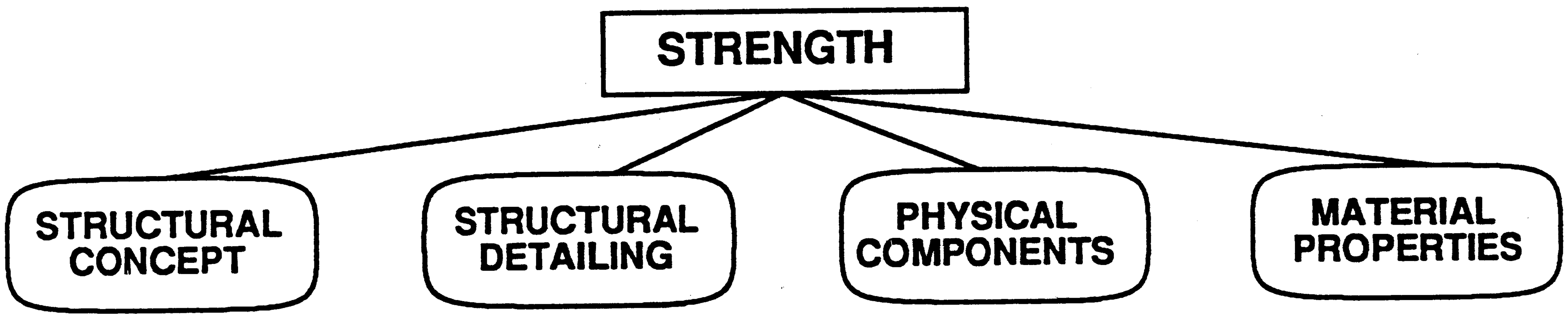


Figure 3.7: STRENGTH and its First Layer of Subissues

Stiffness is defined as a structure's ability to resist deformation under loads throughout its intended lifecycle (construction - maintenance - retirement). Figure 3.8 graphically shows the first layer of subissues for Stiffness. These subissues are:

- Structural Concept
- Structural Detailing
- Physical Components
- Material Properties

* For each issue there are many layers of possible subissues. Decomposition, however, is beyond the scope of this section. Chapter 4 presents a discussion of the subissues.

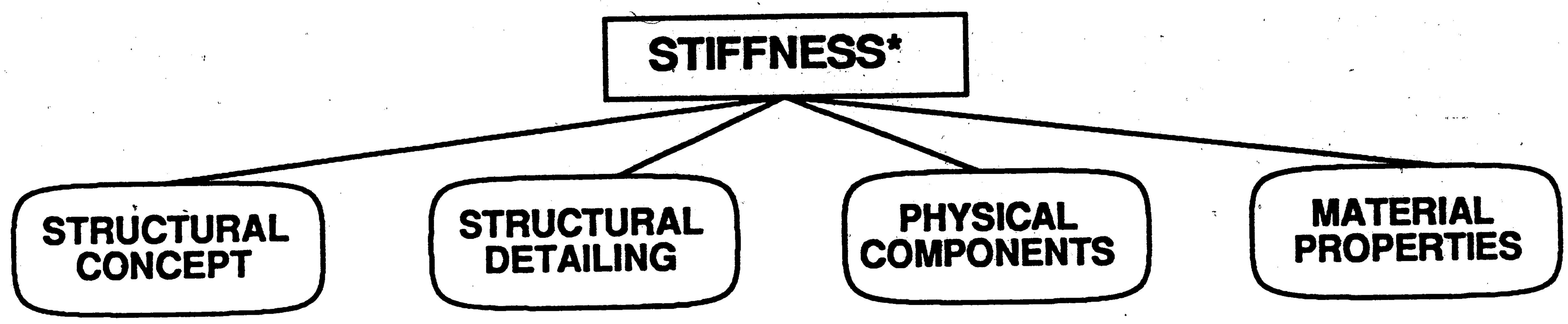


Figure 3.8: STIFFNESS and its First Layer of Subissues

Lifecycle Cost is defined by the cost of a structure when design considers the performance throughout the lifecycle (construction - maintenance - retirement) under service loads. Figure 3.9 graphically shows the first layer of subissues for Lifecycle Cost. These subissues are:

- Structural Concept
- Design Methods
- Construction Procedures
- Material Properties

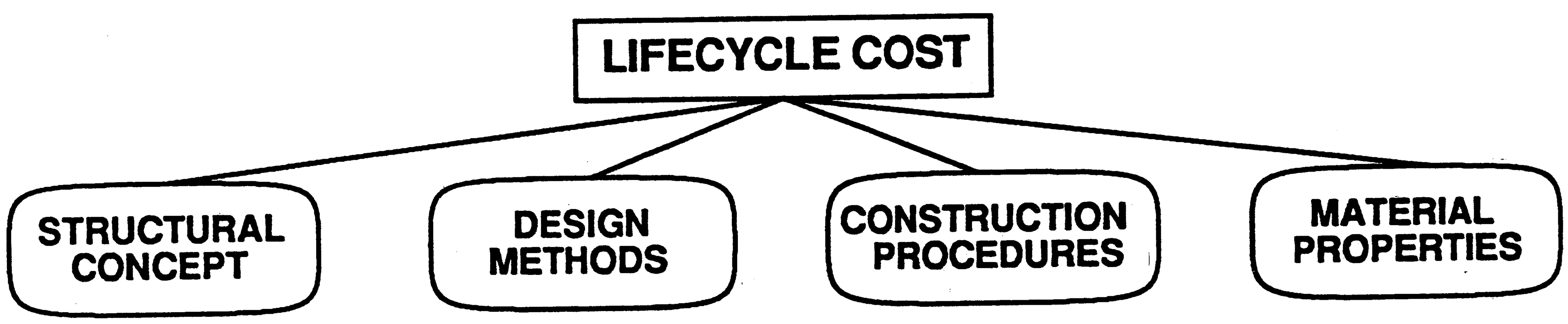


Figure 3.9: LIFECYCLE COST and its First Layer of Subissues

* The subissues for strength and stiffness are "identical", the differences lie at the lower more detailed information levels. This note pertains to all issues that have "identical" subissues.

Reliability is defined as the quality or state of a structure being certain, dependable and non-problematic in supporting loads and resisting deformation throughout its intended lifecycle (construction - maintenance - retirement). Figure 3.10 graphically shows the first layer of subissues for Reliability. These subissues are:

- Design Methods
- Construction Procedures
- Material Properties

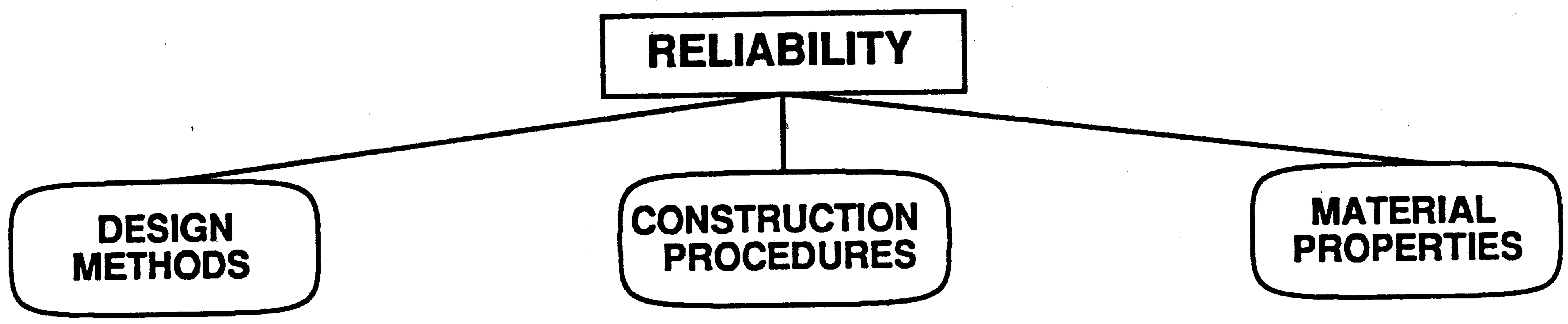


Figure 3.10: RELIABILITY and its First Layer of Subissues

Versatility is defined as the quality of a structure to be adaptable or retrofitted as the anticipated usage and loadings change throughout its intended lifecycle (construction - maintenance - retirement). Figure 3.11 graphically shows the first layer of subissues for Versatility. These subissues are:

- Structural Concept
- Construction Procedures
- Physical Components
- Material Properties

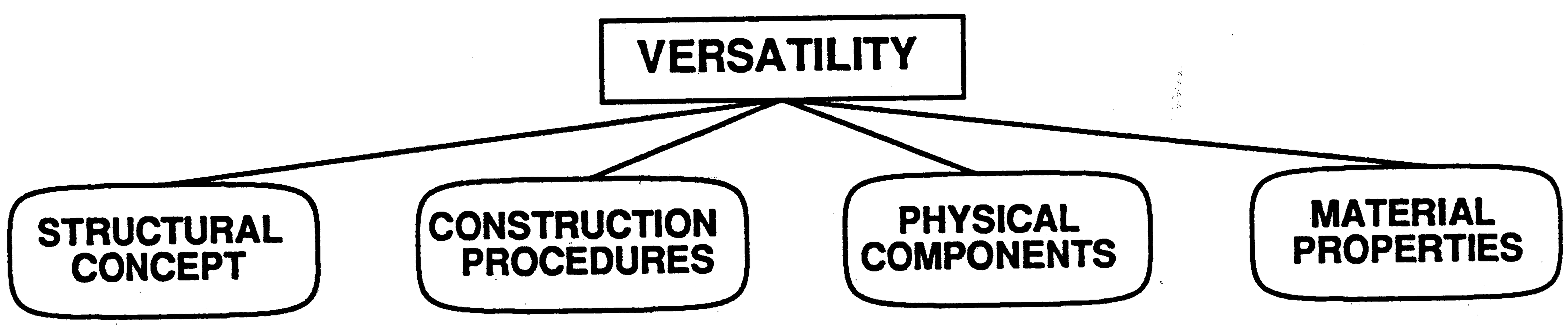


Figure 3.11: VERSATILITY and its First Layer of Subissues

3.2.2 The Fabrication Agent

This subsection will focus on the fabrication agent's concerns and responsibilities in performing the detailed design. Definitions of the three fabrication issues are developed along with a decomposition of the issues into subissues. The fabrication agent's issues, as represented in DFI, are: Fabrication Cost, Fabrication Ease and Material Cost. A graphical representation of the agent issue-subissue network is presented later in this section.

3.2.2.1 Concerns and Responsibilities

The main concern of the fabricator is minimizing the overall fabrication cost of the structure while meeting all of the design specifications. The fabricator uses the preliminary design information to bid the job, and design and detail the connections. The responsibilities of the fabricator include:

a) Ordering the required material from the steel mill.

b) Designing and detailing the connections.

c) Fabricating the components of the structure within the required tolerances.

d) Shipping the fabricated pieces to the construction site on schedule.

e) Developing construction plans to insure the structure can be built.

3.2.2.2 Issues Used in Evaluation

The fabrication issues, as previously mentioned, are: Fabrication Cost, Fabrication Ease and Material Cost. Figure 3.12 shows the fabrication agent and the first level of issues. Each issue is considered to be generic so that the definition is applicable to the fabrication procedures associated with a structure, substructure or a component within the structure.

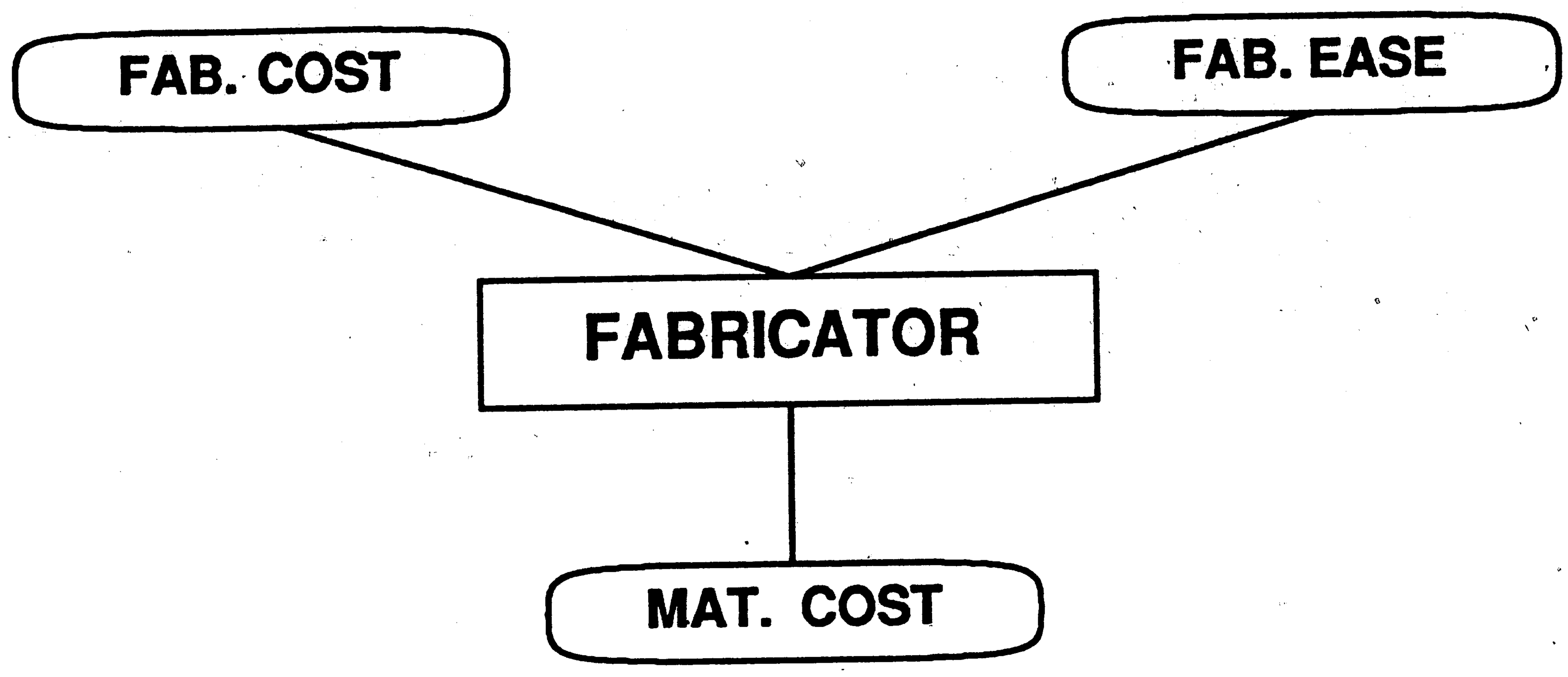


Figure 3.12: Fabrication Agent Issues

The issues are defined below followed by their respective subissues.

Fabrication Cost is defined as the cost associated with the labor and operations required to manufacture the connection details and components of the structure. Figure 3.13 graphically shows the first layer of subissues for Fabrication Cost. These subissues are:

- Structural Detailing
- Fabrication Procedures
- Physical Components
- Material Properties

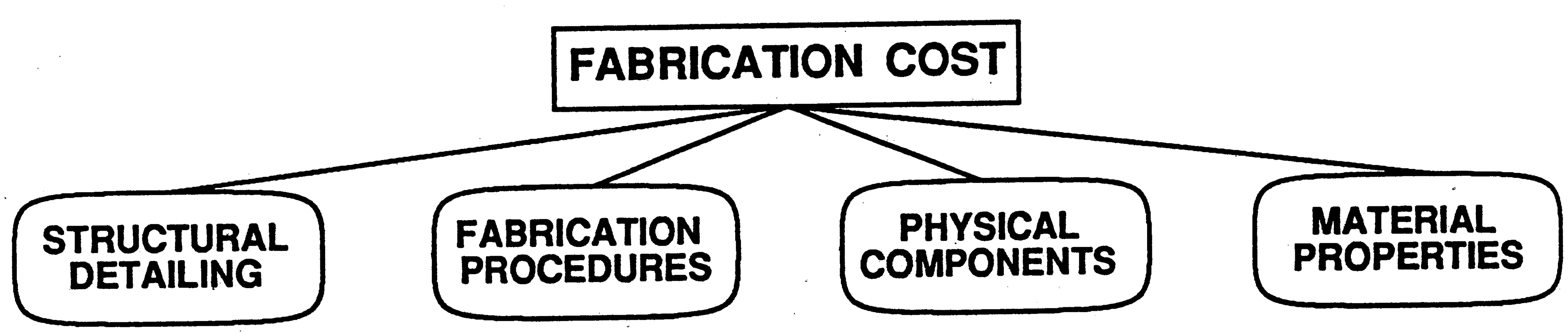


Figure 3.13: FABRICATION COST and its First Layer of Subissues

Fabrication Ease is defined as the relative ease associated with the operations required to manufacture the structural details and ship the components of the structure. Figure 3.14 graphically shows the first layer of subissues for Fabrication Ease. These subissues are:

- Structural Detailing
- Fabrication Procedures
- Shipping Operations
- Physical Components

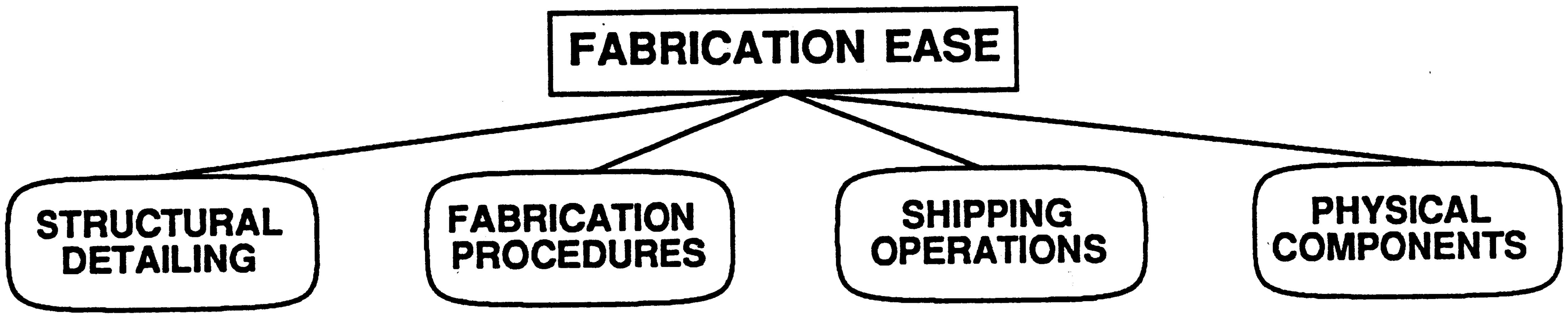


Figure 3.14: FABRICATION EASE and its First Layer of Subissues

Material Cost is defined as the ordering and delivery charges associated the receiving the components of the structure from the steel mill. Figure 3.15 graphically shows the first layer of subissues for Material Cost. These subissues are:

- Shipping Operations
- Physical Components
- Material Properties

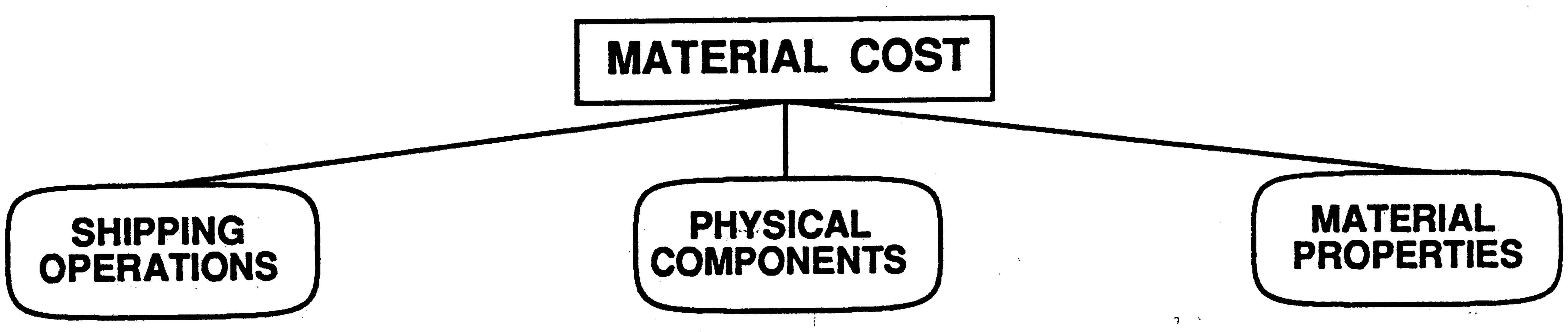


Figure 3.15: MATERIAL COST and its First Layer of Subissues

3.2.3 The Erection Agent

This section will focus on the erection agent's concerns and responsibilities in going from detailed design to construction. Definitions of the three erection issues are developed along with a decomposition of the issues into subissues. The erection agent's issues, as represented in DFI, are: Erection Cost, Erection Ease and Safety. A graphical representation of the agent issue-subissue network is presented later in this section.

3.2.3.1 Concerns and Responsibilities

The erector is most concerned with minimizing the construction costs while assembling the structure safely. The erector uses the construction plans developed by the fabricator to determine the required manpower, use of temporary bracing and falsework, and storage of material. The erectors responsibilities include:

a) Handling and storage of delivered material.

b) Assembling and aligning the building components properly and safely.

c) Meeting the construction deadlines for the steel erection.

3.2.3.2 Issues Used in Evaluation

The erection issues, as previously mentioned, are: Erection Cost, Erection Ease and Safety. Figure 3.16 shows the erection agent and the first level of issues. Each issue is

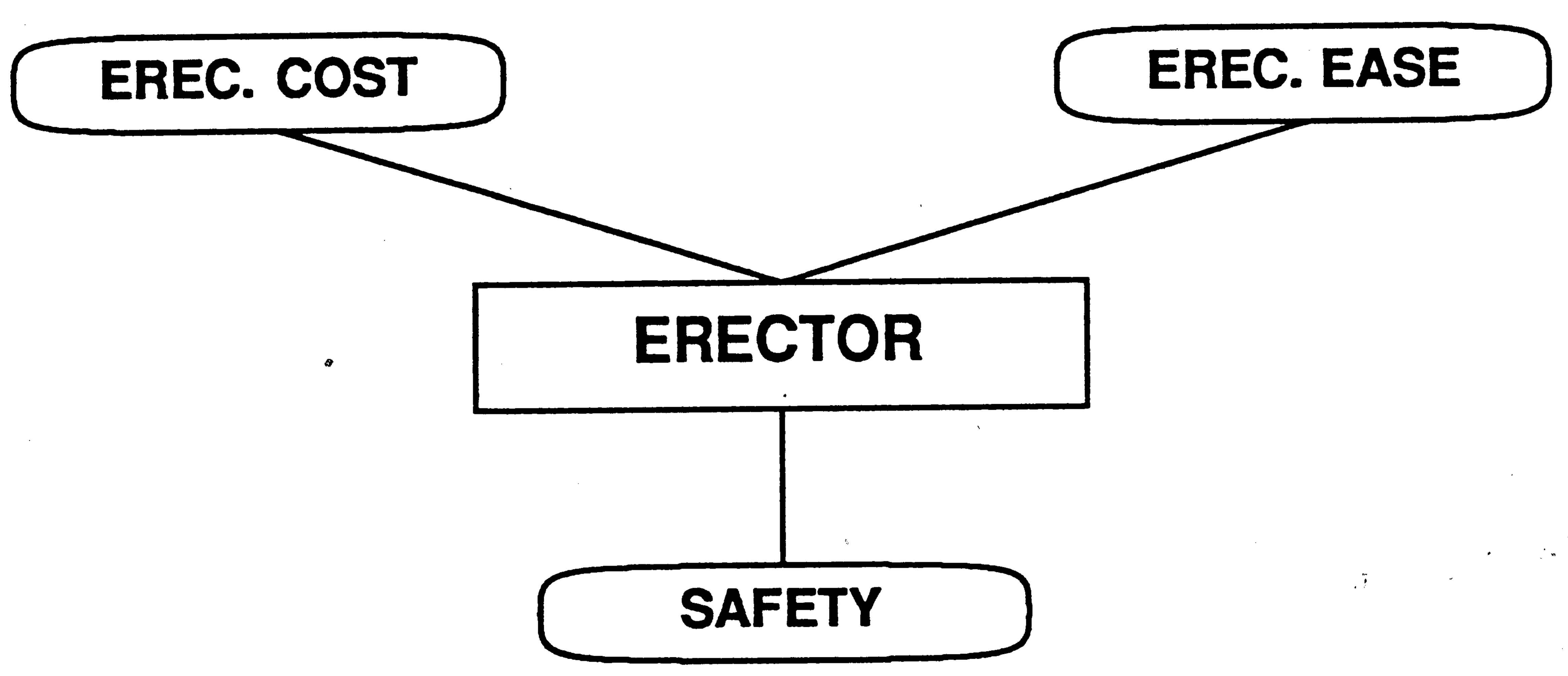


Figure 3.16: Erection Agent Issues

considered to be generic so that the definition can be applied to the erection procedures associated with a structure, substructure or a component within the structure.

The issues are defined followed by their respective subissues.

