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**Structural Design of Tall Buildings Knowledge
Acquisition Study Report**

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Structural Design of Tall Buildings

Knowledge Acquisition Study Report

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Abstract

A knowledge acquisition study in the domain of tall building design was conducted. Domain experts, five structural engineers and one architect, were interviewed. The experts were asked a set of questions divided into design process and design content questions, and asked to simulate a design scenario. The experts were also shown, and asked to critique, a prototype implementation of a design grammar. In this report we describe our objectives in gathering domain knowledge, our techniques for analyzing the interviews, and the resulting domain knowledge acquired from the analysis of the interviews.

1 Introduction

Architecture and structural engineering are sharply divided disciplines in academia. However, in the practice of tall building design architecture and structural engineering are tightly interwoven. The study of the design process and the development of design tools, performed in an academic setting, can benefit in both accuracy and usefulness by inspecting and discussing the design process with practicing designers. This paper describes a knowledge acquisition study performed as part of a research project aimed at both understanding recent tall building design practice and developing tools that help in methodically exploring potential designs. This recounting of the study includes a description of the data collection and analysis methods, a discussion of the majority and dissenting opinions, and a discussion of how current design practice can be modeled by, and benefit from, computer-aided-engineering (CAE) tools.

1.1 Motivation

Research into engineering design methodology has focused on modeling the design process with the dual aims of enlarging the scope of design education and developing tools to assist practitioners as they design. Whether the aim is to assist design education or design practice, the focal activity is the process of practicing designers. Therefore, the practitioner is the primary moderator of what constitutes current design practice. Practicing designers have a wealth of experience from which to describe what information is relevant to the design process, how their design process proceeds, and how the design process can be improved. They are the researchers' greatest resource in determining what information forms the basis of the design problem, how this information is transformed during the design process, and under what criteria these transformations take place. For these reasons we felt it necessary to interview a number of practicing designers before attempting the development of a design theory or process model. We felt it necessary that any generalizations we may put forth be based on experience, even if that experience is not directly our own.

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1.2 Purpose

The purpose of this knowledge acquisition study has been to elicit information on the architectural and structural design of tall buildings. The garnered information forms the basis of hypotheses to be used in modeling the design process. Although practicing designers have a great deal of first-hand experience with design, their main activity is participating in the design process itself rather than developing models of the design process or computer representations advantageous for such models. They have vast experience in performing design and presenting the results of the design process to clients and other participants in the process. However, they have not necessarily had the time or interest to generalize a design methodology from their individual design cases. Furthermore, today's experienced designers began their academic education at a time when design research and computer science were at a much more limited stage of development. Therefore, although the designer may be highly skilled at performing design and communicating the results, they are likely to be less skilled at theorizing and testing computational models of the design process and devising machine representations for such models. Nevertheless, we rely on their ability to retrospectively describe the design process phenomenologically. Therefore, our purpose was to elicit their knowledge so that we may develop and test models of the design process and appropriate representations.

Architectural and structural design are both highly spatial disciplines; as a design develops, both spatial and symbolic information is generated and refined. In the past, and even today, designers relied on drawings and written specifications to separately communicate these portions of the design. The representation and integration of spatial and symbolic information is a focus of much design research. Therefore, eliciting information on how these two types of data are utilized in practice was a central focus of this study.

The purpose of the study can be broadly divided into eliciting information about the organization and control of the design process and eliciting information about the content of the transformations which generate the designs. The design process questions had three general goals. First, to understand the definition and organization of the stages of the design process; to map out who does what and when. Second, to determine what information is available at the beginning of each stage of the design process; what are the problem statements for these stages or subproblems, and how the decisions of one design agent affects other agents. The third area of interest was how the spatial aspects of the design are developed and how these spatial aspects are used by the designer as clues and constraints to further the design state. Many of the questions focused on how the structural engineer processes the spatial information provided by the architect's drawings and infers what structural systems fit within the architectural volumes while providing the most economical support for lateral and gravity loads.

In more detail, the purpose of this study has been to determine:

- how the participants in the design process interact in developing a design, i.e., what information is provided to whom and when;
- what control methods guide the design process, e.g. top-down, bottom-up, opportunistic, etc.;
- what spatial and functional information is needed by each participant at the start of various design phases and how this information is used;
- what spatial and functional information is used in selecting and placing structural systems;

- what spatial and functional information is used in the parametric design of structural systems; and
- how and when computers are currently used during the design process.

An additional aim of this study was to explore the validity of generalizations for a design discipline based on producing one-of-a-kind design objects which take many years to complete and which involve parties who may never work together again.

1.3 Tall Building Design

Tall building design has undergone a rapid evolution over the past few decades in response to changing economic, aesthetic and sociological demands. Increased demand for large interior spaces and a move articulated exterior forms have made the conventions of the initial skyscrapers inappropriate for current tall buildings. From the inception of the tall building at the turn of the century, the conventional structural systems were based first on the bearing wall and then on the beam-column frame system. The Empire State Building, for example, was built in the early 1930s to a height of 120 stories using a steel rigid frame. Yet, for buildings with large height-to-width aspect ratios and reasonable bay sizes, rigid frames are prone to excessive deflections due to the bending of these members. Even for building of much more modest heights, the bearing wall becomes untenably thick when used to resist gravity loads, and is therefore reserved for resisting shear forces. More importantly, present tall building design and construction conditions differ from earlier conditions in three respects. First, larger column spacings are expected in modern office buildings. When the Empire State Building was built a column spacing of 20 feet was acceptable. Today, column spacing in offices is expected to be 40 feet or more. Second, interior partitions are constructed as temporary elements of a building today, and hence cannot be expected to contribute to the rigidity of the structure. Third, the exterior cladding of modern glass curtain walls, as opposed to the stone cladding of earlier buildings, also does not contribute to the rigidity of the structural system. Due to these characteristics of earlier tall buildings, their actual lateral drift was often markedly less than the computed value used in design. However, in contemporary construction the frame must stand entirely on its own and calculated drifts are close to the building's actual performance.

The sizing of members in a frame structure is guided by two factors: gravity loads and their effects, and lateral loads and their effects. Given a building's dimensions, the gravity effects cannot be eliminated by altering the placement or sizing of members. However, the results of lateral load effects *can be* affected by the structural configuration. In a typical frame structure, the lateral drift is itself a sum of three factors: bending moments in the girders contribute almost two thirds of the total deflection; bending moments in the columns contribute almost one sixth, and axial forces in the columns due to overturning moments contribute about one fifth [Khan 67]. The first two effects collectively represent the frame action whereas the last effect is based on cantilever action. If the plane frames were replaced by infinitely stiff plates the frame action would be eliminated. If this rigidity could be achieved in practice, then lateral drift would be reduced to about one fifth the drift of a comparable frame. This rigidity can be approached by structural systems which, rather than acting as rigid frames, act like rigid boxes or tubes composed of the perimeter faces. An objective of structural design of tall buildings since the mid 1960s has been to develop structural systems that make the building act as a unit cantilevered from the ground rather than as a series of frames.

The development of the building structure as a cantilever began at a time when the International Style of architecture was in vogue, and building forms were basically prismatic. The typical building plan was a regular geometric shape, usually a square or a rectangle. The building form was then a simple upward projection of the rectangular plan. This geometric elegance and discipline of architecture made it easier to treat the perimeter of the building as the rigid plates of a thin-walled tube. As architectural styles shifted away from the rectangular plan and the straight sides of the International Style, the structural engineer was confronted by more articulated building forms. The engineer was forced to adapt the structural tube and to develop new systems in response to the new architectural forms.

A more competitive real-estate market also encouraged architects and engineers to alter the building form and interior layout to attract occupants. The desires of the occupants for expanded views, flexibility of partitions and ideal floor dimensions became the mandate of the architect and engineer. These sociological constraints became as important as the constraints imposed by engineering mechanics. This more complex design problem, the highly articulated architecture and the need to subordinate engineering efficiency to the desires of the real-estate market, was the focus of the domain knowledge we hoped to gain from this study.

1.4 A Design Grammar for Tall Buildings

In two thirds of the interviews, a portion of the time was spent viewing and critiquing the computer implementation of a prototype design system. This design system follows the spatial grammar formalism; it is a production system using a representation that integrates a geometric model and symbolic labels. In our case the representation is a boundary solid model with object-attribute-value labels. These two portions of the representation are integrated by using a topological object of the solid model such as a face, vertex or complete solid as the first field of the label. This representation is advantageous for expressing the highly spatial character of buildings along with the necessary non-spatial attributes such as member forces, material properties, etc. Furthermore, this formalism allows for the pictorial display of the spatial portion of the design state during the design process.

The grammar formalism is a means for specifying a design space via discrete productions, or rules, used to generate designs. The productions are *IF - THEN* rules whose condition portion inspects the current design state to determine whether the production's condition applies to the current context. The action portion of the rule alters the current design state if the condition matches this state. As a specification language, the grammar compositionally describes all valid designs. Unlike a conventional expert system, there is no inference engine performing conflict resolution to determine which of the candidate rules to execute. In generating a single design, the interpreter identifies a candidate rule and the user chooses to execute or not to execute it. The discrete nature of this process allowed the subjects to critique individual design transformations and to see the effect of each of the transformations.

The prototype shown to the subjects begins from a simple client brief containing site dimensions, expected occupancy types, required square footage for each occupancy type, and site climatic characteristics. The productions were written as parametric expressions; using variables for geometric values, for occupancy type information and for engineering properties such as material strength and member forces. A parametric grammar allows the individual productions to respond to the individual character of each design. Thus, the resulting designs are generated in response to the client's requirements as embodied in the client brief.

2 Study Procedure

The procedure followed in the study involved interviewing the subjects and analyzing the recorded interviews. The interview sessions were organized into four sections: structured interview discussing design process questions; design scenario simulations; structured interview discussing design content questions; and discussion of a design grammar prototype. The design process questions sought to uncover the organization and concerns of the conceptual stages of building design and how the different agents interact and affect each other's decisions. The design content questions were aimed at gathering information on the objectives and constraints of the more specifically structural design tasks. These content questions explored the mechanisms of the individual transformations which make up the layout and parametric design stages. The design simulations were an opportunity to view the evolution of the design state, or at least an approximation of this evolution; they allowed the experienced designers to explain their design process by doing it rather than by subjective generalization. Finally, the discussion of the prototype design aid presented a logical design process whose specific state transformations could be critiqued for logical consistency and realism. A session itinerary, and lists of questions and design problems, is included as Appendix A.

The interviewed subjects are all experienced in designing tall buildings. Their experience ranges from twenty five to forty years in their profession. Five of the subjects interviewed are structural engineers, and are either principals or senior partners in their engineering firm. The sixth subject is an architect who is likewise a design partner in his firm. Each of the six interviews completed the two structured interview portions, four of the interviews included a discussion of the prototype and three interviews included the design scenario simulations. All but one of the interviews was recorded on videotape, and each design scenario simulation was transcribed from tape to text. The interview sessions were conducted in the subjects' offices and lasted from two to seven hours.

2.1 Domain Questions

The questions used during the structured interview portions were constructed to elicit information about the design process from as early a stage as possible, that is, from the very beginning of the designers' participation in the process. Also, all of the questions were constructed as open-ended queries, rather than as multiple choice or affirm-deny questions, so as to gather as much information as possible and not to prejudice the respondents in any way. The subjects were given a list of questions and these questions were then asked aloud by the interviewer. The domain process questions were on a single sheet placed in front of the subjects, but after they answered the first question the subjects often neglected the printed sheet and followed their own organization of describing the design problem. The subjects provided long responses which touched on a variety of topics, often unexpected. The interviewer steered the conversation back towards specific questions when the topic became less focused on the particular aims of this study, but otherwise allowed the subjects to introduce topics that they felt were relevant to giving a clearer picture of their design process.

2.2 Design Scenario Simulations

The design simulations were an opportunity to view an approximation of a design process as it evolves. This portion of the interview was aimed at determining the organization and control of the design process by the interviewer's observation, so as to augment the subjects' recollections of past cases. The scenarios began by presenting the subject with a client brief reflecting our notion of the information that a real-estate developer might provide. Then the subject proceeded to develop a small number of possible design solutions. When the subject required more information the interviewer acted as the client, providing the mid-process decisions necessary to continue the simulation.

With the limited time available for this study, the design scenario simulation was the only practical method of observing a design process in detail as it happens. An actual design process takes many months or years, and therefore firsthand experience with enough design cases from which to generalize is impractical in a short term research project. It was hoped that this more customary setting allowed the interviewed designers to provide information in a less subjective manner because they were performing their accustomed role.

Additionally, the design scenario simulations were constructed to mirror the design problems used in demonstrating the prototype grammar. A comparison of the methods used in the design simulations, and of the resulting designs, with the method and results of the prototype were intended as a cross-referencing tool to further critique our grasp of the appropriate use of the domain knowledge.

23 Prototype Evaluation

The prototype demonstrates a design grammar based on the works of Dr. Fazlur Khan. Dr. Khan designed many of the seminal tall buildings which utilize the tube structure, including the John Hancock Center and the Sears Tower in Chicago. Chronologically, the study began with the preparation of a prototype design grammar which could be used as a point of discussion at the end of the interviews. The aim of the prototype was to demonstrate to the subjects the type of design method and interaction that are of interest to our specific project. The prototype was implemented on a machine using special graphics hardware unavailable at the design firms visited; therefore a videotape of the prototype was made for viewing at the end of each visit. We delayed the demonstration of our prototype until the final portion of the visit so that during the structured interview and design scenario simulations the subjects would express information about their design process in the manner that was normal for them rather than in any way encourage the subjects to express this information in the terms or organization utilized by our research project. The prototype was used during the interview to prompt for information that simple questions and simulations were inadequate for. However, the reactions and points of discussion we knew would be unpredictable.

For the authors, the prototype served to point out stages in the design process that contained unknown transformations, and transformations whose mechanism we were unsure of. These unknowns prompted many of the questions asked in the structured interview portion of each visit. To the experienced designer, the prototype served to bring up points about design education, design theory and the use of computers as design aids systems.

2.4 Session Analysis

To cope with the breadth of the study problem and the subjects' responses, we used three complementary analysis techniques in drawing conclusions from the interviews. First, for the analysis of the design scenario simulations a protocol analysis was used. Secondly, for analyzing the responses to the process and content questions our analysis method is based on the frequency of similar responses by different subjects and on the frequency of their focusing on similar subtopics when forming their responses. Finally, we sought to correlate the answers to the process and content questions with the design simulations as well as with the projects and built examples by the subjects. There was a reasonable degree of agreement in the response to questions and design problems, all of which were posed in a non-suggestive manner. Therefore, our analysis method was based on developing a consensus both on those questions that initially were thought to be the pertinent to this domain, as well as on those topics which became important during the interviews. Because there was not a unanimous agreement on all of the topics, we also recount the dissenting opinions brought out during the interviews.

