DESIGN FOR MODULAR SPACE TRUSS SLAB

by

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DEGREE OF MASTER OF ARCHITECTURE

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Dear Dean Belluschi:

In partial fulfillment of the requirements for the degree of Master of Architecture, I hereby submit this thesis entitled "Design for Modular Space Truss Slab".

Respectfully submitted,

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ACKNOWLEDGEMENTS

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This thesis concentrates on the development of a modular structural
framing system. Specifically, the design of a space truss slab
incorporating a steel space frame with a top compression slab of
concrete. Incorporating the triangulated distribution design
system of forces, the system has been refined into two structural
components. These components are: (1) a triangulated unit, and
(2) a frame unit. The two structural components are multi-
functional. Three component systems have been prepared using
standard rolled structural steel sections (angle, channel, and
tee) for the main strut members. The total system is designed to
be produced by quality controlled industrial techniques, with
emphasis on a minimum number of multi-functional components.
The joints have been designed to provide continuity to the
structural system. They consist of bolt and plate assemblies
which are readily positioned and secured.
INTRODUCTION

The following introduction defines the general design of buildings as systems under the dynamic progressive leadership of the architect and the engineer(s). Conceptually and physically all design solutions should be systemized to reflect and express the internal function of the structure and the exterior contribution of the structure to its environment. This system or underlying organization must recognize all contributing elements. The complete system is thus three dimensional and all inclusive. The selected system must coincide with all interior and exterior stimuli. Respect for the environment that shall house and contribute to the finished product is most important. Successful integration of a new architectural statement into an environment, suggests the incorporation of an edited system as imposed by all surrounding objects plus program prerequisites.

The geometry selected to structure this system must be analogous to the desired life within and the surrounding activity. This geometry should accommodate all functional requirements and simultaneously provide an aesthetic unification and organization to the structure. All contributing elements must be categorized into echelones as to provide a hierarchy for prominent contributions. This hierarchy structures the conversation between all elements, and allows the designer to emphasize or subdue elements as required.
A system is a set of objects with relationships between the objects and between their attributes. In which these objects are fractional components of the system, the attributes are properties of the objects, and their relationships link the entire system. It is clear from this definition of system, that any given system can be further divided into subsystems or fractional components. We may now state that fractional components are systems in themselves of a lower order.

The fraction or the smallest working system component should be capable of survival during isolation. By multiplying this basic fraction the designer must be able to provide working conditions for all program requirements of varying scales. When this fraction is initially totally complete, the designer has a new tool at his disposal - flexibility.

Structures are normally designed to live on into the distant future. The initial envelope, sum of the fractions, shall be the stage for a long dynamic performance which must be adaptable and flexible to accommodate long range unforeseen changes. Increasing and decreasing the numerator of this fraction does not destroy or alter the denominator, thus the designer has provided a constant frame of reference. Flexibility is normally an internal desire, external alteration suggests growth.
Growth of or from the original envelope may be easily facilitated provided that the designer originally refined a total fractional component. This self efficient component can be integrated into the existing and thus contribute to the whole without subjecting the original structure to any additional or undue load or strain. The designer should structure and refine his total statement, interior and exterior, to conform to this fractional unit. If this refinement is achieved, expansion or growth shall contribute to the original, and thus render the same expression as progressive technology and changing aesthetic values permit.

Growth may not be the objective of the designer, for his initial statement may be designed to stand externally unaltered due to program or site conditions. Specific projects may be initially complete and totally composed, as to suggest no participation in overall growth. The increasing or decreasing of any fractional components to or from such structures may destroy the original composition, and should be discouraged.

The presentation on systems thus far assumes that there exists a system which is adaptable to human needs, and which receives from and continually contributes to life's stimuli. Human life is an organization of contributing interdependent biological systems. This statement suggests that our building organization
format or system reflect this type of biological interdependency. Rigid modular systems may channel life into predetermined areas of activity, and thus limit creativity. The complete system must recognize the physical structure and the psychological motives of its inhabitants.

CREATIVE ENGINEERING TO ADVANCE BUILDING TECHNOLOGY

The architect as the leader of the interdependent organization of designers, planners and engineers must be capable of selecting only those elements which contribute to and express his ideas. The engineer should not only be a man of figures and calculations, but a man with knowledge of aesthetics, sociology, economics and planning. The pure isolated technician is of very little consequence to the architect.