Erection Cost is defined as the cost associated with the labor and operations required to field assemble the structural details and align the components of the structure. Figure 3.17 graphically shows the first layer of subissues for Erection Cost. These subissues are:

- Structural Detailing
- Construction Procedures
- Physical Components
- Material Properties

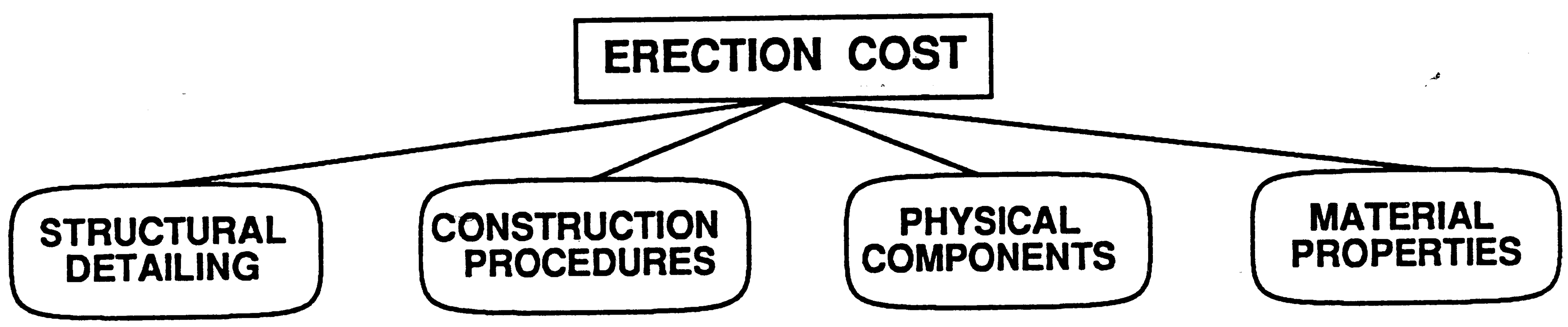


Figure 3.17: ERECTION COST and its First Layer of Subissues

Erection Ease is defined as the relative ease associated with the operations required to handle and field assemble the structural details and align components of the structure. Figure 3.18 graphically shows the first layer of subissues for Erection Ease. These subissues are:

- Structural Detailing
- Construction Procedures
- Physical Components
- Material Properties

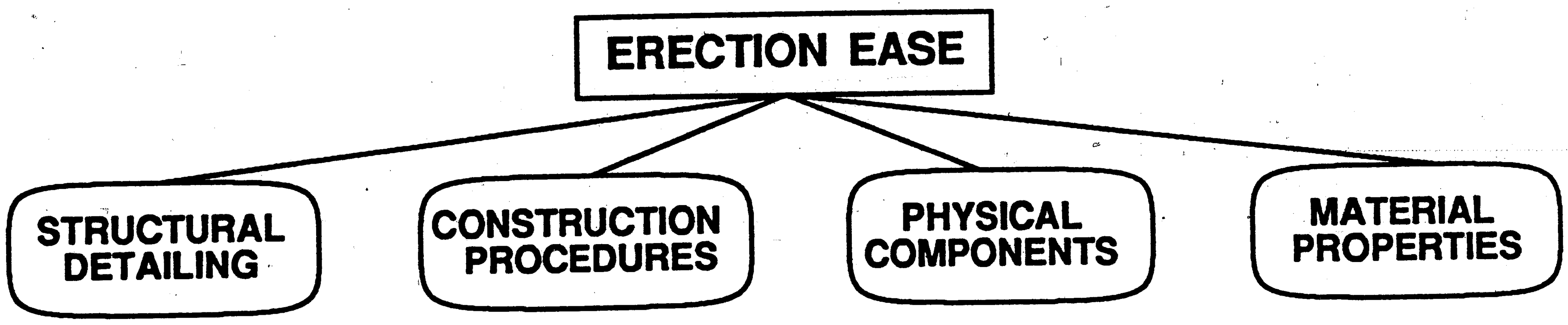


Figure 3.18: ERECTION EASE and its First Layer of Subissues

Safety is defined as the confidence level associated with the operations and schedule being used to assemble the components of the structure. Figure 3.19 graphically shows the first layer of subissues for Safety. These subissues are:

- Structural Concept
- Structural Detailing
- Construction Procedures
- Material Properties

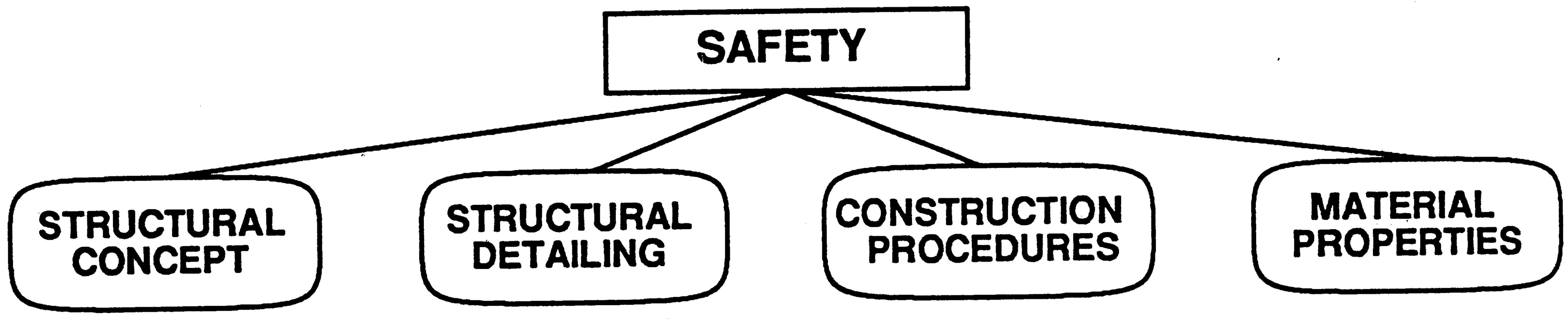


Figure 3.19: SAFETY and its First Layer of Subissues

3.2.4 Agent Information Models*

Building networks of the respective issues and subissues formulated the agent information models. Figures 3.20 to 3.22 graphically present the three agents issue-subissue networks. In these figures rectangles depict agents. The issues are directly "linked" to the agent. For example in Figure 3.20, the issues of strength, stiffness, lifecycle cost, reliability and versatility are tied directly to the designer. The outermost boxes represent the first layer of subissues. The solid lines show direct relationships between issues and subissues while the dotted lines represent the links that exist between subissues. Tracing a possible path through the design agent issue-subissue network (see Figure 3.20) from the design agent to the physical components subissue, would involve beginning at the designer then following the link to the strength issue . Strength is then linked to the physical components subissue. This is one of many paths that may be taken from the designer to the physical components. The complexity of these networks is due to the problem being modeled. Evaluating a particular connection is thus quite difficult when considering many issues.

The next stage of developing these models involved the further decomposition of subissues into characteristics and metrics that are specific enough to be given quantitative values. In Chapter 4, lists of the identified characteristics for each subissue are formulated along with more detailed figures showing the information decomposition of each agent.

Once the decomposition of each agent was completed, the three models were assembled into a single network. The process of defining the relational network between agents is also discussed in Chapter 4.

3.3 Incorporating the Other Agents into DFI

This chapter has shown the systematic decomposition of agent viewpoints into issues and subissues. By beginning with a general definition of each issue, a constrained set of subissues were formulated and represented. This process was performed for the designer, fabricator and erector in attempt to develop a framework to serve as a mechanism which

* This thesis is not intended to formulate completely the agent information models. This work lays the foundation for further refinement of the models presented here.

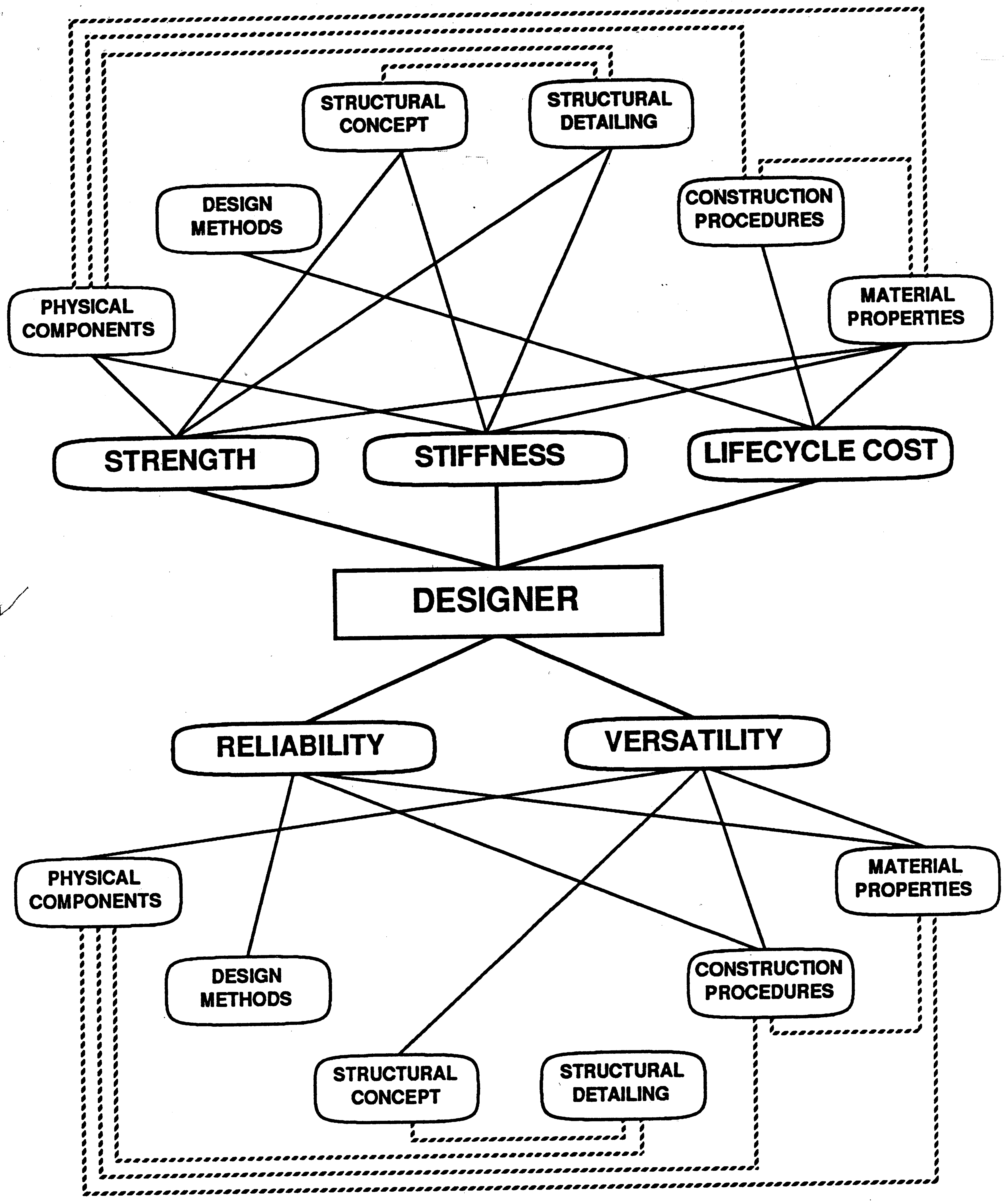


Figure 3.20: Design Agent Issue-Subissue Network

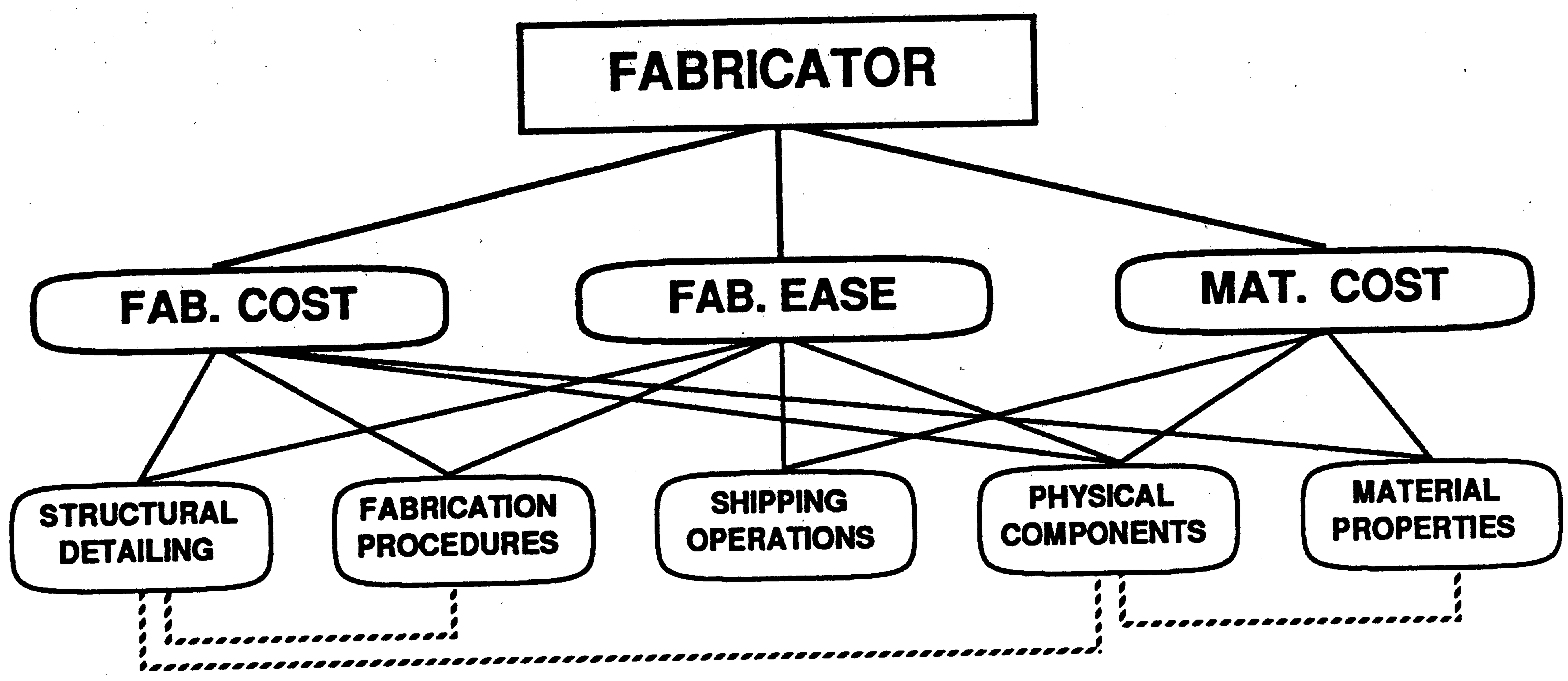


Figure 3.21: Fabrication Agent Issue-Subissue Network

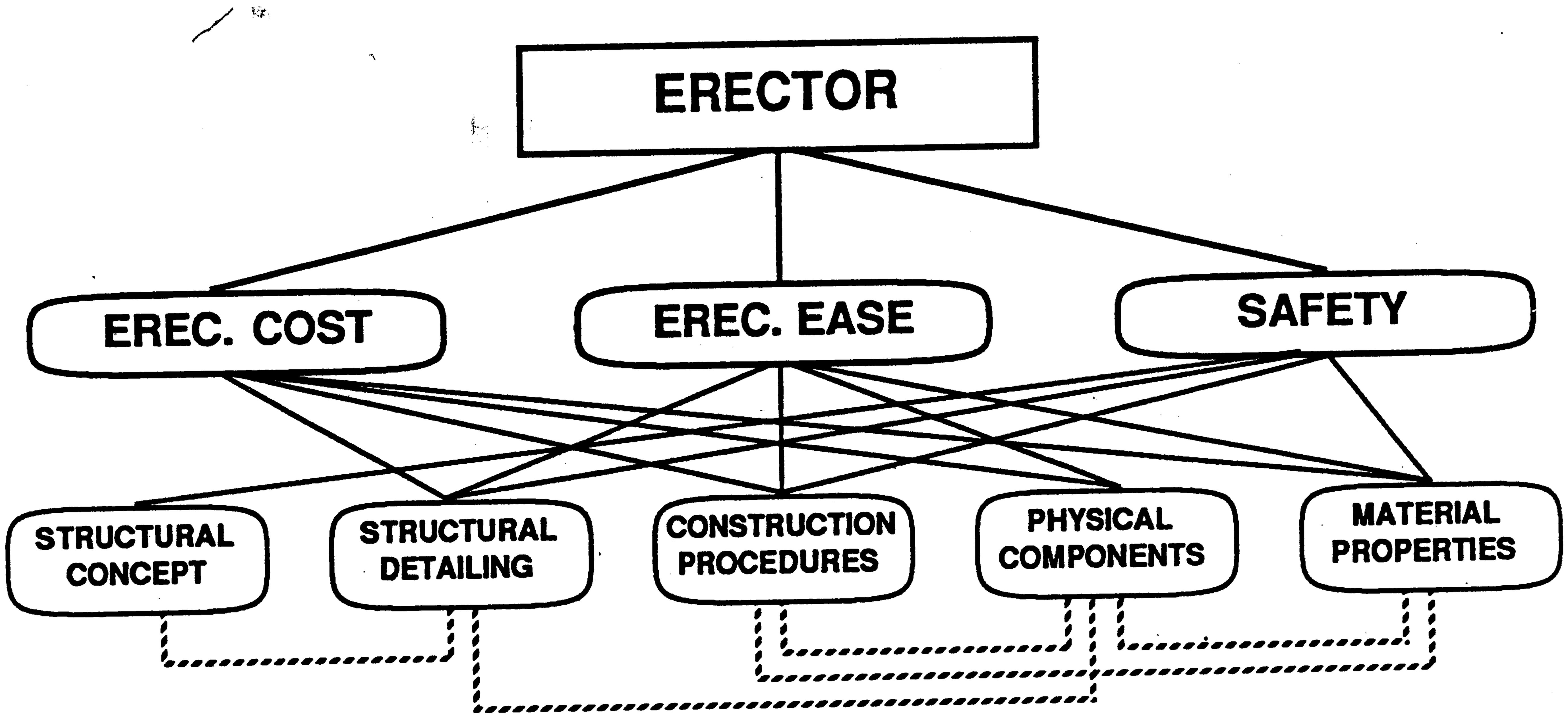


Figure 3.22: Erection Agent Issue-Subissue Network

could be implemented to bridge the information gap between the preliminary and detailed design stages.

The incorporation of other agents into the framework can be accomplished by undertaking the following sequence of steps. First, identify the agent that is to be added. Second, determine the issues the new agent will use to evaluate a connection (structure). Then decompose the new issues into subissues and formulate the new agent's network.. This completes the new agent's preliminary information model. Relationships between the new and old agents' issues and subissues would then need to be established. These relationships would be required to build the proper dialog between the new and old agents, to ensure cooperation and coordination of activities and knowledge during the evaluation.

The next chapter formulates more detailed agent information models through further decomposition of the issues and subissues into characteristics and quantifiable metrics. The DFI relational network is also presented. Relationships among each agent, and between the agents are developed to show the possible interactions during a DFI evaluation. Finally, an illustrative example of a typical problem encountered in the field due to poor initial design decisions is described along with a discussion on how the models can be used to tackle such situations.

4. A Relational Agent Interaction Scheme

The intent of this chapter is to extend the ideas presented in Chapter 3 which identified some of the agents and issues involved in the design and construction process. The decomposition of issues into subissues was not extensive enough to relate agents. In this chapter, properties, referred to as "characteristics," which may be associated with a more detailed breakdown of the subissues are presented. These characteristics are shared between the agents to provide a method of relating the three viewpoints (designer, fabricator and erector).

This chapter is organized in the following manner. First, the implemented relational scheme is discussed. This discussion includes a description of the implemented relational network, and the relationships that exist between issues. Next, detailed agent information models are developed, and a description of the subissue decomposition into characteristics is provided. Following this, a description on an extended relational network is presented along with a discussion of the formulated relationships among and between the agents. Next, an illustrative scenario discusses the application of the DFI relational network. The chapter is concluded with a summary of the relational interaction scheme along with a description of its potential usefulness.

4.1 DFI Relational Network - Implemented Scheme

This section reviews the relational network initially presented in Section 2.2.3. The process used to develop it is discussed. The implemented agent relationships that link the network together are then described.

4.1.1 Description of the Network

Figure 4.1 shows a schematic of the implemented relational network. The network centers around a connection which is made up of functional, component and fastener aspects as discussed in Section 2.2.3.

The formulation of this network involved the identification of important agent

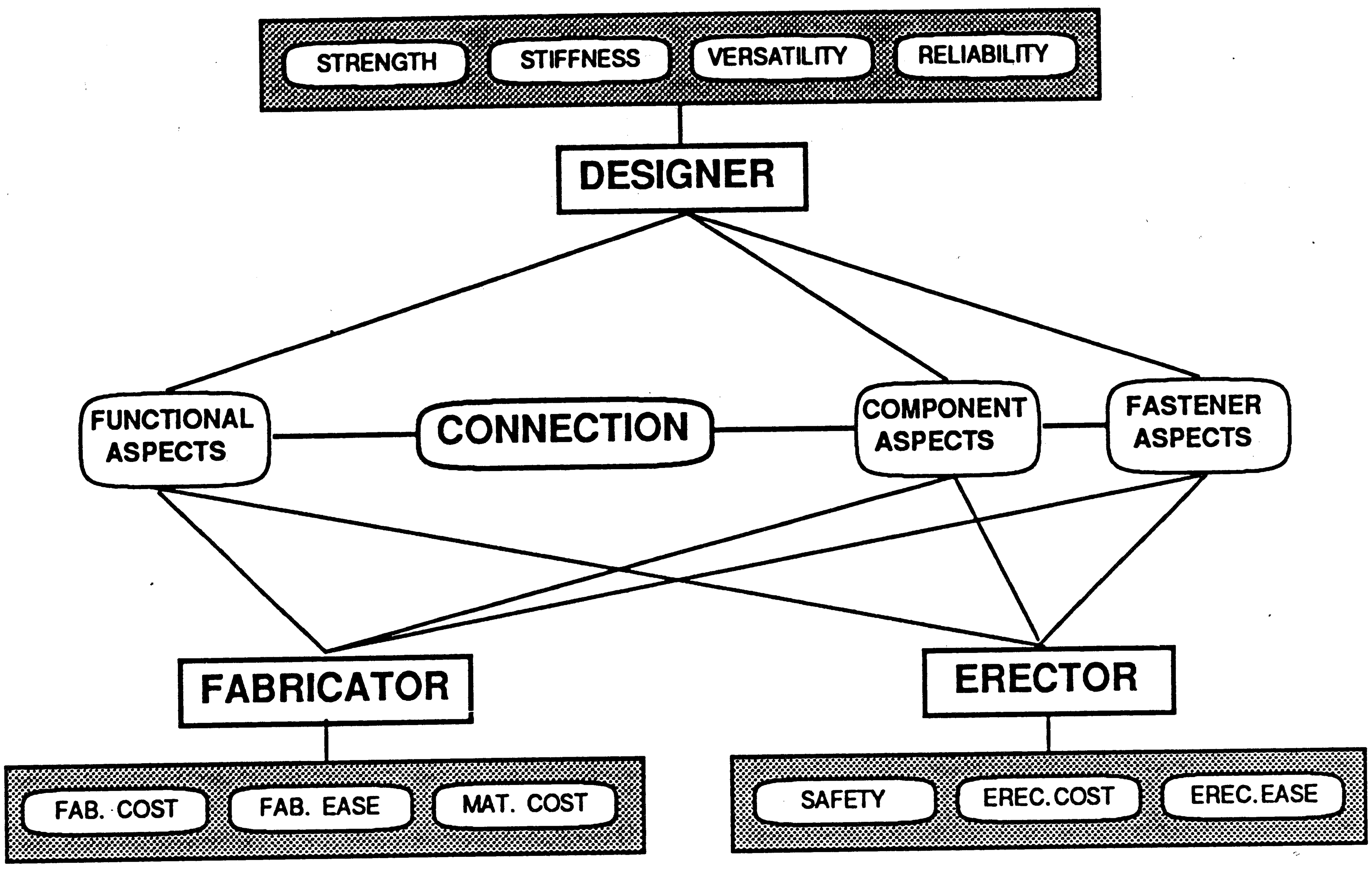


Figure 4.1: Implemented DFI Relational Network

issues for the evaluation of connection designs. A decomposition was not done for the issues to simplify the implementation of the prototype system. Each issue was related to the functional, component or fastener aspects of the connection. Next, relations between the issues were formulated. The author formulated these relationships using industry input and knowledge acquired through course work in connection design.

The agents communicate their important issues to one another through the relations that exist. The messages passed between the agents during an evaluation are tied directly to the relational network. Simply stated, the messages that are posted for review to the user summarize the relationship that exists between the two last posted issues to the evaluation blackboard. These messages act as an explanation facility on both the user and internal agents so that the evaluation process may be monitored and reviewed. This is demonstrated in the case study presented in Chapter 5.

4.1.2 The Issue Relationships

The implemented network uses two types of inter-agent relationships - expense and performance. These were chosen because they are the main concerns of the practitioners [Hooper 88], [Becker 88b].

Figure 4.2 shows the relationship template and an example relationship used in DFI. Formulating the relationships required the selection of two different agents (agent1 and agent2), issues (issue1 and issue2), and the identification of each issue's relevant network aspect (aspect1 and aspect2), e.g., functional, component or fastener, as shown in Figure 4.1. Next, keywords defining the potential problem areas were attached to each agent's issue. Finally, the relationship type (expense or performance) was determined. The

RELATIONSHIP TEMPLATE

```
relation( Type{expense, performance},
        [agent_issue(agent1, issue1, aspect1, [Keywords1]),
         agent_issue(agent2, issue2, aspect2, [Keywords2])]).
```

DESCRIPTION OF RELATIONSHIP COMPONENTS

Type: relationship type, expense or performance

agent_issue: list containing the agent, issue, aspect and associated keywords.

Keywords:

type_conn: how the type of connection affects the issue in the relationship

detail_mat: how the connection components affect the issue in the relationship

shop_ops: how the fabrication operations affect the issue in the relationship

field_ops: how the erection operations affect the issue in the relationship

EXAMPLE RELATIONSHIP

```
relation( performance,
        [agent_issue(designer,strength,functional,[type_conn]),
         agent_issue(fabricator, fab_cost,components,[shop_ops])]).
```

Figure 4.2: Example DFI Relationship

example performance relationship shown in Figure 4.2 is between the designer's strength issue and the fabricator's fabrication cost issue*. For the strength issue, `functional` is the identified aspect and `type_conn` is the only attached keyword. Each issue may have more than one keyword attached to it. Appendix B lists all the relationships used in the DFI prototype.

4.2 Detailed Agent Information Models

A summary of issues and subissues associated with the designer, fabricator and erector agents is shown in Table 4.1. Next, a description of the eight subissues, previously formulated in Chapter 3 is presented. Following this, the formulation of the agent information models is discussed.

4.2.1 Decomposition of Subissues

The eight subissues described in this section are:

- Structural Concept
- Structural Detailing
- Design Methods
- Construction Procedures
- Fabrication Procedures
- Shipping Operations
- Physical Components
- Material Properties.

Each of these subissues is next described in turn.

The **structural concept**** of a building, in this discussion, is limited to the topology and connection designs. A building's topology is defined by the type of structural frame,

* For the example relationship shown in Figure 4.2, agent1 = designer, issue1 = strength, aspect1 = functional, keywords1 = type_conn, agent2 = fabricator, issue2 = fab_cost (fabrication cost), aspect2 = components and keywords2 = shop_ops (shop operations).

** A listing of characteristics which provide a more detailed breakdown of the subissues is presented in Appendix C.

Table 4.1: Listing of Agent Issues and Subissues

AGENT	ISSUES	SUBISSUES*
DESIGNER	STRENGTH	***Structural Concept, Structural Detailing, Physical Components, Material Properties***
	STIFFNESS	Structural Concept, Structural Detailing, Physical Components, Material Properties
	LIFECYCLE COST	Structural Concept, ***Design Methods, Construction Procedures,*** Material Properties
	RELIABILITY	Design Methods, Construction Procedures, Material Properties
	VERSATILITY	Structural Concept, Construction Procedures, Physical Components, Material Properties
FABRICATOR	FABRICATION COST	Structural Detailing, ***Fabrication Procedures,*** Physical Components, Material Properties
	FABRICATION EASE	Structural Detailing, Fabrication Procedures, ***Shipping Operations,*** Material Properties
	MATERIAL COST	Shipping Operations, Physical Components, Material Properties
ERECTOR	ERECTION COST	Structural Detailing, Construction Procedures, Physical Components, Material Properties
	ERECTION EASE	Structural Detailing, Construction Procedures, Physical Components, Material Properties
	SAFETY	Structural Concept, Structural Detailing, Construction Procedures, Material Properties

* The bold and italic subissues shown represent the subissues first occurrence in the table. These eight unique subissues are further decomposed into characteristics later in this section. Appendix C provides a listing of the subissues and their characteristics which are further broken down into sets of evaluation metrics.

typical floor plan, elevation profile and floor spacing. Connection designs include the sizes and material properties of the components and fasteners.

Structural detailing focuses on the joints in the building. Joints can be defined as the coming together of two or more components [Becker 88a]. In buildings, joints can be classified into two groups: connections (as described above) and other details. The moment-curvature relations are also important in determining the connection's rigidity. Other details include openings in members and stiffener details.

The **design methods** include the codes and assumptions used. Typical codes include ASD (Allowable Stress Design), LRFD (Load and Resistance Factor Design) and Plastic Design. Some of the design assumptions are related to selecting the critical loading combinations, predicting the actual frame and connection behavior from a computer model, and determining the effective building stiffness of the structure.

The **construction procedures** consist of the schedule and field operations necessary to complete the building by a specified deadline. The construction schedule includes, for example, the fabrication and erection plans. The field operations include the fastening methods and falsework.

The **fabrication procedures** consist of the shop operations necessary to deliver completed components on time to the construction site. Possible shop operations include cutting, drilling, punching, welding, shop assembly and jig set-up.

The **shipping operations** assume on-time delivery of material from the steel mill to fabrication shop and from the fabricator to the construction site. The methods of delivery, i.e., truck or train, handling procedures, and the obtainment of necessary safety permits to ship oversized components must also be dealt with at this subissue.

The **physical components** are the actual members which make up the building. Structural members include columns, beams, braces, shear walls and cores. Other structural members include the connection components and fastening operations. Structural function along with member properties, such as, geometric dimensions, tolerances, and material properties, should also be considered for each component.

The **material properties** include strength and serviceability related characteristics. The possible strength related characteristics are the yield and ultimate tensile and compressive strength. Characteristics which may be related to serviceability include the weldability, corrosion properties, toughness, ductility, hardness, resilience, and deviations associated with imperfect materials, e.g., mill tolerances.

4.2.2 Formulating the Agent Models

Tables 4.2 to 4.4 list the issues, subissues and characteristics formulated for each agent (designer, fabricator and erector). In Table 4.2, for example, the design issue of Strength has four subissues: Structural Concept, Structural Detailing, Physical Components and Material Properties. The characteristics identified for the subissue, Structural Concept, are Building Topology and Connection Designs.