3 Protocol Analysis of Design Scenarios

In the design scenario simulations the subjects were given a list of building requirements containing our notion of what a developer would present to the architect and engineer at the beginning of the design process. We then asked the subjects to think out loud as they developed a few conceptual designs for a building that would satisfy these requirements. Any questions that they might have for the real estate developer were answered by the interviewer. The first problem was to develop a design for an apartment building with approximately 800,000 square feet of rentable space that also included some commercial space and a lobby. The second problem was for a mixed-use building containing the same square footage and uses as the John Hancock Center in Chicago: lobbies, commercial space, parking and approximately 1 million square feet of office space and apartment space each, totalling over 2.5 million square feet. Both of the buildings were to sit on a 150* by 250* site. In the six interviews there was time for only three of the subjects to perform the design scenario simulations. The complete problem statements are shown in Appendix A.

This section begins by describing the designs that were generated by the subjects, and then focuses on specific stages of their design process, or issues such as process control. The protocol itself is divided into sections on the content and processing of the problem statement; setting the building's bulk and form; the structural critique of the architectural form; design team interaction; structural system selection; and process control. The section ends with a discussion of the protocol analysis method.

3.1 Generated Designs

The three subjects who participated in the design scenario simulation discussed the information that they expect to receive from the architect and client, and the interaction that occurs during the development of the building form so that an efficient structure can be designed. However, only two of the subjects produced specific structural concepts for the developed architectural forms. The third subject focused solely on the architectural form and the structural engineer's feedback during the form's development.

3.1.1 The First Subject's Designs

The first subject preferred to skip the apartment building problem saying that it had too many possible solutions to work out from the given information. He said that any structural solutions would respond to the form of the building which would be an outcome of the intended market and architectural organization of the apartments themselves, and that this architectural stage would have to come first. Nevertheless, he offered that the most economical apartments end up using "some kind of slab/" and that even though it is inelegant "the double-loaded corridor is cheapest." Also, some information about a dedicated apartment building can be drawn from his comments about the apartment portion of the mixed-use building.

For the mixed-use building, the subject sought the maximum square footage that the site could accommodate, stating that most developers would want approximately 25,000 square feet per office floor and in the absence of site constraints an office building would tend towards a square plan. He doubted that a square footprint would be allowed due to anticipated zoning requirements of a site setback, and therefore a ISO* by 150' building footprint would be unlikely. Thus, he tried to get a rectangle on the site that could provide the required amount of square footage and started with a 125' by 200' building footprint.

He was already thinking ahead that he would be trying to get a thinner building in the apartment levels because "all you can use realistically is maybe the 30' perimeter." He suggested turning the apartment level plans into a special configuration such as an H or U-shape. Remarking that the economy of apartment construction is as important as any other aspect, he emphasized that apartment floor construction is completely different than office floor construction, favoring the concrete flat slab over the steel composite floor. For these reasons the subject stated that many engineers have come to the conclusion that they would build a concrete apartment building on top of a steel office building, that apartments can be built with a steel staggered truss system or steel floors but that it is infrequently done.

In developing an architectural scheme he said that "since the building appears to be turning out to be a rectangle it would end up not being a very good tube." Then he began developing supplementary systems, first suggesting a tube-in-tube solution but then developing a parallel tube solution. The first parallel tube contained two relatively square framed tubes with a shared frame between the two long sides of the plan. The core was kept in the center so the interior frame would not excessively intrude on the rental space. He said that now he would have to figure how to get all the gravity loads onto the tube frames. Also, he would investigate the economy of transfers at the top of the office building to have a setback and change the plan for the apartment building. With the setbacks the apartments could also be built as a narrower double-loaded corridor section. Even though he was now focusing on structural solutions, he stopped and said that with a double-loaded corridor half of the units face one way and half face the other, but the view is usually in only one direction. This causes a problem for apartments which are frequently sold on the quality of their view.

Next, he changed his design to three tube cells in line with each other, and with the service core in the central cell running between the two interior frames. He suggested that the central cell terminate above the offices and the apartments continue as the two outer cells. The apartments would need a skylobby that could be located at the top of the three-cell portion and in this skylobby the apartment tenants could transfer to elevator banks in each apartment cell. This would provide a place where apartment security could be maintained, where the tenants could walk to an elevator closer to their apartment, and where the three tubes could be reinforced against local stresses using a full story truss or heavier frame. Alternately, two of the

tube cells could be terminated to leave only one apartment cell, or the proportions of the three cells could be different to provide a greater separation between the two apartment cells. With this three cell bundled tube, the subject remarked that the service core in the apartments would cause problems if it was used as a structural core because it would have to be picked up in the lower portion. However he would structurally utilize the service core in the office portion because "just giving it up would be nutty."

Thus, the first subject developed designs to differing levels of refinement. The building's bulk was developed first and then used by each of the subsequent structural schemes. The three-cell bundled tube design reached the greatest refinement as well as architectural and structural integration of the offices and apartments, but the tube-in-tube solution and the office tube transferring to a shaped apartment configuration was also offered.

3.1.2 The Second Subject's Designs

The second subject who developed structural schemes began with the apartment problem. He started from an assumed building bulk and remarked that this would more than likely be a concrete flat slab building because of the permanent partitions between tenants on every floor, and because that is how most of them have been built regardless of where they are located. He assumed that there would be approximately 30,000 square feet per floor and therefore the building would have a height to width aspect ratio of about 2.5. Such a low aspect ratio lead him to say that this building wouldn't pose much of a problem at all. Next he said in a few different ways that he would really need to see the floor plans that the architect would develop to see where the shearwalls would go, but that he was confident that a flat slab and shearwall system would be the most flexible in terms of column placement and the most economical. When it was suggested that the architect might want considerably less than 30,000 square feet per floor, he quickly estimated a new building height and said that now he would really want to see the plans because he had gotten to the upper limit of this system. Then he related how he would also consider variants of combined rigid frame-shearwall systems. He briefly described using a moment frame on the exterior and, if the perimeter columns could be closely spaced, he could delete the interior columns and span all the way to the shearwalls. Alternately, he would investigate using a haunch girder and pan joist system in conjunction with the shearwalls. He said that he doubted that he would consider a tube or any more exotic system for apartments because the developer would be emphasizing the exterior view to prospective tenants, they might also want to have balconies, and the fixed partitions are ideal locations for interior bracing.

For the mixed-use building the subject initially focused on fleshing out the program with the amount and location of the parking and the need for a below-grade service area for off-street truck delivery. He preferred to locate the parking "next door" because the building was so big and "you are going to have column spacings that are not going to be conducive to parking." He said that his rule of thumb was that a typical apartment bay is less than 30' by 30', that an office bay is at least 30' by 40', and that a typical garage bay is probably 30' by 55'. "None of these mix very well." Playing the role of the developer, the interviewer asked him to keep a small portion of the parking within the building. The subject next vertically ordered the occupancy types, placing the apartments above the offices and the parking between the offices and the commercial space with the lobby at ground level. He estimated that the building would be in the 80-story range as a minimum, and therefore the lateral load resisting system would need considerable attention. For

this reason he wanted to know in what city the building would be located. The interviewer suggested Dallas because the subject had more experience with southern cities. This eased the subject who remarked that Dallas was a rather benign location and he moved on to asking for more specific information about the layout of the leased spaces and discussing the trucking area and the mechanical equipment. In Dallas the mechanical equipment is typically below grade and at the roof level and therefore he would discuss, but not assume, the use of a mechanical floor at the junction of the different occupancy levels.

The organization of the building form, as recounted by the subject, would begin with the floor plans of the apartments because his real question was whether it would be better to have a mechanical floor or skylobby below the apartments to transfer the columns from a 30' by 30' grid to something else for the offices. He also wanted to see how the columns in the apartments would mesh with the commercial space partitions. He explained that he would prefer not to have to transfer any columns and that this would be where he would sit down with the architect and discuss the details of the floor plans for different functional volumes. He said that the major column meshing problem was integrating the apartments and the offices; that at first he would forget about what went below the offices and focus on these two major components of the mixed-use building. He would also like to see whether the two major volumes could fit on the same width. Settling these questions with the architect occupied a great deal of his description of the design process, and it became clear that these issues were going to be the major components of the structural design problem that he would be solving.

Next, the subject discussed a few structural systems for each of the major uses of offices, apartments and parking, independently of the other sections of the building. Then he discussed methods of integrating the upper two uses, having the apartments above the offices, by using a transfer level. However, with 70 floors or so above the parking, he said that after transferring the apartment system he would likely stay with the envelope dimensions and column spacing of the office levels for the parking and below. The structural systems for the apartments were similar to those discussed for the first design problem: using a concrete flat plate with shearwalls, taking that down to a service floor where the systems, member locations and even the construction material could be changed. At the service floor he said that he would have to provide a great deal of bracing and then switch the system to the exterior where he would look first at a steel tube system on a different column spacing than the apartments. He would think about using steel for the office portion because of its greater flexibility, but if the apartments and then the parking are concrete it might be better to remain with concrete for the office portion as well.

He again cautioned that he would really need to see the floor layout of the apartments to ensure that there was a place for his shearwalls. He assumed that there would be separate elevators for the offices and apartments and also that he would locate his shearwalls around the apartment elevators. He said that he would be very opinionated about the elevators in the apartments to make sure that they were symmetrically located, because they would be high up in the air and that was what he was relying on as his lateral load resisting system at the apartment levels.

The parking levels would pose the next column meshing problem, but he said that he was not overly concerned with the efficiency of the parking and didn't think that he could transfer the large loads on the system now. At this point he got a bit weary of the speculative character of this design problem, saying he doubted that the building would be a simple 120' by 180* box. He said that undoubtedly today there would

be some shaping to the building and that this shaping would either accommodate or determine the column spacing and column meshing problems. He said that "this is why I don't design the architectural part of it too." Nevertheless, he continued the problem saying that next he would look at the lower volumes and see how the commercial space was laid out and how the lobby entrances affected the system that was now largely on the perimeter. Additionally, the below grade service area would need entrances for trucks and that with the perimeter system of closely spaced columns "you've locked yourself in jail."

He commented that if the apartment space was replaced by office space the building wouldn't need to be any different than most tall office buildings. Removing the special circumstance of this mixed-use building would leave a much less constrained problem that could be solved without discussing column transfers and switching systems and materials. He said that this building would probably be too tall for a slipformed core and that he would probably want to have the structure on the outside. For the dedicated office building he favored a tube type building with closely spaced columns or X bracing. He said that there would probably be a skylobby for elevator efficiency, so that there wouldn't be so many elevator banks dropping off and reducing the floor efficiency. With a skylobby, he would investigate the use of an outrigger and belt truss system as long as the architect would accept the visual impact of that. There would be many more options now that the apartment and office columns didn't need to be meshed together, that the parking and circulation problems would be reduced and the whole building would be easier to design.

3.2 Generalizations

The following subsections generalize from the design scenario simulations, concentrating on specific stages and issues in the design process. Identifiable sections of the subjects' design process are discussed in terms of the timing of design subtasks and the definition of subtasks separated from specific site and programmatic constraints. These subsections focus on the types of transformations involved in the subjects' design process rather than on the output of the transformations as discussed in the previous section.

3.2.1 Informational Content of Problem Statement

The subjects initially focused their attention on understanding the problem statement. They spent from 5-15 minutes just reading the 10 item list of requirements and asking clarification questions. Individual clauses in this requirements were qualitative statements such as "The building must accommodate the uses of lobby, commercial, office space and apartment space." or simple quantitative requirements such as "The site is 250* by 150' and 75% may be used for the building footprint" and "There should be approximately 800,000 square feet of apartment space." The time spent studying these requirements can be assumed to be used for integrating the individual clauses into a larger picture of overall requirements.

The subjects said that the problem statement needed to be extended to include specific amounts of parking either within the building, on another portion of the building site or on a neighboring site. Additional information requested of the interviewer was the locale of the proposed building because that would: provide zoning constraints and information about the urban context to help orient the building on the site; determine the nature of the lateral loading from wind or seismic activity; and ensure that no exceptional constraints were imposed by the geological substructure.

After considering the extended problem statement the subjects said that this information would be sufficient for beginning the architectural design* but because we did not provide floor plans and elevations the problem statement was insufficient for them to suggest anything more than very general structural schemes. The lack of floor plans left an underconstrained problem that the engineers did not want to tackle. "That program would leave me completely in the dark because there's a zillion different ways of organizing apartments."(W.L.M.)¹ "There are an infinite number of ways of solving this problem."(W.M.)

The subjects also wanted to have more extensive definitions of some of the occupiable volumes besides their overall function. For example, they wanted to know whether the commercial space was retail space for small shops, laundries for the apartments, restaurants, fitness centers, etc. They explained that each of these commercial space subtypes have different acceptable partition configurations or bay sizes. Retail space may have columns on a regular grid or shearwalls may be used to divide a few of the spaces. On the other hand, a fitness center or a meeting room cannot tolerate a column or a shearwall coming down and dividing the pool or a conference table. This information would be provided by the architect's floor plans, but more specific characterizations of the building's uses would determine what options could be discussed as the design progressed.

The distinction that we made in the client brief of separating general office space from executive office space was described as unimportant from the standpoint of organizing the whole building. Each tenant would want some general office space and some executive office space on each floor, but they would be mixed with each other throughout the building. The exact proportion and needs of the executive space would be determined by the tenant. A more important distinction requested would be the type of market the office space and the apartments were aimed for. The target market for offices would imply the minimal size of the offices, which in turn would help determine the organizing architectural module. The target apartment market would determine the number of bedrooms and baths, the size of the larger rooms, and in turn the smaller dimension of the floor plan.

3.2.2 Setting the Building's Bulk and Form

The rough shape of the building, its gross size and proportions, were often referred to as the building's bulk. The subjects were comfortable describing the probable bulk of the building based on the site dimensions and typical dimensions for the uses required in the building. However, the team or cooperative nature of the design process was evident from the structural engineer's reliance on the architect to develop the external, detailed form of the building. After describing the architectural constraints each subject echoed that to "continue this to... my structure, I really have to design an architectural solution first"(W.L.M.) Adding to that, each engineer who drew a floor plan, drew it as a square or rectangle, explained a structural system, and then said "You don't find buildings with this kind of shape anymore."(W.M.)

After considering the architectural program, and completing it by requesting more information from the client, two of the three subjects focused on the horizontal dimensions of the more important functional volumes of the building, such as office space, apartment space and parking areas. The other subject skipped to the next step of describing a structural concept based on the dominant uses before returning to this step.