Programming design solutions is the responsibility of all the contributors that shall be present in the end statement. Communication between all contributors, using a vocabulary common and knowledgeable to all is of utmost importance. We must establish a common basis for the understanding of design and its inherent qualities - a denominator reached through objective findings and research verses through personal interpretation. The science, design, and use of modern technology can not be incorporated without proper communication during the programming stage.
architect in his attempt to produce inventive statements of the highest quality has to rely heavily upon his resources in technology. No matter how creative the architect, the operation of the structure is dependent upon creative engineering practices.

The creative engineer should continually research new paths of knowledge. With this constant expanse of knowledge, he is capable of proposing alternative courses to the architect; and thus remain flexible in his contribution. All engineering principles employed must contribute to the fractional component of any system. For this component to be self-sustaining, it must be capable of accommodating all engineering operations as required. Engineering contributions are not always 'behind the scenes', but may be visually expressed in a creative fashion. Structural and major mechanical systems (including transportation) may be designed to read as separate entities or integrated into the total statement. The architect is responsible for combining the correct and appropriate elements to implement his total system which expresses the function of his statement.

Four general classifications of engineering contributions and their respective responsibilities and direction follows:

STRUCTURAL ENGINEERING

Structural engineers often determine the configuration of the
total envelope or structure. The physical structure of the building should perform many operations in addition to supporting and stabilizing the building frame. The progressive engineer should seek new courses of activity for his material and additional operations during and after construction. He has to recognize and accept physical and mechanical circulation in a manner which is inherent to his system. Thus, the structural engineer must actively project himself into the team of contributors in order to fulfill his responsibility in a creative and efficient manner. His operating efficiency may dictate the success or failure of the structure.

MECHANICAL ENGINEERING

The mechanical engineer(s) are currently faced with a most difficult task. Daily improvements and technological advancements foreshadow yesterday's contribution, and thus constant contact with research findings and development is essential. The mechanical engineer has to satisfy the biological senses of man and thus creatively facilitate our activity within and about new structures. This functional requirement that dictates his contribution provides an ever challenging hurdle to the mechanical engineer. He must provide comfort and safety to the participants and inhabitants of the structure in an efficient manner and still remain within the parameters of expression as outlined by the architect. His solutions also have to be internally flexible, capable of growing,
and creatively integrated into the total system.

SYSTEMS ENGINEERING

Design is the essential function of the systems engineer. His initial objective is the recognition of a need and the conception of an idea to meet and implement this need. He proceeds with the definition of the problem, and through a program of directed research and resulting development, which leads to the construction and evolution of a prototype unit.

The systems engineer must be responsive to economic forces and technological advances. He is also subjected to political, social, and other cultural factors that constitute the whole environment of society. He must recognize and examine the environment which greatly affects his design project; at the same time he must note that this immediate environment is itself reciprocally affected by the consequences of his new statement. The interactions between existing and proposed systems should be brought into common focus during the programming stage of development.

Total design is a complete description of a structure or building and in turn the prescription for its production, thus it must be a complete self-sustaining statement. The architect therefore, like the systems engineer, must be a complete organization man.
CONSTRUCTION ENGINEERING

The construction engineer is most vital to the total programming team. His responsibility to construct and erect the desired structure deserves recognition and thought from the beginning. Before field activity he must project himself into the stages of physical development and program the sequence of construction operations. His creative and ingenious capacity to build, offers to the architect the opportunity to produce new and dynamic structures incorporating contemporary methods and materials to their fullest behavioral capacity. He must be efficient, knowledgeable, and highly organized in order to produce a sequential program that permits rapid continuous progress and development on all fronts. He also must be a very creative in his use of alternatives and improvisations due to interim changes and climatic conditions. His immediate adaptability to these varying conditions results in a smooth development schedule and provides a constant organization and frame of reference for the development of the structure.

THE PATH OF ARCHITECTURE IN THE FUTURE

The architect must be a communal leader, rendering a service to his community. In lieu of defining the architect and his profession, which is highly opinionated and most difficult, the following basic responsibilities that shall confront tomorrows architects
and their architecture is now presented.

The architect must be a complete organization leader. He must be capable of formulating dynamic programs for all human needs, and he must have the capacity to interpret his clients desires and motives (current and future), and from this insight draft his path of attack. Programming his solution requires constant contact with his supporting economist, sociologist, engineers, planners and technicians. He must be able to refine this fountain of varied ideas and approaches into a single statement, self-expressive and totally functionable and flexible.