The formulation of the agent models involved the identification of various levels of information. First, the agents and their unique sets of issues (or concepts) were identified. Once identified, the issues were rated by industry experts. The rating process, of course, is highly dependent on experience, and therefore, is subjective. The next level in formulating the agents' models dealt with subissues. For the DFI system to perform in a cooperative manner, there must be interaction among the subissues. The final level of decomposition used to formulated the models dealt with the characteristics (or properties) which are associated with a more detailed breakdown of the subissues. These characteristics are used to relate the agents' viewpoints (refer to Section 4.3).

Figures 4.3 to 4.5 graphically represent the information listed in Tables 4.2 to 4.4. In these figures, the issues are associated directly with the agents. The subissues are then associated with their respective issues. Many interactions take place between the issue and subissue levels of information. This is caused by the complexity of the design and construction process. An effective design not only considers the functional aspects of a structure, but also the labor, time and resources required for fabrication, construction and operation. Incorporating these varied aspects into a single design is a difficult process and requires the consideration of many issues as represented by the intersecting lines in Figures 4.3 to 4.5.

Next, the characteristics are associated with the subissues. The final level of information shown in these figures are possible sets of metrics that could be used to quantitatively evaluate the characteristics of a connection.

The systematic decomposition of the agent viewpoints into shared characteristics

Table 4.2: Design Issues, Subissues and Characteristics

ISSUE	SUBISSUE	CHARACTERISTICS
STRENGTH	Structural Concept	Building Topology Connection Designs
	Structural Detailing	Connection Designs Other Details
	Physical Components	Structural Members Connection Designs
	Material Properties	Strength Related Serviceability Related
STIFFNESS	Structural Concept	Building Topology Connection Designs
	Structural Detailing	Connection Designs Other Details
	Physical Components	Structural Members Connection Designs
	Material Properties	Strength Related Serviceability Related
LIFECYCLE COST	Structural Concept	Building Topology Connection Designs
	Design Methods	Design Codes Analysis & Assumptions
	Construction Procedures	Construction Schedule Field Operations
	Material Properties	Strength Related Serviceability Related
RELIABILITY	Design Methods	Design Codes Analysis & Assumptions
	Construction Procedures	Construction Schedule Field Operations
	Material Properties	Strength Related Serviceability Related
VERSATILITY	Structural Concept	Building Topology Connection Designs
	Construction Procedures	Construction Schedule Field Operations
	Physical Components	Structural Members Connection Designs
	Material Properties	Strength Related Serviceability Related

Table 4.3: Fabrication Issues, Subissues and Characteristics

ISSUE	SUBISSUE	CHARACTERISTICS
FABRICATION COST	Structural Detailing	Connection Designs Other Details
	Fabrication Procedures	Construction Schedule Shop Operations
	Physical Components	Structural Members Connection Designs
	Material Properties	Strength Related Serviceability Related
FABRICATION EASE	Structural Detailing	Connection Designs Other Details
	Fabrication Procedures	Construction Schedule Shop Operations
	Shipping Operations	Shipping Schedule Shipping Methods
	Physical Components	Strength Related Serviceability Related
MATERIAL COST	Shipping Operations	Shipping Schedule Shipping Methods
	Physical Components	Structural Members Connection Designs
	Material Properties	Strength Related Serviceability Related

Table 4.4: Erection Issues, Subissues and Characteristics

ISSUE	SUBISSUE	CHARACTERISTICS
ERECTION COST	Structural Detailing	Connection Designs Other Details
	Construction Procedures	Construction Schedule Field Operations
	Physical Components	Structural Members Connection Designs
	Material Properties	Strength Related Serviceability Related
ERECTION EASE	Structural Detailing	Connection Designs Other Details
	Construction Procedures	Construction Schedule Field Operations
	Physical Components	Strength Related Serviceability Related
	Material Properties	Strength Related Serviceability Related
SAFETY	Structural Concept	Building Topology Connection Designs
	Structural Detailing	Connection Designs Other Details
	Construction Procedures	Construction Schedule Field Operations
	Material Properties	Strength Related Serviceability Related

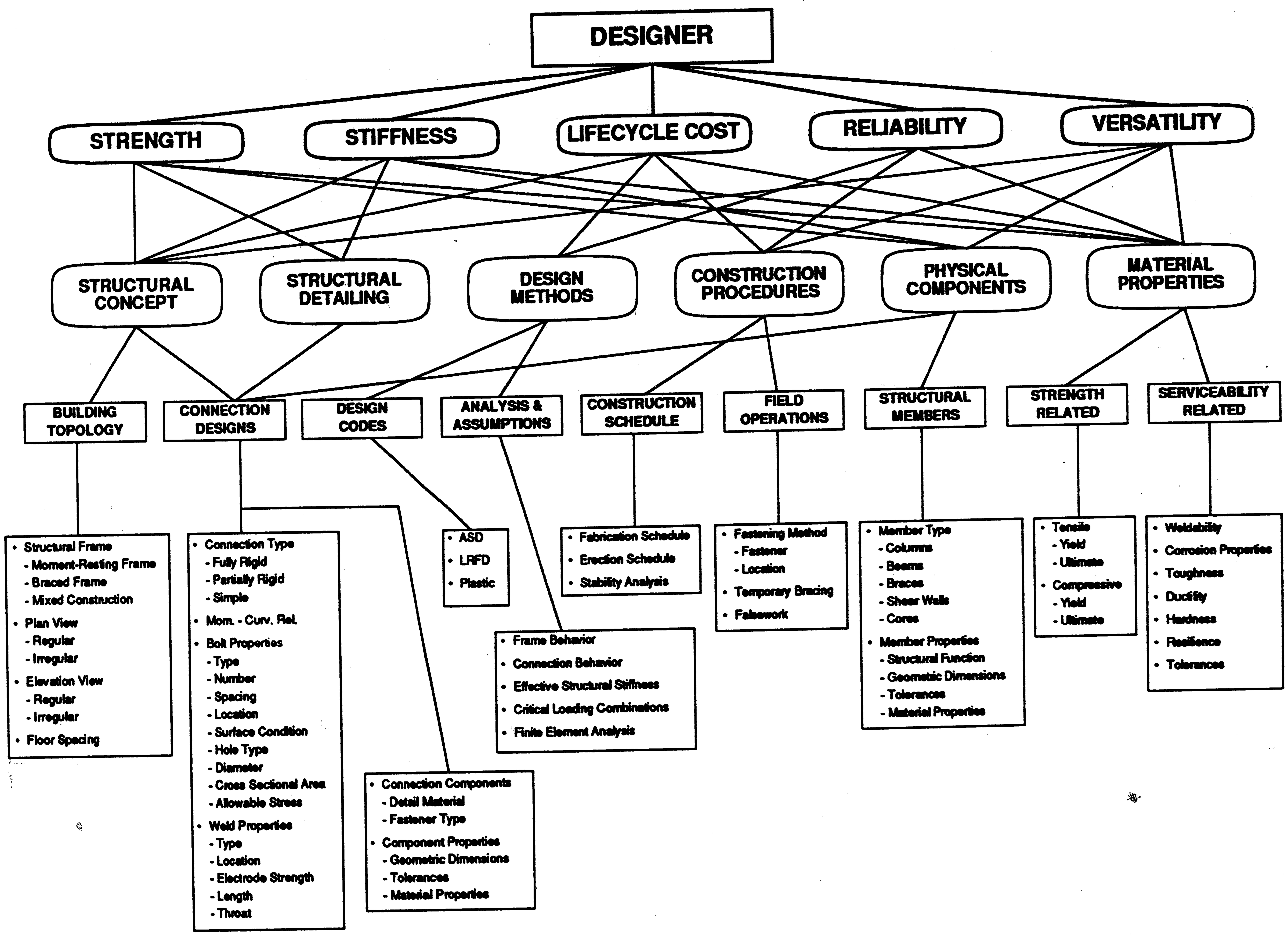


Figure 4.3: Detailed Designer Information Model

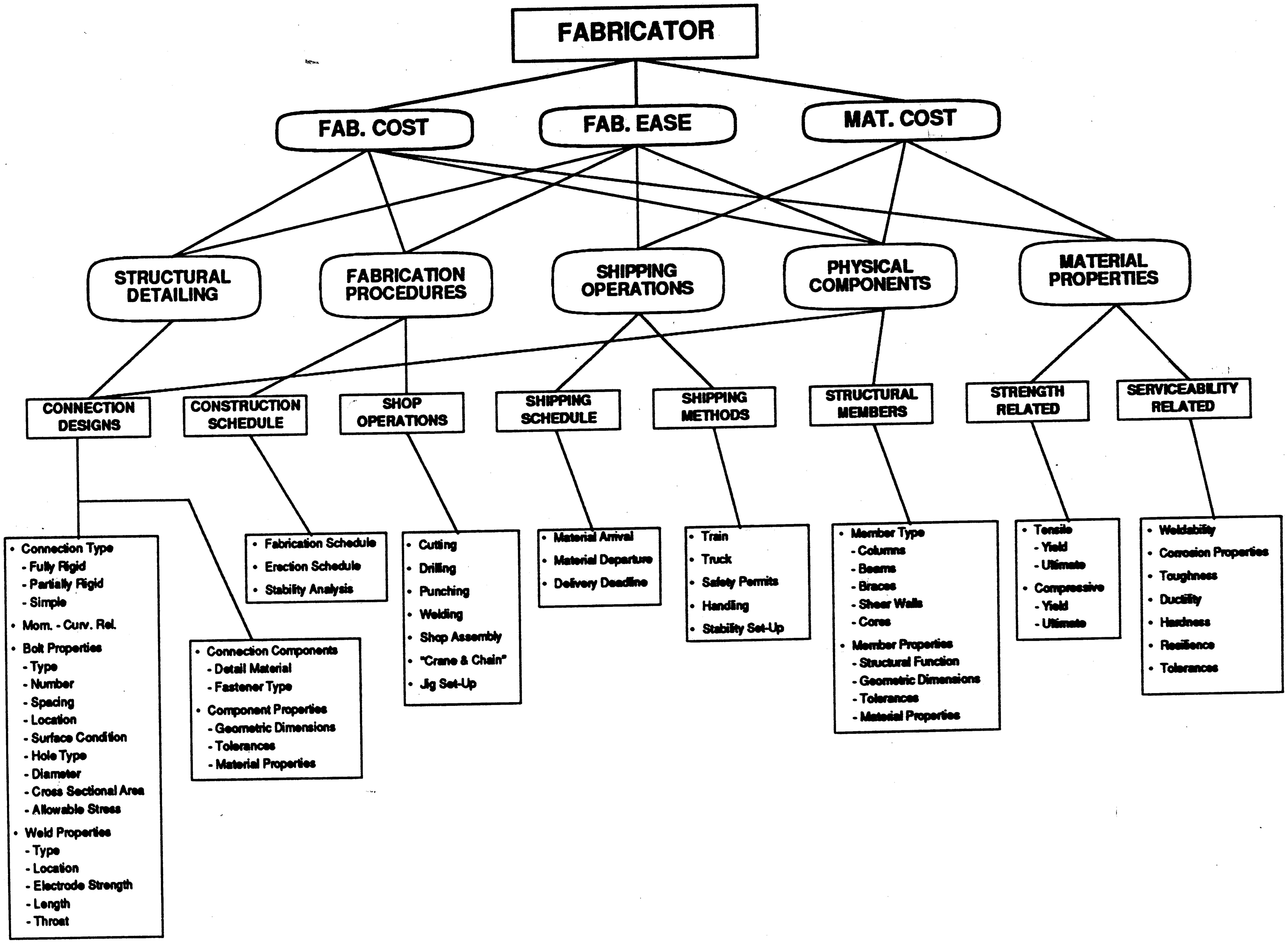


Figure 4.4: Detailed Fabricator Information Model

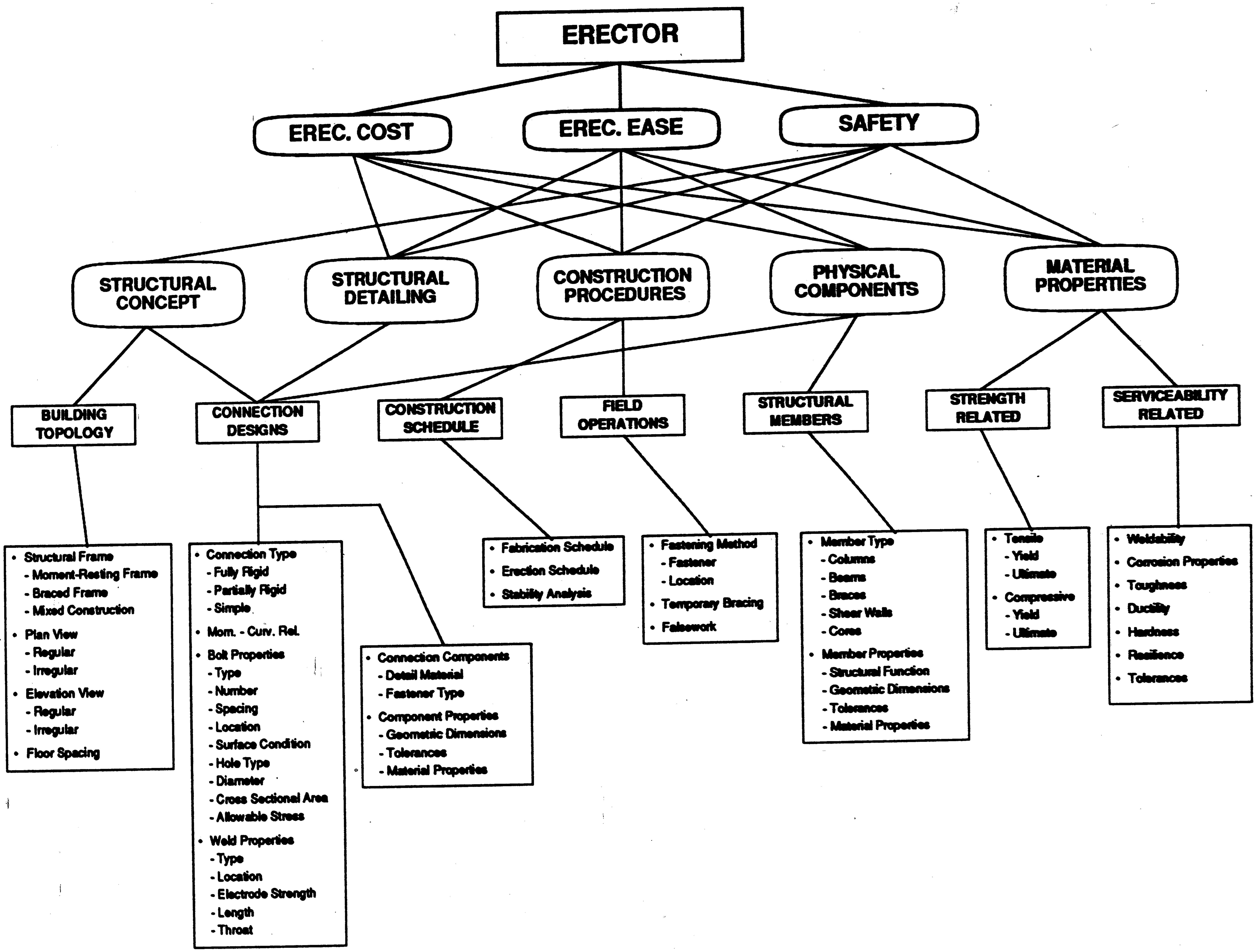


Figure 4.5: Detailed Erector Information Model

of information related to a building provides the level of detail necessary to relate the different agents. Establishing a globally understood level of information eliminates the need to develop complicated transformations between the agents because each agent is capable of using the shared building characteristics in their own respective domains while communicating their important issues, subissues and characteristics to the other agents. A method of relating the agents, issues, subissues and characteristics is described in the next section.

4.3 Relating the Agent Information Models

The agent information models described previously have been treated as separate entities. This section discusses an approach to relate the design, fabrication and erection viewpoints to evaluate a structure. An extended version of the DFI Relational Network based on the agent information models previously discussed and a set of conceptual relations developed in [Sowa 84] is presented. The ideas summarized in this section describe some of the author's domain research activities. The author extended the implemented scheme, discussed in the Section 4.1, to investigate, in detail, the interactions and relationships that exist between agents in the design and construction process. This type of detailed investigation is difficult to implement into the working DFI system because of the team nature of the research. Attempting to implement a highly detailed scheme would have required the computer science researchers to have an in-depth understanding of civil engineering. Therefore, the less detailed and more easily understood implementation model of Section 4.1.1 was developed by the author.

This section contains a description of a more detailed, extended relational network. Next, the relationships that exist within a each unique agent (intra-agent) are formulated and discussed for the extended scheme. Finally, an approach is presented to relate the agents (inter-agent relationships) through the use of shared information.

4.3.1 Description of the Network - Extended

Figure 4.6 shows a schematic of the extended relational network. In this network, the connection is made up of the functional and physical aspects. The aspects can be

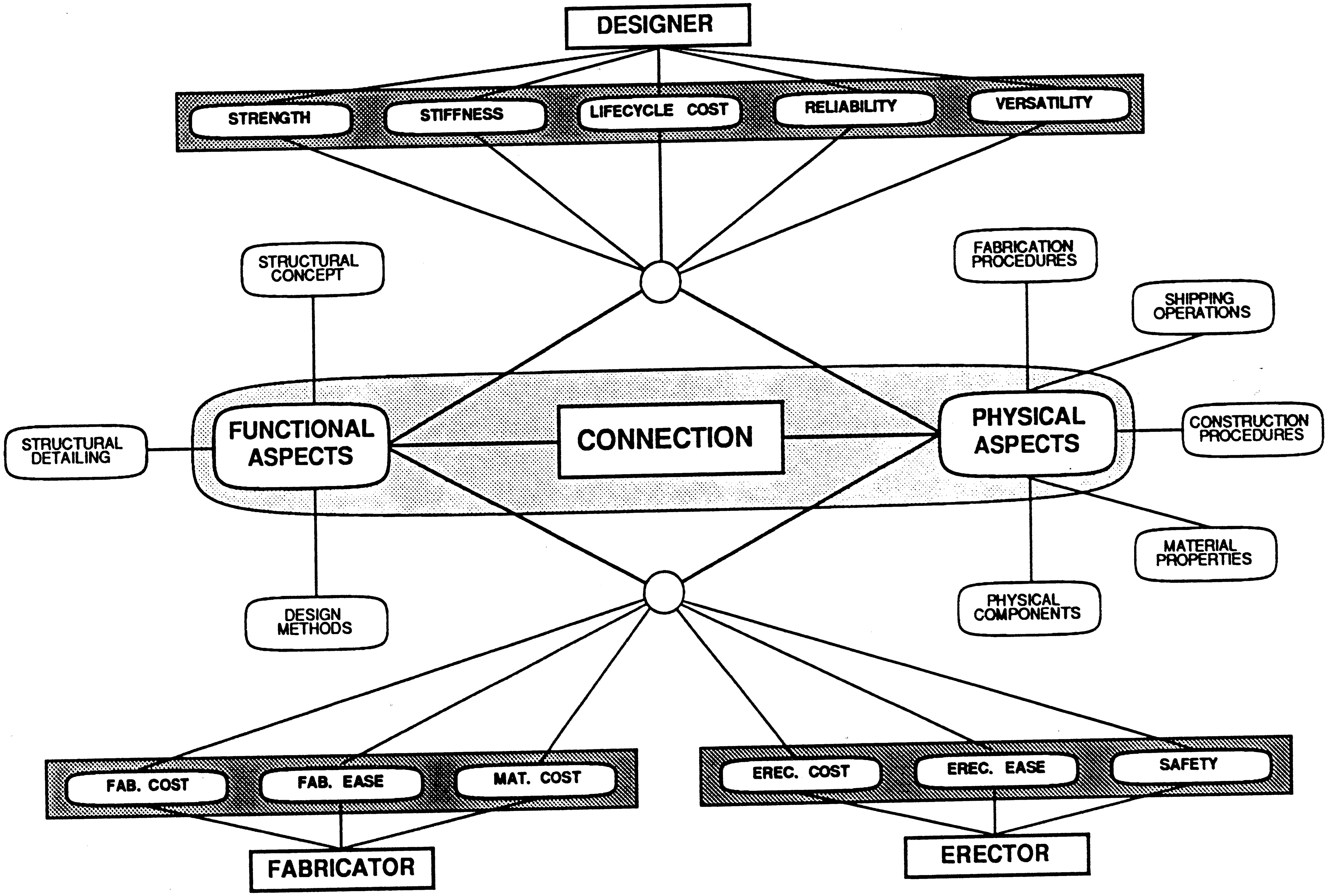


Figure 4.6: Extended DFI Relational Network

considered as databases of relationships that exist between the issues, which are located adjacent to each agent in grey boxes, and the subissues, which surround the aspects. For example, the Functional Aspects of the connection are: Structural Concept, Structural Detailing and Design Methods. To avoid unnecessary confusion the relational network does not show any level of detail beyond the subissues.

The formulation of the network involved using the agent information models to establish the relationships that exist within an agent and between the agents. Once, these relationships were established they were given names using concepts discussed in [Sowa 84].

4.3.2 Relationship Types

After formulating the network, a set of relationship types were developed to describe the various associations. The following relationship types were identified using [Sowa 84] as a guide:

- `needs_to_know`
- `influenced_by`
- `attribute`
- `destination`
- `duration`
- `instrument`
- `measure`
- `method`
- `part`

Each relationship type is defined below with a description of the levels it associates in the network. The relationship types are described below.

- **`needs_to_know`**: This is a global relationship type linking the agents to the issues, e.g., designer `needs_to_know` about the strength characteristics of the structure. This relationship defines the qualities of the structure which the agent is interested in.
- **`influenced_by`**: Another global relationship type linking the issues to the subissues, e.g., strength is `influenced_by` the structural concept. This relationship defines the features of the structure which effect the issues.

- **attribute***: Links two entities where one is an attribute of the other, e.g., an `attribute` of the structural concept is the building topology.
- **destination**: Links an action to an entity towards which the action is directed, e.g., the `destination` of the shipping operations is contained in the shipping schedule.
- **duration**: Links an operation to a time-period during which the operation takes place, e.g., the `duration` of the construction procedures is determined by the construction schedule.
- **instrument**: Links an entity to a tool used to perform the operation, e.g., an `instrument` for the design methods is a design code.
- **measure**: Links an entity to a physical property or dimension of that entity, e.g., a `measure` of the material properties is a strength criterion.
- **method**: Links an operation to a way of performing the operation, e.g., a `method` used to complete the construction procedures is a field operation.
- **part**: Links two entities where one is a component of the other, e.g., a `part` of the physical components are the structural members.

A summary of these relationships is presented in Table 4.5.

4.3.3 Intra-Agent Relationships

Using the relationship types defined in the previous section, links were established to show a complete set of paths through the agent information models as shown in Figures 4.3-4.5. Tables 4.6-4.8 summarize the relationships established for each agent. Table 4.6, for example, presents the intra-agent relationships for a designer. Following a path along the first row in that table, one can see that the designer has a `needs_to_know` relation to the issue of strength. Next, an `influenced_by` relation links the strength issue to the structural concept subissue. The association that ties the structural concept subissue to the building topology characteristic is an `attribute` relation.

The intra-agent relationships determine how the agents view the information associated with their respective issues. These relationships are not ranked or prioritized -

* The remainder of the relationships are local and link the subissues to the primary metrics. These relationships names are taken from [Sowa 84] with modifications to their definitions to make them more appropriate to the domain of Civil Engineering.

Table 4.5: Summary of Relationship Types

RELATIONSHIP	TYPE	DEFINITION
`needs_to_know`	Global	Defines the characteristics (issues) of the structure which the agent is interested in.
`influenced_by`	Global	Defines the attributes (subissues) of the structure which effect the issue.
`attribute`	Local	Links two entities where one is an attribute of the other.
`destination`	Local	Links an action to an entity, towards which the action is directed.
`duration`	Local	Links an operation to a time-period, during which the operation takes place.
`instrument`	Local	Links an entity to a tool used to perform the operation.
`measure`	Local	Links an entity to a physical property or dimension of that entity.
`method`	Local	Links an operation to a way of performing the operation.
`part`	Local	Links two entities where one a a component of the other.

they are simply grouped by the characteristics as shown in the right most column of each table. The example relational path described above: Designer - `needs_to_know` - Strength - `influenced_by` - Structural Concept - `attribute` - Building Topology, can be seen by following the lines furthest to the left in the design agents detailed information model as shown previously in Figure 4.3. The reason for grouping the relationships according to the characteristics was to facilitate the formulation of the inter-agent relationships which are discussed next.

Table 4.6: Intra-Agent Relationships - Designer

AGENT	RELATION	ISSUE	RELATION	SUBISSUE	RELATION	CHARACTERISTIC
Designer	needs to know	Strength	influenced by	Structural Concept	Attribute	Building Topology
		Stiffness		Structural Concept	Attribute	Building Topology
		Lifecycle Cost		Structural Concept	Attribute	Building Topology
		Versatility		Structural Concept	Attribute	Building Topology
		Strength		Structural Concept	Attribute	Connection Designs
		Stiffness		Structural Concept	Attribute	Connection Designs
		Lifecycle Cost		Structural Concept	Attribute	Connection Designs
		Versatility		Structural Concept	Attribute	Connection Designs
		Strength		Structural Detailing	Method	Connection Designs
		Stiffness		Structural Detailing	Method	Connection Designs
		Strength		Physical Components	Part	Connection Designs
		Stiffness		Physical Components	Part	Connection Designs
		Versatility		Physical Components	Part	Connection Designs
		Lifecycle Cost		Design Methods	Instrument	Design Codes
		Reliability		Design Methods	Instrument	Design Codes
		Lifecycle Cost		Design Methods	Method	Analysis & Assumptions
		Reliability		Design Methods	Method	Analysis & Assumptions
		Lifecycle Cost		Construction Procedures	Duration	Construction Schedule
		Reliability		Construction Procedures	Duration	Construction Schedule
		Versatility		Construction Procedures	Duration	Construction Schedule
		Lifecycle Cost		Construction Procedures	Method	Field Operations
		Reliability		Construction Procedures	Method	Field Operations
		Versatility		Construction Procedures	Method	Field Operations
		Strength		Physical Components	Part	Structural Members
		Stiffness		Physical Components	Part	Structural Members
		Versatility		Physical Components	Part	Structural Members
		Strength		Material Properties	Measure	Strength Related
		Stiffness		Material Properties	Measure	Strength Related
		Lifecycle Cost		Material Properties	Measure	Strength Related
		Reliability		Material Properties	Measure	Strength Related
		Versatility		Material Properties	Measure	Strength Related
		Strength		Material Properties	Measure	Serviceability Related
		Stiffness		Material Properties	Measure	Serviceability Related
		Lifecycle Cost		Material Properties	Measure	Serviceability Related
		Reliability		Material Properties	Measure	Serviceability Related
Designer		Versatility		Material Properties	Measure	Serviceability Related

Table 4.7: Intra-Agent Relationships - Fabricator

AGENT	RELATION	ISSUE	RELATION	SUBISSUE	RELATION	CHARACTERISTIC
Fabricator	↔ needs to know ↔	Fabrication Cost	↔ influenced by ↔	Structural Detailing	Method	Connection Designs
↕		Fabrication Ease		Structural Detailing	Method	Connection Designs
		Fabrication Cost		Physical Components	Part	Connection Designs
		Material Cost		Physical Components	Part	Connection Designs
		Fabrication Cost		Fabrication Procedures	Duration	Construction Schedule
		Fabrication Ease		Fabrication Procedures	Duration	Construction Schedule
		Fabrication Cost		Fabrication Procedures	Method	Shop Operations
		Fabrication Ease		Fabrication Procedures	Method	Shop Operations
		Fabrication Ease		Shipping Operations	Destination	Shipping Schedule
		Material Cost		Shipping Operations	Destination	Shipping Schedule
		Fabrication Ease		Shipping Operations	Method	Shipping Method
		Material Cost		Shipping Operations	Method	Shipping Method
		Fabrication Cost		Physical Components	Part	Structural Members
		Fabrication Ease		Physical Components	Part	Structural Members
		Material Cost		Physical Components	Part	Structural Members
		Fabrication Cost		Material Properties	Measure	Strength Related
		Material Cost		Material Properties	Measure	Strength Related
		Fabrication Cost		Material Properties	Measure	Serviceability Related
Fabricator		Material Cost		Material Properties	Measure	Serviceability Related

Table 4.8: Intra-Agent Relationships - Erector

AGENT	RELATION	ISSUE	RELATION	SUBISSUE	RELATION	CHARACTERISTIC
Erector	needs to know	Safety	influenced by	Structural Concept	Attribute	Building Topology
		Safety		Structural Concept	Attribute	Connection Designs
		Erection Cost		Structural Detailing	Method	Connection Designs
		Erection Ease		Structural Detailing	Method	Connection Designs
		Safety		Structural Detailing	Method	Connection Designs
		Erection Cost		Physical Components	Part	Connection Designs
		Erection Ease		Physical Components	Part	Connection Designs
		Erection Cost		Construction Procedures	Duration	Construction Schedule
		Erection Ease		Construction Procedures	Duration	Construction Schedule
		Safety		Construction Procedures	Duration	Construction Schedule
		Erection Cost		Construction Procedures	Method	Field Operations
		Erection Ease		Construction Procedures	Method	Field Operations
		Safety		Construction Procedures	Method	Field Operations
		Erection Cost		Physical Components	Part	Structural Members
		Erection Ease		Physical Components	Part	Structural Members
		Erection Cost		Material Properties	Measure	Strength Related
		Erection Ease		Material Properties	Measure	Strength Related
		Safety		Material Properties	Measure	Strength Related
		Erection Cost		Material Properties	Measure	Serviceability Related
		Erection Ease		Material Properties	Measure	Serviceability Related
Erector		Safety		Material Properties	Measure	Serviceability Related

4.3.4 Inter-Agent Relationships

The relationships between the agents are formulated by connecting the intra-agent relationships via the shared characteristics. An example inter-agent relational path can be seen in Figure 4.7 where the characteristic, connection designs, is linked both to structural concept and to structural detailing subissues. The subissues are then linked to the issues: strength and fabrication cost respectively. The relational path terminates with the issues being tied to the agents: designer and fabricator.