¹Quotes are attributed by the subject's initials. See Appendix B for biographical information on each subject

Both of the problem statements contained the requirement of a lobby but none of the subjects initially showed concern for the dimensions of the lobby even though that would be the ground floor volume.

The subjects emphasized that establishing the spatial envelope was the domain of the architect and the subjects could only recount guidelines that architects follow in current design practice. The major concerns for each of the subjects, when selecting horizontal dimensions for a typical floor, were to stay within an industry-established range for the lease spans, for total rentable square footages per floor and the desire to provide a minimally sized service core. These factors, plus the site dimensions' constraints, served to establish ideal horizontal dimensions for each functional volume. The desire to minimize the overall height of the building encouraged the use of a maximum size floor plan. The horizontal dimensions of this envelope were discussed as the combination of three components: lease span, corridor and service core. The setting of the ideal lease span dimensions for apartments, offices, parking, etc. was largely predicated on the useful size of such spaces. For example, parking floors need space for two cars with a double driving lane between them. On the other hand offices and apartments are dimensioned based on a maximum acceptable distance from an external window in offices and apartments. It was described by the subjects that although a structurally ideal bay size may be 30', offices are built close to 40' - 45' from core to perimeter because of overriding leasing requirements. However, even with the standard core-to-perimeter depth known beforehand there are an infinite number of floor plan shapes that can satisfy this depth.

Thus, the second stage of the design process involves the architect developing a series of floor plans that satisfy the functional requirements of the occupancy types needed in the building. When the dimensions of different functional volumes within a building differed dramatically, finding a way to mesh the conflicting dimensions became the focus of the subsequent architectural design stages. The subjects considered the possibility of indenting the envelope to form an H or U shaped plan, opening up the center to form an atrium, or some similar shaping of the floor plan that maintained the perimeter while providing a smaller lease span. Thus, either the spatial definition of one of the volumes was changed, or a method was developed for integrating the disparate configurations by using a skylobby or a mechanical level at the juncture.

The ordering of occupancy types within a mixed-use building was another decision about which the engineers provided an assumed solution and then said that it was really the client's and architect's domain to decide the final ordering. Each subject said something to the effect of "the apartments are presumably on the top of the building,** stating the typical ordering but qualifying their statement with a 'presumably.' However, two subjects described cases where the offices were put on top of the hotel or apartments in order to increase the leasability of the office space.

Each subject warned about drawing conclusions from our general problem statement, saying that even a typical building will have many individual circumstances that impart a special character to the problem, pushing the design towards a smaller set of solutions out of the multitude of general solutions. Subjects repeatedly emphasized that they would need to see the floor plans before they could solve the lateral load problem or locate the vertical members on the plan.

3.2.3 Structural Engineer's Critique of the Architectural Form

During the initial stage of architectural development, the engineers stated that they would be keenly observing the development of the building form and floor plans for sources of structural difficulties. They said that

during this time they would also be learning the "rules" of the particular building in terms of the expected real-estate features and desired architectural impression. Therefore, one of the first structural engineering stages of the design process would be learning what are the leasing and aesthetic criteria governing this particular building and providing a critique of the building form's structural ramifications.

One subject remarked that he would probably use a shearwall system for the apartments, but that he would have to see the floor plans to know what he could and could not do with regard to the shearwalls. Knowing that there would have to be elevators and stairwells, he said that he would be focusing on where these architectural elements were placed on the floor plans. He said that he might have to suggest a shift in the location of these elements so that a structural core or shearwall could be symmetrically located in the building form around these architectural elements in order to make the structural system work properly.

Other sources of structural difficulties that the subjects said they would be looking for would be: large setbacks that could cause column meshing problems; highly asymmetric plans and offset service cores that would cause torsional problems; large parking areas in a tall building that would need long-span spaces and that would disrupt the lateral load resisting system. To a lesser extent, balconies on the exterior of a tall apartment building would need special attention, as would the relative placement of columns and plumbing chases in an apartment building that would be likely to use a flat slab system. The subjects said that if these sources of structural difficulties arose, they would estimate a price to build a structural system for the configuration that the architect first suggested, discuss its structural implications, and then discuss alternatives that would be less expensive.

3.2.4 Design Team Interaction

The cooperative nature of building design was also evident from the structural engineer's reliance on the architect, the building services engineer and the elevator consultant to help settle the issue of whether service levels such as mechanical floors or skylobbies would be inserted into the building. The structural engineer's comments would proceed from considering the structural advantages of a service floor, then remarking that he would ask the building services engineer or the elevator consultant if they could use a mechanical floor or skylobby at a location that was structurally advantageous, and then discussing with the architect and client whether it would be architecturally acceptable. If the service consultants said that it would be too expensive to locate the mechanical equipment or a skylobby at a structurally advantageous level, the structural engineer would look for another solution. If the service floor was dismissed by the architect for aesthetic reasons or by the client for their own reasons, the structural engineer would look for another solution. Thus, a structural systems that would require a level of non-rentable space devoted to structure would only be suggested when this floor could also be used for a skylobby or mechanical floor. The subjects explained that they would discuss many options with the architect and the service and elevator engineers before developing even a conceptual structural scheme transferring the column spacing within a skylobby or mechanical floor.

Each of the subjects characterized the solution process as everyone on the design team sitting down and working out these problems together. The subjects felt that every member of an experienced team would have gone through these difficulties before and that the client, architect, mechanical engineer, structural engineer and elevator consultant would all be anticipating these types of problems. They all commented

that they would be watching the architect to see how he worked out the lobby, the floor layouts and the elevators. One subject said that he wouldn't really worry about what happens underground yet; that they would be solving the column meshing problem for the apartments, offices* commercial and lobby areas, but that they still haven't reached the ground. Although the service area below grade would have a big impact on the lateral load resisting system the foundation was going to be the least of their problems.

3.2.5 Structural system selection

Once the envelope dimensions were defined, the subjects wanted to see the floor plans that would have been developed by the architect. They specifically asked to see the plans, several plans, so as to inspect architectural elements to help determine where structural elements could be placed in the plan and on the exterior walls. Although they could suggest simple plans, the subjects repeated that these days they wouldn't see rectangular prismatic buildings, and therefore the simple floor plans that they would suggest would not reflect the type of problems they face in current tall buildings.

Even before seeing the plans, though, they frequently said that they could suggest the most likely structural system and construction material since the majority of the buildings of a common use, height and height-to-plan aspect ratio are built in this manner regardless of their location in the country. They said that that this prevalent system would be their first consideration, but that the frequency of exceptions to this rule would make them consider additional options as a hedge against the frequently occurring changes in the requirements. For example, the subjects stated that from the point of view of economy the apartment building is almost invariably built using a variety of concrete slab structures and that the double-loaded corridor is the cheapest even though it may be the least elegant. This latter point emphasized the importance of determining the building's intended market. They remarked that it always requires discussion and perhaps convincing for the developer and architect to accept interior members in offices since each tenant wants the flexibility to partition the space that they lease. These are some of the "rules" that the engineers referred to in discussing their participation during the architectural scheme development.

To locate their initially favored structural systems, each subject said that he would look at the plans for continuous vertical and horizontal architectural elements which could be also used as structural elements. In an apartment volume, one subject described how he would look for collinear walls spanning the building that were only broken by a narrow corridor so that the walls could become shearwalls. Alternately, the service core of elevator shafts and stairwells was seen as a typically available vertically continuous volume which could possibly be utilized structurally. Unfortunately, the core of a very tall building might have too high a height-to-width aspect ratio to provide much resistance to lateral sway and an additional system would have to be located. Vertical continuity was then searched for in architectural elements around the perimeter or in permanent interior walls which were continuous from floor to floor.

The availability of horizontally and vertically continuous spaces lead to a selection of a general structural concept that satisfies the use, height and aspect ratio requirements. This concept was described in purely qualitative terms such as "this would be a concrete building with a flat plate and shearwall structural system" or "I'd investigate a moment frame in conjunction with shearwalls," describing only the type of structural system and perhaps the construction material. At this stage no mention was made of quantitative attributes such as bay size, floor heights, component dimensions, material strengths, etc.

In addition to building use, the building height and height-to-width aspect ratio was used as a guide to the most likely structural system options. After suggesting a shearwall system for the apartment building, when the building appeared to be reaching 45 floors, one subject remarked that "I don't think I've ever done a shearwall building much over 30 floors, so 45 floors is really stretching it." The plan aspect ratio was also used as a structural system selecting guide, indicating the effectiveness of a framed tube system. One subject said that when the plan aspect ratio was approximately 1.6 the high aspect ratio would increase the shear lag on the long sides and reduce the effective tube action. Therefore, he would need a supplementary system to take some of the shear. He suggested adding a structural core for a tube-in-tube system, or using parallel or bundled tubes.

The ratio of the tenant uses also could lead to an architectural form and structural system favoring the predominant use but that could also accommodate a secondary use. In the second design problem of a mixed-use building containing significant amounts of offices, apartments and parking, one subject suggested that since the parking and apartments would probably be constructed in concrete the offices probably would not make as much sense in steel even though offices are typically built in steel. Circulation problems were also considered in selecting a structural system, particularly for the mixed-use building. The security of the apartments would require either a skylobby or separate entrances and elevator cores for the offices and apartments. Service areas for loading and unloading trucks and parking requires openings in the perimeter and long spans that can lead to local difficulties in an otherwise elegant structural system. In all, the predominance of special circumstances made the subjects cautious about recommending a solution before they were given more specific information than what was offered by the simulation problem statement

3.2.6 Control

The design process control methods observed during the design scenario simulations can be generalized as a stepwise refinement and revision of an abstract solution. However, this generalization proved deficient in detail because the subjects frequently backtracked to refine or revise a previous step even if that step had not lead to a certain failure. Also, the subjects frequently switched from discussing purely structural concerns to discussing the interrelationship of architectural, elevating and building services requirements. One subject commented that they would probably be sitting around for the better part of two and a half months on a job like the second problem, just trying out different combinations of architectural and structural options and discussing these options with the whole design team. This subject said that until the architect really fixes the architectural design the engineer wouldn't seriously start developing a structural scheme; that these systems of structure, elevators, and building services are so complex in their interrelationship that things are bound to change dramatically. This relatively uncontrolled stage—trying out different architectural and structural combinations and exploring their implications without committing to any one scheme—is probably more akin to the process observed during the design scenario simulation than the stage of generating a structural scheme for a (relatively) fixed architectural design.

The roles played by the structural engineer as well as by the architect, developer and other agents switched between generating additions or changes to the design state and critiquing the design state in terms specific to that agents' domain. An example of this alternating of roles would be that at first the structural engineer observes the architect laying out the apartment elevators and stairs and critiques the size

and placement of these elements for their structural implications, offering the architect advice about the impact of his output on the cost of the building as a whole. Then the structural engineer changes roles from an advisor to a generator by placing and sizing shearwalls around the elevator and stairwell shafts or generating some other structural system. Similarly, the architect generates an architectural module and facade treatment and then observes the structural engineer place and size beams and columns, for example, on the facade. Then the architect critiques the architectural impact of structural members that the engineer generated.

The controlling agent would certainly be the client or real-estate developer. After the client, the architect would be in charge of the decision making process. Thus, the design process would be controlled by marketing issues, and then sociological and aesthetic issues before structural concern would enter into the priorities. Other than the economic control exercised by the developer, each of the design agents also would help control the processes of the others by providing constraints from their domain that affect another's domain. However, the building is initiated as an economic venture first and foremost. The recounting of how apartments initially required on top of the Citicorp Building in New York were eliminated by the developer because they were costing too much in circulation expenses demonstrates the scale of changes during the design process. Additionally, the greater finishing expenses of a concrete framed tube over a conventional concrete frame, because of its use as the architectural facade in addition to its structural function, demonstrates that the economics of the total building project often lead to a more expensive local solution to produce a less expensive global solution. Therefore, the control of the structural design process must be subsumed within the control of the total building design process.

3.3 Discussion of Protocol Analysis **Method**

The protocol analysis method has gained favor over other knowledge acquisition techniques because it is regarded as the only method which collects actual data. Other methods based on retrospection have been seen as unreliable by the psychological community since these methods rely on the subjective memory of the participant [Ericsson 84]. We accept that for studying the cognitive processes used for such tasks as subtraction [VanLehn 87] or human-computer interaction [Bietz 90, Cuomo 89] protocol analysis is a desirable knowledge acquisition method. However, for the abstraction level of the tasks we were investigating, and for the number of subjects tested, protocol analysis did not provide the most useful information for two reasons.

The simpler reason was that the task simulation was just that, a simulation and not a real task. The subjects could not be expected to address the large task of developing a realistic building design in the time allotted. An actual design process takes many months of discussion between the various participants, as well as within the structural engineer's office. We attempted to simulate this process with only one member of the design team in a period of less than an hour. The design scenario also could not simulate the impact of stringent and detailed architectural or client requirements which are unique to each design case. Furthermore, real-estate developers and design professionals tend to be forceful in expressing their opinions and working to satisfy their aspect of the design. On the other hand, as an academic exercise the subjects had little interest in initiating this type of dialogue. Also, the nature of the simulation and the protocol analysis method is to observe rather than participate in the process, yet the subjects also had to be

prompted for deeper reasons for the operations they performed. The subjects used statements such as "An architect will tell you that they like to have somewhere in the range of 10 -12,000 square feet per floor for a square building." This statement required a question from the interviewer about how this number was derived before the more basic factors of ideal lease span and leasability in general were brought out. This forced backtracking became a distraction to the subjects.

The second reason for the limited success of our protocol analysis stems from the dual purpose of this study: to find out the exact problem that the building design team is addressing and how they solve this problem. This brought up a version of Heisenberg's uncertainty principle; the impossibility of measuring both what is the current position of the structural design problem and also supplying the proper information to allow the subjects to solve a useful problem. We asked the subjects to make decisions which we learned were the domain of other design team agents. However, these structural engineering experts admitted that they were hardly more expert than the interviewer at developing an external building form or laying out the service core. By not having a fully assembled design team available, the simulation devolved into discussing what information the engineers lacked and what information they would be looking for from other agents on the design team. The scenario would have been more profitable if, along with the client brief, one or more architectural schemes in terms of floor plans and exterior treatment had been presented. This would have allowed the observation of the engineers critiquing the architect's initial building form. However, before the engineers could proceed to developing a structural scheme the interviewer would have to consider hastily revising the architectural scheme in response to this criticism, a task that the interviewer could not perform at the same level of expertise as the architects that these engineers were used to cooperating with.