The architect must always remain a student, for his productions must reflect current technology, materials, and construction methods. He must consistently study and investigate all sources of research and development that may implement his creations and offer physical structure to his conceptual ideas.

The architect has to constantly provide the dynamic stimulus for his supporting contributors and his community in order that they continually search for the highest quality of expression in their desires and contributions. Architecture does not just house life, but it must provide the physical and psychological stimuli for this activity.
Architecture, like all physical bodies, is subject to time and its inherent hurdles. Structures of an earlier period do not automatically attain unquestioned quality with age. The initial structure must accommodate and facilitate the days activity and be flexible enough to accept change and growth without destroying the first statement. The mark of quality in architecture is for a structure to live and die a life of only one occupation. Most facilities with age become warehouses for unrelated multi-activity groups seeking shelter. To confront this use and physical deterioration, the architect must program his creation to accept rational change and select materials of long operating efficiency. Then with periodical programming changes and maintenance his statement can blend and bend with future needs as they vary in function and scale.

The architecture of today shall prove resourceful to the historians of tomorrow if these fore-mentioned challenges and responsibilities are met and conquered. We cannot itemize all the forces that shall be placed on our buildings in the future, but we can project general trends and nearly estimate operational changes and material behavior. Here the architect need be an artist and paint an accurate portrait of the future.
DESIGN OBJECTIVES FOR THESIS

Specific design objectives are now presented. These initial objectives formulated the direction and final execution of this structural framing system. The primary thesis of this investigation is the composition and design of modular component units for a space truss slab.

1) Design a structural system with a minimum number of prototype multi-functional modular units to reduce tolerance allowances and to accelerate erection.

2) Design one typical prototype bolted connection or joint assembly to transfer internal stresses without prohibitive eccentricity.

3) Take advantage of industrial quality control in prefabricating component units of such a size and weight as to permit handling by a maximum of two men during transportation and erection.

4) Design an erection procedure that deletes the use of temporary scaffolding and shoring.

5) Design a typical internal column supporting system for a continuous frame, (one complete bay to be developed).

6) Design the upper chord to facilitate the following requirements:

   a) framing system for floor or roof construction.

   b) continuous fireproofing for framing below.

   c) shear connector for bond and transfer of shear from the
structural steel to the concrete slab above.

d) temporary working surface before placement of final flooring material.

7) Design the lower chord to facilitate the following requirements:
   a) continuous fireproofing for structure above.
   b) ceiling system that expresses the structure above.
   c) ceiling system that accommodates lighting, mechanical systems, and provides for acoustic qualities.
   d) facilitates union between bottom chords and partition units.

HISTORY
The space truss or space frame path of history is irregular and non-coherent. For this reason the historical reach of this thesis shall only focus on those individuals whose contributions and efforts have directly influenced the design and development of this system. Early engineers suggested courses for determining the internal stresses in non-coplaner truss assemblies, but only during recent times has this fragmentary information been assembled and used to approximate the stresses and their distribution in space frame design.

The space truss is a member of the articulated structure family.
An articulated structure is composed of struts assumed to be connected by frictionless pins at the joints, and arranged so that the area enclosed within the boundaries of the structure is geometrically subdivided by the struts into triangulated units.

Early engineers contributing to the analysis of articulated structures and their respective contributions follows. Andrea Palladio (1540) is believed to have first used trusses, although his designs were not the result of rational analysis. Simon Stevin (1580) published the first design manual dealing with statics. He understood the composition and resolution of forces and he introduced the principle of triangular force distribution. August Ritter (1863) published his 'method of sections' and demonstrated how stresses in an articulated structure can be computed by the principle of moments. James Maxwell (1870) expressed the necessary conditions for geometric coherence by a set of equations in which the variables were the redundant stresses. This was the first method developed for systematic analysis of indeterminate structures. Mohr, Williot, Castigliano, and many others since the mid-eighteen hundreds have refined and developed analytic approaches for articulated structural design.

Space trusses may be divided into two primary groups dependent upon their internal configuration. Rectangular space frames are
are a combination of Vierendeel trusses positioned normal to each other. Additional diagonal struts are required in each vertical plane to prevent racking and to stabilize the structure.

The distribution of forces in this type of system is two directional within each plane.