Figure 4.7 shows only one relational path between two agents. The number of relational paths that exist in DFI between the agents are: 53 between Designer and Fabricator, 103 between Designer and Erector, and 46 between Fabricator and Erector. The myriad of relationships that exist are due to the highly interactive and iterative process used in designing and detailing structures while considering constructability issues. This could reflect a combinatorial explosion of relationships when all stages of the design and construction process are modeled. When attempting to implement integrated systems, the possible combinatorial explosion of relationships could be controlled by assembling highly related agent issues, such as, strength and stiffness or fabrication cost and fabrication ease, into a single agent issue in which all the information is stored locally within the agent's model

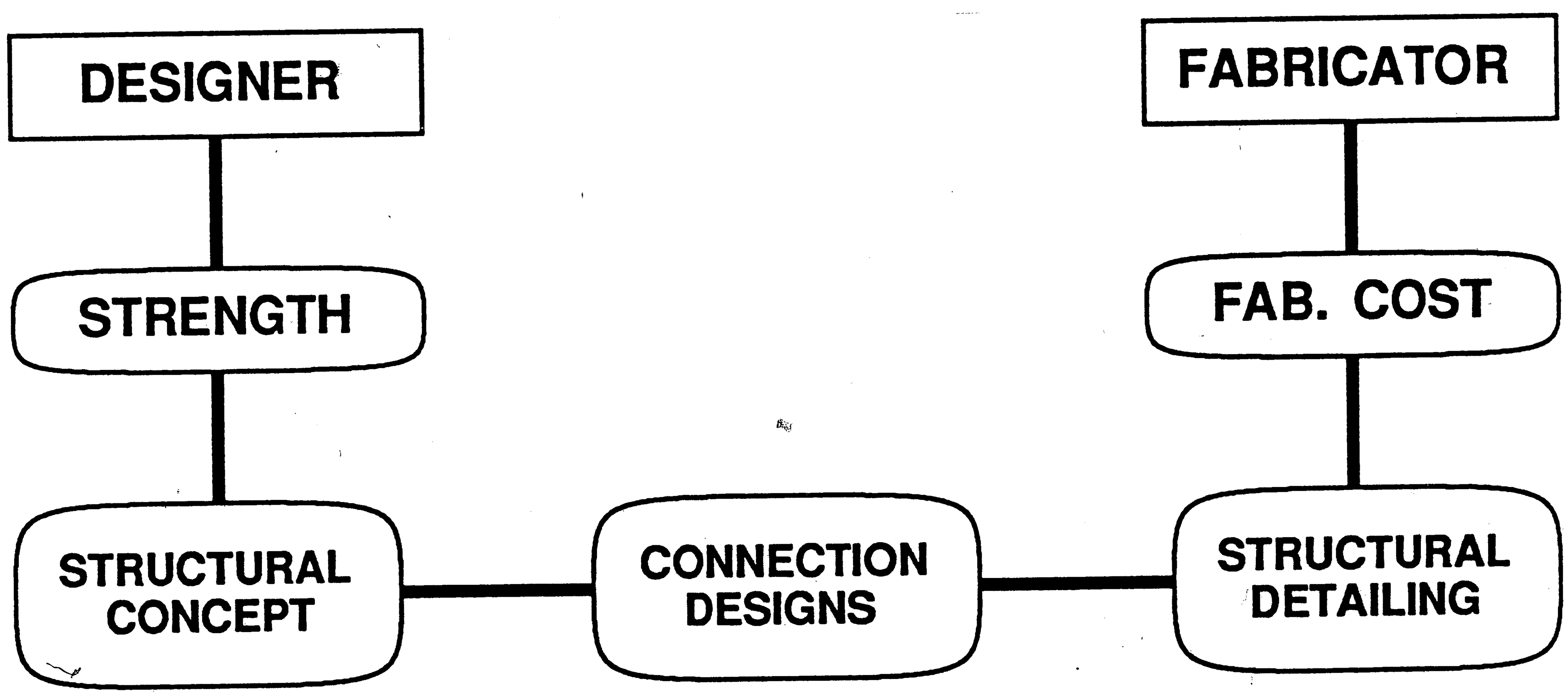


Figure 4.7: An Example Inter-Agent Relational Path

but is not shared with the other agents. The object-oriented paradigm is well suited for assembling information in this fashion.

The number of relationships that exist between agents does not show the "closeness" but simply describes the possible overlaps in information. By looking at the number of relational paths between agents, previously listed, one might assume the designer and erector are highly related since the most relational paths exist between these two agents. In reality, however, this is not the case.

Looking at a common characteristic, field operations, the designer's view focuses on the reliability of the connection while the erector is mainly concerned with the cost associated with performing the field operations. For example, a field welded structure may be viewed as unreliable by designer because site conditions make it difficult to weld, and possibly more important, difficult to inspect. The erector has the same site difficulties, but he must deal with the assembly of the connection (which does not directly concern the designer).

This example demonstrates how designing for construction (or relating the designer and erector in this case) could be used to determine the preferences of each agent so that one understands the limitations and concerns of the other and becomes more willing to compromise, thus achieving a potentially better solution*.

4.4 Demonstration of the Relational Network

This section shows the potential usefulness of the relational network in solving and identifying potential problems during the design and construction process. First, a scenario is described to show how initial design decisions can have multiple fabrication and erection problems associated with them. Next, a demonstration of the network's application to this scenario is presented.

4.4.1 Illustrative Scenario

This illustrative scenario is taken from [Becker 89] and points out some potentially dangerous problems due to a designers lack of understanding of standard construction

* For the example, the designer and erector may want to consider using a bolted connection configuration.

procedures. The structure, a sixty story tower, was designed using the mixed construction concept where a steel frame is used to carry the gravity loads while a concrete core carries the lateral loads. Every effort was made by the designer to minimize the amount of steel in the structure, i.e., minimize the total initial cost. This was the cause of many problems.

One of the most severe design oversights was that the construction loads were not calculated at the preliminary design stage. These loads would have dictated the size of some critical components. For example, column shapes (AISC W members) were used for tensile reinforcement in the concrete core - these members were not designed to carry compression. Therefore, the members were not capable of supporting the derrick crane which was necessary to erect other members. A second problem with these members was that the column shapes were not deep enough to connect beams to their webs. As a result of these two problems, these members had to be doubled in size, i.e., doubling the material cost, to facilitate construction.

The coordination between the steel and concrete trades is also crucial because the tolerances differ greatly for each. In steel construction, dimensions must be held to 1/8" while concrete tolerances can vary by as much as 2". The construction schedule is critical to sequence the erection activities for each trade. In a mixed structural frame, stability is not achieved until the steel and concrete are connected. This can take up to seven days after the concrete is poured*. During this period, temporary bracing is used to carry wind loads.

Without going into more detail about the structure, each one of the above listed problems will be discussed in the next section with a summary of how the relational network could be used to identify and alleviate the problems.

4.4.2 Application of the Network

The first problem of not considering the construction loads during the preliminary design could be solved by first establishing an erection schedule which would include a description of the equipment and methods to be used during construction. The crane loads could then be used as a critical load case to analyze the adequacy of the preselected beams and columns. A check could also have been done on the column shapes to determine

* At seven days an ordinary concrete mix has roughly 70% of its ultimate strength. Additives can be mixed in to the concrete to speed up the curing process.

whether connections were possible. If these two checks were incorporated into the preliminary design, the amount of rework would have been significantly reduced.

The problem associated with the tolerances could be handled by relational paths each agent has to the structural members characteristic. This characteristic contains information about the tolerances associated with the components of the structure. If two connecting members do not have similar tolerances, this could be pointed-out and construction specifications could be generated to address this problem.

The information stored within the construction schedule characteristic could provide insight to the agents on problems associated with the stability of the frame. This characteristic could be tied to an external software module which performs a frame stability analysis with output being used to generate a safe erection schedule while minimizing the temporary bracing which can be quite expensive.

4.5 Modeling Towards CIC

As illustrative of a step towards CIC, this chapter has provided a scheme to relate different agent viewpoints. Detailed agent information models were formulated along with a set of relationship types to link the issues, subissues and characteristics making up each model. The shared information at the characteristics level in the agent information models was used to devise a method of establishing relationships between agents. The inter-agent relationships begin with a characteristic that is shared between two agents, the links to the subissues, issues and agent are then traced back to make a "relational path" between two agents. An example relational path was shown in Figure 4.7.

The application of the developed models was described by examining an illustrative scenario and presenting possible solutions to encountered problems. Since three different viewpoints were modeled, the proposed solutions consider many different kinds of issues. DFI, unlike other design oriented knowledge-based systems addresses construction related issues.

The models presented in this chapter are intended to be a step towards relating agent viewpoints. Many other tools such as general explanation systems, negotiation methods and more detailed evaluation schemes, are required to implement an integrated design and construction system. DFI is one of the first implemented systems to use multiple, independent viewpoints to evaluate and generate alternative connection configurations in a cooperative problem-solving environment

The next chapter presents a demonstration of the working DFI system. A summary of the implemented system is also given. A narrated test case of the evaluation process is presented and discussed.

5. Demonstration and Validation of DFI

This chapter presents a demonstration of the working DFI system. The chapter is organized as follows. First, a summary of the implemented system is presented. Next, a description of a representative test case is provided. This description includes a review of the system input, evaluation process and output. The chapter is concluded with a critical review and evaluation of the DFI system by industry participants.

5.1 Summary of Implemented System

A prototype environment has been developed for the selection of a preliminary connection configuration. This was accomplished by combining user input, design, fabrication and erection agent heuristics, and models of these agent viewpoints in a cooperative problem-solving environment.

The system takes a user specified datafile of building information which is composed of a tabular beam schedule, column schedule and framing plan, and checks the consistency of data in that file. Next, the user interactively enters a connection. During input, the system ensures that a standard connection is detailed by applying constraints based on general design, fabrication and erection knowledge represented in the connection information forms. The user then selects a key issue to start the agent evaluation. Each viewpoint (design, fabrication and erection) presents to the user implications or problems associated with the proposed connection and also suggests alternative connection configurations based on the agent viewpoint and user specified key issue. As the evaluation takes place, the user is provided with the specific agent's evaluation of the proposed connection, suitable alternative connections based on the agent's evaluation, and summary of each proposed connection. Upon completion of the evaluation, the user may enter a different key issue to provide a new rating and evaluation of the initial proposed connection. This interaction, between the user and the system, can take place until all the issues have been investigated or until the user is satisfied with a particular connection configuration.

5.2 Description of Test Case

This section presents a representative example of DFI's connection evaluation process. An endplate connection was selected as the starting point for this evaluation. This connection configuration was chosen because of its inherent erection problems. The test case demonstrates, in part, DFI's ability to recognize the erection problem and suggest "better" alternatives.

In this section, the input is briefly reviewed through the use of a screen capture that shows the state of DFI at the end of the input sequence. Next, the agent evaluation is described along with a series of screen captures to show the proposals made by the agents. Finally, the system output is reviewed and graphically presented.

5.2.1 Review of System Input

Figure 5.1 shows a screen capture of the completed connection input. The four windows in the figure are:

- Plan View
- Elevation View
- System Debug Window
- Designer/Fabricator Interpreter Tool.

The purpose of each window and the information contained in each one is briefly described below.

The **Plan View** window displays a floor plan that is generated by assembling information contained in the beam schedule, column schedule and framing plan*. For this example, the second floor of "Marc's Place" (a research prototype building) was selected.

The **Elevation View** window graphically depicts the connection specified by the user. In this case, beam (HB1), column (C1), and endplate connection using field bolting for the column fastener and shop welding for the beam fastener was selected.

The **System Debug Window** provides a trace of what actions are taking place in the system. The DFI developers use this window to flag errors during an evaluation. This

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* For simplicity only the beam-to-column connections are shown in the **Plan View** window. However, data exist for beam-to-girder connections in the beam schedule, column schedule and framing plan.

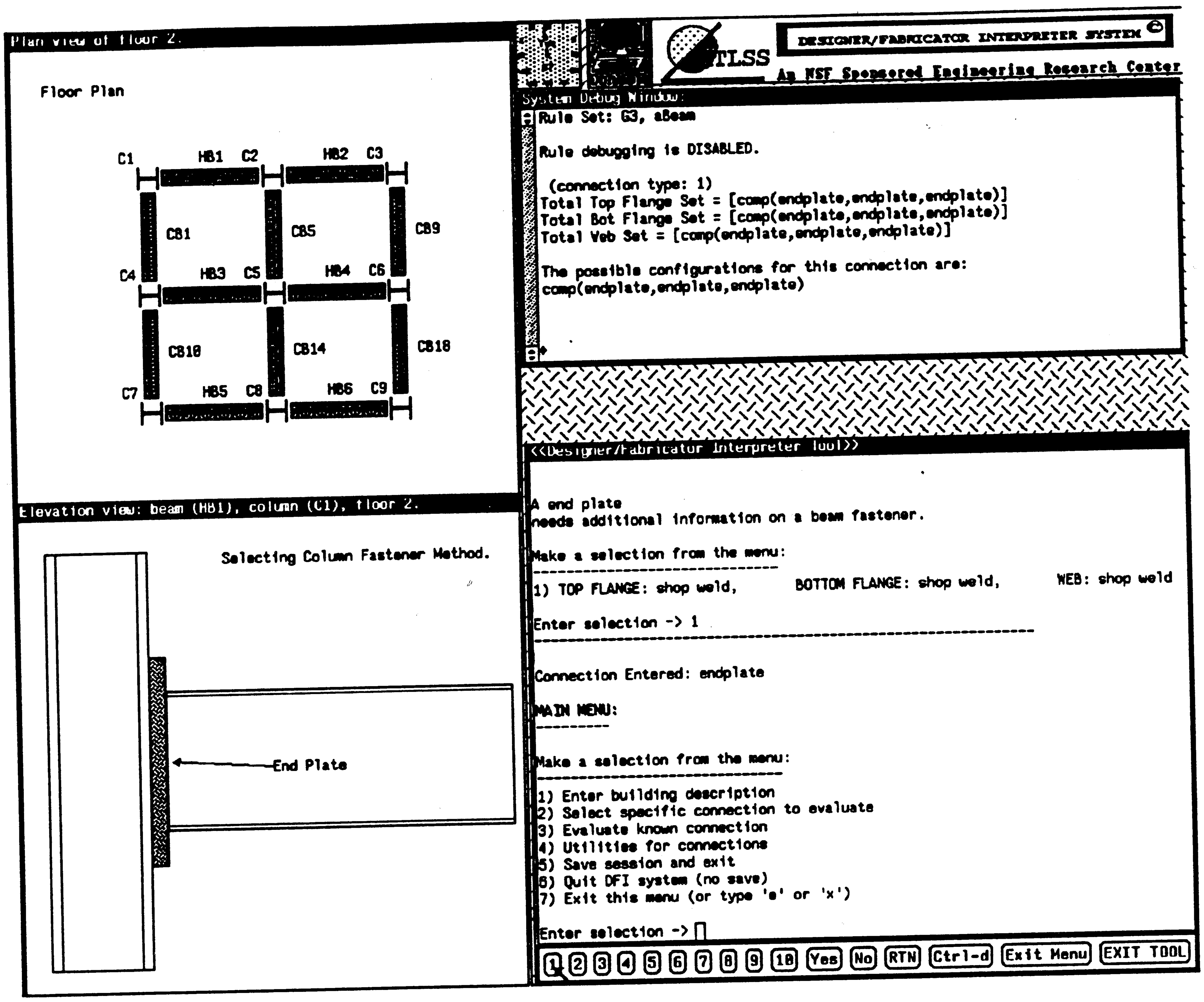

Figure 5.1: View of Completed Connection Input

window is typically not open during an interactive DFI session.

The **Designer/Fabricator Interpreter Tool (Input/Output)** window is where DFI's interaction with the user takes place. Input is requested from the user, and output is provided to the user through this window.

5.2.2 Review of Evaluation Process

After the user enters a connection and selects the evaluate option, the system performs a doubler plate and column stiffener check. The results are presented in the I/O window. The user is then asked for a single, most important, key issue which is maintained by all agents during their proposal of alternate connection configurations. In this example, the user specified an endplate connection with a key issue of strength as shown by the selection of button 1 at the bottom of Figure 5.2.

Each agent has unique knowledge about connections including a standardized qualitative rating scheme for the issues related to each connection. The higher the value, the more acceptable it is. The agents suggest alternative connections that are of the same connection type and have the same or higher value for strength as the user specified

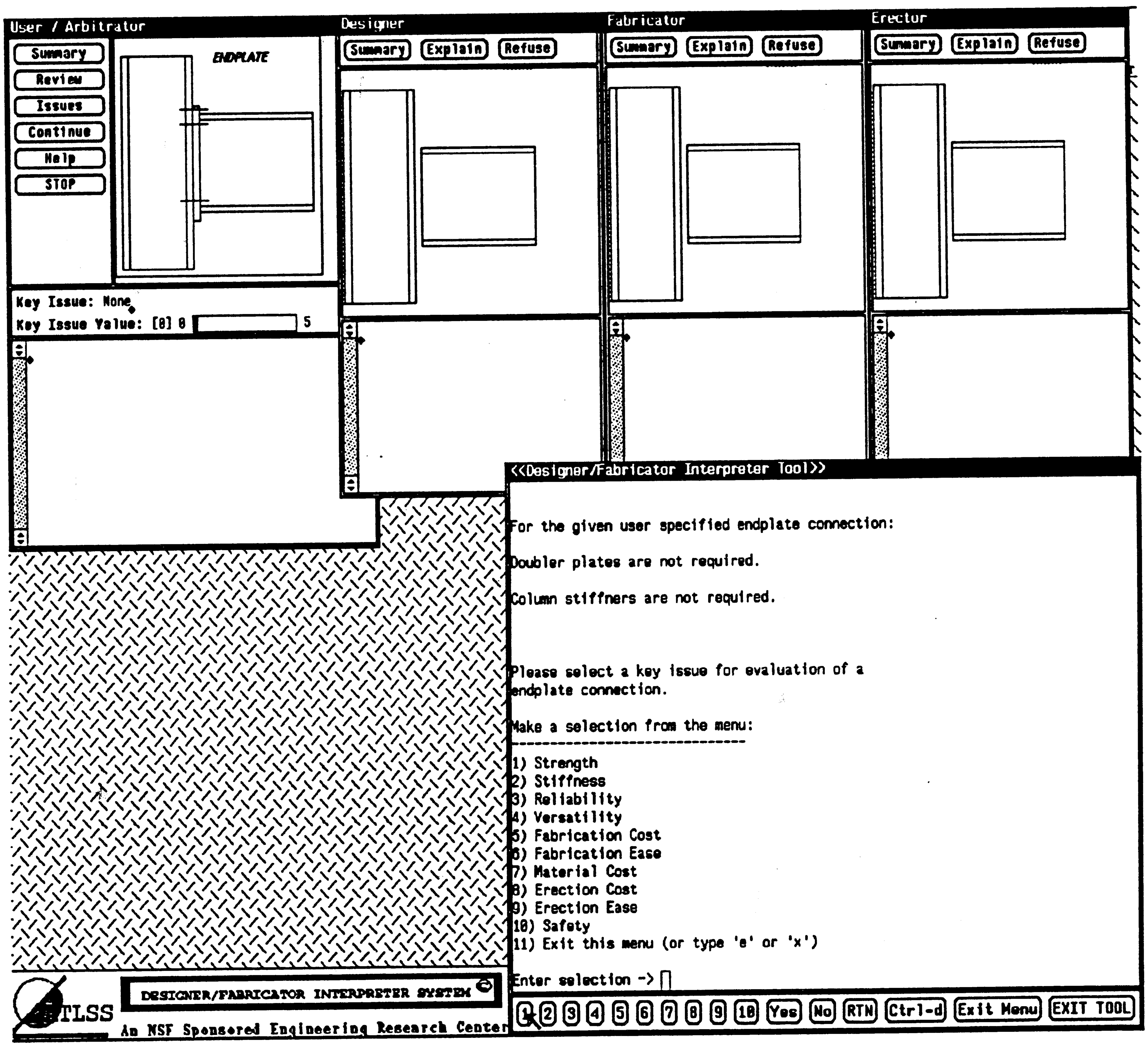

Figure 5.2: Start of Agent Evaluation and Key Issue Menu

endplate connection. Initially, the arbitrator **commands*** the design agent to **accept** the user's endplate connection using strength as the positive supporting issue in the first cycle of negotiation. The design agent then **informs** all agents of the key issue and requests that the proposed connection be evaluated. The designer's request is shown graphically in the designer's window in Figure 5.3.

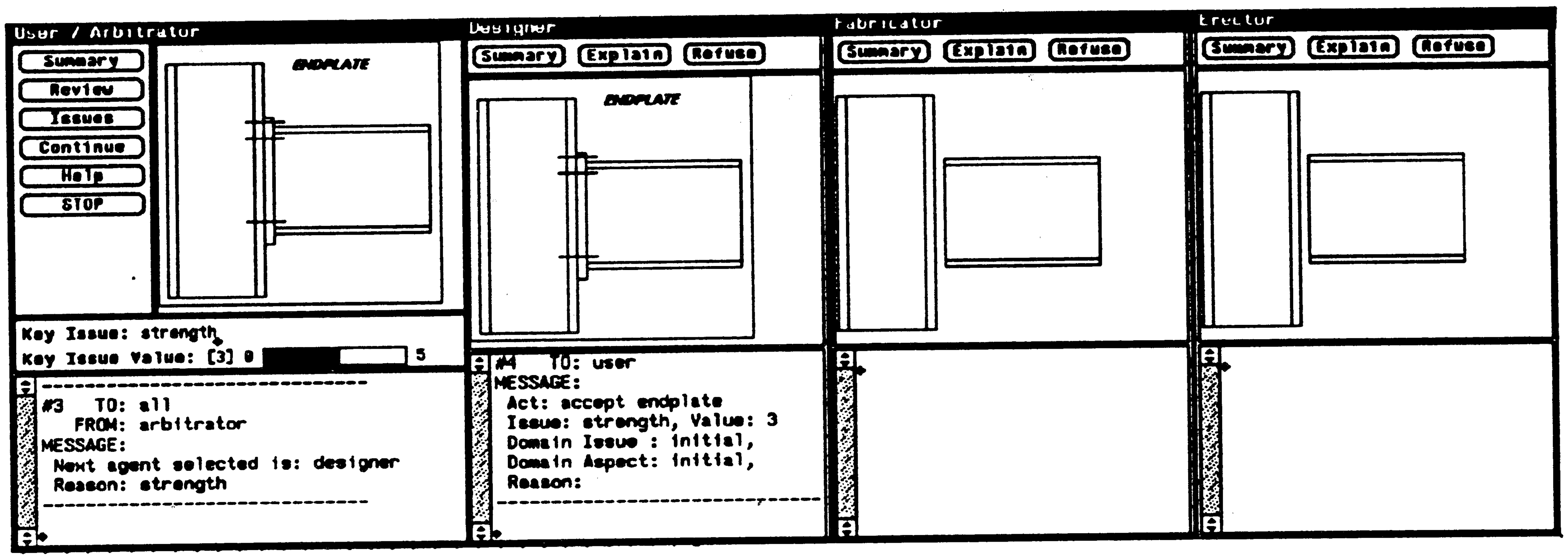

Figure 5.3: Designer Accepts the User's Connection

Before each agent's evaluation, the arbitrator reviews all proposed connections and selects the most detrimentally affected agent to go next. In this case, the erector is the worst affected by the designer's endplate proposal. The erector determines that the designer's proposal is unacceptable because the endplate connection has a low value for erection ease. Therefore, the erector **refuses** (objects to) the designer's connection and then checks the fabricator's connection (this is a default action of the system). The evaluating agent checks with both of the other agents to determine if their connections are acceptable to him. At this stage, the fabricator has no connection proposal, so the erector selects a connection configuration from the connection database. The erector **requests** the plates_tee (top and bottom plates with shear tee) because it satisfies the erection ease issue as well as the user specified key issue. This proposal is shown in the erector's window in Figure 5.4.

* The bold words represent implemented actions that the agents use during an evaluation [Werkman 90].

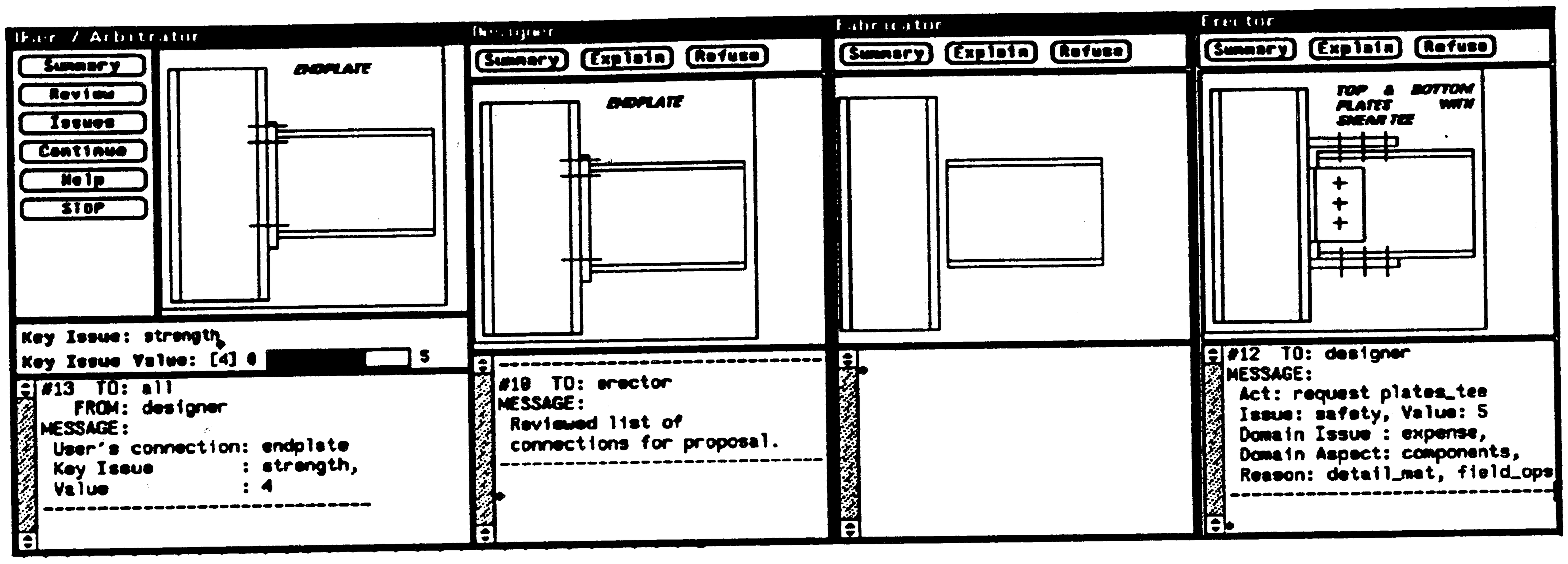

Figure 5.4: Erector Proposes plates_tee Connection

It is important to note that the erector has directed the proposed connection back to the designer for review. The designer **accepts** the erector's proposal because it exceeds the key issue of strength. Also, the value of the key issue has been increased to 4. The value associated with the erector's proposed plates_tee connection is higher than the original value of 3 for the designer's strength key issue on the endplate connection. By increasing the value of the key issue, the search space of possible connection alternatives is reduced, thus causing the agents to converge more quickly on a set of acceptable connections. The designer's acceptance is seen graphically in the designer's window in Figure 5.5.