The subjects clearly understood that these interviews were a learning experience for the interviewer, and as such they tended to spend a large amount of time describing the information that they would need to know from the other agents without following up with examples of how they would respond to the various possible combinations of this information. It is likely that they were very accustomed to the specific constraints of real design cases and were reticent to speak in hypothetical terms about how they would respond to the infinite combinations possible in hypothetical situations. Unfortunately, these design scenario simulations were just such an unreal situation. In summary, the simulation was certainly a useful exercise, but in terms of gathering psychologically valid data it was not very successful. It is questionable whether a design scenario simulation can give an accurate picture of the higher levels of the design process and whether any valid generalizations can be made from such a small number of protocols.

4 Structured Interview Results: Consensus and Dissension

During the structured interview portion of the interviews we focused on specific topics either because we lacked basic information, or because we sought to validate our hypotheses. The first half of the structured interview focused on the information that begins the design process and the organization of the process. The second portion of the structured interview focused more specifically on structural system selection, system placement and member dimensioning.

The information beginning the design process was discussed starting with the process of identifying design requirements. In this first portion we sought to get a clearer idea of how this initial information

comes about, and whether it is stated explicitly or if it is only recognized when the implied constraints are violated. We sought to uncover what information is provided by the design team of client, architect, and engineers that then becomes the problem definition for the structural designer. We discussed how the design process is organized in terms of design team interaction, when different domains transform or add information to the design state according to their own criteria and how inter-domain conflicts are resolved.

The second portion of the structured interviews focused on how the structural designer selects, locates and dimensions advantageous structural systems. If the architectural design is presented as sketches and drawings, how does the structural engineer identify systems that fit within the architectural form? We sought to uncover the spatial and functional relations or constraints that help the structural engineer identify structural systems that are the most likely to be efficient and meet the constraints of the design team, before a quantitative analysis is performed.

Throughout the interview we could not avoid discussing the historical development of innovative structural systems. Therefore, this section recounting the structured interviews ends with a historical perspective on recent changes in the structural design of tall buildings.

4.1 Informational Content of Problem Statement

When asked explicitly about the content of the client brief, the subjects provided a description of a larger body of information than was given by the interviewer during the design scenario simulation. This information can be broken down into two categories based on their source: (1) site requirements; and (2) market requirements. Site requirements may not be given explicitly by the client, but they are a direct function of the client's chosen site. Site requirements include zoning regulations, climate information, geological information and the construction climate of the selected city. Market requirements are typically the result of market studies and include total and per-floor square footage requirements; lease spans; intended occupancy types; ground floor and top floor details, such as whether there is a large plaza which affects the lobby; the 'image' or economic class desired from the building; and the importance of showcasing the external views. Additionally, there are often factors affecting the design that are not obvious:

The design of buildings often gets into what can be called imponderables. Tall buildings have a lot to do with ego. They are money machines, but they also involve ego. You have to sift that out and find what the person is really asking for. These intangible qualities are often the most interesting."(MM.)

The client requirements have a more direct effect on the architect's design process than on the engineers' but these requirements must be honored by the engineers whose tasks follow the architect's. The client requirements are transformed into a building form by the architect, and it is supporting this architectural form that becomes the structural design problem. The architect's building form not only determines the external size and shape of the structural skeleton, but it also influences the architectural module of internal subdivisions which in turn determine the possible internal column spacings, as well as influencing the facade treatment which helps determine the possible perimeter column spacings. The importance of the external view affects the location and dimensions of structural members placed on the perimeter. Also, any openings in the building form, such as entrances and loading docks, add localized structural problems to the global

structural system. The structural engineer must be aware of the intent of the architectural design so as to avoid violating these architect-imposed or client-imposed constraints. Generally, the structural engineer becomes aware of these intentions through the preliminary discussions between the client and the architect

Site-imposed requirements can greatly affect the architectural form through imposed zoning requirements of site setbacks and allowable square footage, as well as through imposed building setbacks. Additionally, the site requirements bear directly on the structural design in determining the local building code requirements for lateral loads imposed by wind and seismic activity. Also, the decision of construction materials can be greatly affected by the material costs and the labor market of the intended city. The local climate also has a great effect on the economics of mechanical system placement, affecting the availability of structural floors for the use of belt truss systems or system transfers.

In summary, the architectural program is a list of requirements given in the following terms.

- Site requirements:
 - A set of zoning requirements including:
 - * allowable total square footage as a function of site area and occupancy types,
 - * percentage of the site that can be built on,
 - * setbacks that determine where on the site the building may be placed,
 - * permissible ground floor uses,
 - * required or allowable parking as a function of total square footage and occupancy types,
 - * sky exposure plane describing allowable profile types,
 - * allowable curb cuts;
 - Typical wind loads;
 - Exceptional climatic conditions such as hurricane wind loads and seismic activity; and
 - Labor and weather conditions affecting material selection.
- Client requirements:
 - A list of occupancy types and the intended market for those occupancy types;
 - A corresponding total square footage and per floor square footage for each occupancy market;
 - A required lease span for each occupancy type;
 - A characterization of the occupancy types detailing number of occupants, patterns of internal subdivisions from sizes for typical spaces such as offices or apartment rooms, special spaces such as percentage of fancy offices, auditoriums, conference rooms, etc.; and
 - An agreed architectural 'look' based on importance of external views, marketing image and urban context.

In addition to the client requirements given to the architect, the design or production architect may have to flesh out the program before the bulk may be turned into an architecturally complete form. These additions include such spaces as off-street parking for service trucks, building service areas for HVAC

systems, areas for maintaining the security of different occupants in a mixed-use building and a skylobby if needed for elevating efficiency. Thus, the information beginning the structural design process is a small set of architectural forms and a list of desired building features.

4.2 Client-Architect-Structural Engineer Interaction

In their recounting of the design process, the subjects emphasized the team aspect of the process. They repeatedly emphasized that the objective of their structural design process was the best total building rather than simply the most economical structure. To achieve this objective they recognized that they must respect the constraints imposed by the other participants' domains. The tenor of these discussions was softened, perhaps, in their retelling of the design team interaction, but the core of their attitude remained:

"Some of these things go back and forth, but there's a very good give and take between the three parties. It's a team concept with everyone inputting into the pot to get a very good overall solution to the problem."(J.C)

"I wouldn't tell the mechanical guy that I want a mechanical floor. I would say that it would be interesting if there was the opportunity. I don't know if I want to do it, but it's the sort of thing that we have to talk about. If the mechanical engineer on the building says that that's a terrible place to put all my equipment, it's going to cost umpty-ump dollars to operate, blah blah blah, then I'm going to lose that fight. I'm just bringing it up, as I look at the problem, as an option that I may or may not have. I'm certainly going to suggest it. We've got to work together to see if we can solve the problem." (W.M.)

"We can't insist on putting mechanical floors where we want them. We have to play along with whether the building wants to be a central mechanical in which case we would have several mechanical levels spaced once every 25 stories, or is the climate such that you have floor by floor fan rooms - so you have some mechanical equipment on each floor. You have to know what type of mechanical system is most appropriate." (H.I.)

Through the interviews it became clear that the members of the design team rely on each other for meeting all the varied needs of the building. It became apparent that the architect cannot design the structure, that the engineers cannot perform the architect's job nor can the structural engineer perform the elevator consultant's job. The experienced team member can sometimes anticipate difficult areas of the design for other domains, or anticipate the basic output of the other members. However, even though they have been through the design process many times, the design team members do not fully understand how that output is derived or how to solve the problem areas for the other domains. They all need each other to produce a design of a functioning building. Of course the acceptance of this fact does not prevent the team from engaging in heated discussions.

The first interaction of the structural engineer with the other members of the design team is likely to involve observing the client and architect discussing building requirements and proposed building bulks or forms. At such meetings the structural engineer, building services engineer and elevator engineer act as consultants, answering questions from the client and architect about large cost differences between building forms and features under consideration. The consultants are also asked whether there any difficulties in

these designs being considered that the client should be warned about. If the building forms and features under consideration present no major problem and have little cost difference the consultants may not need to provide much advice at all. However, during these discussions the engineers are assimilating the building requirements and constraints that they must live within during the remainder of the design process.

The architect and client are open to suggestions from the engineer to modify the architectural form. The extent of modification considered is in proportion to the building's difficulty. For example, the building form of the John Hancock Center in Chicago was modified considerably by the structural engineer because of the extreme problems posed by the initial design of this huge mixed-use building. More recent buildings have benefited from the experience of the team members in how to solve such problems or that it is better to avoid such situations altogether. More typically, an engineer will suggest slight shifts in column locations to align members within a system or less drastic profile setbacks to ease load transfers.

The common denominator for each of these inter-domain negotiations is costs versus return. More specifically the decisions are based on material cost, construction cost, construction time and operating costs versus leasing utility added to the building. The costs of materials and construction can be estimated by the structural engineer when the design is at a preliminary stage, but later in the process the contractor provides a more detailed estimate of construction costs and times. Operating costs are largely given by the building services engineer. The architect may be in charge of organizing these discussions, but the final judge in this decision making process is typically the client. When the client is a real-estate developer, it is his reputation and perhaps his money that is at risk and therefore he employs many leasing and financial advisors to help him make these decisions. When the client is the owner or major tenant the architect has more responsibility for these decisions. Regardless of the client's status, the engineers and architect place dollar values on the construction costs and times for the available options, and the client or architect estimates their respective real-estate implications in making the decision.

4.3 Organization of the preliminary design process

To describe the flow of control in the design process two of the subjects used the same image.

"Design is like climbing a helix that keeps coming around to the base point all the time. Hopefully you're getting to a higher and higher level. It doesn't always work out that way." (W.L.M.)

"But the design process is cyclical or a helix, where you go around and around until you get up to the point where it ought to be. What always seems to happen is it sort of winds up until everyone's gotten what they want and then you find out it's over budget and you have to uncycle and see what can be done." (W.M.)

In explaining the non-linear nature of the process, each of the subjects emphasized the frequent, large scale changes that occur during the design refinement process. As conceptual schemes become more specific the members of the design team may realize that previously assumed details in the configurations must be changed. These changes cascade and cycle from one domain to the other causing additional changes. Nevertheless, a simplified linear progression was presented by one subject with the caveat that they often have to backtrack and redo a previous step. The organization he described concurred with the less explicit

descriptions given by the other subjects. This organization of the design process is extended with details from other subjects and described in the following eight steps. Each of these steps is listed along with its primary agents. Throughout these steps the client or architect would be overseeing and making the selective decisions while the other agents would be commenting on the implications for their aspect of the design process. The representation used by each agent is also described in the following list to show the transformation of information in terms of its form and format

1. **Market study** - Client.

For a given site and time period, the client studies what features to incorporate in the building to maximize its economic utility. The output of the study is a set of relations between occupancy types and demand for building space. These relations can be used to speculate on the returns for office, apartment or retail space for different economic classes of these markets. The market study also identifies relations between occupants and special features that attract specific occupant types such as corner offices, health clubs, etc.

2. **Architectural program** - Client & design architect

For a given site and market study results, a list of building requirements is developed by the client and the design architect. These requirements are given in terms detailed in Section 4.1.

3. **Architectural floor plans** - Design architect & elevator consultant

For a given architectural program and an architectural 'bulk*' that suits the site, the design architect develops floor plans for each occupancy type and major change in vertical profile. The elevator consultant lists the number and type of elevator cars meeting the circulation requirements, and suggest configurations of these cars into banks contributing to the service core configuration. **The** design architect completes the core configuration by adding janitor's closets, mechanical closets, plumbing chases, toilets and fire stairs to the chosen elevator configuration. Thus, the floor plans depict the shape of the architectural envelope, the location and shape of the service core, and establish the architectural module and the dimensions of profile changes.

4. **Architectural form** - Design architect.

By correlating and refining the given architectural bulk and set of floor plans, the design architect develops a three dimensional architectural form that meets the desired image and external views. This architectural form also classifies the architectural facade as stone, glass or metal and dimensions facade elements that can house structural elements.

5. **Conceptual structural engineering** - Structural engineer.

For a given architectural form and space planning requirements, the structural engineer qualitatively describes a small set of structural schemes that most economically meet the structural requirements of strength, stability, stiffness and ductility as well as architectural requirements of servicability and image. The structural scheme is described in terms of system type, location of members on the plans and elevations, rough member dimensions, construction materials and architectural implications for space planning and building services.

6. Value engineering - Contractor & structural engineer.

For a small set of structural schemes, the structural engineer lays out the configuration of the structural system and dimensions the members so that a contractor can price the building. The construction costs are given in terms of a dollar amount per square foot and a duration for construction. The client then selects one structural scheme.

7. Detailed architectural design - Production architect

The basic architectural floor plans developed by the design architect are refined by the production architect to improve the leasing efficiency of the rental space and to minimize the service core. The location and dimensions of interior elements such as doors, stairs, etc. are checked with building and fire codes, and adjusted if necessary.

8. Detailed structural design - Structural engineer.

From the detailed architectural design and the selected structural scheme, the structural design is detailed as to member location and size along with connection details. The structural system configuration is pictorially described by overlaying the structural system and the detailed architectural design. Connection details are pictured separately and members are listed in schedules.

This description of a linear design process is helpful as a guide to the major design tasks but, as mentioned before, the actual design process is far from linear. The design team members are not simply waiting for the previous steps to be completed before they contribute to the design. Often a designer discusses preliminary notions with other team member and then makes assumptions or approximations about a related domain in order to complete a design task. Thus, each of the above tasks may involve every member of the design team. The major agents may be generating information that alters the design state while the consulting agents provide supporting information and critiques to help the major agents perform their task. For example, the design architect may discuss the building's layout with the structural engineer before assuming a long span or may discuss circulation requirements with the elevator consultant before roughly configuring the service core. Combining the previous remarks about design team agents critiquing the design state with this linear process, and understanding that agents can work concurrently on parallel stages, we present the following table showing the roles and outputs of the design agents at various stages of the design process. The design agents are listed along the top of the table with the duration of the design process extending down the table's vertical axis. The rows of the table correspond rather roughly to the previously listed eight steps. Additional rows have been inserted to describe the selection and critiquing roles played by the client and other agents. This table is meant to complement the previously listed eight steps by describing the parallel tasks and roles of additional agents during various stages of the building design process. Again, this is a simplification of the described helical nature of the process and it should be assumed that backtracking and repair of the design state will be required when conflicts cannot be resolved.

Step	Agent's Role					
	Client	Architect	Structural Engineer	Contractor	Bldg. Services Engineer	Elevator Consultant
1	Site & market study					
2	Building program	Building program				
3 & 4		Volume, mass, & rough floor plans	Comments on feasibility & costs		Comments on feasibility & costs	Comments on feasibility & costs
	Architectural concepts) selected					
5			Structural concepts		Bldg service concepts	Elevating concepts
	Critique & mesh concepts	Critique & mesh concepts	Critique & mesh concepts	Critique & mesh concepts	Critique & mesh concepts	Critique & mesh concepts
3		Floor plans with arch, module, partitions & service core				
5			Member location, approximate size			
		Adjust proposed structural systems	Adjust proposed structural systems			
6				Material cost, construction cost, construction time		
	Structural system & materials selected					
7 & 8		Detailed architectural design	Detailed structural design			
		Adjust architectural design	Adjust structural design		Adjust mechanical design	

Table 1: Table of design agents' output at various stages of the design process.