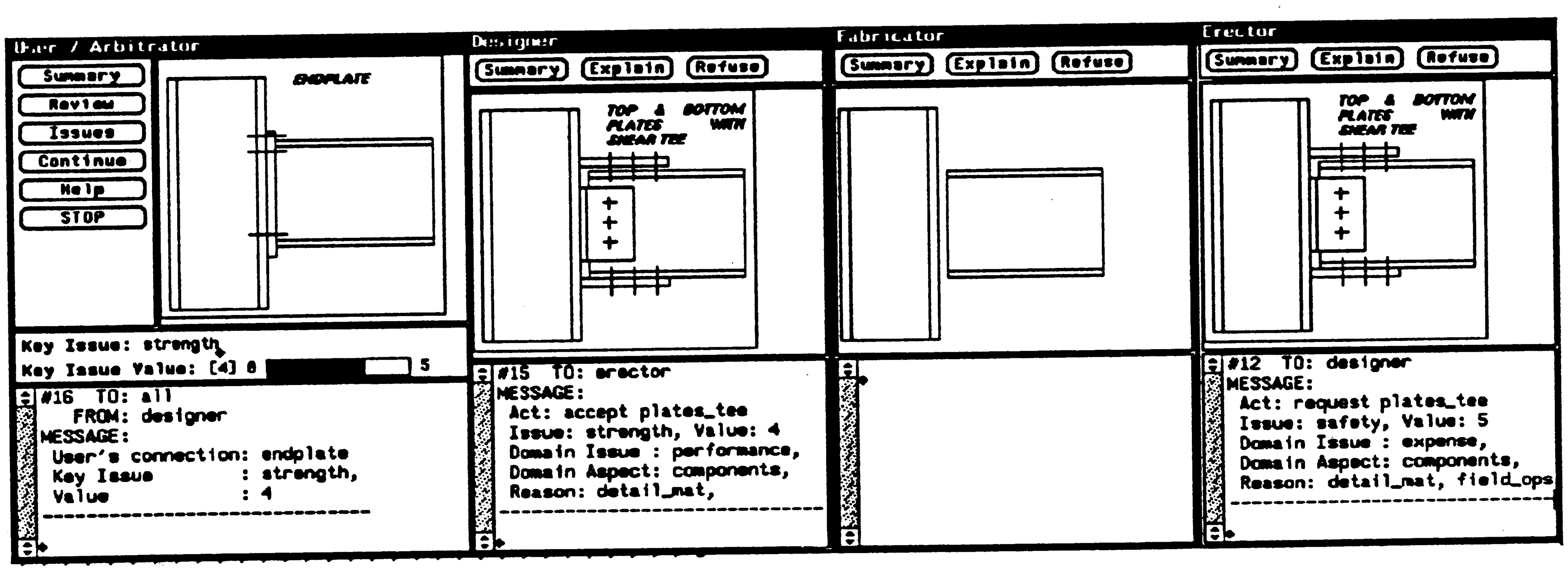

Figure 5.5: Designer Accepts Erector's Proposal

Next, the arbitrator reviews the agent proposals and notices that two agents have proposed the same connection. Usually, this would cause the arbitrator to **inform** all agents of a halting (agreement) condition. This is not the case here because an "unfair" evaluation has occurred - unfair in the sense that the fabricator has not yet had a chance to contribute to the evaluation. Thus, the arbitrator gives control to the fabricator who looks at the designer's connection and immediately notices that material cost is the problem issue. Since both the designer's and erector's connection are the same, the fabricator needs only to review the plates_tee connection and propose an alternative. In this case, the best connection, from the fabricator's viewpoint, that maintains the key issue value of strength as well as improving the fabricator's material cost issue is the flange_weld_plate (direct flange weld with shear plate) connection as seen in the fabricator's window in Figure 5.6.

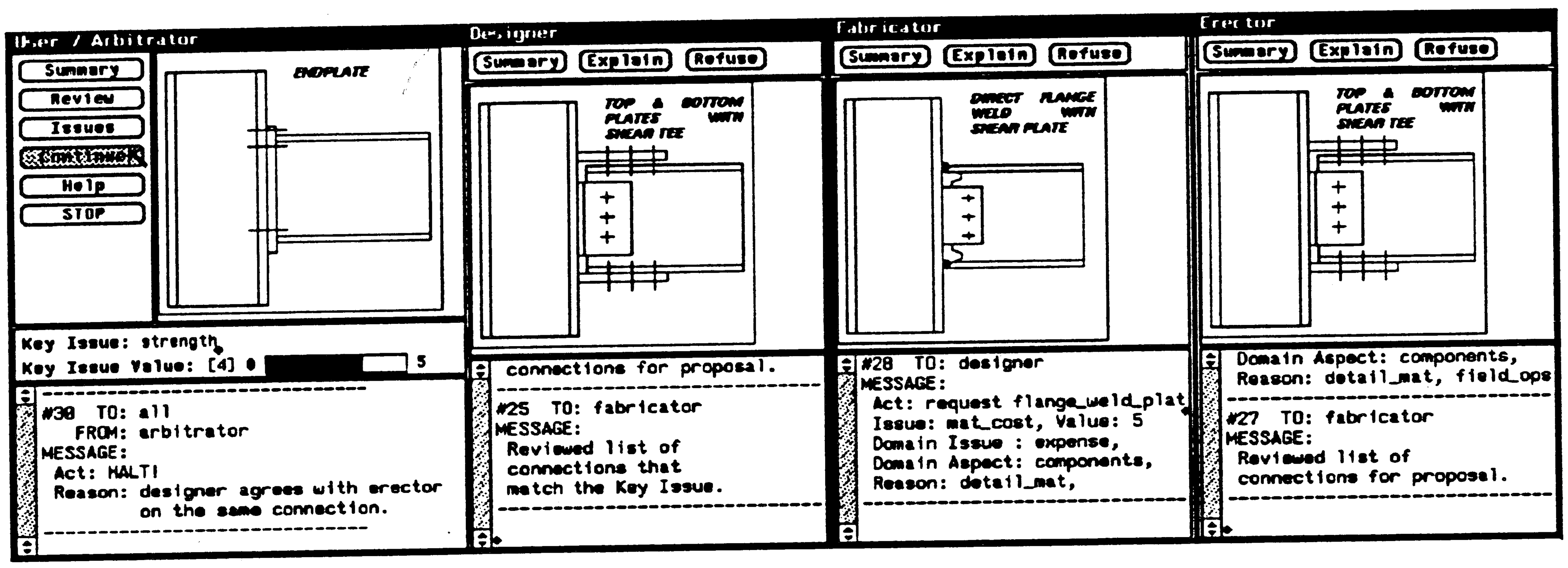

Figure 5.6: Fabricator Proposes flange_weld_plate Connection

Again, the arbitrator reviews the evaluation process and notices that two agents have agreed on a connection, and that each agent has had a chance at proposing an alternative*. There is also the possibility that an agent may not be able to suggest an alternative. The arbitrator **informs** the agents of a halting condition and control is returned to the user. At this point the user can ask any agent to **explain** its proposed connection or

* This is called an unsatisfied condition. The arbitrator is consulted to assist the agents in arriving at a satisfactory solution.

continue with the evaluation. If the user **continues**, the arbitrator reviews the situation and notices that no particular agent is in "peril." Therefore, whichever agent received the last message is given a chance to respond to it. In this case, the fabricator proposed a connection to the designer. The design agent, upon reviewing this connection, notices that the fabricator's connection is also acceptable. Thus, the designer **accepts** the fabricator's proposed flange_weld_plate connection as seen in the designer's window in Figure 5.7.

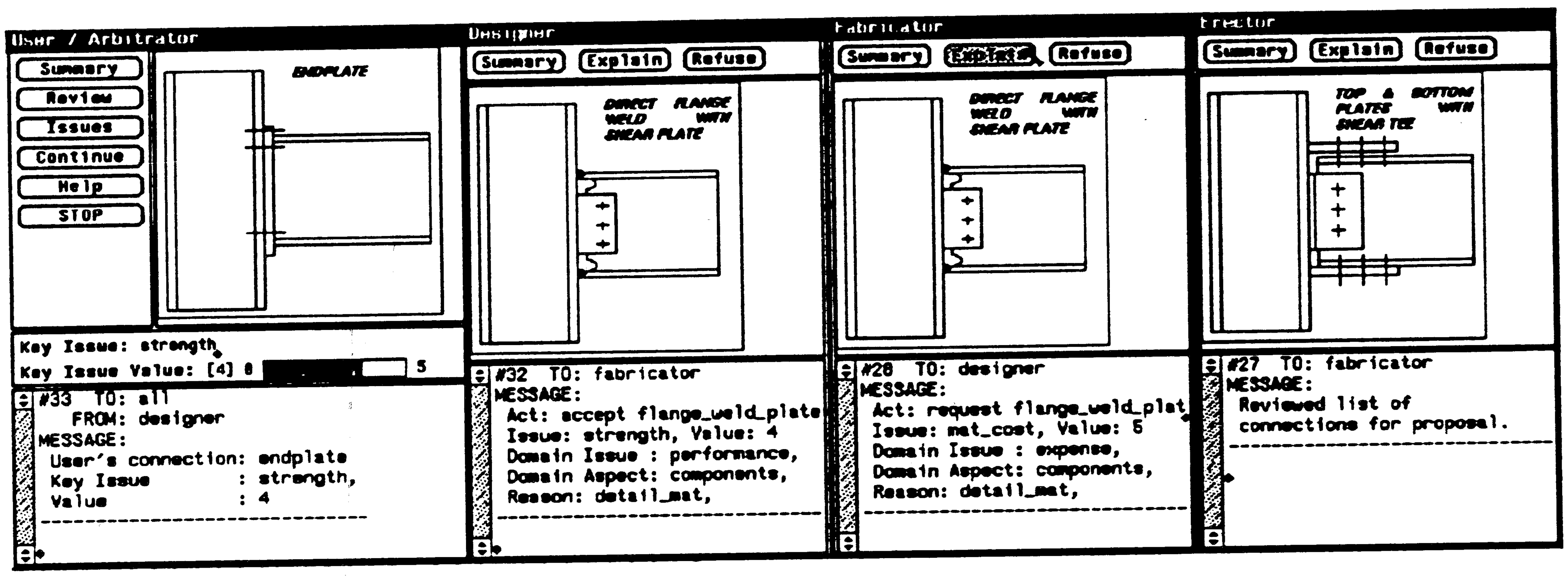

Figure 5.7: Designer Accepts Fabricator's Proposal

Once again two agents agree on the same connection thus, causing another halting condition. The arbitrator returns control of the system back to the user. At this point, the user has many options which are described in the next subsection.

5.2.3 Review of System Output

The user may select any of the buttons from either the User/Arbitrator window or agent (Designer, Fabricator or Erector) windows shown in Figure 5.7. Selecting buttons from the User/Arbitrator window allows the user to obtain a **Summary** of the initial connection, **Review** the agent dialog of the entire evaluation process, change the overall key **Issue** which focuses the evaluation, **Continue** the agent evaluation, ask for **Help**, or **STOP** the agent evaluation and exit.

As stated, the buttons from the agent windows allow the user to obtain a

Summary for each agent's proposed connection. This action is shown in Figure 5.8 where the user has selected the **Summary** button. The connection information form associated with the design agent's connection is displayed beneath the User/Arbitrator window.

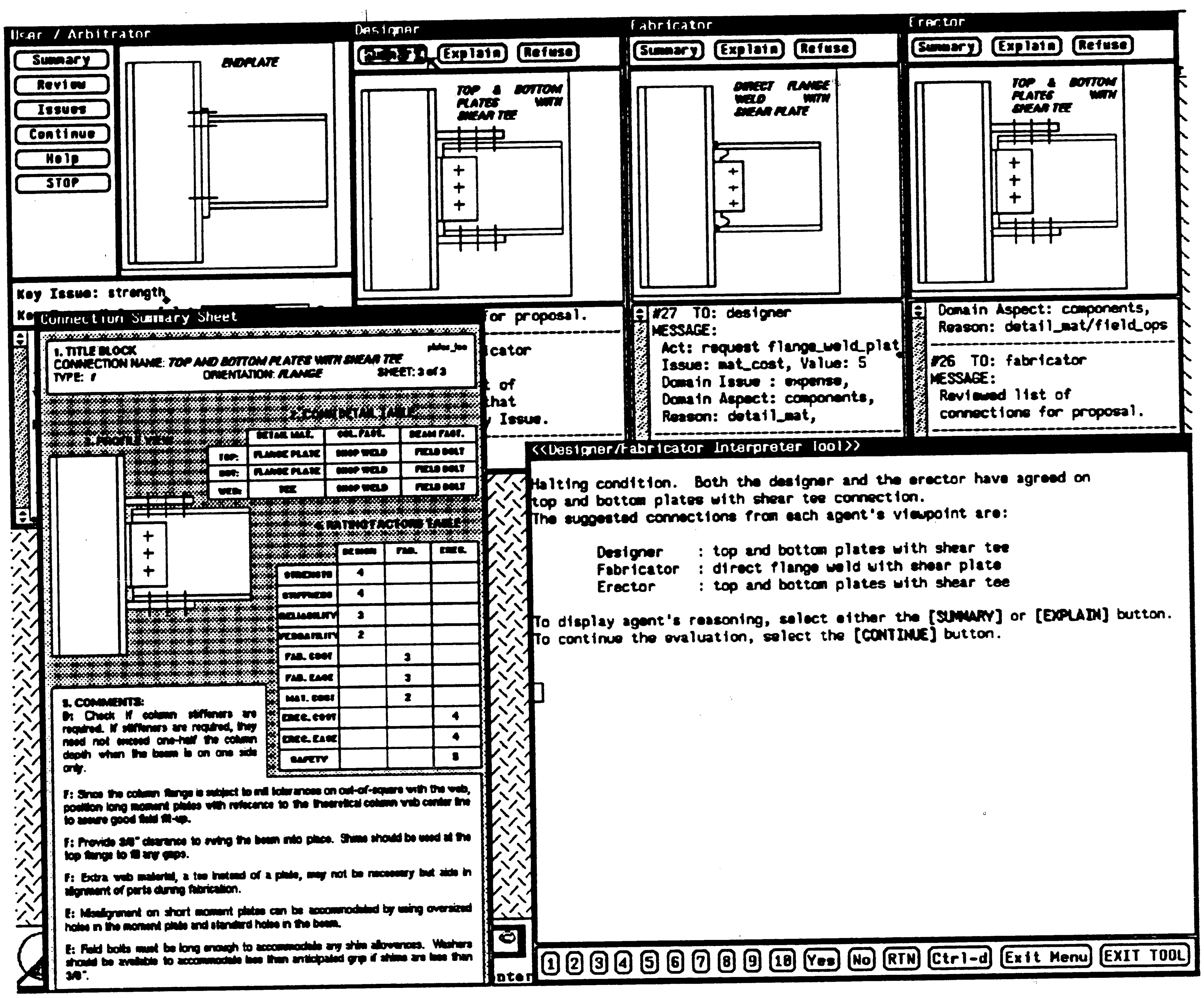

Figure 5.8: Halting Condition with a Connection Summary Sheet

In Figure 5.9, the user has selected the **Explain** button from the fabricator's window. The explanation of the agent's last evaluation cycle appears in the system's I/O window located beneath the agent windows. The explanation includes the key issue, the connections being reviewed, the agent's response to the reviewed connections, i.e., the acceptance or rejection of other agent's proposed connection, the reasons for the actions, and the connection proposed by the evaluating agent (in this case the fabricator). Currently, the explanation of the agents' actions are in the form of keywords taken directly from the DFI relational network.

At times, it is also useful for the user to be able to **Refuse** (object to) and remove a connection from the evaluation process, if the user knows that a particular connection is not acceptable.

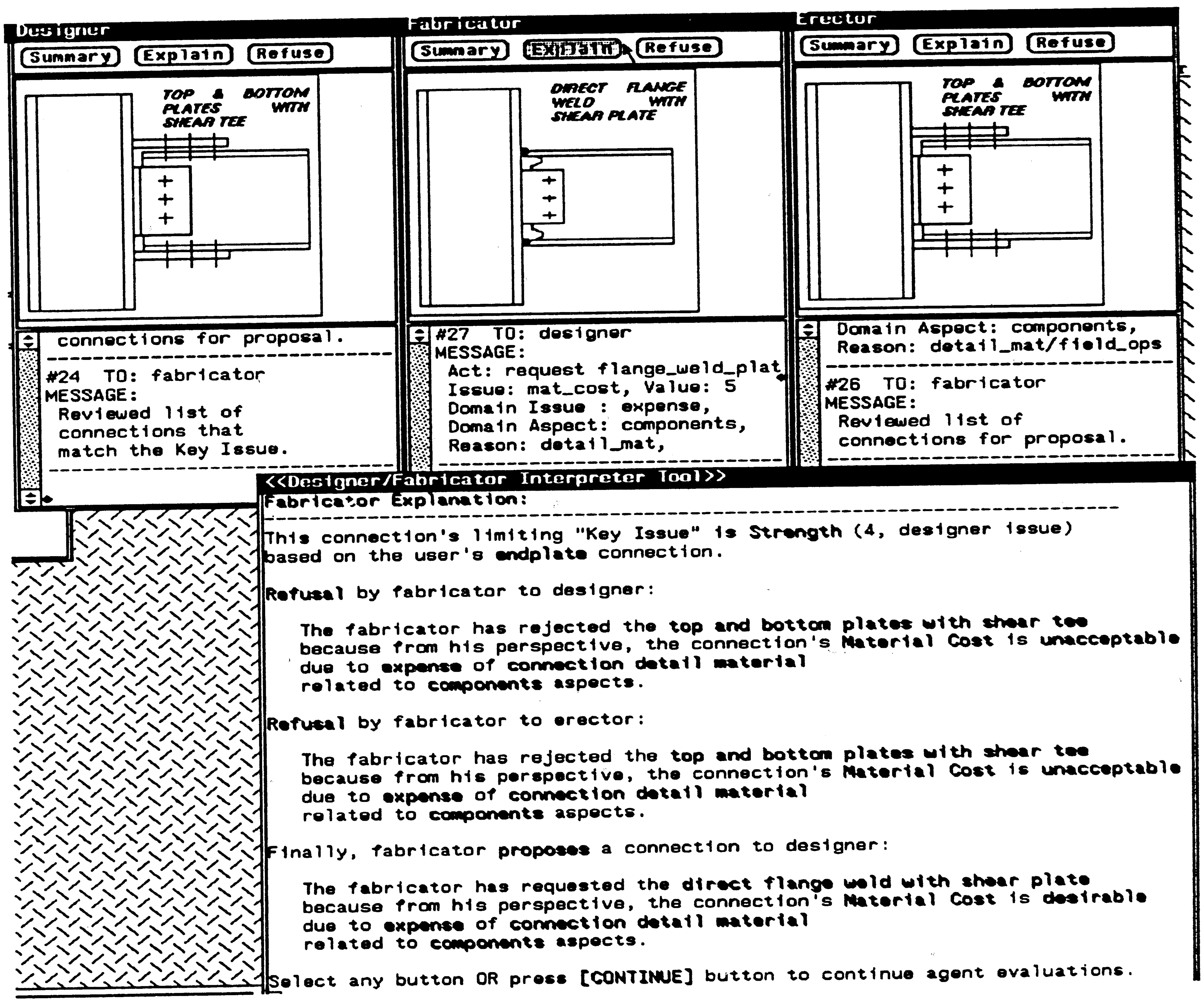

Figure 5.9: Fabricator's Output of Explain Button

5.3 Critical Review and Evaluation of DFI

This section provides a critical review and evaluation of the DFI system. Numerous parametric studies have been performed to identify if DFI:

a) Provides realistic alternative connection configurations

b) Points-out the correct problematic agent issues, and

c) Explains its actions correctly

These studies were conducted through close interaction on a regular basis with industry participants. Extensive industry interaction was also used to formulate and validate the connection database.

First, this section profiles Mr. Ira Hooper, a design expert, whose input has been instrumental in developing DFI. Next, the acceptability of the systems performance is discussed. Finally, suggestions for enhancements to the system, as viewed by practicing professionals, are presented.

5.3.1 Profile of an Industry Participant

Mr. Ira Hooper, P.E., is the Vice President and Chief Structural Engineer at STV/Seelye Stevenson Value & Knecht. He has provided valuable input to the development of DFI through knowledge acquisition sessions. His experience and knowledge of the responsibilities of the designer and fabricator in today's construction industry make him an excellent choice to validate DFI. Mr. Hooper has over forty years of structural design experience and is an active member of many professional societies. Since 1969, he has served on the AISC Specification Committee reviewing and updating the Specification for Design, Fabrication and Erection of Structural Steel for Buildings. Mr. Hooper has published and presented several papers on the design of rigid frames, arches, composite construction and lateral bracing. He also has received several awards, one of them being selected the ASCE New York Metropolitan Section Civil Engineer of the Year 1988.

5.3.2 Acceptability of System Performance

While working through the test cases with industry participants, the following aspects of DFI were evaluated and found acceptable:

- Using the connection forms as a method of capturing and representing data and knowledge.
- Providing a doubler plate and column stiffener check prior to evaluating the connection.
- Identifying the correct problematic agent issues during the evaluation.
- Proposing realistic connection alternatives which are "better" on the identified problem issue.
- Allowing the user to continue past a halting condition so that other proposals may be viewed and considered by the user to make a more educated final decision.
- Providing an explanation facility to review the evaluation process.

The above listed items indicate the system is working properly for the level of detail which it uses. However, many system enhancements were identified and are discussed in the next section.

5.3.3 Suggestions for Enhancements

This subsection lists the suggested enhancements to the DFI system that were pointed out while reviewing the system.

The suggestions for enhancements, as viewed industry participants, are:

- Implementing different column stiffener checks for different connection configurations, as opposed to simply using a worst case check.
- Improving the agent messages to enhance their clarity and descriptiveness. For example, in Figure 5.4, the erector refused the endplate connection and listed "fasteners" as a potential problem, it was suggested the message read "dimensional tolerances" or "fit-up problem" [Hooper 88].
- Minimizing the amount of autocratic messages. For example, the **Refusal** message should be changed to **Objection**.
- Applying relative importance or weighting factors to the agents. A suggested scheme weights the designer 0.5 while the fabricator and erector have weights of 0.3 and 0.2 respectively.
- Performing extensive industry tests to determine if the quantitative manipulation of the qualitative rating factor values is valid and arrives at the correct evaluation.

- Generating a set of connection databases that group connection configuration preference across demographic parameters, such as, company size and geographic location.

This list of enhancements provides a basis for future research. It also re-establishes the need for frequent industry interaction to coordinate the academic research with the needs of the practicing professionals.

The next chapter provides a summary of the thesis. Chapter 6 also presents observations that have been identified by the author during the development of DFI.

6. Summary and Observations

This chapter presents a summary of this thesis and observations made during the development of DFI. This chapter is organized as follows. First, a summary of the thesis is presented. Next, observations related to the industry impact and intellectual contributions of the DFI research are discussed.

6.1 Summary

This thesis began with an introduction describing the need and potential application of integrated design and construction systems (Chapter 1). A summary of the DFI system was then presented (Chapter 2). Next, the design and construction process was described along with the definitions for the design, fabrication and erection issues and subissues used in evaluating structures (Chapter 3). Detailed agent information models were then formulated with a method of relating them (Chapter 4). A demonstration and validation of the system was described and conducted (Chapter 5).

The research has provided the author opportunities to venture outside of "traditional" civil engineering and explore areas of applied artificial intelligence, such as, knowledge-based systems, problem-solving, negotiation and concurrent design. To complete this research, the author had to first get an understanding of the design and behavior of connections*. Next, the techniques associated with developing large-scale knowledge-based systems had to be learned. These two seemingly opposite disciplines complement each other nicely when attempting to solve and model complicated problems. Young, graduate level engineers are taught to attack problems very systematically, but often have to regenerate their solution procedures since they may not be familiar with techniques to model generalized solution procedures. Knowledge-based systems using frame-based or object-oriented representation environments provide paradigms to logically assemble a generalized problem-solving model and apply it to many, possibly different situations.

* Connection design is usually not taught at the undergraduate or graduate level. Lehigh is an exception offering a graduate course in connection design.

6.2 Observations

This section presents observations assembled by the author while researching, developing and implementing the DFI system. First, the industry impact of DFI is described. Next, the intellectual contributions of the research are listed. Finally, a brief discussion on why DFI is a step towards CIC is presented.

6.2.1 Industry Impact

The implementation of systems, like DFI, will provide practicing design professionals with tools to assist in designing for constructability. DFI specifically attempts to improve the communication between designers and fabricators during the preliminary connection design process.

Integrated design and construction systems can give users the ability to predict downstream problems as a result of upstream decisions. This could lead to more economical designs which consider aspects of constructability to improve reliability and to reduce field rework and overall costs. These systems could integrate knowledge and databases to encompass more aspects of the structure. For example, considering the recent advances in "intelligent" CAD, these systems could be combined with construction knowledge-based systems and finite element packages to facilitate a situation where the intent of what the designer is trying to accomplish can be related to field activities. The construction knowledge-based systems would be responsible for pointing out potential field problems, the intelligent CAD systems would maintain component tolerances and determine interference problems.

The present DFI prototype system is not intended for production use in industry. It does, however, demonstrate how the integration of different viewpoints during an evaluation can provide "better" connection design alternatives. DFI also provides a mechanism for sharing knowledge across various perspectives to improve the communication between designers and fabricators while allowing each to maintain a their own view of the situation.

6.2.2 Intellectual Contributions

The development of DFI has provided a preliminary framework for cooperative problem-solving. A systematic approach was used to represent and relate connection design and construction information across three different viewpoints.

It is suggested that contributions of the DFI research include the following:

- Formulation and implementation of a multiagent negotiation scheme [Werkman 90].
- Development of a flexible knowledge and data representation to model aspects of building information.
- Development of a practical application for conceptual graphs and relations.
- Formulation of a structured decomposition of agent information into issues, subissues, characteristics and their metrics.

The author's important contributions to this research involved acquiring and synthesizing relevant civil engineering domain knowledge so the computer science implementation team could code the system. The author was also responsible for the formulation of the connection knowledge and databases, agent information models, and relational networks.

6.2.3 A Step Towards CIC

By providing a tool which enables communication early in the design and construction process, DFI attempts to bridge the information interface gap between design engineers, fabricators and erectors of structural steel systems. This research has provided a method of integrating three unique viewpoints to evaluate connection designs "better" through a consideration of constructability issues.

DFI is a small step towards CIC since it deals only with connections, and the agents involved in their evaluation. The system demonstrates a concept that could be expanded to consider the entire lifecycle (from planning to construction) of a structure.

The final chapter of this thesis presents some suggestions and extensions that could be implemented to extend the connection evaluation, enhance the user interface, and lead to the evaluation of entire building configurations.

7. Extensions

The DFI prototype evaluates steel beam-to-column connections to determine if physical fit-up is possible and point out potential problems from the viewpoints of design, fabrication and erection. The system is capable of generating alternative connection configurations that alleviate the identified problems. The intent of this chapter is to formulate possible extensions for improving DFI.

This chapter is organized in the following manner. First, the extensions necessary to improve the current connection evaluation are discussed. Next, possible user interface improvements are presented. The chapter is concluded with a description and listing of a suggested set of steps which would make DFI capable of evaluating entire building configurations.

7.1 Extending the Connection Evaluation

This section describes and lists possible extensions to improve the current connection evaluation scheme used in DFI. The extensions could include the following:

- Expanding the connection database to include additional Type 1 connection configurations.
- Extending the connection database to include Type 2 and 3 connections.
- Generating a set of connection databases that group connection configuration across demographic parameters.
- Developing a testing scheme to systematically validate the rating factor values present on the connection information forms.
- Incorporating a method to dynamically generate the rating factor values for the connection information forms using the proposed agent information models.
- Developing a more comprehensive connection evaluation that uses specific agent heuristics.

The first two items would be straightforward to complete by developing more connection information forms and obtaining industry input on the values for the rating factors. The third item, generating a set of connection databases that group connections demographically, implies surveying many design, fabrication and erection firms to determine statistically what differences exist in connection configuration preference across many demographic parameters such as company size and geographic location. Validating the rating factor values would involve systematically testing many case with experts to determine their correctness.

The last two items are more difficult to complete. Dynamically generating values for the rating factors would involve developing a set of rules that compile a score by looking at the quantitative information slots that make up the lowest level of issue decomposition in the agent information models. To implement a more comprehensive connection evaluation, specific agent heuristics would have to be formulated that could act on the issues, subissues and characteristics to evaluate potential problems associated with other agents' proposed connections.

7.2 Improving the User Interface

This section focuses on improving the system feedback to the user [AAAI 88], cosmetic enhancements are not be discussed. User interface improvements should focus on the explanations the system provides.

Formulating a user model [ACL 88] to determine what level of design experience (novice, intermediate or expert) the user has would enhance the interface by the following:

- Dictating the input sequence based on the user's experience.
- Providing intermediate explanations to educate novice users.
- Tailoring the final system output to reflect the user's experience.

By incorporating a user model, the system would be capable of working as an "educator" for the novice or a "surrogate consultant" for the expert user.

Another useful tool to improve the explanation facility would be the development of a discourse model [ACL 88] to maintain a record of the user and agent interactions. A discourse model would work similarly to the blackboard facility in DFI but would be more "intelligent." The blackboard is simply an area where messages are posted for reference by the agents. A discourse model could be used for the posting and interpretation of messages, this could eliminate the need for an independent arbitrator agent.

Research on both user and discourse modeling is currently underway and should be included in future versions of DFI.

7.3 Evaluating Entire Building Configurations

This section lists a set of possible implementation steps to evaluate entire building configurations. The purpose of the proposed steps is to develop a more comprehensive evaluation*.

A suggested summary of implementation steps is listed below:

- Evaluate the interaction of multiple connections framing into a single column.
- Evaluate connections at both ends of a beam simultaneously.
- Evaluate the interactions of an entire floor plan. This includes the repeated modules and any different ones that are required for the architectural features.
- Examine the interactions between floors to evaluate the entire building configuration.

The implementation of each step could further improve communication between designers and fabricators while providing industry with additional tools to improve present practice.

This thesis has attempted to show the progress DFI is making towards CIC but, from the extensions previously discussed, it is obvious that working systems that incorporate all aspects of the design and construction process are in the formative stages. The DFI approach of tackling a constrained problem and implementing a working system appears to be an appropriate method of making strides towards CIC while, at the same time, developing intermediate tools that can be useful to industry.

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* To perform a complete evaluation of a building design other aspects, such as, HVAC, electrical, and mechanical designs must be considered, but as mentioned earlier, these topics are beyond the scope of this thesis.

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Appendices

Appendix A: Connection Information Forms

Appendix B: Listing of Implemented Relationships

Appendix C: Listing of Subissue Decomposition

A. Connection Information Forms

The purpose of the Connection Information Form is to provide a mechanism for information transfer and knowledge acquisition between ATLSS researchers and the industry partners associated with the Designer-Fabricator Interpreter. These sheets are used to build a knowledge base wherein designers can access general fabrication and erection knowledge in the pre-bid phase of the connection design in order to help alleviate the mismatch between the intent of the designer and the capabilities of the fabricator to perform economically and productively.

This Appendix will describe the Connection Information Forms, define the issues (as presented to the reviewing experts) and provide a listing and set of completed forms used in DFI.

A.1 Description of Forms

The Connection Information Forms were developed using FrameMaker™, a desktop publishing program, running on Sun™ workstations. The author developed a modular sheet format divided into five sections:

1. Title Block.
2. Connection Detail Table.
3. Profile View of the Connection.
4. Rating Factors Table.
5. Comments.

A blank template was first produced along with a connection component object library so these forms could be generated quickly and consistently. The layout of the form was quite important because they were being sent to the experts for comment and review. Therefore, an extremely crowed layout would be difficult to read.

Another feature of the development environment was that Postscript™ (standard graphics language) files could be generated quite easily from FrameMaker™. This allowed the researchers to write a simple postprocessing program that could read the Postscript file and automatically write a correctly formatted database for DFI from the graphic sheets.

A description of each area of the connection information form is presented below, along with some example input.

1. **Title Block**: In this area the connection name, type of construction and orientation are given. The small text in the upper right corner of this block is a connection identifier for computer storage and retrieval.

   - **Connection Name**: Describes the connection configuration.

   - **Type of Construction**: As described by AISC Manual 9th Edition.

     Type 1: Fully Rigid Moment Connection

     Type 2: Simple (Pinned) Connection

     Type 3: Partially Rigid Connection.

   - **Orientation**: Describes the orientation of the connection either to the column FLANGE or the column WEB.

2. **Connection Detail Table**: Here the connection (i.e., top, bottom and web) components are detailed along with the type of fastener (i.e., shop welding, field bolting) used to connect to the column and beam ends of the connection.

3. **Profile View of the Connection**: A display of the information detailed in the Connection Detail Table is presented to assist in visualization of the connection.

4. **Rating Factors Table**: The issues used to evaluate the connection are listed along with a rating on that issues from 1 to 5. The issues are grouped from the viewpoint of DESIGN, FABRICATION and ERECTION. Please note that a specific viewpoint may not have a rating on a specific issue because that viewpoint does not have knowledge about that particular issue (i.e., the DESIGN viewpoint may not be familiar with the EREC. COST issue).

5. **Comments**: In this area comments about the connection are listed. The letter (D, F or E) that precedes each comment indicates the viewpoint from which the comment is made.

A.2 Issues and Rating Values

The industry experts were asked to evaluate each connection on the following ten issues:

- **STRENGTH**: The "ultimate" strength of the connection.
- **STIFFNESS**: The ability of the connection to resist deformation.
- **RELIABILITY**: The ability of the connection to perform its intended function during in-service life.
- **VERSATILITY**: The adaptability to be modified or "retrofit" when the intended use of the structure is changed from the initial design conditions.
- **FAB. COST**: The relative shop fabrication cost based on labor.
- **FAB. EASE**: The relative ease to shop fabricate the connection.
- **MAT. COST**: The material and delivery cost of the connection detail material from the mill.
- **EREC. COST**: The relative field erection cost based on labor.
- **EREC. EASE**: The relative field erection ease.
- **SAFETY**: A relative measure on how safe the connection is to field erect.

The experts reviewed only the issues related to their particular area of expertise and were also asked to provide any comments from past experiences that should be included on each sheet.

The issues were rated using the following scale:

- 5 = Most Desirable Condition.
- 4 = More Desirable Condition.
- 3 = Moderately Desirable Condition.
- 2 = Less Desirable Condition.
- 1 = Least Desirable Condition.

This rating scale was suggested by [Hooper 88] during a meeting to develop the layout of the forms. The scale was chosen to complement the level of detail DFI uses to perform an evaluation. A more accurate scale would be suspect since the specific details of the connection are not included on the sheet or used in the current version of DFI.

A.3 Listing and Completed Forms

Listed in Table A.1 are the completed Connection Information Forms appended to this section. Please note the forms have been reduced to 85% of their original size for inclusion in this thesis.

Table A.1: Listing of Connection Information Forms

Type	Orientation	Name	Identifier
1	FLANGE	End Plate	endplate
1	FLANGE	Direct Flange Weld with Shear Plate	flange_weld_plate
1	FLANGE	Direct Flange Weld with Shear Angel	flange_weld_angle
1	FLANGE	Direct Flange Weld with Shear Tee	flange_weld_tee
1	FLANGE	Direct Flange Weld with Web Welded	flange_weld_weld
1	FLANGE	Top and Bottom Plates with Shear Plate	plates_plate
1	FLANGE	Top and Bottom Plates with Shear Angle	plates_angle
1	FLANGE	Top and Bottom Plates with Shear Tee	plates_tee
1	FLANGE	Top and Bottom Tees with Shear Plate	tees_plate
1	FLANGE	Top and Bottom Tees with Shear Angle	tees_angle
1	FLANGE	Top and Bottom Tees with Shear Tee	tees_tee
1	WEB	Direct Flange Weld with Shear Plate	web_type1_welds
1	WEB	Top and Bottom Plates with Shear Plate	web_type1_plates

1. TITLE BLOCK endplate

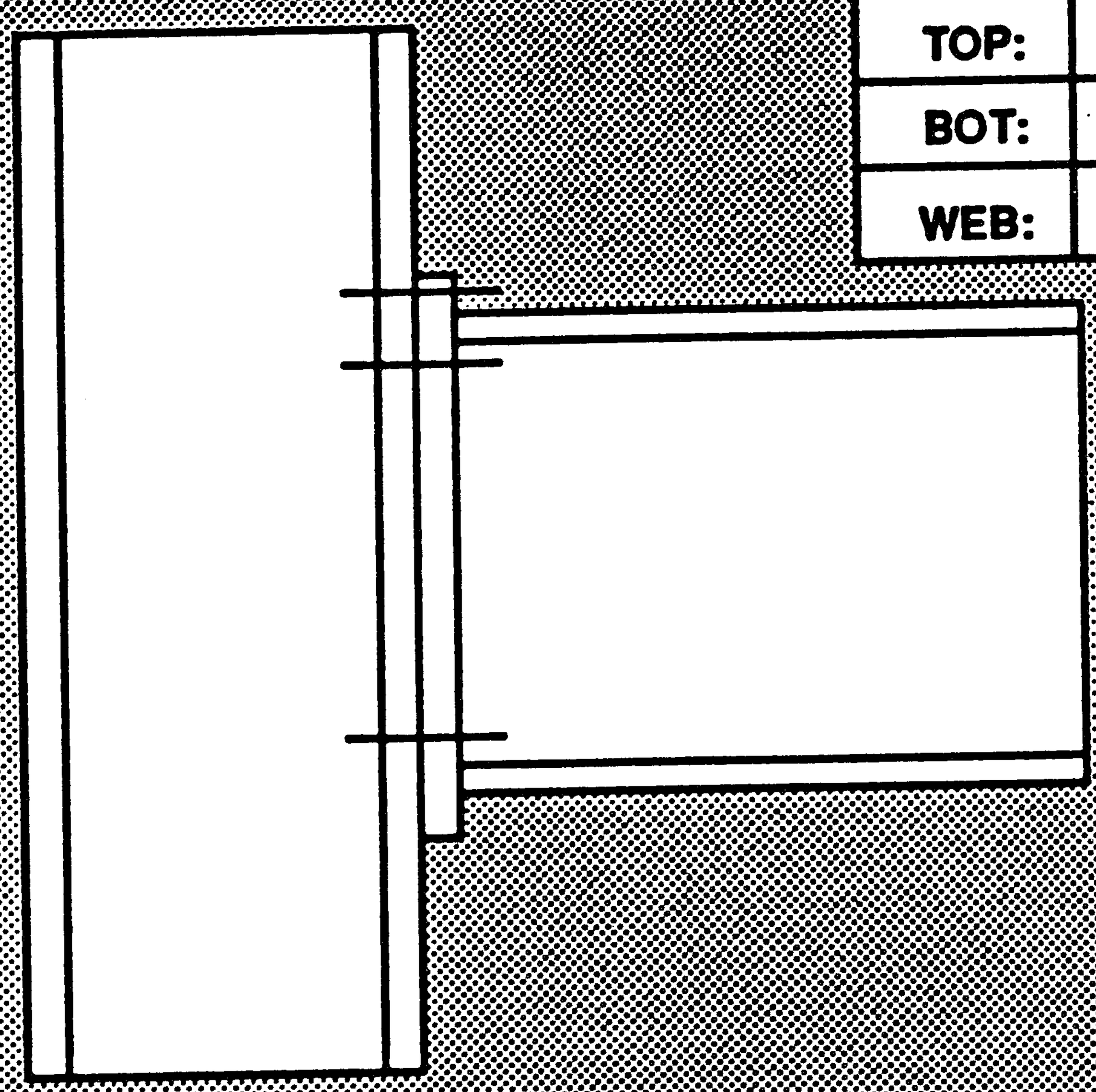
CONNECTION NAME: ***ENDPLATE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 1 of 1

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	ENDPLATE	FIELD BOLT	SHOP WELD
BOT:	ENDPLATE	FIELD BOLT	SHOP WELD
WEB:	ENDPLATE	FIELD BOLT	SHOP WELD

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	3		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		4	
FAB. EASE		3	
MAT. COST		4	
EREC. COST			2
EREC. EASE			2
SAFETY			3

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required they need not exceed one-half the column depth when the beam is on one side only.

D: For fillet weld > 1/2" to attach the endplate consider using full or partial penetration groove welds with reinforcement.

F: Endplate connections require dimensional control to tight fit-up to column flanges, which is affected by column flange-to-web squareness, beam camber and squareness of the beam end.

F: Shim space may be provided for accommodating mill and fabricating tolerances. Use "finger" shims entered from each side where feasible.

E: Field bolts must be furnished long enough to accommodate any shim allowance.

Figure A.1: endplate Connection Information Form

1. TITLE BLOCK flange_weld_plate

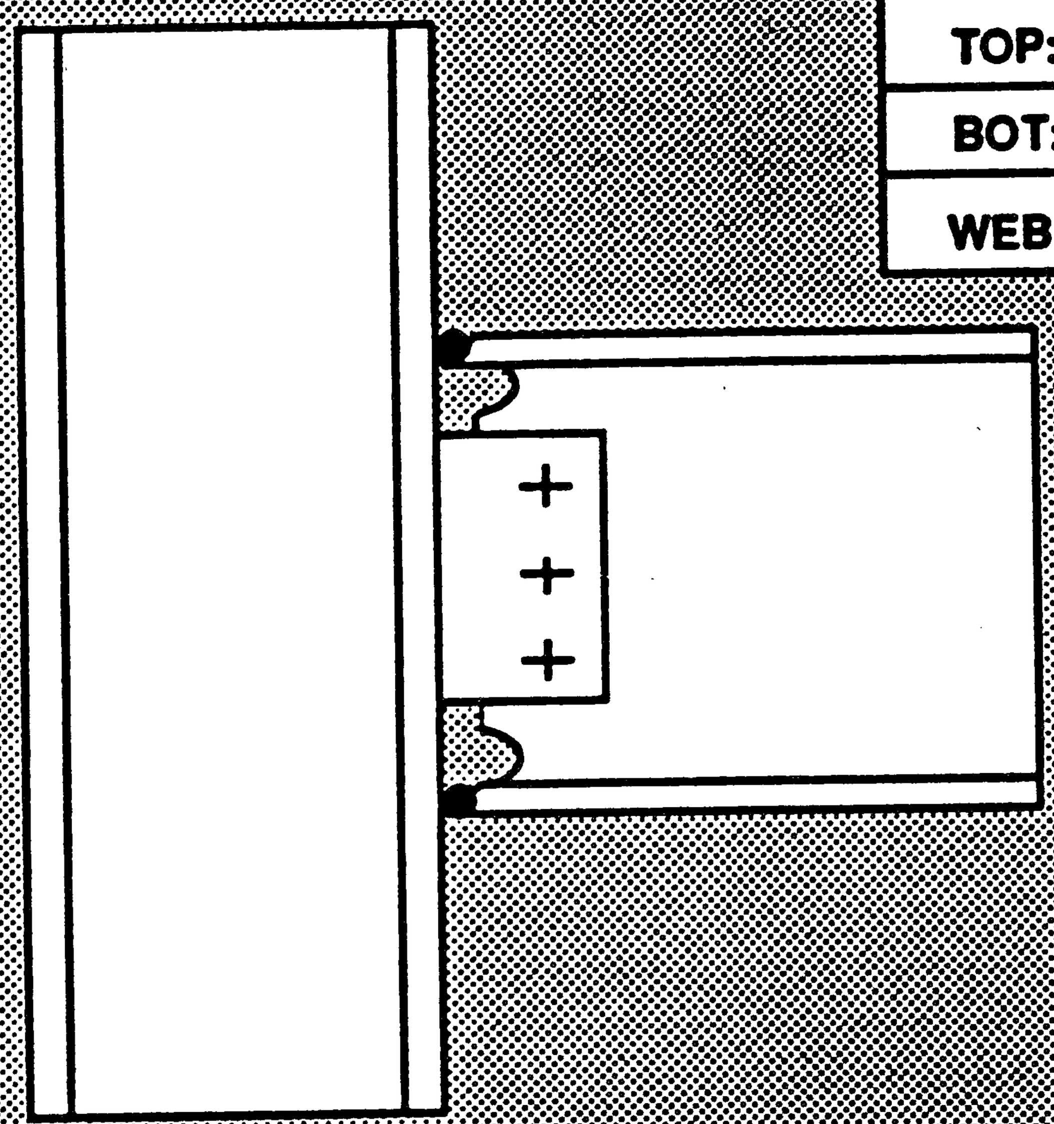
CONNECTION NAME: ***DIRECT FLANGE WELD WITH SHEAR PLATE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 1 of 4

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE WELD	FIELD WELD	FIELD WELD
BOT:	FLANGE WELD	FIELD WELD	FIELD WELD
WEB:	WEB PLATE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		4	
MAT. COST		5	
EREC. COST			2
EREC. EASE			2
SAFETY			3

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

D: Unnecessarily thick stiffeners and full penetration groove welds should be avoided since they may contribute to lamellar tearing.

F: Allowances must be made for weld shrinkage, beams should be fabricated longer than required by the amount of the expected shrinkage. A typical rolled section will shrink about 1/16 in. per welded joint.

E: Horizontal short slotted holes should be used in the plate to aid in erection. Use one std. hole near the centroid of the beam to maintain frame alignment. Some fabricators will not like using different size punches this an extra operation which costs extra.

E: The connection should be able to withstand the construction loads without having the flanges welded since the welding usually takes place much later than the erection of the member.

Figure A.2: flange_weld_plate Connection Information Form

1. TITLE BLOCK flange_weld_angle

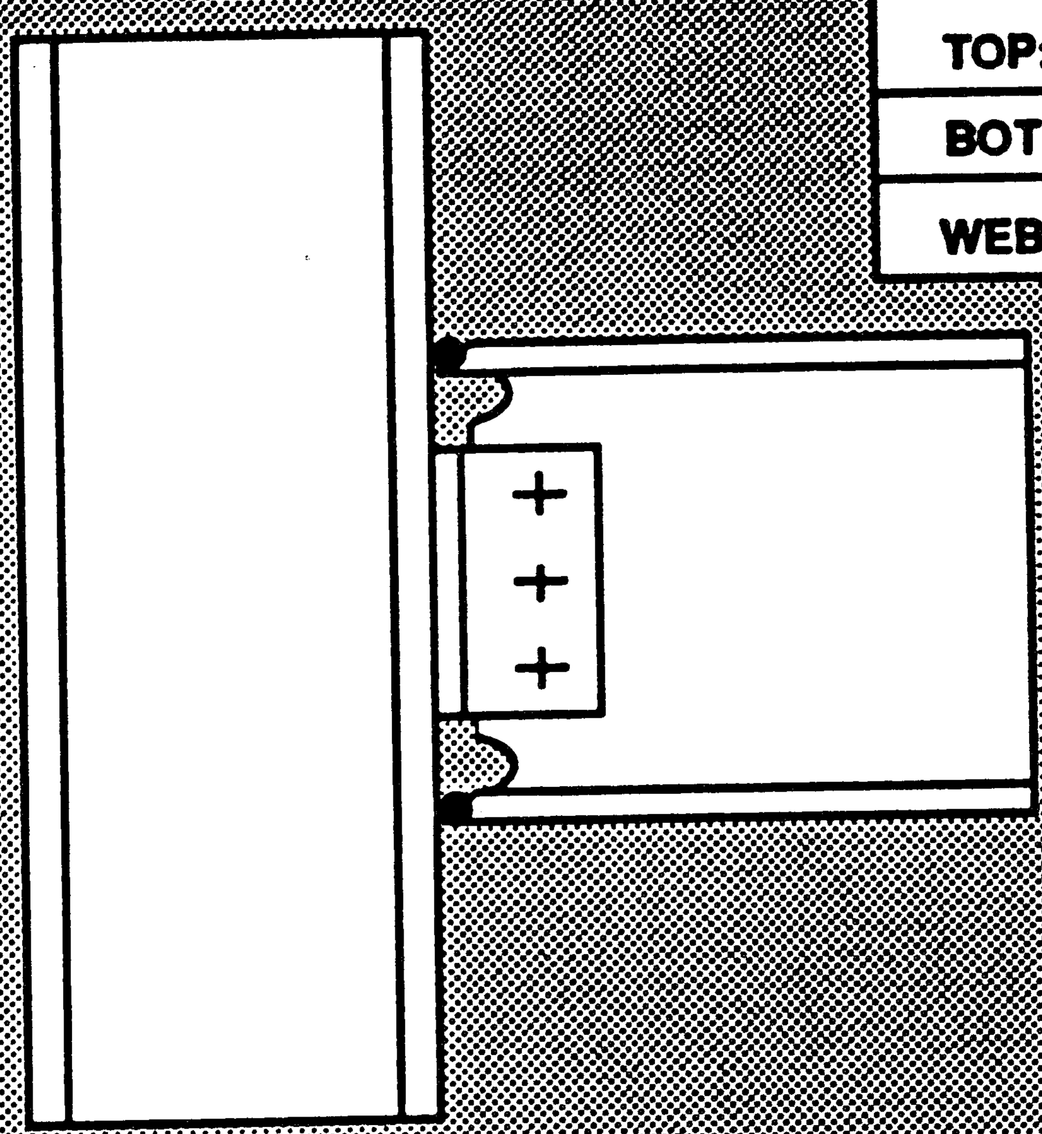
CONNECTION NAME: ***DIRECT FLANGE WELD WITH SHEAR ANGLE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 2 of 4

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE WELD	FIELD WELD	FIELD WELD
BOT:	FLANGE WELD	FIELD WELD	FIELD WELD
WEB:	ANGLE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		4	
MAT. COST		4	
EREC. COST			2
EREC. EASE			2
SAFETY			3

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

D: Unnecessarily thick stiffeners and full penetration groove welds should be avoided since they may contribute to lamellar tearing.

F: Allowances must be made for weld shrinkage, beams should be fabricated longer than required by the amount of the expected shrinkage. A typical rolled section will shrink about 1/16 in. per welded joint.

F: Extra web material, an angle instead of a plate, may not be necessary but aids in alignment of parts during fabrication.

E: Horizontal short slotted holes should be used in the angle to aid in erection. Use one std. hole near the centroid of the beam to maintain frame alignment (see sheet 1).

E: The connection should be able to withstand the construction loads without having the flanges welded since the welding usually takes place much later than the erection of the member.

Figure A.3: flange_weld angle Connection Information Form

1. TITLE BLOCK flange_weld_tee

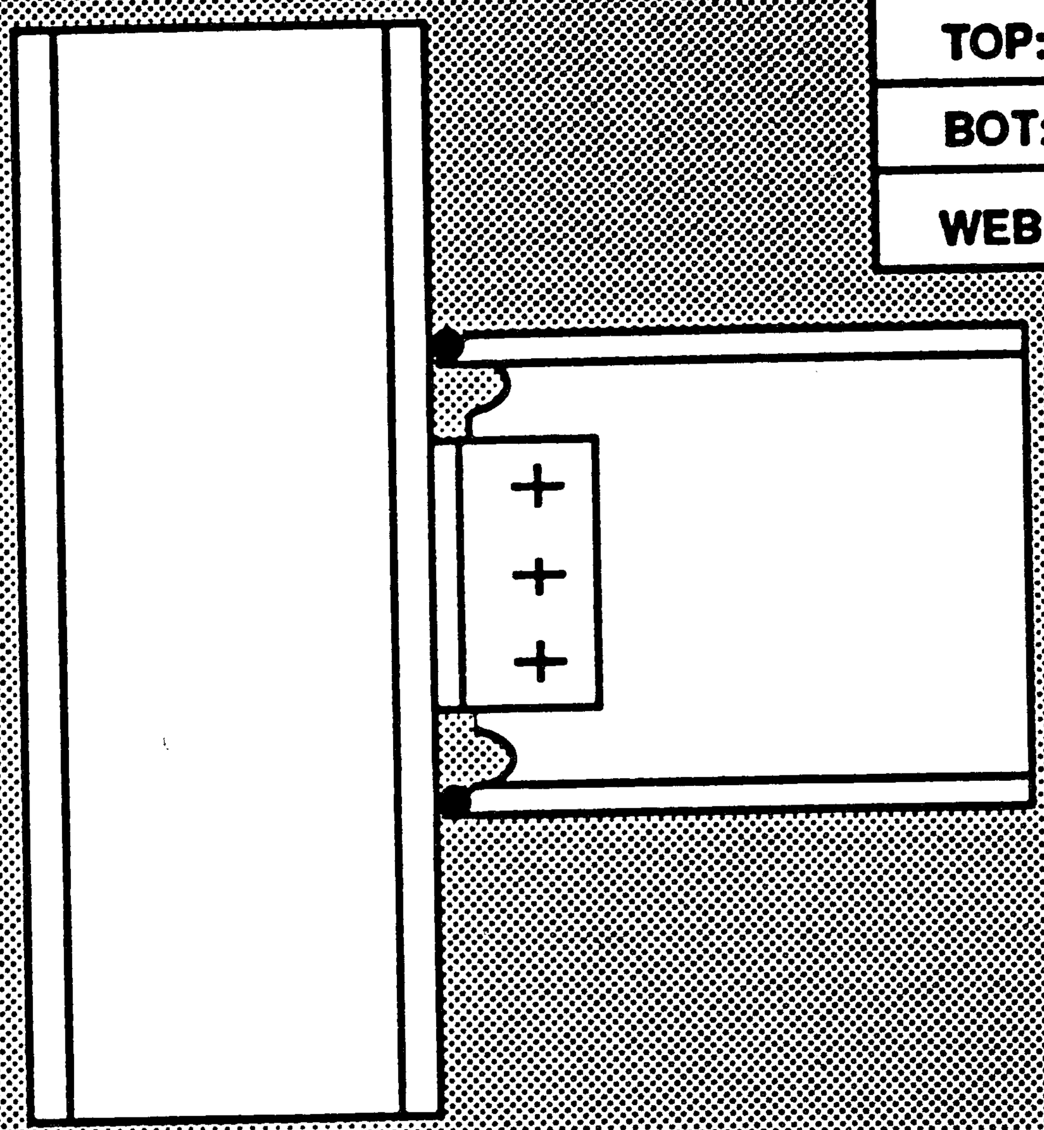
CONNECTION NAME: ***DIRECT FLANGE WELD WITH SHEAR TEE***

TYPE: ***1*** ORIENTATION: ***FLANGE*** SHEET: 3 of 4

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE WELD	FIELD WELD	FIELD WELD
BOT:	FLANGE WELD	FIELD WELD	FIELD WELD
WEB:	TEE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		4	
MAT. COST		2	
EREC. COST			2
EREC. EASE			2
SAFETY			3

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

D: Unnecessarily thick stiffeners and full penetration groove welds should be avoided since they may contribute to lamellar tearing.

F: Allowances must be made for weld shrinkage, beams should be fabricated longer than required by the amount of the expected shrinkage. A typical rolled section will shrink about 1/16 in. per welded joint.

F: Extra web material, a tee instead of a plate, may not be necessary but aids in alignment of parts during fabrication.