4.4 Methodical Process for Conceptual Structural Design

The previous description of the building design process places the conceptual structural design task within a context of available and expected design information. The development of conceptual structural designs starts from the architectural program and the preliminary architectural form. The output is a small set of schemes comprised of structural system type, construction material, and the placement of members so that they meet leasing and architectural constraints. An approximate sizing of the members checks that they can fit within these constraints. Articles by Fazlur Khan have presented charts of appropriate structural systems as a function of height and construction material [Khan 72]. However, we assume that the process of system selection is more complex than a simple table lookup, and that total height is merely an approximation of the expected lateral loads for one climate and expected height-to-width aspect ratio. What other subtasks are involved in system selection?

The leasing and architectural constraints, along with expected servicability and economic advantages of various system types and construction materials, must be weighed together before balanced criteria can be used to determine optimal structural systems. As stated before, the most economical structure does not necessarily lead to the most economically advantageous building. Nevertheless, we found a validation for the use of the table lookup method as a heuristic often expressed as using 'tools from our toolkit'. However, since the publication of Dr. Khan's charts the structural schemes within the designer's toolkit have become even more composite in nature than the composite construction material Dr. Khan helped to popularize. Recent buildings have employed both structural steel systems and concrete or composite systems stacked on top of each other or abutted side-by-side within one building. Additionally, the more articulated architectural forms have required a combination and adaptation of previous systems along with the innovation of new systems. Such adaptation and innovation assumes a more liberal attitude to the previously uniform systems and materials. Therefore, the considerations voiced by the subjects interviewed can be organized as a sequence (or cycle) of formulating requirements and constraints; a search of a system, subsystem and element toolkit; followed by a pruning and ordering of selected schemes.

A computational model of the generation of conceptual structural designs (step 5 in Section 4.3) can be organized as follows:

1. Formulate structural requirements from the architectural design as a spatial model with applied loads.
2. Reformulate the architectural program as structural system selection constraints.
3. Formulate leasing incentives as structural system placement constraints.
4. Formulate constructibility difficulties as structural system selection constraints.
5. Formulate market conditions and construction schedules as a relative evaluation function.
6. Search the 'toolkit' for a small set of conceptual design solutions to the architectural requirements.
7. Use the previously formulated constraints to limit the size of the set of potential structural solutions.
8. Use the previously formulated evaluation function to order the set of potential structural solutions.

The organization above assumes a method of matching conceptual design solutions to architectural requirements. The elements of this method can be found in the following sections describing spatial recognition of potential locations for structural systems; system selection; and heuristics used in guiding the search process, or selecting and sizing elements of those systems.

4.4.1 Spatial recognition of potential structure locations

The information that the structural designer receives to begin the conceptual structural design stage typically has no explicit location for structure demarcated by the architect or client. The architect presents the engineers with a design in the form of drawings and a small list of qualitative specifications. In addition to the architectural program, these pictorial representations of the design imply the requirements that the engineers must satisfy. How does the spatial representation of the architect become translated into structural engineering requirements, and how does the structural engineer decide that one structural system can be advantageously placed in an architectural configuration and another system type cannot? These two topics are intertwined, and constitute a central problem in structural design: how does the structural designer look at a spatial representation of an architectural design and see structural needs and opportunities? These questions are partially answered by the subjects' frequent comments about wanting to see several floor plans and to cross-reference them to find continuous regions for system placement:

"In those floor plans I'd be looking for places where I could put shearwalls and places where I could put my columns just to make sure that my columns will lay out That we can work with the stairwells and the elevators." (W.M.)

"What element in this building has the kind of continuity and the kind of solidity that you could use it as a core element? Or what kind of element could be a frame with punched windows? Vertical continuity is one of the things, one of the major things that you look for both in the core - especially in the core, there are very few buildings that transfer the core - but also on the exterior of the building vertical continuity is very important and you try to steer the client from major exterior transitions." (H.I.)

"Here is a simpleminded drawing of the [Norwest Building's] architectural concept. Past the center nothing is symmetrical. The building is highly serrated along the sides, with parts of the floor dropping off in different sections. This [central part] is the only part.. going straight up and down through the whole height. We called that the spine. We decided to keep our main structure there and treat the sides, for lack of a better term, as 'add-ons' from the structural standpoint Because they're so highly articulated you couldn't get a framed tube to go around the perimeter." (J.C.)

The first quote shows the subject inspecting the architectural design for elements that can house known structural systems and that 'will lay out,' that is, the elements can be composed into a system. The second quote describes a principle of spatial recognition by basing the inspection on 'continuity and solidity.' The third quote describes how some systems are removed from the set of potential designs and the type of piecewise continuity used in recent structural innovations. These comments suggest a method for the spatial recognition of structural system locations that contributes to a method for selecting appropriate structural

systems. Architectural elements are inspected for vertical and horizontal continuity to see whether they can be used to house the continuous members of a structural system. Through experience, the structural designer of tall buildings knows that these architectural elements are most often found on the building's perimeter, or on the service core's perimeter and internal partitions. However, in each case the floor plans and facades must be inspected for structural possibilities. Architectural elements such as permanent interior partitions between apartments can be inspected for adequate size and shape for becoming shearwalls. Shearwalls of an adequately closed form can be used as an interior tube system. Masonry-clad elements in the architectural facade hint at the possibility of a punched wall if the facade is sufficiently planar and dense. Punched walls surrounding an adequately compact plan can be combined into a framed tube system. Thus, structure location can be implied by matching the continuity and density of architectural elements to a continuity and density of structural elements that fulfill a needed structural function. Each of the above mentioned architectural elements have openings for circulation or vision. The importance of the exterior view was often discussed as a factor influencing the structural design, requiring that certain perimeter location be kept free of obstructing elements. Thus, the density of perimeter structural systems is constrained by architectural requirements.

Additionally, this method assumes that the architect has designated portions of the building form as being solid and permanent. The glass-walled office building may have only the service core as a solid vertical elements, and this core may have a very high height-to-width aspect ratio. In such cases the antithesis of geometric continuity, the locations of corners and jogs in the floor plan perimeter and setbacks and overhangs in the building's profile, may be used as suggested locations for structural elements. The architectural module may then be used for identifying additional locations for elements of a system, basing a structural grid on the fixed locations of discontinuities in the architectural form.

Moreover, with the frequent use of vertical profile changes and the termination of elevators as their need ends, vertical continuity cannot be assumed on the perimeter or within the service core. Therefore, the search for potential structure locations becomes one of inspecting the architectural form for horizontal and vertical *piecewise* continuity while recognizing system-dependent bounds on the combination of pieces into systems. Therefore, each of the ⁴'tools from our toolkit' used in matching with the architectural design expresses constraints on the target architectural element in order to maintain the 'tool's' characteristic structural behavior. These constraints may be expressed as the minimum density or as the geometric continuity of a target architectural element.

These observation bring up a related topic on the representation of information during the conceptual design process and the subsequent critiquing of them. The question is whether designers think in a particular dimensionality? In a highly three-dimensional domain the use of two-dimensional representations such as drawings can be a hindrance. The current practice of using two-dimensional plans and elevations to describe a three-dimensional building succeeds because designers (frequently) can combine the two representations into a three-dimensional mental model. While discussing the difference between design architects and production architects, one subject remarked that

"Designers are people who can conceive of things, who can see things, in three dimensions." (J.C.)

The structural systems designed by the subjects for realized tall buildings and unrealized projects have relied on the systems' three-dimensional character to provide greater efficiency than orthogonal plane frames. The

introduction of the tube systems, the supercolumn system, the two-way Vierendeel flooring systems and other unnamed system types have relied on the designer thinking in multiple dimensions. Fitting with the above method for locating potential structural systems, it was evident during the structured interviews that the designers search for regions of a dimension equivalent to the loads they are seeking to resist and equivalent to the system they are trying to instantiate. Thus, when considering the floor system and trying to bring gravity loads down to a support, the designer will search for one-dimensional continuity for inseting columns. When trying to resist lateral shear along the short dimension of a building, the designer may search for two-dimensional continuity for inserting shearwalls, and when trying to resist the moment caused by lateral loads the designer may search for three-dimensional continuity for instantiating a structural core or perimeter tube. This implies a multi-dimensional toolkit. More importantly, it also underscores the need in a computational model of structural design for formulating the structural requirements as a multi-dimensional architectural model *with* the applied loads. Thus, a method for recognizing the spatial locations for potential structural systems involves formulating the architectural design as a spatial model with applied loads; formulating a toolkit of structural elements, subsystems and systems with the loads they can resist or transfer and with spatial constraints on their applicability; and then seeking matches between the building's needs and the available combination of 'tools'.

4.4.2 Structural System Selection

In discussing the selection of appropriate structural systems for a given architectural form, each of the subjects repeatedly emphasized that the selection of a structural system is based on a balancing of building concerns. The design architect is most concerned about how the facades of the building read from the exterior. The developer is also concerned about the facades as a way of attracting tenants, but he is equally concerned about the amount of leasable space inside and that a good rent can be charged. In a typical design these two concerns come before the structural economy in terms of pounds of material per unit volume of building. The charts published in Fazlur Khan's articles appear to be based on only one of the multitude of criteria for a structural system — the quantity of material used per unit volume of building. To accurately reflect the concerns of the client, each of the subjects explained how the criteria used in structural system selection must consider the most economical overall package of architecture, structure, building services and elevating. Also, the servicability requirements can motivate a preference for certain systems and construction materials because of their leasing advantages for a particular intended market

Most of the subjects explained that residential buildings are currently built as concrete slab systems regardless of their location because a concrete slab flooring system provides the desired sound isolation and fire rating; a concrete slab flooring system can be built much thinner than a steel system thereby saving on building skin, elevators, stairs, etc.; and the flat slab system gives the flexibility of placing columns off the fixed grid needed in a frame system². Since all the services can be run through the fixed interior walls, there is no need for horizontal ductwork under the floors of an apartment building, and therefore the underside of the slab can be used as a finished ceiling. On the other hand, an office building is typically built in steel for the flexibility of modification such as cutting a stairway for a two-story tenant, and because of the more

²It should be remembered that the tallest current residential building is in the neighborhood of 50 stories.

economical span-to-weight ratio of steel floors for the size spans needed in office buildings. Therefore, the intended use of a building not only influences the desired lease spans or architectural form, but also must be part of the structural system and construction material selection process.

However, such straightforward rules as "residential buildings are built as reinforced concrete slab and shearwall structures", and "office buildings are built with steel floors" must be taken in a limited historical and economic context. The probing of justifications for design heuristics brought warnings from the subjects that the influential factors of a building's design are both time and location dependent. For example, they warned that the desire of developers for a quick return on their investment is not necessarily the case in foreign markets where tall buildings are increasingly appearing, that the lease spans desired in the United States are larger than those allowed by law in many places in Europe, and that advances in construction materials and methods might lead past designs to be more economically built using other systems if they were built today. Discussing the John Hancock Center in Chicago, one subject explained that no one in the structural design office seriously considered a concrete structure for the 100 story building because at that time the tallest concrete building was about one third the height of the Hancock's architectural design. Today, concrete or composite construction would be an equally competitive construction material. The use of past building structures as a guide for the current use of the *toolkit' needs to consider the difference in the chronological and geographic context of the past and current design cases. The subjects also recounted that many advances were evolutionary rather than quantum leaps to 100 story buildings. Thus, although recent buildings are used as guides for new structures, their bounds are being stretched by design, material and construction innovations. At the same time, the criteria for selecting one system over another are shifting as well.

The importance of architecturally emphasized leasing incentives and the changing architectural and construction climate call for the structural designer to generate a number of varied conceptual designs. The design team must be offered a small set of structural schemes in order to find the most economically advantageous total design meshing structural concerns with the requirements of the other domains. One subject recounted how he convinced a contractor to price a conceptual structural design 'just for fun* along with more conventional schemes even though the contractor wanted to throw the novel scheme out of consideration because he was unsure how to construct it. After the engineer developed the design further and the contractor thought about construction methods in more detail this unusual scheme became the built design. Thus, the offered conceptual designs must have enough variety to meet the varied architectural, leasing and mechanical constraints of the design team.

Fazlur Khan's charts and the implied recommendations of past buildings must also be considered within their expected lateral loading environment. At the beginning of this study the effect of the building site for influencing the structural system was thought to be most important for influencing the choice of construction material. However, the difference in lateral loading for various cities must be factored into any heuristic for relating appropriate structural systems to the building height. In discussing the selection of a structural system for an actual building in Atlanta versus for Houston, one subject commented on the relation between system selection and the lateral loading expected in the building's location:

"We selected that structural system to produce those tremendous views for the architect I couldn't have done that [system] in SO stories in Florida, I couldn't do that in SO stories in

Houston. But I could do it there. You have to recognize where you've reached the limit of a certain system and where special structure is required. So Atlanta has the same problems that a Houston or a Florida has, it's just that you can go a little taller in Atlanta before you reach those limits. But it will reach that limit, its just a question of where." (W.M.)

Previous discussions of appropriate system for a given height have often assumed the lateral loading of New York City and Chicago because that was where the majority were erected until the late 1970s. Another subject described the need to adapt the selection process to realistic expected wind loads in the building's city and the overemphasis on rules of thumb such as the height over 400 lateral deflection limit:

"When the people in New York developed that criteria, for a long time they always talked about this H/ 400 business, 500 and 600. They were always talking about 20 pounds because the old New York code said 20 pounds [per square foot wind load] until 1960. That was what the wind was and it didn't matter how tall. They really were talking about the absolute stiffness requirement of a minimum of 8,000 pounds per square foot per radian. And I wouldn't be against that for a 30 story building either, in some places. But just as a starter, I would use 12,000. The building we ended up with in Houston was more like 20,000 in the same language, absolute stiffness, because of the dynamics problem." (W.L.M.)

Through the discussions of structural system selection it also became evident that a change in building priorities has occurred. The uniform systems described in Fazlur Khan's charts, and the praise of the tube system as economical in its use of material and therefore architecturally optimal, were the outcome of the International Style's devotion to sculptural purity and the aesthetic of the machine age. These criteria have changed, and rather than recognizing the efficiency of diagonal braces such as the perimeter braces in Chicago's John Hancock Center, current clients talk disparagingly about diagonal braces:

"I have proposed this idea many times to people for office buildings, and people say 'we don't want rafters coming through our office space'."(W.L.M.)

Additionally, in response to the varied demands of the tall building, whether to the incompatible lease-span requirements of a mixed-use building or to the desires for an extremely open view in portions of the perimeter, the structural engineer has become accustomed to piecing together a unified structural system from different subsystems:

"That is one thing that interests me because what we used to do in the 60's and 70's is not what we do today. Of course, we learned from them. We've learned how the structure behaves, and how we can manipulate structures, and how pieces from different vocabularies are efficient when we use them in combination, how we can borrow a piece out of this and a piece out of that and make a whole out of it. I think that that is one of the fun thing about this." (H.L.)

Two different types of system unifications were described that can be classified broadly into *stacking* and *side-by-side* union. The need for stacking different structural systems comes from many sources:

- Incompatible lease-spans and construction materials of the occupancy types in a mixed-use building;
- A desire to reduce the square footage of floors for leasing to different markets;
- The need to insert service floors such as skylobbies and mechanical floors;
- A desire to introduce structural floors for transfers, reinforcement or additional building stiffness; or
- Removing columns in the lobby perimeter and the attendant need to adjust the mezzanine.

Any combination of these motivations may inspire the stacking of structural systems. Another type of stacking used by the subjects was the parametric vertical variation of a single system, either by reducing member sizes within one topological configuration or the deletion of individual elements as the building progresses upward due to reduced overall shear and moment

The horizontal piecing together of structural systems may also be motivated by many factors including an architectural desire to open the exterior views of one or more portions of the perimeter and the need to reinforce geometrically difficult portions of the perimeter. Therefore, because of architectural and leasing concerns the piecewise continuity discussed in the previous section on spatial recognition is reflected in the process of structural system selection to meet the current varied demands of the tall building. Perhaps the task of structural system selection would be more accurately named structural system *composition*.

The density of the framed tube's facade has also become less desirable, especially for residential buildings, because the exterior view is often one of the major selling points. Thus, the structural efficiency of the framed and braced tube may be less important than the structural system's architectural and leasing ramifications. On the other hand, the interior freedom offered by the tube systems may attract a client more than the restricted views displease him or her, especially in an office building. When the subjects were asked to generalize on how the client decides which system to approve, the engineers generally threw up their hands and said that they were glad they didn't have that job.

Bearing these factors in mind, the subjects often remarked that a building with few extenuating circumstances would probably have a structural system not very different from previous designs³. One subject remarked that he would start from past designs and then see if anything else presented itself after looking at the architectural scheme. He explained that he would try combining standard subsystems that fit the architectural design to identify problems and potential solutions. Another subject, noted for not following beaten paths, laid out his guidelines for system selection based on a hierarchy of both systems and concerns:

"I think on rational grounds, some type of braced system is always better than any rigid jointed system. But my first problem is will the owner, or the architect, or both, buy that? If

³The subjects implied that they were not seeking to be innovative strictly for the sake of innovation. The novel systems developed by these designers were motivated by a specific, architecturally-inspired, structural problem. For example, the staggered truss system developed by one subject was motivated by U. S. Steel seeking to increase their share of the residential building market. The stub girder system developed by another subject was inspired by the need to economically reduce the floor sandwich depth of composite floor systems while providing easy paths for ductwork.

they won't then we have to do something else. Very simple. Then we may look for a concealed bracing system which is inside the building, that doesn't bother the architecture there. We certainly would look at some kind of Vierendeel tube on the outside. That's a natural thing because people will build columns and beams and link them together. It's especially natural with concrete when the rigidity comes almost as a matter of the construction technique, but we know how to do it in steel too. We do it all the time, we have lots of precedence and prototypes.

But before I ever began, I would have to categorize the building into one of two classes. Is this a building which is motion sensitive or not? Is the stiffness of the building going to be a dominant consideration or isn't it? Probably most buildings under 500 feet high, and if they're office buildings, you wouldn't have to worry too much. But if you get higher than that, or at any time they're more slender than about 6:1 or 7:1 proportion, then you should always worry about the dynamic behavior of the building. The criteria then are always set, in my experience, by some kind of experimental study to be done on the site, the weather history of that place, the relationship with other buildings, and so forth.

Given the tube, we've made up our mind that that's something we're going to look at, the architect doesn't want any diagonals, shearwalls in the perimeter are out. So you've got a tube whether you like it or not. Then the question is more sharply defined." (W.L.M.)

These remarks emphasize the subject's first concern is design setting criteria of dynamics, stiffness or strength. Then multiple systems are generated and inspected. The structural systems hierarchy begins with an exterior braced system, an interior braced system, and a Vierendeel tube on the perimeter. Two of the notable tall buildings by this subject have deviated from this hierarchy. The first building uses a large hollow tube core with lease spans cantilevered from it. The second system uses a Vierendeel floor framing system to rigidly connect widely spaced columns that are drawn in from the perimeter to provide an equivalent cantilever system with unobstructed views. These buildings represents a class of structures discussed in the interview as a favorite scheme of the subject's: an equivalent cantilevered tube drawn in from the perimeter either a full lease span or one office depth with floors cantilevered from it

In sum, when faced with relatively standard building forms, the controlling criteria can be mainly economic and less heavily architectural or building services oriented. In these simpler cases the tried and proven solutions are likely to be the optimal. However, the recent emphasis on architectural shaping in tall buildings requires adapting systems used in prismatic forms to the special circumstances of nonprismatic forms. Nevertheless, in discussions of various structural systems there was, in fact, a frequent use of building height as a guide to system selection, although it was tempered with consideration of building location, intended occupancy, plan dimensions and architectural form. In all, the subjects emphasized the need to experiment with a number of systems and combinations of subsystems to find which schemes meet the needs of the client and mesh with the schemes of the other members of the design team.

4.4.3 Parametric Design Heuristics

The portions of a conceptual design process discussed in the previous sections describe how locations for structural subsystems are recognized, what building concerns guide the selection or composition of structural

systems, and the need to offer a variety of structural schemes. Thus, this process involves exploring which subsystems from the structural 'toolkit' can be used to address the global or local structural problems presented by the architectural design. In this section a variety of systems are discussed, focusing on the use and dimensioning of specific structural systems.

Framed Tube. For buildings over 40 to 50 stories, the service core may have too high a height-to-width ratio to provide sufficient lateral stiffness and an exterior system becomes more attractive. The exterior framed tube offers a freedom of plan shape difficult to achieve with orthogonal rigid frames, and also frees the interior of columns that cause space planning difficulties. The critical attribute used in designing a framed tube is the column spacing, which must be an integer multiple of the architectural module. With a typical module being five feet, the column spacing may be five, ten, fifteen or twenty feet. Beyond twenty feet the tube behavior deteriorates for any reasonable spandrel depth. The allowable spandrel depth is determined from the architecturally allowable reduction of the window height. For example, with a 12 foot floor-to-floor height and an 8 foot tall window the spandrel can be no deeper than 4 feet. The spandrel depth determines the range of spandrel lengths, and therefore column spacings, within which the spandrels will be stiff enough to achieve sufficient tube action. Depending on the spandrel depth, column breadth and applied loads, twenty feet is near the maximum column spacing to achieve a tube system. Currently three modules, or fifteen feet, is a typical compromise between a close column spacing and an open view. By consensus two modules, or ten feet, is the ideal achievable column spacing from a structural point of view. Of course a five foot spacing would produce a stiffer tube but the cost of constructing so many columns would generally be prohibitive and the reduction in exterior view undesirable. One subject stated that a column spacing of half the story height is ideal, strictly from a structural point of view, but like any optimization function, near the optimum the function is fairly flat and a column spacing near a full story height is the best compromise between architecture and structure. Therefore, a framed tube design heuristic would be as follows:

1. Critical attribute of framed tube is the column spacing.
Column spacing is an integer multiple of the architectural module.
2. Second most critical attribute is the spandrel depth.
Spandrel depth is less than or equal to the floor-to-floor height minus the expected window height
3. Given the allowed spandrel depth, select column spacings that provide the required system stiffness with similar beam and column cross-sections.
4. Use largest allowable column spacing to reduce construction costs and open exterior view.

Relative Proportioning of Members. The selection of member sizes for a structural system, including the framed tube, can be readily accomplished once the locations and relative proportions of the members has been chosen. Preliminary analysis methods such as the cantilever method or matrix methods can size members for such criteria as a desired strength or deflection limit. Optimization methods can find the best member sizes once the geometry and the criteria are set. The possible locations are the result of recognizing potential structural locations as discussed in Section 4.4.1. However, the relative proportions of members

must be chosen to accomplish a desired structural behavior. For example, the corner columns provide very little gravity load resistance when using a standard floor framing system because of their small tributary area. On the other hand, the corner columns are the most effective for lateral load resistance due to their distance from the building's neutral axes. The relative proportioning of these columns was discussed to uncover the typical starting point of a tube system's preliminary design.

One of the properties of a framed tube, like the bearing wall, is to provide the stiffness to attract the gravity load from the floor system to the perimeter system. Enlarging the corner column attracts a larger proportion of the gravity load to it, and therefore, the corner column of a framed tube should be at least as big as the mid-face columns to keep them in compression. Also, the corner columns are subjected to moments in the direction of both faces. Therefore the preliminary sizing method of one subject would begin with the corner columns approximately 1.2 times the size of the mid-face columns. In nonrectangular concrete structures the corner columns generally need to be enlarged to provide space for the columns to catch the beams coming in at odd angles and to have enough room to lead the reinforcement from one member to another. It is desirable to limit the number of different types of columns for the sake of standardized construction. Therefore, most framed tube structures have a uniform column sizing across the face of the building except for the corner column which may be about 20% larger. In a concrete building the reinforcement ratio may be varied in the columns across the face. In a steel building the plate thicknesses may vary keeping the depth of the members constant. Vertically, the face dimensions would be kept constant and the out-of-plane dimensions varied a few times up the building, reducing the size of members in the upper floors where both gravity and lateral loads are smaller. In concrete an alternative is to vary the concrete strength, thereby saving on changes in formwork.

Occasionally the architectural design will specify removing the corner column to improve the external view. From a structural standpoint however, this merely splits the single corner column into two corner columns set back from the geometric corner. One subject referred to the framed tube facade as a Vierendeel 'wallpaper' that can be shifted half a module without much detrimental affect. The spandrels are assumed to have a midspan point of inflection that can occur at the geometric corner of the building. This principle of using the shifted Vierendeel was utilized in one building to allow the architect to incorporate small setbacks and overhangs without harming the tube effect. Both of these corner columns could be increased in size a similar 20% over the mid-face columns, but a well designed framed tube facade has the ability to equalize loads along the face, and corner columns equal in size to the mid-face columns would not markedly reduce the system's efficiency.

In designing a tube with diagonal braces, the subjects explained two possible models. In a megaframe model all the strength is placed in the corner columns with diagonals transferring the shear from one side to the opposite one. The corner columns must receive the gravity loads from individual floors. In theory this can be accomplished either by making the spandrels span the **full** width of the building and having the perimeter columns between adjacent floors connected by shear connections only, or by also connecting the spandrels to the diagonals. However, this model would present many construction problems. In the model on which the John Hancock was designed, the diagonals are intended to function as wind braces, but they participate in resisting the gravity loads as well. Mid-face columns also participate in the complete

mechanism by intersecting the diagonals at a spandrel⁴ and thereby sharing lateral and gravity loads. The equalization of loads along the face of the building is accomplished by a comparable sizing of members and by the truss-like three-member connection of diagonals, columns and spandrels. The spandrel takes a proportion of the horizontal component of the diagonal member's force. The column then takes the vertical component of an equivalent proportion of the diagonal member's force. The size of the diagonals must be comparable to the size of the mid-face columns to attract gravity loads, or they will have tremendous tensions on them, and it is preferable to have the whole tube system working in compression. Thus, the stiffness of the diagonals has to be comparable to that of the columns, and the angle of the diagonal should be kept close to 45 degrees, say, plus or minus 15 degrees. The geometric exercise of ensuring that diagonals and columns intersect at a spandrel allows the loads to be equalized across the face of the tube. This equalization of loads results in a braced tube exhibiting very little shear lag and the distribution of axial forces in the columns approaches an ideal cantilevered tube.

Structural Transitions. Even in the sculptural purity of the International Style architecture, the prismatic building form typically used several levels of structural transition. Typically a different structural configuration was used at the ground floor level and in the upper floors, requiring a structural transition at the mezzanine level. More recently, for architectural or zoning purposes, distinct transition levels have also occurred at mid-height where setbacks in the building form required strengthening due to load transfers and stiffness changes. Structural levels also occur at the building crown when mechanical floors are placed there or where hat trusses tie the core and perimeter together structurally. Furthermore, structural systems have been varied around the perimeter to reinforce narrow ends of an elongated plan or to open up an external view along sections of the perimeter, forming a vertical line of transition between systems placed side by side. During the structured interview we discussed what special attention the engineers paid to these transitions.

The opening of the ground floor typically occurs with little fanfare. One subject remarked that "you can take a good framed tube and place it on four corner columns" as long as the shear could be transferred from the mezzanine to the ground, say, by the structural core. The key would be to retain the overall stiffness with the remaining members. Typically the column spacing is increased at the ground floor by removing every other column, two out of three columns, etc. The remaining columns are increased in size and the mezzanine spandrel enlarged to accommodate the increased span. Sometimes the mezzanine level will be a full story deep beam or truss, providing a pedestal on which to place the upper stories.

A few of the structures designed by Fazlur Khan pay special attention to the transition between the ground floor and the upper system. In Two Shell Plaza (Figure 1.) four out of every five ground floor column are removed and the spandrel depths and column widths of the next five floors are varied. The Midland Marine Bank Building (Figure 2.) uses a constant spandrel depth throughout the structure above the ground floor with a column spacing five times that of the upper framed tube. The column depths of

⁴In the John Hancock Center the spandrels are separated into primary and secondary members. In a typical tier of the structure every third spandrel is either a primary member, or a tie, intersecting the diagonals and columns. Two out of three spandrels are secondary structure, designed to transmit gravity loads to the adjacent columns.

the first three upper floors are varied, becoming shallower away from the ground floor columns. The result is a structurally promoted, and visually expressed, arching action in the lower floors between the framed tube upper system and the widely spaced ground floor columns. A subject who worked with Dr. Khan remarked that this was a choice made during the architectural and structural design process. They could have provided a strong spandrel above the ground floor to transfer all the column loads at the mezzanine level, but they felt that it was a more elegant solution to express the arching that occurs in an equivalent bearing wall when placed on widely spaced columns. They forced the loads to be unevenly distributed across the face of the tube, favoring the columns reaching the ground level, by not providing a deep beam pedestal. The unequal sizing of the transition level members begins the redistribution of the member forces higher up and expresses this structural mechanism architecturally. Thus, separate behaviors are possible depending on the stiffness of the lower spandrels and beams; either providing the stiffness in the first level spandrels to promote equal column forces in the flange of the tube, or providing a variable stiffness in the lower beams and spandrels that will attract and channel the loads into an arching path.