E: Horizontal short slotted holes should be used in the tee to aid in erection. Use one std. hole near the centroid of the beam to maintain frame alignment (see sheet 1).

E: The connection should be able to withstand the construction loads without having the flanges welded since the welding usually takes place much later than the erection of the member.

Figure A.4: flange_weld_tee Connection Information Form

1. TITLE BLOCK flange_weld_weld

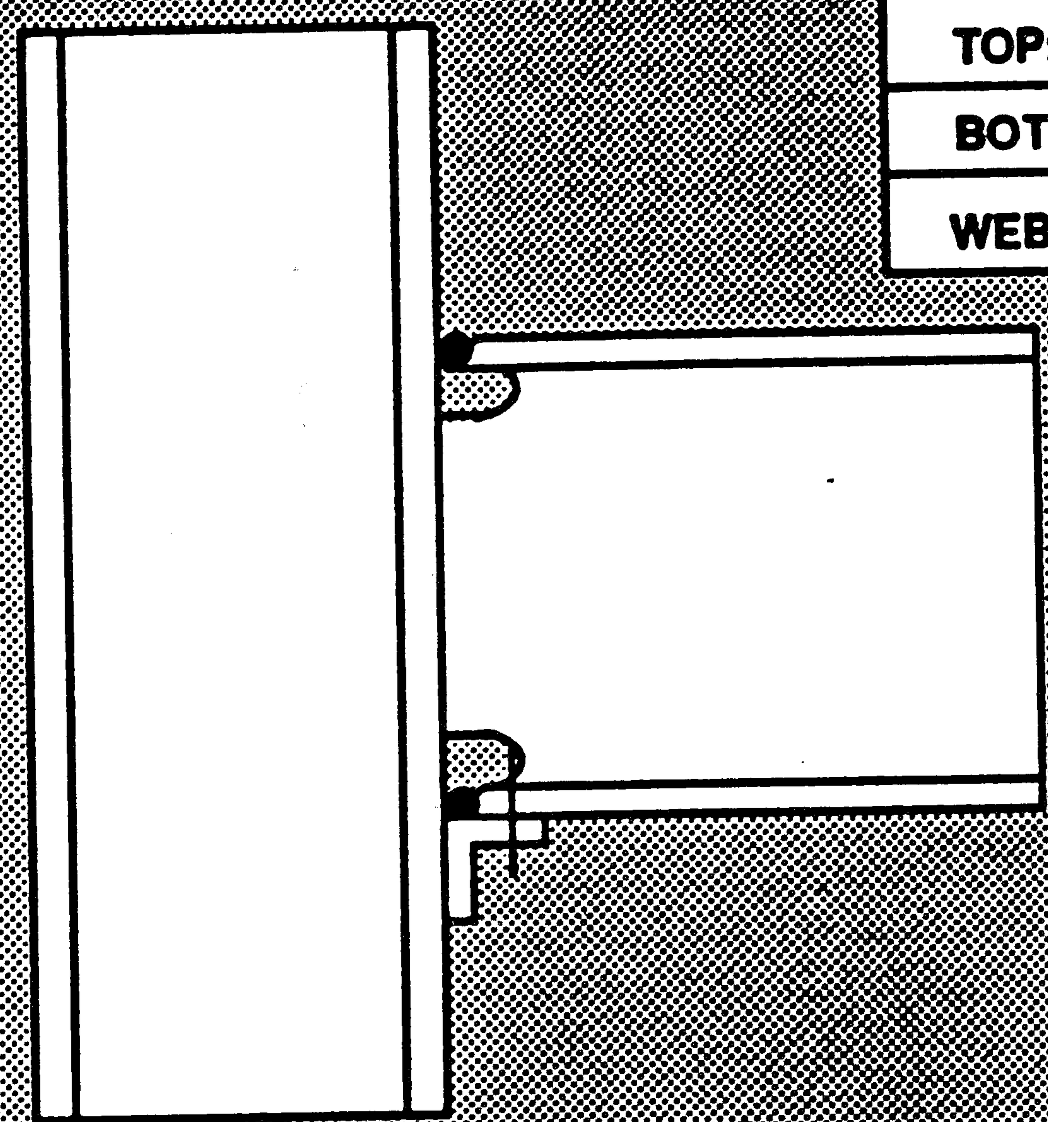
CONNECTION NAME: ***DIRECT FLANGE WELD WITH WEB WELDED***

TYPE: ***1*** ORIENTATION: ***FLANGE*** SHEET: 4 of 4

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE WELD	FIELD WELD	FIELD WELD
BOT:	FLANGE WELD	FIELD WELD	FIELD WELD
WEB:	WEB WELD	FIELD WELD	FIELD WELD

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		2	
MAT. COST		4	
EREC. COST			2
EREC. EASE			3
SAFETY			3

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

D: Since the connection is completely welded to the column the stress flow is smooth (well behaved) around this connection.

D: Unnecessarily thick stiffeners and full penetration groove welds should be avoided since they may contribute to lamellar tearing.

F: Allowances must be made for weld shrinkage, beams should be fabricated longer than required by the amount of the expected shrinkage. A typical rolled section will shrink about 1/16 in. per welded joint.

F: Tolerances for this connection are very tight since the entire connection is directly welded to the column. Overrun and underrun tolerances must be held to a minimum.

E: The connection seat angle should be able to withstand the construction loads without having the flanges or web welded since the welding usually takes place much later than the erection of the member.

Figure A.5: flange_weld_weld Connection Information Form

1. TITLE BLOCK plates_plate

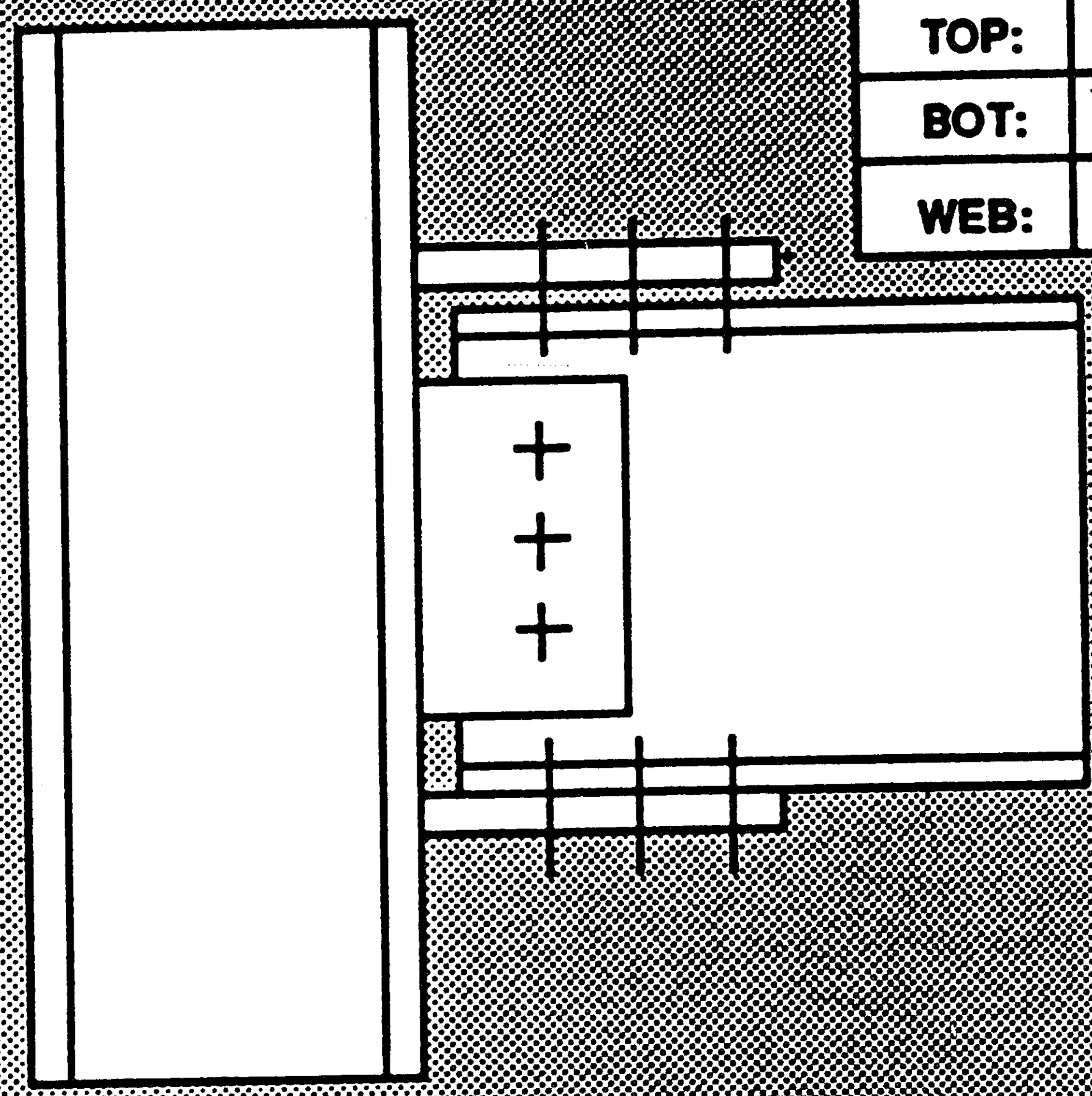
CONNECTION NAME: ***TOP AND BOTTOM PLATES WITH SHEAR PLATE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 1 of 3

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE PLATE	SHOP WELD	FIELD BOLT
BOT:	FLANGE PLATE	SHOP WELD	FIELD BOLT
WEB:	WEB PLATE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		4	
MAT. COST		4	
EREC. COST			4
EREC. EASE			4
SAFETY			5

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

F: Since the column flange is subject to mill tolerances on out-of-square with the web, position long moment plates with reference to the theoretical column web center line to assure good field fit-up.

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

E: Misalignment on short moment plates can be accommodated by using oversized holes in the moment plate and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

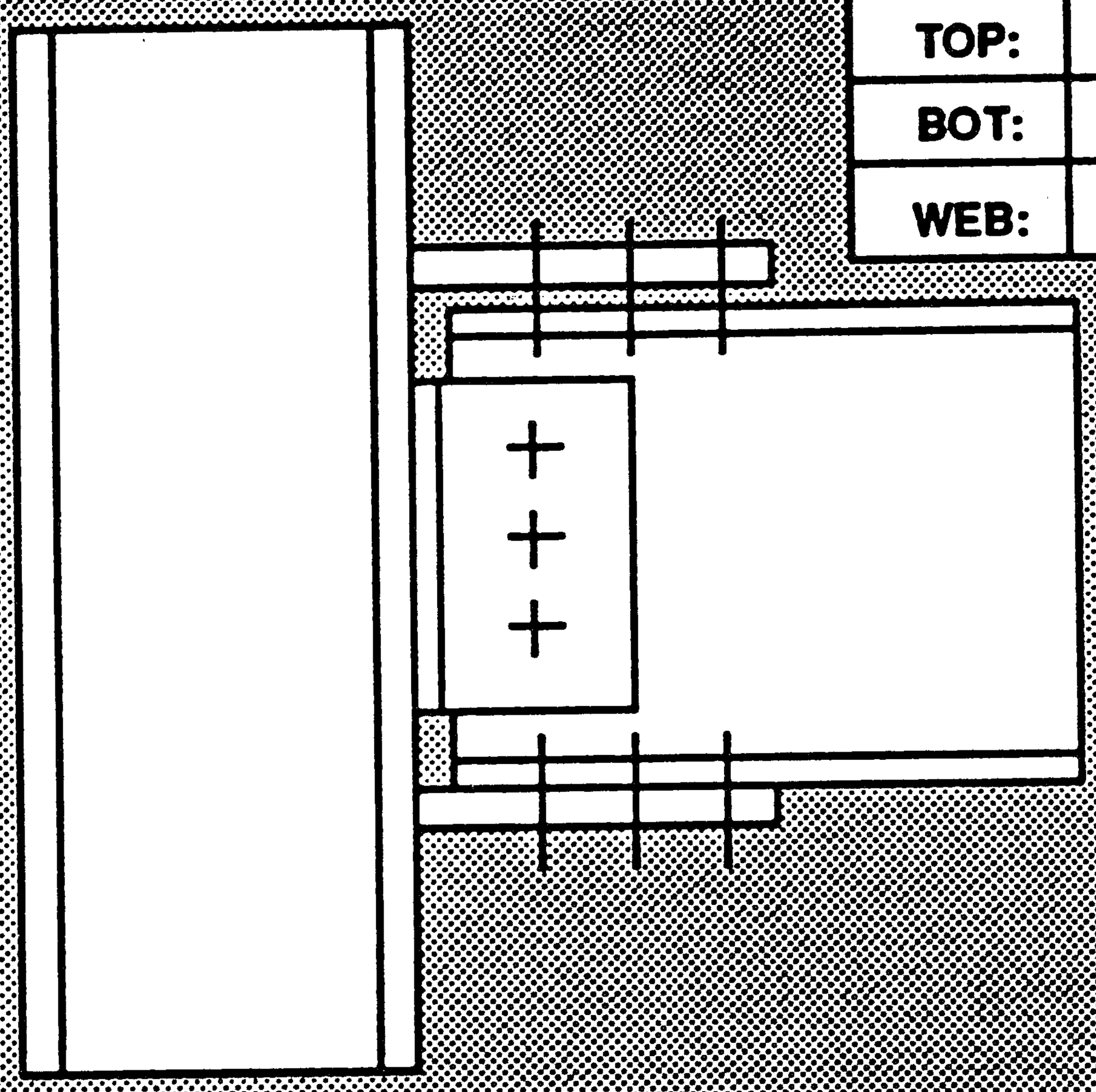
Figure A.6: plates_plate Connection Information Form

1. TITLE BLOCK plates_angle
CONNECTION NAME: ***TOP AND BOTTOM PLATES WITH SHEAR ANGLE***
TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 2 of 3

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE PLATE	SHOP WELD	FIELD BOLT
BOT:	FLANGE PLATE	SHOP WELD	FIELD BOLT
WEB:	ANGLE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		3	
MAT. COST		3	
EREC. COST			4
EREC. EASE			4
SAFETY			5

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

F: Since the column flange is subject to mill tolerances on out-of-square with the web, position long moment plates with reference to the theoretical column web center line to assure good field fit-up.

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

F: Extra web material, an angle instead of a plate, may not be necessary but aids in alignment of parts during fabrication.

E: Misalignment on short moment plates can be accommodated by using oversized holes in the moment plate and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

Figure A.7: plates_angle Connection Information Form

1. TITLE BLOCK plates_tee

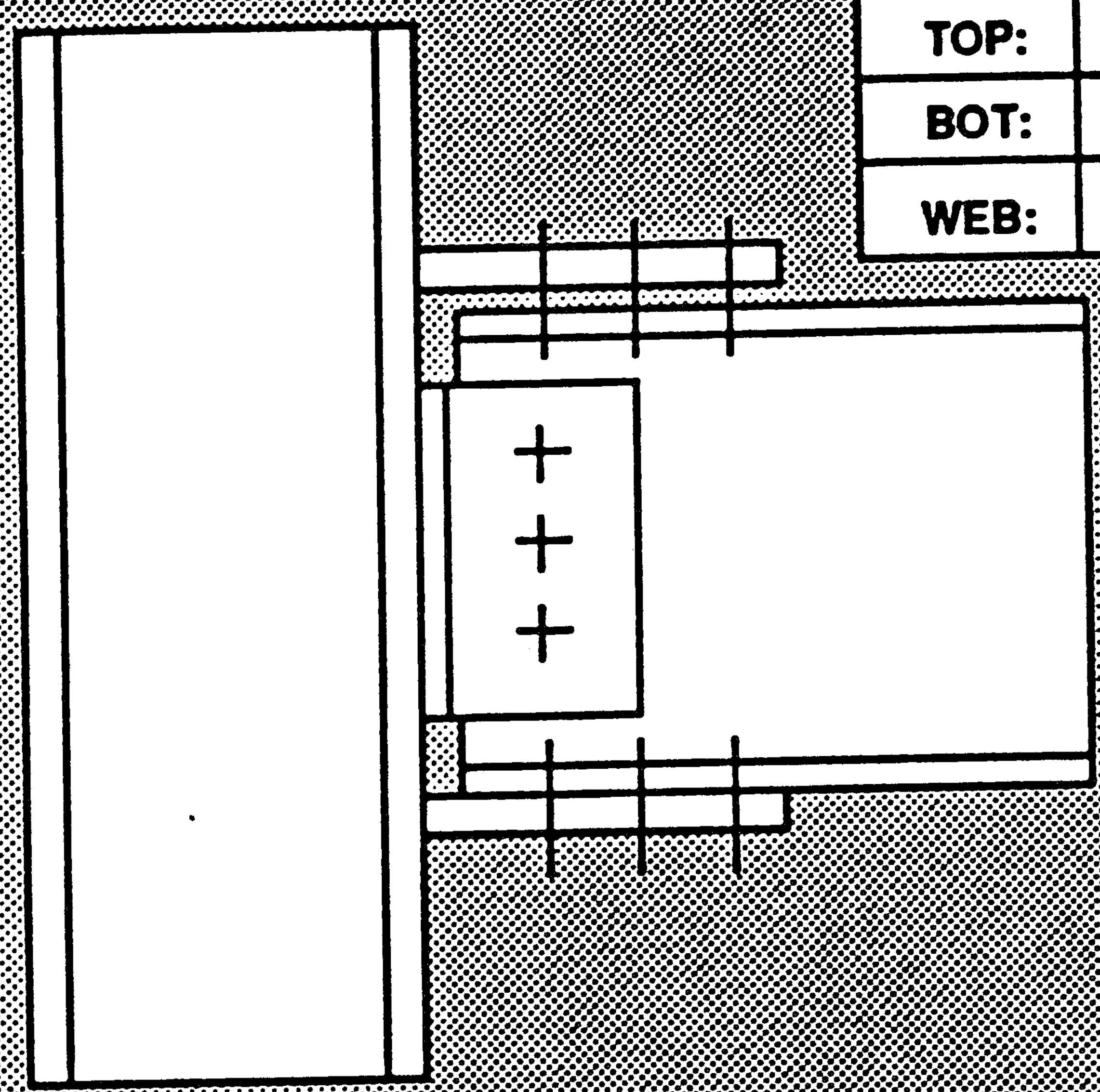
CONNECTION NAME: ***TOP AND BOTTOM PLATES WITH SHEAR TEE***

TYPE: ***1*** ORIENTATION: ***FLANGE*** SHEET: 3 of 3

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE PLATE	SHOP WELD	FIELD BOLT
BOT:	FLANGE PLATE	SHOP WELD	FIELD BOLT
WEB:	TEE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		3	
FAB. EASE		3	
MAT. COST		2	
EREC. COST			4
EREC. EASE			4
SAFETY			5

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

F: Since the column flange is subject to mill tolerances on out-of-square with the web, position long moment plates with reference to the theoretical column web center line to assure good field fit-up.

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

F: Extra web material, a tee instead of a plate, may not be necessary but aids in alignment of parts during fabrication.

E: Misalignment on short moment plates can be accommodated by using oversized holes in the moment plate and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

Figure A.8: plates_tee Connection Information Form

1. TITLE BLOCK tees_plate

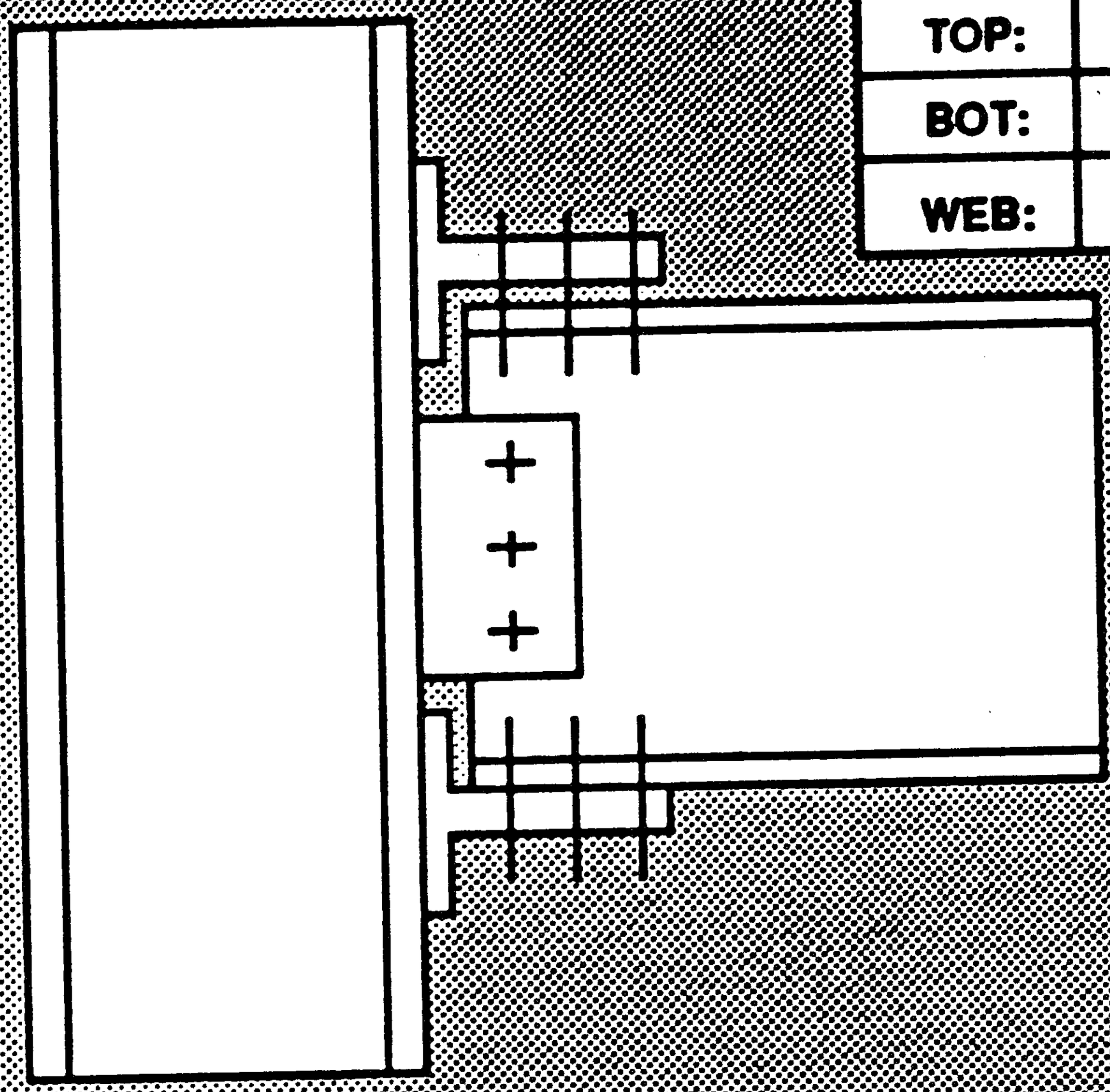
CONNECTION NAME: ***TOP AND BOTTOM TEES WITH SHEAR PLATE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 1 of 3

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	TEE	SHOP WELD	FIELD BOLT
BOT:	TEE	SHOP WELD	FIELD BOLT
WEB:	WEB PLATE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		2	
FAB. EASE		3	
MAT. COST		2	
EREC. COST			4
EREC. EASE			4
SAFETY			5

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

F: Tees are relatively expensive and may not be available from the mill unless they are ordered in sufficient tonnage.

E: Misalignment on connections can be accommodated by using oversized holes in the leg of the tee and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

Figure A.9: tees_plate Connection Information Form

1. TITLE BLOCK tees_angle

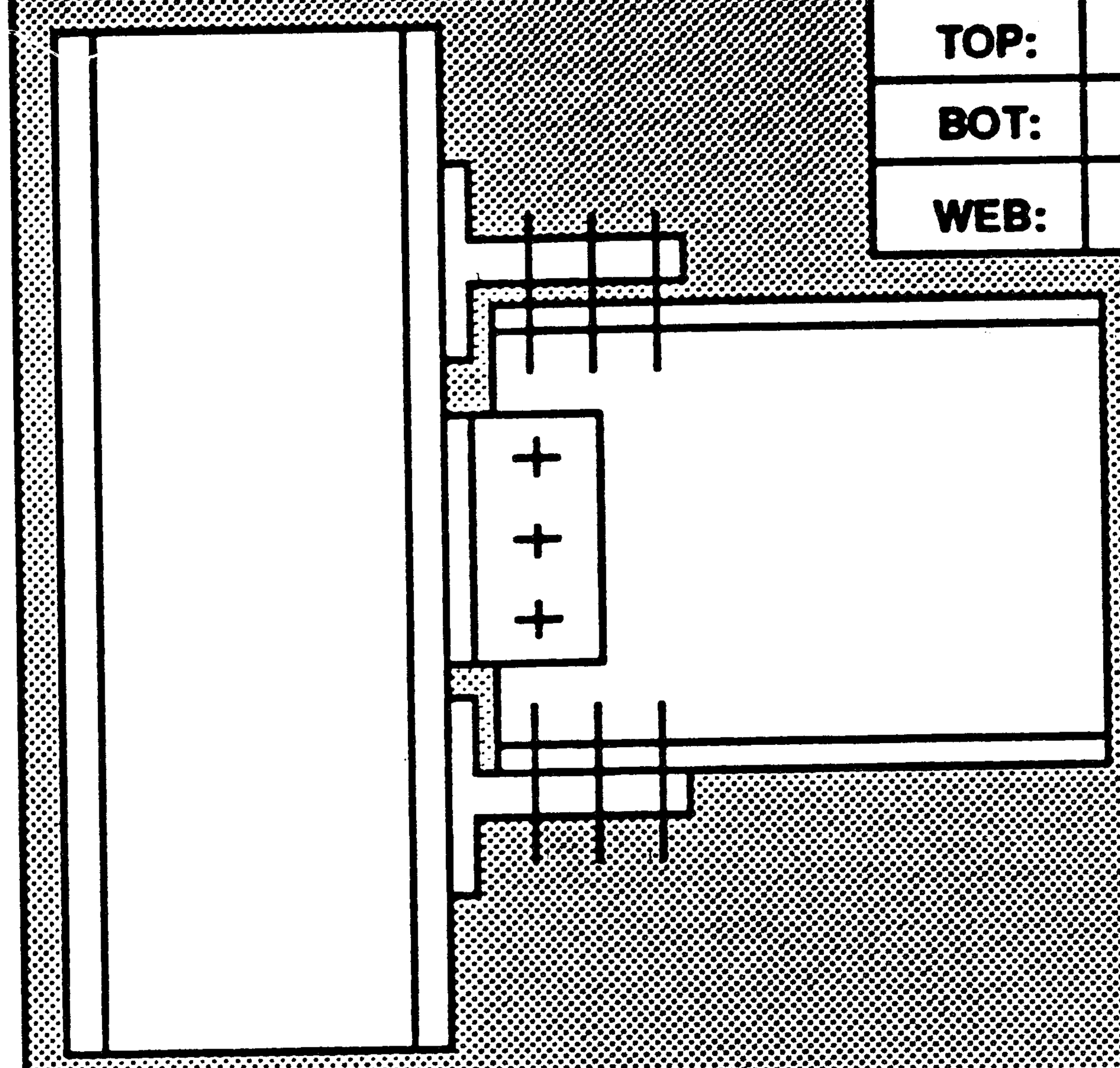
CONNECTION NAME: ***TOP AND BOTTOM TEES WITH SHEAR ANGLE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 2 of 3

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	TEE	SHOP WELD	FIELD BOLT
BOT:	TEE	SHOP WELD	FIELD BOLT
WEB:	ANGLE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		2	
FAB. EASE		3	
MAT. COST		1	
EREC. COST			4
EREC. EASE			4
SAFETY			5

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

F: Tees are relatively expensive and may not be available from the mill unless they are ordered in sufficient tonnage.

F: Extra web material, an angle instead of a plate, may not be necessary but aids in alignment of parts during fabrication.