Figure 1. Two Shell Plaza, Houston Texas



Figure 2. Midland Marine Bank, Rochester N.Y.

The structural levels within the Sears Tower also focus on the local stiffness of a structural subsystem, but are used to equalize member forces, rather than to transfer loads. The vertical members are continuous from the top of their cell to the ground, but the changes in building form as cells of the bundled tubes terminate results in local stress concentrations from differential gravity loads where multiple cells are joined. Also, the sudden change in the building's form results in a drastic change in the building's lateral stiffness. The multi-story trusses constructed by diagonalizing each panel relieve these stress concentrations. The trusses that wrap around each of the cells at geometric transitions and at the lower mechanical level also increase the overall stiffness of the building and reduce differential column shortening by tying the perimeter and interior cell columns together, thereby equalizing member forces. However, it should be remembered that the availability of structural levels was predicated on the availability of mechanical levels at frequent heights throughout the building, a design choice influenced by the economics of building services in Chicago.

The shear lag that reduces the effectiveness of central columns in the flange of a tube has been utilized to open the perimeter by eliminating closely spaced columns where they would be ineffective. In Onterie Center, a concrete tube designed by Fazlur Khan, the structure is in the form of two tube channels allowing a large section in the center of the long sides to be free of dense structure. The side-by-side systems do not require more of a transition than the sizable columns at the channel end, and the alignment of the spandrels on either side. Another design described by one of the subjects minors this concept using two concrete channel-shaped walls with punched windows and a light steel-framed curtain wall between them. Again, the transition didn't require a separate structural system.

The most common transition levels after the mezzanine, are levels for the structural reinforcement of setbacks and transfer floors. Architectural designs with setbacks in the profile typically require some reinforcement to handle the two column grids meeting at the setback and the changes in building stiffness. Although, many methods of transfers are structurally possible, the design problem is a question of what can be done economically. A structural transfer floor is usually combined with a mechanical level, and therefore the problem becomes one of providing a transfer girder or truss that does not interfere with the mechanical systems because of the girder's depth or placement.

In many systems the floor itself is used as a transfer level, typically to transfer shear between the perimeter and the core. To open up the ground floor level, the perimeter columns are widely spaced and sized for axial loads. Then, a stiff mezzanine floor transfers the shear forces to the structural core. In the staggered truss system the floors act as transfer levels for transferring shear between trusses in adjacent floors. Thus, the floor is used as a transition level between different systems by providing the shear stiffness to attract and channel forces. The two systems may be either different types of systems or geometrically different systems.

Through the discussions it became apparent that the problem of transfer levels was a problem of creating two column grids that could be meshed economically. Designing the actual transfer girder or truss in terms of laying it out or sizing the members was not extensively discussed. What was frequently discussed, in comparison, was the problem of making the vertical members of the two systems overlap sufficiently so that the transfer system's depth was economical in terms of cost and space. The grids must have some degree of geometric intersection or alignment so that a transfer girder or truss can span the lower columns and also support the upper columns. This was particularly true in the discussions of mixed-use buildings, but was also a concern during discussions of recent architectural trends towards profile changes. The clients' willingness to spend the cost of transfers as an additional construction expense is another large question in the design process.

Of course the severity of the transfer is a topic of discussion during the preliminary design process. One subject said that he might advise an architect to limit his setback size:

"You try to steer the client from major exterior transitions. You try to get the architect to setback 10' not 30' so you take it in small doses, so that you have a way of dealing with these changes. Unless you can come up with a complete restructuring, like the Sears Tower, where you can take a whole cell that is a structural element and just take that out Then that becomes the basic vocabulary for changes in the form. Unless it's organized into that kind of a logic you try to limit it to smaller size steps, or fewer steps."(H.I.)

Another instance of structural transition used in tube buildings is less localized and involves the gradual diminishing of required stiffness at the top of the building. A building designed by one of the subjects architecturally expresses the theoretical question of when does a perimeter frame become a framed tube. In this building, although the exterior form is prismatic, distinct changes of column spacing express the gradual change in the proportion of allowable shear frame distortion and cantilever action. Above a closely spaced framed tube the column spacing doubles and then doubles again to become a widely spaced perimeter frame where the view is more important than the frame's stiffness. In the lower portion the structural frame is modeled as a stiff bearing wall whereas the upper portion is modeled as a frame whose lateral drift is not as crucial to the overall structural performance.

Thus, the transitions are not especially troublesome in themselves when they are used as a logical connection between two adjoining systems. The logic discussed was based on the systems' modularity and terminating each system at a complete module. The effects of each system were considered and any imbalance in the two combined systems must be countered or transferred by the transition structure. The relative stiffness of the transfer level determines the distribution of forces within the transition level and adjacent systems.

4.5 The Evolving Vocabulary of Structural Systems

One of the starting points of this study was an interest in the tube structure system as a most efficient system for tall buildings. The tube system was popularized by Fazlur Khan in the early 1960s⁵ and demonstrated an evolution in structural form over the previous reliance on orthogonal rigid frames. The tube system has been embodied in many specific structural systems such as the framed tube, braced tube and bundled tube. However, the intent of the tube concept transcends specific systems in seeking to use the whole building form as a cantilever rather than filling it with a collection of separate frames working individually. In the writings of Fazlur Khan and other literature on structural systems, the tube system is praised for its efficiency in terms of quantity of steel or concrete per building volume and in freeing the leased spaces of interior columns. Why then is the tube system not used in every tall building? The structural and architectural limits of the tube system were explored through the structured interview questions and by discussing specific buildings that the subjects had designed.

Evolution is characterized as a response to a changing environment, and the real-estate market and architectural context that encouraged the tube system has changed since the 1960s and '70s. The inspiration for the architectural expression of structure in many of the buildings designed during the 1960s and '70s was the technological advances of building technologies and the remaining interest in the Modernist aesthetics of the machine age. From the late '70s on, the shift away from structural expression towards historicism, contextualism, pluralism, etc. has changed both the structural design problem as well as the role that the structural engineer plays within the design team.

⁵In the interest of historical accuracy it would be unfair to credit any one engineer with 'inventing' the tube system. The tube evolved from the structural designers' experience spurred by architectural demands. Tube systems were first used in such buildings as the CBS Building by Aero Saarinen and Paul Wckilinger, the DeWitt Chestnut Apartments and the John Hancock Center, Chicago by Skidmore Owings and Merrill with Fazlur Khan as the structural designer, and in the World Trade Center by Yamasaki and Robertson.

The architectural form that defines the structural problem shifted from a prismatic form to a highly sculptured form. When architects are not seeking structural expression they are also not necessarily interested in the structural ramifications of an architectural form at the early stages of the design process, and then the structure becomes a lower priority. With an increased concern for the speculative marketing of buildings, the architectural implications for leasing can make the structural cost and elegance less of a priority. The structural engineer becomes a participant later in the process, perhaps after a building form has already been accepted by the client.

The architecture of the International Style fit well with the orthogonal rigid frame that was the complete structural repertoire until the late '60s. The introduction of braced core structures, tube structures, etc. began when the building was still prismatic. More recently new structural schemes such as the supercolumn system have been developed to handle the highly articulated building forms.

"Buildings of the 1980s are often highly articulated on the sides, so that's why we developed the spine concept for these buildings. Now if you go back to the 1970s that's not true. In the '70s you pretty much had buildings whose exterior was sacrosanct, they went straight up and down. It might taper or have something very minor at the top, but the building basically went straight up and down. Then you could have an exterior tube very easily and integrate architecture and structure very easily. In the '80s all that fell by the wayside as architecture became a dominant force & they began to drive the design.

The pendulum swings. In the '60s & '70s tall buildings were driven by structural engineering concepts. You came up with ideas & the architect was trying to articulate the structural ideas. Engineering was fairly paramount. Those were the days when the engineer had input very early in the game. He'd really come in with ideas. I did that here in Houston all during the '70s, I'd get called and they'd ask what's the best way to do a 40 story building? I'd go in and start talking and these things would evolve. We developed a lot of systems, partial tubes, wide bay composite systems, shearwall systems. We had a lot of development but it was all based on structural ideas. We had ideas and the architect had needs, so we said lets try this.

In the '80s there was the reaction that these kinds of buildings had no character, no aesthetic appeal, so they came out with brand new things that had no engineering coherence. Now your position was that you had to make the building work." (J.C.)

The 1960s and '70s were times of rapid education for the structural engineer, architect and developer in the practical aspects of designing and constructing tall buildings. The systems developed by the structural engineer may not fit the architectural demands of today, but the principles learned from the system development carry over into the current architectural context

⁴The tubular building, yes the concept of the tubular building was one of attempting to utilize the exterior form and we still need to be involved in that kind of concept to generate regular stiffness for a very tall building, but you don't necessarily have to do it by using regularly spaced columns. You can use the concept of the tube but it does not have to be in the form of a tube."(H.I.)

In a timely coincidence, the advent of computers and structural analysis software have allowed the structural engineer to analyze complex systems that would have been extremely difficult and time consuming to analyze by hand. Tube structures and other systems developed in the 1960s and '70s required three-dimensional analyses which provided an impetus for the further development of automated analysis methods. The availability of large scale analysis programs that allowed three dimensional analyses also allowed the structural designer to investigate geometrically complex building forms that would have been impractical with hand calculations, and to rapidly investigate a larger variety of systems. Without the availability of rapid and accurate computer analyses the effort and approximate nature of hand calculations would have required highly sculptured buildings to be conservatively built and the economics would have retarded the expressiveness of today's architectural forms. The computer was also described as an aid to confirming the engineers intuition about the structural mechanism of potential systems. Every one of the engineers interviewed discussed the great benefit that automating structural analysis has had for their work.

Two of the subjects have recently developed designs that add a new aspect to the structural repertoire. Tall building dynamics has always been a concern, and a lighter, more shaped perimeter can make this problem even more difficult. To alleviate some of the dynamic problems of tall buildings these engineers have worked with the architect in developing designs that pierce the architectural form near the top or at mid-height to reduce aerodynamic effects.

⁴⁴ We can bring in at the very early stage the notion of the top of the building. The top of the building, in a very tall building, can bring in a great deal of aerodynamic effects, aerodynamic sensibilities. That particular building is perhaps a leading example. When we did the structure at that early stage we realized that the building at that height would be sensitive to the perception of motion. We wanted a building that would be as stiff as possible and at the same time we wanted to see if there was anything available in the area of aerodynamic mitigation that we could put into the building. We said I think there are advantages to be gained if the top was not flat and if there were a series of holes that the air could go through. That could have a great benefit in terms of the oscillations of the building. In this particular case we said let's see if we can somehow make some holes in the top, let's see if we can make the top somewhat more aerodynamically advantageous. We were able to put in four holes at the top and build an architectural crown that has the holes in it. We didn't know exactly what advantage we would get from it, but we had the notion that we would get at least some reasonable advantage. We built that in, we said let's keep that in our pocket in case we want it" (H.L.)

Thus, the evolution of structural design has been a combination of architectural motivation, market demand, technological development in other fields such as computers and aerodynamics, and the understanding of the principles behind specific structural systems. The experimental inclination of the structural engineers themselves should not be overlooked. A number of the subjects recounted that many of their ideas came from discussions in their own offices or from thinking about new structural systems abstracted from a specific building project.

5 Critique of Prototype Grammar

The prototype solid grammar presented to half of the subjects was an experiment in representing and utilizing information on tall building design in a computational model of the design process. The critique of the grammar provided a venue for the subjects to discuss formal methods of design and the interaction of architects, engineers and computers. The topics discussed during this portion of the interviews can be separated into process, content and presentation issues.

The subjects were divided in their views on the possibility of a successful embodiment of the design process within a logical computational method. Half of the respondents remarked that the design process was relatively rational and could be described in logical steps. The other half saw this as a limited view of design saying that architecture was a domain of 'imponderables' and structural design is the process of constructing an armature for an unpredictable sculpture. With those subjects who were doubtful about the usefulness of a formal design method this topic occupied the majority of the time spent critiquing the prototype. These two opinions can be seen from the following two remarks:

"It's a hopeless task. The minute that you've got it you'll want to do something else... The problem of designing a building is more like writing a poem than writing a sentence. The subtleties of that are so immense that you can't hope to duplicate it... The structural engineering of buildings, I think, is like being a builder of armature for sculpture. The stuff that's inside the Statue of Liberty is Eiffel's. To try to write a computer program that would anticipate every sculpture that a sculptor could come up with would be sort of a big waste of time, I think, although somebody might argue."(W.L.M.)

"Other than these comments, I think you're on the right track. I like the idea of developing a grammar to establish the entire vocabulary, to establish the set of rules of how you can operate within the process."(J.C.)

The first comment should be tempered with the understanding that the grammar incorporates a stage that generates a prismatic architectural form. The prismatic building form was used in the buildings of Fazlur Khan, the target of our grammar. However, this architectural form is now passe and therefore the structural problems posed by the prismatic form is only a portion of the current design task. Still, the development of a formal method for the integrated architectural and structural design of tall buildings is aiming at a moving target. However, like the mathematically NP-complete problems that can never really be solved in theory, the investigation of methods for addressing realistic portions of the tall building design problem is interesting and promises some degree of pedagogic and practical success.

The content of the grammar brought little discussion, one subject said explicitly that he had no problems with the demonstrated logic. Another subject had doubts about the combination of professions embodied in some of the steps. He remarked that it was easy to say yes or no to a suggested step, but few people have the broad education and experience to make well informed decisions about such diverse topics as service core layout, column location and architectural form transformations. Therefore, he suggested that this method would be useful for a few members of the design team to use simultaneously if the steps could be isolated by domain. Otherwise, it would be better to focus on one domain.

The presentation of information about the current design state that would be useful in making decisions about transformation of the state brought more comments from those subjects who could accept the idea of a computational method for the design process. As an alternative to drawings the solid model must have at least a comparable level of detail. The grammar has the opportunity for even greater levels of detail and a more coordinated presentation of views. This was recognized in many stages of the design process shown, but in a few instances the prototype was seen as lacking detail by more than one of the subjects. The graphically displayed analysis results were described as helpful and appropriate, but the subjects said that they needed a more detailed presentation. The service core was shown as a simple rectangle, but the subjects remarked that they would need to see the internal organization of the core even if they would only use it for resisting gravity loads. However, the opportunity for a more organized and accurate presentation of visual information was viewed as very helpful to the design team and to the structural engineer in particular. Unfortunately, the prototype was demonstrated on a small television monitor from a videotape recording and was not really a proper display of the prototype's capabilities. Nevertheless, the subjects' comments about needing to see detailed floor plans, and the possibility of overlaying multiple floor plans to spatially cross-reference different sections of the building are appropriate criticisms of the prototype.