E: Misalignment on connections can be accommodated by using oversized holes in the leg of the tee and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

Figure A.10: tees_angle Connection Information Form

1. TITLE BLOCK tees_tee

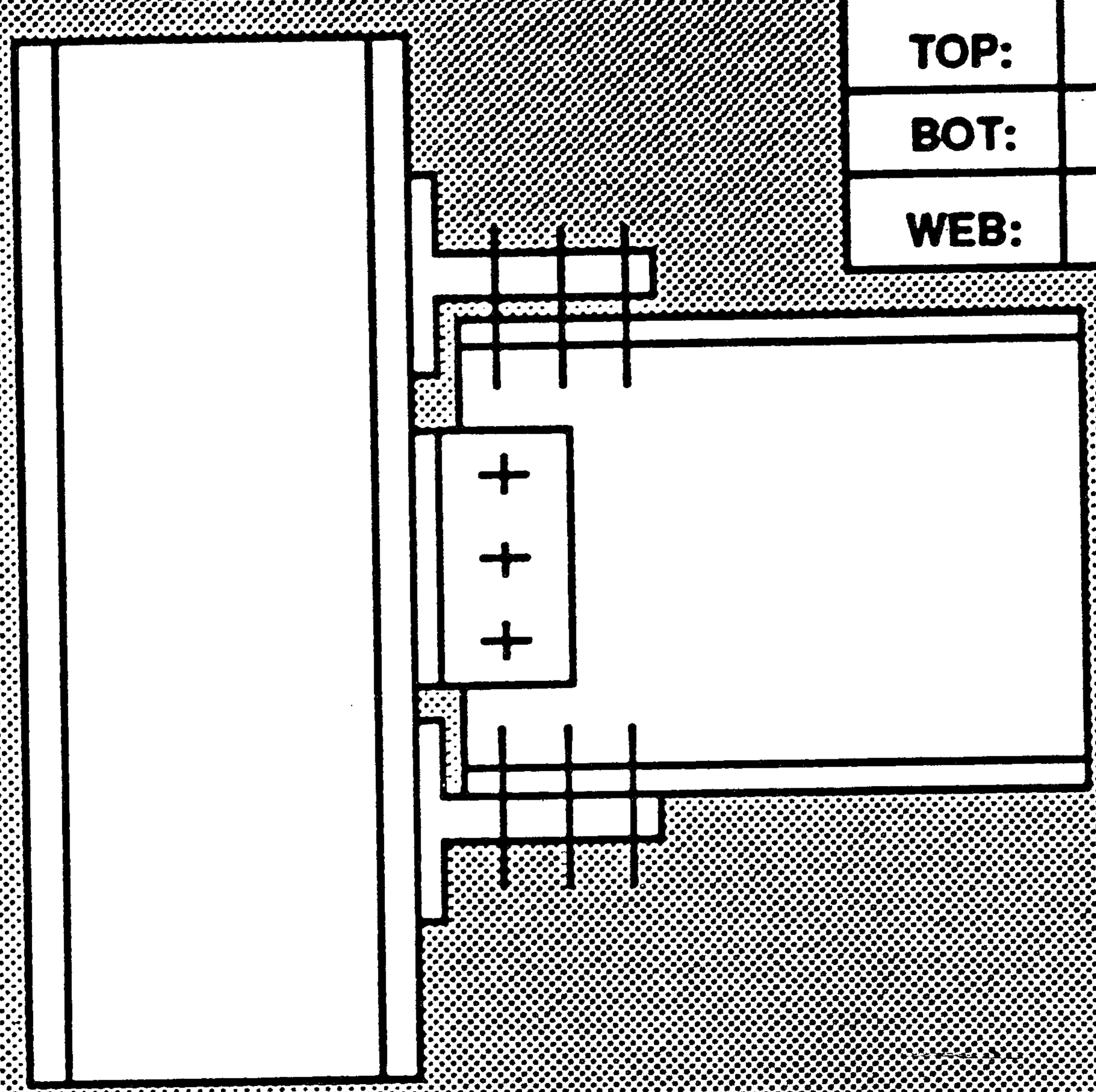
CONNECTION NAME: ***TOP AND BOTTOM TEES WITH SHEAR TEE***

TYPE: *1* ORIENTATION: ***FLANGE*** SHEET: 3 of 3

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	TEE	SHOP WELD	FIELD BOLT
BOT:	TEE	SHOP WELD	FIELD BOLT
WEB:	TEE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		2	
FAB. EASE		3	
MAT. COST		1	
EREC. COST			4
EREC. EASE			4
SAFETY			5

5. COMMENTS:

D: Check if column stiffeners are required. If stiffeners are required, they need not exceed one-half the column depth when the beam is on one side only.

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

F: Tees are relatively expensive and may not be available from the mill unless they are ordered in sufficient tonnage.

F: Extra web material, a tee instead of a plate, may not be necessary but aids in alignment of parts during fabrication.

E: Misalignment on connections can be accommodated by using oversized holes in the leg of the tee and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

Figure A.11: tees_tee Connection Information Form

1. TITLE BLOCK web_type1_welds

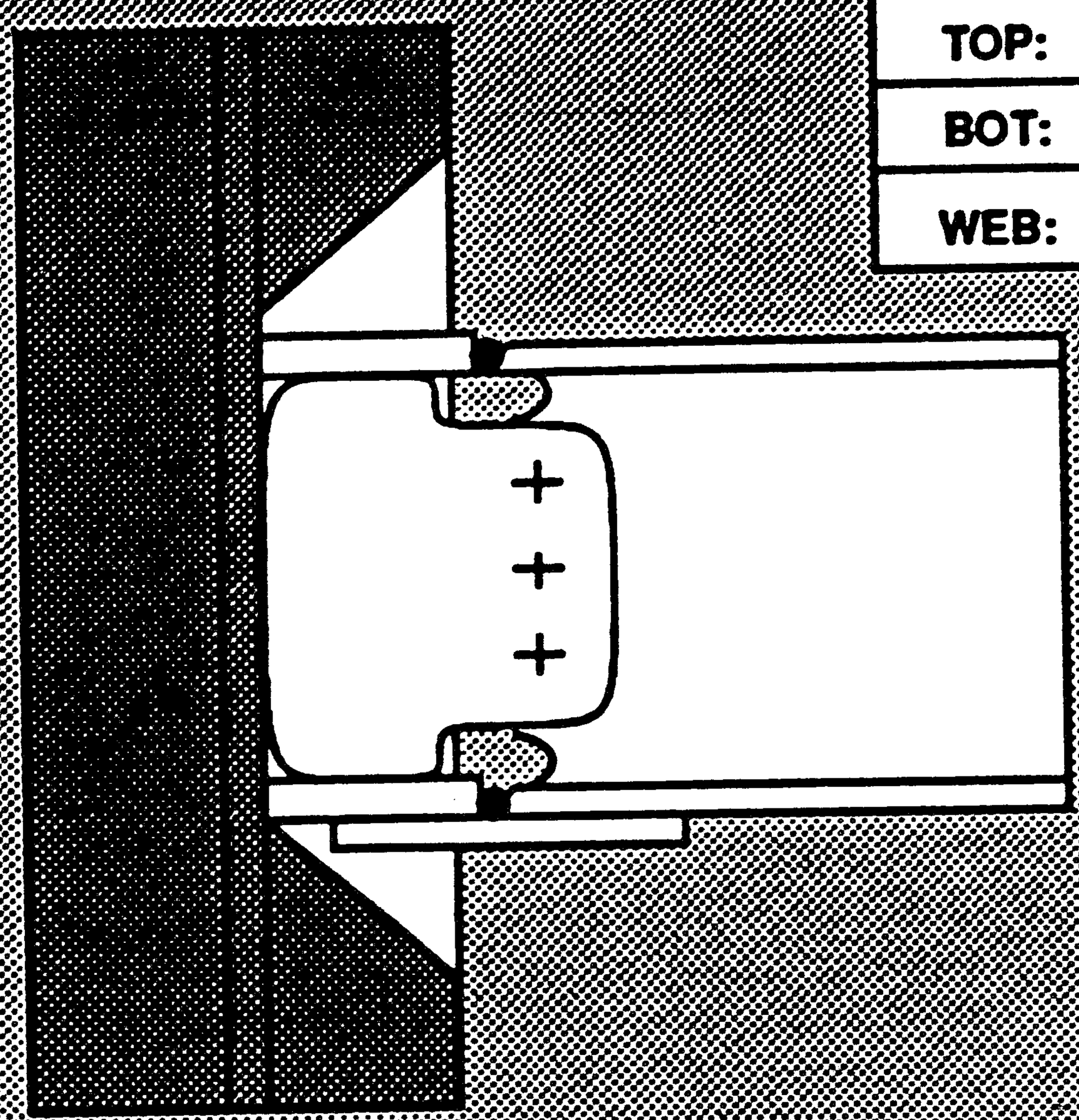
CONNECTION NAME: ***DIRECT FLANGE WELD WITH SHEAR PLATE***

TYPE: ***1*** ORIENTATION: ***WEB*** SHEET: 1 of 2

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	WELD PLATE	SHOP WELD	FIELD WELD
BOT:	WELD PLATE	SHOP WELD	FIELD WELD
WEB:	WEB PLATE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	4		
RELIABILITY	2		
VERSATILITY	2		
FAB. COST		2	
FAB. EASE		2	
MAT. COST		2	
EREC. COST			3
EREC. EASE			2
SAFETY			3

5. COMMENTS:

D: Full penetration groove welds should be avoided, since they may contribute to lamellar tearing.

F: The top and bottom plates should be the same thickness as the beam flanges. An additional plate, fastened to the lower flange plate, serves as a seat plate to aid in erection.

F: Allowances must be made for weld shrinkage, beams should be fabricated longer than required by the amoûnt of the expected shrinkage. A typical rolled section will shrink about 1/16 in. per welded joint.

E: Horizontal short slotted holes should be used in the web plate to aid in erection. Use one std. hole near the centroid of the beam to maintain frame alignment. Some fabricators will not like using different size punches this an extra operation which costs extra.

E: The connection should be able to withstand the construction loads without having the flanges welded since the welding usually takes place much later than the erection of the member.

Figure A.12: web_type1_welds Connection Information Form

1. TITLE BLOCK web_type1_plates

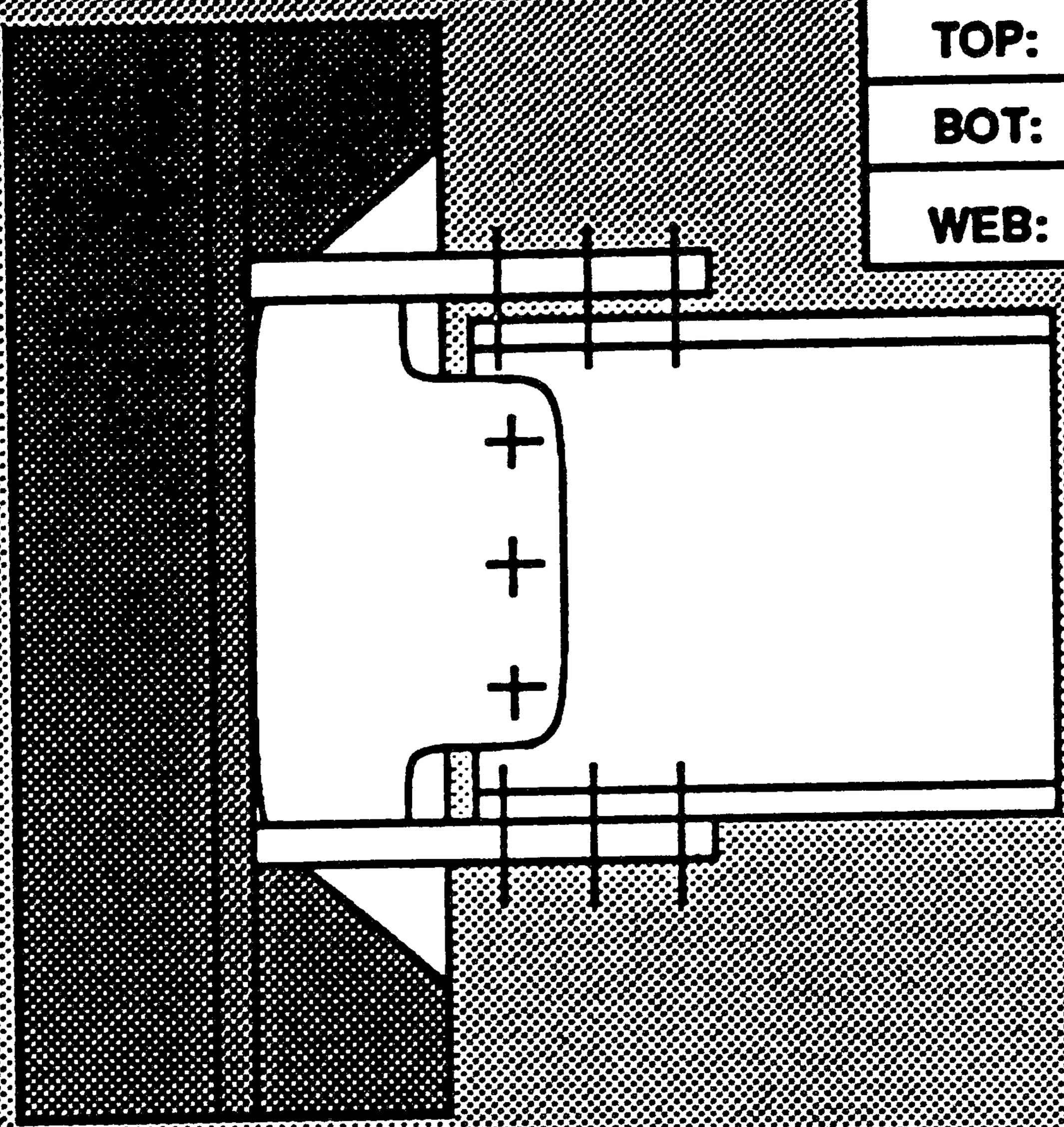
CONNECTION NAME: *TOP AND BOTTOM PLATES WITH SHEAR PLATE*

TYPE: *1* ORIENTATION: *WEB* SHEET: 2 of 2

2. CONN DETAIL TABLE

	DETAIL MAT.	COL. FAST.	BEAM FAST.
TOP:	FLANGE PLATE	SHOP WELD	FIELD BOLT
BOT:	FLANGE PLATE	SHOP WELD	FIELD BOLT
WEB:	WEB PLATE	SHOP WELD	FIELD BOLT

3. PROFILE VIEW



4. RATING FACTORS TABLE

	DESIGN	FAB.	EREC.
STRENGTH	4		
STIFFNESS	3		
RELIABILITY	3		
VERSATILITY	2		
FAB. COST		2	
FAB. EASE		2	
MAT. COST		2	
EREC. COST			2
EREC. EASE			3
SAFETY			3

5. COMMENTS:

F: Provide 3/8" clearance to swing the beam into place. Shims should be used at the top flange to fill any gaps.

E: Misalignment on short moment plates can be accommodated by using oversized holes in the moment plate and standard holes in the beam.

E: Field bolts must be long enough to accommodate any shim allowances. Washers should be available to accommodate less than anticipated grip if shims are less than 3/8".

E: Beam should be cut short so that all bolts will be outside the column flange. This simplifies erection of the beam and allows the use of an impact wrench to tighten all bolts.

Figure A.13: web_type1_plates Connection Information Form

B. Listing of Implemented Relationships

This appendix acts as a complement to the description of the agent relationships presented in Chapter 4. Section 4.2.1.2 describes the template and components of the relationships. All relationships are considered to be bi-directional therefore not all the issues in the network need to have relationships originating from them. The relationship groups are:

- Strength
- Stiffness
- Versatility
- Reliability
- Fabrication Cost
- Fabrication Ease
- Material Cost

The reader should note that issue of Lifecycle Cost for the designer was not considered in the implemented prototype of DFI. Table B.1 summarizes the listing of the coded relationships in DFI.

B.1 Strength Relationships

```
relation(performance,
    [agent_issue(designer, strength, functional, [type_conn]),
     agent_issue(fabricator, fab_cost, components, [shop_ops]) ]).

relation(performance,
    [agent_issue(designer, strength, functional, [type_conn]),
     agent_issue(fabricator, fab_ease, components, [shop_ops]) ]).

relation(performance,
    [agent_issue(designer, strength, components, [detail_mat]),
    agent_issue(erector, safety, components, [detail_mat, field_ops]) ]).

relation(performance,
    [agent_issue(designer, strength, functional, [detail_mat]),
     agent_issue(erector, erec_ease, fasteners, [field_ops]) ]).
```

```
relation(expense,
    [agent_issue(designer, strength, components, [detail_mat]),
     agent_issue(fabricator, mat_cost, components, [detail_mat]) ]).

relation(expense,
    [agent_issue(designer, strength, functional, [detail_mat]),
     agent_issue(erector, erec_cost, fasteners, [field_ops]) ]).
```

B.2 Stiffness Relationships

```
relation(performance,
    [agent_issue(designer, stiffness, functional, [type_conn, detail_mat]),
     agent_issue(fabricator, fab_cost, components, [detail_mat, shop_ops]) ]).

relation(performance,
    [agent_issue(designer, stiffness, functional, [type_conn, detail_mat]),
     agent_issue(fabricator, fab_ease, components, [detail_mat, shop_ops]) ]).

relation(performance,
    [agent_issue(designer, stiffness, components, [detail_mat]),
     agent_issue(erector, safety, components, [detail_mat, field_ops]) ]).

relation(performance,
    [agent_issue(designer, stiffness, functional, [detail_mat]),
     agent_issue(erector, erec_ease, fasteners, [field_ops]) ]).

relation(expense,
    [agent_issue(designer, stiffness, components, [detail_mat]),
     agent_issue(fabricator, mat_cost, components, [detail_mat]) ]).

relation(expense,
    [agent_issue(designer, stiffness, components, [detail_mat]),
     agent_issue(erector, erec_cost, fasteners, [field_ops]) ]).
```

B.3 Versatility Relationships

```
relation(performance,
    [agent_issue(designer, versatility, components, [type_conn]),
     agent_issue(fabricator, fab_cost, components, [detail_mat]) ]).

relation(performance,
    [agent_issue(designer, versatility, components, [type_conn, detail_mat]),
     agent_issue(fabricator, fab_ease, components, [shop_ops]) ]).
```

```
relation(performance,
    [agent_issue(designer, versatility, components, [detail_mat]),
     agent_issue(erector, erec_cost, fasteners, [field_ops]) ]).

relation(performance,
    [agent_issue(designer, versatility, components, [detail_mat]),
     agent_issue(erector, erec_ease, fasteners, [field_ops]) ]).
```

B.4 Reliability Relationships

```
relation(performance,
    [agent_issue(designer, reliability, fasteners, [detail_mat]),
     agent_issue(fabricator, fab_cost, fasteners, [shop_ops]) ]).

relation(performance,
    [agent_issue(designer, reliability, fasteners, [detail_mat]),
     agent_issue(fabricator, fab_ease, fasteners, [shop_ops]) ]).

relation(performance,
    [agent_issue(designer, reliability, fasteners, [detail_mat]),
     agent_issue(erector, erec_cost, fasteners, [field_ops]) ]).

relation(performance,
    [agent_issue(designer, reliability, fasteners, [detail_mat]),
     agent_issue(erector, erec_ease, fasteners, [field_ops]) ]).
```

B.5 Fabrication Cost Relationships

```
relation(expense,
    [agent_issue(fabricator, fab_cost, components, [detail_mat]),
     agent_issue(erector, safety, components, [detail_mat]) ]).

relation(expense,
    [agent_issue(fabricator, fab_cost, components, [detail_mat, shop_ops]),
     agent_issue(erector, erec_cost, fasteners, [field_ops]) ]).

relation(expense,
    [agent_issue(fabricator, fab_cost, fasteners, [detail_mat, shop_ops]),
     agent_issue(erector, erec_ease, fasteners, [field_ops]) ]).
```

B.6 Fabrication Ease Relationships

```
relation(expense,
    [agent_issue(fabricator, fab_ease, components, [detail_mat, shop_ops]),
     agent_issue(erector, safety, components, [detail_mat, field_ops]) ]).

relation(expense,
    [agent_issue(fabricator, fab_ease, fasteners, [shop_ops]),
     agent_issue(erector, erec_cost, fasteners, [field_ops]) ]).

relation(expense,
    [agent_issue(fabricator, fab_ease, fasteners, [shop_ops]),
     agent_issue(erector, erec_ease, fasteners, [field_ops]) ]).
```

B.7 Material Cost Relationships

```
relation(expense,
    [agent_issue(fabricator, mat_cost, components, [detail_mat]),
     agent_issue(erector, erec_cost, components, [detail_mat]) ]).

relation(expense,
    [agent_issue(fabricator, mat_cost, components, [detail_mat]),
     agent_issue(erector, erec_ease, components, [detail_mat]) ]).

relation(expense,
    [agent_issue(fabricator, mat_cost, components, [detail_mat]),
     agent_issue(erector, safety, components, [detail_mat, field_ops]) ]).
```

Table B.1: Listing of Implemented Agent Relationships

AGENT 1	ISSUE 1	ASPECT 1	KEYWORDS 1	RELATION	AGENT 2	ISSUE 2	ASPECT 2	KEYWORDS 2
Designer	strength	functional	type_conn	performance	Fabricator	fab. cost	components	shop_ops
Designer	strength	functional	type_conn	performance	Fabricator	fab. ease	components	shop_ops
Designer	strength	components	detail_mat	performance	Erector	safety	components	detail_mat, field_ops
Designer	strength	functional	detail_mat	performance	Erector	erec. ease	fasteners	field_ops
Designer	strength	components	detail_mat	expense	Fabricator	mat. cost	components	detail_mat
Designer	strength	functional	detail_mat	expense	Fabricator	erec. cost	fasteners	field_ops
Designer	stiffness	functional	type_conn, detail_mat	performance	Fabricator	fab. cost	components	detail_mat, shop_ops
Designer	stiffness	functional	type_conn, detail_mat	performance	Fabricator	fab. ease	components	detail_mat, shop_ops
Designer	stiffness	components	detail_mat	performance	Erector	safety	components	detail_mat, field_ops
Designer	stiffness	functional	detail_mat	performance	Erector	erec. ease	fasteners	field_ops
Designer	stiffness	components	detail_mat	performance	Fabricator	mat. cost	components	detail_mat
Designer	stiffness	components	detail_mat	performance	Erector	erec. cost	fasteners	field_ops
Designer	versatility	components	type_conn	performance	Fabricator	fab. cost	components	detail_mat
Designer	versatility	components	type_conn, detail_mat	performance	Fabricator	fab. ease	components	shop_ops
Designer	versatility	components	detail_mat	expense	Erector	erec. cost	fasteners	field_ops
Designer	versatility	components	detail_mat	expense	Erector	erec. ease	fasteners	field_ops
Designer	reliability	fasteners	detail_mat	performance	Fabricator	fab. cost	fasteners	shop_ops
Designer	reliability	fasteners	detail_mat	performance	Fabricator	fab. ease	fasteners	shop_ops
Designer	reliability	fasteners	detail_mat	performance	Erector	erec. cost	fasteners	field_ops
Designer	reliability	fasteners	detail_mat	performance	Erector	erec. ease	fasteners	field_ops
Fabricator	fab. cost	components	detail_mat	expense	Erector	safety	components	detail_mat
Fabricator	fab. cost	components	detail_mat, shop_ops	expense	Erector	erec. cost	fasteners	field_ops
Fabricator	fab. cost	fasteners	detail_mat, shop_ops	expense	Erector	erec. ease	fasteners	field_ops
Fabricator	fab. ease	components	detail_mat, shop_ops	expense	Erector	safety	components	detail_mat, field_ops
Fabricator	fab. ease	fasteners	shop_ops	expense	Erector	erec. cost	fasteners	field_ops
Fabricator	fab. ease	fasteners	shop_ops	expense	Erector	erec. ease	fasteners	field_ops
Fabricator	mat. cost	components	detail_mat	expense	Erector	erec. cost	components	detail_mat
Fabricator	mat. cost	components	detail_mat	expense	Erector	erec. ease	components	detail_mat
Fabricator	mat. cost	components	detail_mat	expense	Erector	safety	components	detail_mat, field_ops

C. Listing of the Subissue Decomposition

This appendix acts as a complement to the textual description of the eight identified subissues presented in Chapter 4. Sets of possible characteristics for each subissue are listed. The subissues are*:

- Structural Concept
- Structural Detailing
- Design Methods
- Fabrication Procedures
- Construction Procedures
- Shipping Operations
- Physical Components
- Material Properties

C.1 Structural Concept

1. Building Topology
   - Structural Frame
     - Moment-Resting Frame
     - Braced Frame
     - Mixed Construction
   - Plan View
     - Regular
     - Irregular
   - Elevation View
     - Regular
     - Irregular
   - Floor Spacing

* The numbered items listed below each subissue are the characteristics. The other subitems decompose the characteristics into quantifiable metrics or variables.

2. Connection Designs (see Item C.2)

C.2 Structural Detailing

1. Connection Designs
   - Connection Components
   - Connection Type
     - Fully Rigid
     - Partially Rigid
     - Simple
   - Moment - Curvature Relationships
   - Bolt Properties
     - Type
     - Number
     - Spacing
     - Location
     - Surface Condition
     - Hole Type
     - Diameter
     - Cross Sectional Area
     - Allowable Stress
   - Weld Properties
     - Type
     - Location
     - Electrode Strength
     - Length
     - Throat
2. Other Details
   - Openings
   - Stiffener Details

C.3 Design Methods

1. Design Codes
   - ASD
   - LRFD
   - Plastic
2. Analysis & Assumptions
   - Frame Behavior
   - Connection Behavior
   - Effective Structural Stiffness
   - Critical Loading Combinations
   - Finite Element Analysis

C.4 Construction Procedures

1. Construction Schedule
   - Fabrication Schedule
   - Erection Schedule
   - Stability Analysis
2. Field Operations
   - Fastening Method
     - Fastener
     - Location
   - Temporary Bracing
   - Falsework

C.5 Fabrication Procedures

1. Construction Schedule
2. Shop Operations
   - Cutting

- Drilling
- Punching
- Welding
- Shop Assembly
- "Crane & Chain"
- Jig Set-Up

C.6 Shipping Operations

1. Shipping Schedule
   - Material Arrival
   - Material Departure
   - Delivery Deadline
2. Shipping Methods
   - Train
   - Truck
   - Safety Permits
   - Handling
   - Stability Set-Up

C.7 Physical Components

1. Structural Members
   - Member Type
     - Columns
     - Beams
     - Braces
     - Shear Walls
     - Cores
   - Member Properties

- Structural Function
- Geometric Dimensions
- Tolerances (Mill, Fabrication, Erection and Construction)
- Material Properties

2. Connection Designs
   - Connection Components
     - Detail Material (Top, Bottom and Web)
     - Fastener Type (Beam End and Column End)
   - Component Properties
     - Geometric Dimensions
     - Tolerances (Mill, Fabrication, Erection and Construction)
     - Material Properties

C.8 Material Properties

1. Strength Related
   - Tensile
     - Yield
     - Ultimate
   - Compressive
     - Yield
     - Ultimate
2. Serviceability Related
   - Weldability
   - Corrosion Properties
   - Toughness
   - Ductility
   - Hardness
   - Resilience
   - Tolerances

Vita

Marcello "Marc" Barone was born in Montevideo, Uruguay on June 29, 1966, the son of Francesco and Rosina Barone. Marc became a naturalized citizen of the United States in 1985.

He received his Bachelor of Science in Civil Engineering from the University of Maryland in May, 1988. He then continued on to graduate school and received his Master of Science degree in Civil Engineering from Lehigh University in June, 1990.

While at the University of Maryland, Marc was inducted into Chi Epsilon, National Civil Engineering Honor Society; Tau Beta Pi National, Engineering Honor Society; Omicron Delta Kappa, National Leadership Honor Society; and awarded the American Society of Civil Engineers Outstanding Senior Award. At Lehigh, Marc has served as an ATLSS Center Scholar concentrating on the integration of design and construction systems through the development and implementation of the Designer-Fabricator Interpreter. The material in this thesis is part of the research for the National Science Foundation sponsored Center for Advanced Technology for Large Structural Systems (ATLSS).

Marc has accepted employment as a research engineer for Bechtel National, Inc. working in the Engineering and Construction Technologies Group. He is a member of the American Society of Civil Engineers, the Association of Computing Machinery, SIGART, and the American Association for Artificial Intelligence.