"Eventually you've just got to see it You can't possibly have all that memorized in your head. People are just not that smart. The more talented designers who are really interested in the sculpture of the building, they need to know what they are forcing on he inside of the building. So they need to take a look at it. I think that would be very important: to see where you arc."(W.M.)

The subjects also described their need for a more accurate method of computing quantitative information such as material quantities, and emphasized the benefit of integrating this information within the decision process of design development. Thus, the critiques of the prototype that should be incorporated in a subsequent refinement of the design grammar include:

- Giving the designer of subjective design tasks, such as the development of the building form, the tools for design development but not impose a specific design method;
- Providing the ability to inspect non-prismatic building forms and formulate the structural problem for these complex forms;
- Providing structural system choices that combine multiple subsystems and transition zones, and formalize when such combined systems are appropriate;
- Showing the floor plan in more detail with architectural, structural, and service elements;
- Acknowledging that the service core is important system by developing the core layout in a similar manner as the rentable spaces and show the core in detail rather than just treating it as a solid element;
- Providing information for the subsequent value engineering phase; in particular, material quantities.

6 Conclusion

Knowledge acquisition is an important, but difficult, aspect of developing a realistic model of the design process. The objectives and constraints used by practicing designers are not necessarily the same as those taught in academia. Academia and design practice each have their own focus, but each can benefit from a discussion of their mutual and separate interests. The subjects interviewed in this study all spoke of their interest in education and the benefits to their practice that has come from academic research. In the study of design methodologies and the construction of design process models, it is the practicing designer who is the judge of the appropriateness of the organization, objectives and constraints applicable to a realistic model of design. However, practicing engineers are accomplished at developing designs and presenting these designs to clients. They are unlikely to be versed in the methodology of design formalization and computational models of design. The subjects who participated in this study were very gracious in describing design cases and recounting the motivation for their design decisions, but these discussions were understandably more like fireside chats than complete and detailed explanations of their design process. The generality that was an objective of this study was lacking in discussions of individual design cases, and perhaps there is little generality in a domain that focuses on the design of unique artifacts that respond to the unrepeatable site, market and architectural demands and take many months or years to become a reality.

6.1 Knowledge Acquisition Process

There were two possible orientations for this study: either to focus purely on the structural concerns and ignore the architectural, marketing, mechanical and elevating concerns; or to explore the interrelation of these domains from the inception of the design process and learn the impact that other domains have on the structural design process. The first focus risks ignoring information that would make a design solution impractical or irrelevant. The latter focus covers too much ground to ever be complete, but is a necessary orientation for developing any meaningful view of design practice. In following the second focus for this study, the most difficult aspect became the analysis of the recorded visits due to the scope and volume of the subjects⁹ responses.

The scope of the design task addressed in this study, and the scope and volume of responses provided by the subjects, differs from previous knowledge acquisition studies in engineering and architectural design. Previous studies in engineering design have focused on rather narrow subproblems within the larger topic of overall design. A study performed in the mechanical engineering domain [Stauffer 87, Ullman 88] presented subjects with two problems: designing the plastic envelope for three batteries to power a computer's clock, and designing a "flipper-dipper" mechanism to hold an aluminum plate as it was dipped to receive a chemical coating and flipped to coat the other side. A study of the architectural layout problem [Akin 87] likewise focused on a relatively small problem of laying out an engineering office for three engineers, a conference room and support staff given the boundary dimensions and window location of three office shells. Another study in structural design presented the subjects with three architectural designs and recorded their generation of a structural framing system [Baker 87]. Each architectural design in the problem statement consisted of a floor plan showing the plan dimensions and the placement of the service core, the number of floors of the proposed building, and a floor-to-floor height. The aspect ratio of the proposed buildings

ranged from 1.5 to 3, thus all of these buildings were of modest height where gravity loads can be assumed to control the structural design. These studies in mechanical, architectural, and structural design, relied on design simulations which were then analyzed using protocol analysis to provide design protocols. It is unclear whether the results of these protocol analyses can be extrapolated to more complex problems which begin from poorly, or incompletely, defined functional requirements and less predetermined geometries.

In contrast to previous studies, this study focused less on modeling a domain independent design process, and concentrated on organizing domain knowledge. The uncovering of the problem definition must precede the uncovering of a solution method. Our knowledge acquisition process was hampered by the interviewer's lack of an accurate perspective on the domain at the high level of abstraction being studied. However, gaining this perspective was one of the objectives of this study. The need to investigate the basic organization of information exchanged between the participants meant that the use of any automated knowledge elicitation tools risked presupposing an inaccurate organization and the availability of information that would not be known at this stage of design development. Thus, we were left no choice but to rely on a structured interview method of knowledge elicitation and the consensus method of analysis.

6.2 Domain Knowledge Acquisition

The domain knowledge gathered through building a consensus of the interview responses was discussed extensively in the previous pages. Briefly, the domain knowledge uncovered can be summarized as follows:

- The design process of each participant includes constraints from other disciplines. The early stages of the design process involve the client and architect generating design information and transformations. During these stages every member of the design team is involved in critiquing the design state for the implications of the design to their domain.
- The problem statement for the structural engineer is given as an architectural form and verbal or written specifications. The architectural form is presented in terms of drawings and perhaps a three-dimensional model. The specifications are presented in terms of qualitative relationships expressing architectural and marketing objectives.
- The structural engineer inspects the architectural form in light of the qualitative specifications to formulate the structural problem. In tall buildings the structural designer aims to utilize the exterior form of the building to develop the structural mechanism of an equivalent cantilever.
- The structural designer inspects the architectural plans for regions of piecewise continuity to house structural elements, subsystems and systems. These elements, subsystems and systems are taken from an evolving vocabulary of an accepted structural repertoire. The principles behind this vocabulary are used to develop new elements, subsystems and systems that provide new solutions to changing architectural and marketing demands.
- Each participant's design process alternates between generative phases and critiquing phases. These may be modeled as iterative composition, refinement and pruning of multiple potential solutions. The prevalence of changes in previous design commitments means that multiple solutions must be generated and maintained at the early stages of design, and that a backtracking mechanism is essential.

A Session Itinerary and List of Questions

A.1 Itinerary

1. Statement of Purpose.
2. Process questions.
3. Design Scenario Simulation.
4. Content questions.
5. Brief explanation of spatial grammars;
Video of Prototype;
Critique of prototypes logic / process.

A.2 Process Questions

- To start with, please tell me if this is a fair assessment of the type of information about a building that you have when you begin the conceptual structural design.
 - I assume you have a rough architectural form and the basic plans of a few typical floors?
 - Do you use a required square footage to derive the specific number of stories, or is **there more** often a height limit for you to squeeze in as many floors as feasible?
- When you look at the building plan, elevation, or at the model is there an implicit location or boundaries for the potential structural systems?
- Do you inspect the architectural zones for certain planes or volumes where concentrations of structure can be effective. Other than the service core and the perimeter of a compact plan how do you identify these zones?
- Is there an implicit class of structural systems which is indicated in some way by the drawings. Are there particular classes of structural systems which you favor or discount for some reason?
- What information in a design's description leads you towards investigating some of the structural tube systems over others?
- While the design team is developing the building form, are there specific structural considerations which have a major effect on the development of the architectural form?
- We've talked about a few specific structural systems. Are there circumstances when you would avoid any of these systems? What other systems might you explore in these circumstances?
- Does structural functionality only become an overriding factor for "special cases" e.g. John Hancock, Sears, Citicorp? Are all TALL buildings "special cases"?
- How important is the shape of the core in choosing to utilize it structurally, and vice versa?

A.3 Design Scenario

In the following design scenarios please describe in detail:

- What additional information do you need to make any decisions?
- Is any information in the problem statement irrelevant?
- Develop a preliminary building design describing, where appropriate:
 - plan,
 - section,
 - structural system type and placement,
 - structural materials.

Problem 1:

Site: 150' x 250'
25% plaza
75% bldg footprint

Uses:

Lobby		
Commercial	80,000	sqr. ft.
Apartment	800,000	sqr. ft.

Problem 2:

Site: 150' x 250'
25% plaza
75% bldg footprint

Uses:

Lobby		
Commercial	125,000	sqr. ft.
Parking		
General office	800,000	sqr. ft.
Executive office	200,000	sqr. ft.
Lobby		
Apartment	950,000	sqr. ft.
Studio	60,000	sqr. ft.
Observatory & Restaurant	20,000	sqr. ft.

A.4 Content Questions

- In a framed tube are column spacings determined by the architectural module, by an optimal spacing, or some other means? Is the tube's effectiveness very sensitive to varying column spacing?
- In developing a framed tube design how do you proportion the relative sizing of the corner columns vs. mid-face columns?
- In framed tubes, are there dimensional limits on the spandrels and columns either for construction or architectural reasons. How do you fulfill the strength/stiffness requirements when faced with these limits?
- In the preliminary design of braced tubes how do you proportion the relative sizing of the bracings vs. the corner columns vs. the mid-face columns?
- Do you design for the braces to transfer all the lateral loads via shear, and with the mid-face columns only taking the gravity loads of individual floors?
- In the John Hancock, the seminal braced tube, there are many large vertical members other than the corner columns. In other proposed or built braced tubes the only large vertical members are the corner columns. Were the large mid-face columns in the John Hancock introduced to make fabrication and erection easier?
- How do you decide where to add/remove material to reduce/relax lateral deflections?
- When iterating over member sizing process, what is the loop's exit criteria?
- Does your preliminary structural design focus on strength, stiffness, or dynamics?
Does your more detailed design stage size members beginning from strength, stiffness or dynamic requirements and then check for their conformance with the other requirements
- How do you evaluate floor framing studies? How do you balance the conflict between minimizing the weight of the flooring system and minimizing its thickness by spending a few more dollars on the floor framing and thereby need less skin?
- Does your floor-to-floor height change for each floor framing design?
- In many buildings, there are a number levels of structural transition, the mezzanine of Two Shell Plaza and others, setbacks, of the Sears Tower, mechanical floors, hat trusses, etc. Could you describe some of the structural difficulties incorporating them into a building's design?
- Is your composite construction design process and member sizing procedures very different from your concrete design process?
- Does your conceptual design process differ from one construction material to another, and in particular with composite construction?

B Biography of Participants

William LeMessurier is Chairman of the Board of Sippican Consultants International, Inc.; President, LeMessurier Associates/SCI as well as Adjunct Professor at the Harvard Graduate School of Design, and Senior Lecturer in the Department of Civil Engineering at MIT. Mr. LeMessurier graduated from Harvard University (A.B.c.l.) in 1947 and Massachusetts Institute of Technology (M.S.) in 1953. Although professionally an engineer, Mr. LeMessurier trained originally as an architect at Harvard. His design engineering practice is directed to structural innovation with a goal of constantly advancing the state of the art, combined with a special concern for structural aesthetics related to architecture. The Staggered Truss System and the use of Tuned Mass Dampers are two examples of this innovative spirit. He has been involved in structures from Houston to Singapore, including the Citicorp Center in New York, Boston's New City Hall and Federal Reserve Bank, the Singapore Treasury and Dallas MainCenter*.

Joseph P. Colaco is currently President of CBM Engineers, Houston and an Adjunct Professor at Rice University. Dr. Colaco received his Ph.D. in Civil Engineering from the University of Illinois, Champaign-Urbana in 1965. During the 1960s he was a close associate of the late Fazlur Khan of Skidmore Owings and Merrill, Chicago, working closely with Khan on such notable buildings as the John Hancock Center in Chicago and One Shell Plaza and Control Data Building in Houston. At CBM he has worked on such buildings as the Pennzoil Building with Philip Johnson and the Norwest Tower with Cesar Pelli⁷.

Walter P. Moore Jr. is Chairman and President of Walter P. Moore & Associates in Houston. Dr. Moore received his Ph.D. in Civil Engineering from the University of Illinois, Champaign-Urbana in 1964. In addition to the structural design of such tall buildings as the IBM Building in Atlanta, One Houston Center, America Tower and First City Tower in Houston, the Walter Moore office has also focused on large-span stadia from the Houston Astrodome in 1965 to the recent Target Center in Minneapolis. Mr. Moore has served on the Council on Tall Buildings and Urban Habitat along with Fazlur Khan, contributing to and editing the volume "Tall buildings systems and concepts".

Hal S. Iyengar is a Partner and Director of Structural Engineering with Skidmore Owings and Merrill, Chicago. He received his BSCE degree from the University of Mysore, India, in 1955, a Master of Hydraulic and Civil Engineering Degree from the Indian Institute of Science, Bangalore, India, in 1957 and a Master of Science in Civil Engineering from the University of Illinois at Urbana, in 1959. He worked closely with the late Fazlur Khan on many projects, and has been a project engineer on many high-rise concrete and steel buildings, among them the 110-story Sears Tower, the 100-story John Hancock Center, the Gateway III Building, and Equitable Building in Chicago⁸.

⁶From the 1985 International Engineering Symposium on Structural Steel.

⁷From *Civil Engineering* May, 1983

⁸From *Civil Engineering Practice* Spring, 1988.

Matthys P. Levy is a Principal of Weidlinger Associates Consulting Engineers, in New York City. He received his BSCE degree from City College of New York and M.S. and C.E. degrees in Applied Mechanics from Columbia University. He served with the Army Corps of Engineers from 1952-54 before joining Weidlinger Associates in 1956. He has served as a visiting critic at Yale University and is presently an Adjuna Professor of Architecture at Columbia University. Mr. Levy was the partner in charge of many award winning designs, is the author of numerous technical papers and articles, and is joint author with Mario Salvadori of the book "Structural Design in Architecture".⁹

Michael A. McCarthy is a General Partner with Skidmore Owings and Merrill, New York City. He received his B.Arch degree from Cornell University in 1957, and after receiving his M.Arch from the Harvard Graduate School of Design in 1964 he joined the New York office of Skidmore Owings and Merrill. With SOM/New York Mr. McCarthy has worked on such projects as the Georgia-Pacific Center, a mixed-use 52 story building in Atlanta; the Kuwait Chancery in Washington D.C.; the 44-story Park Avenue Plaza with fellow SOM/New York partner Raul de Armas and a recent tall building in Manila. Mr. McCarthy is on the advisory council of the Cornell School of Architecture, and has served as Secretary of the American Institute of Architects' urban design committee from 1969.¹⁰

⁹From Who's Who in Engineering.

¹⁰From *American Architects Directory*, and *Skidmore, Owings & Merrill, Architecture and Urbanism, 1973-1983*

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