Triangulated space trusses are composed of multi-directional struts which in turn distribute internal stresses in a triangular pattern. This system is more interdependent than the rectangular system due to its internal geometry.

The following discussion includes recent system developments for flat surface space frames and trusses. Curved, radial, and warped space frame component systems as mastered by Buckminster Fuller with his 'geodesic design' have been purposely omitted from this thesis.

The Mannesmann system (1945) for temporary scaffolding using tubular struts of a constant diameter and length in a three dimensional truss is a recent example of space frame design. This tubular system has the disadvantage that its connectors always transmit internal forces eccentrically, thus subjecting the individual tubular struts to bending which is most undesirable. An alternate solution might have been to use a ball joint to
secure and transmit these multi-directional and intersecting forces.

The Mero system (1954) uses the spherical connector to eliminate eccentricity at the joint. However, this solution has the disadvantage of using one type of connector and only one type of tubular compliment. Increasing the capacity of the connector and modulating its effectiveness by varying the size of the tubular components would have increased the usefulness and scope of this system.

The Unistrut system (1955) is the most refined, flexible, and permanent system to date. This system has two principle components. The first of which is a channel shape strut of constant length fabricated of light bent plate. The connectors are pressed steel plates facilitating both horizontal and diagonal struts which in turn are secured with bolts. This system is again limited to a single loading condition due to prototype section and its monofunctional use. The actual carrying capacity of this system can only be empirically analyzed. The major advantage of this system is the minimum number of components involved, but this over simplicity demands more field time for erection, a greater respect for tolerance control, and a limited load carry capacity.

Mies van der Rohe successfully employed the space frame structural
system in his design for the Chicago Coliseum (1953). Konrad Wachsmann has also developed a prefabricated tubular space frame system. The original intention of his design was to roof air plane hangars with a structural system that could be easily dismantled. Recently with moderate success, others have experimented with varied component units.

SPACE TRUSS SLAB DESIGN

This system is composed of two structural units plus two complementary joint pieces. The units and their respective joint assemblies are illustrated on the drawings. For this thesis three separate component systems have been designed. The gross geometry of all the solutions is similar. When assembled the individual units form a space truss. The upper and lower chords are formed by two parallel struts and the diagonals consist of single angular struts. The diagonals may also be doubled by inverting adjacent triangulated units.

Preliminary analysis indicates that the upper and lower plane chord members carrying the largest loads would be at mid-span between column supports. The diagonal or web strut subject to the largest load would be at the column support. The actual distribution of all internal stresses only can be empirically analyzed. For this reason a correction coefficient is required
to compensate for the approximation. The path of this variable distribution is known, but its corresponding coordinate values can only be approximated. Illustrative structural calculations appear in the appendix for a forty foot and a sixty foot span. Graphical media is presented on drawing #1 to support this analysis.

This structural system has built-in reserves of strength to enable it to facilitate local overloading. The interdependency of all chord and diagonal struts creates an internal network of multi-directional force resistors. The space truss slab is an indeterminate structure of unusual dimension.

The calculations only represent gravity loading conditions, so that approximate sections could be selected. The joints between columns and truss are assumed to be pinned. In reality this joint would be partially fast and have moment capacity. Where two web members are placed parallel to each other they have to be connected at mid-length to prohibit buckling due to compressive stresses.

Cantilevering the space truss beyond the exterior row of columns often helps to reduce the maximum bending moment and may result in the use of a smaller and lighter section. The deflection of
such cantilevers under various stages of loading may be excessive and should be studied.

Deflections can be approximately obtained by treating the space truss slab as a series of beams and computing the accumulated deflection. For example, the deflection at mid-span is the sum of two deflections; one due to a continuous beam along the column line, and another due to a perpendicular continuous beam at mid-span. Thus the effect of interdependency and elastic flow has been omitted.

The joints are designed to transmit all chord and diagonal forces. The joint provides continuity to the total structure by transferring all intersecting force paths. Eccentricity must be recognized and controlled to delete excessive bending in the joints and struts. Shear studs are provided to transfer this stress to and through the connector plates. The function of the bolt is to secure the joint plates and not to transfer any internal stress. This single bolted joint assembly is fast to assemble and deletes the use of welding or riveting equipment in the field. Joint designs for the three perposed systems are illustrated on drawings #2, #3, and #4.

Fabrication of the two primary structural units incorporates and
takes advantage of factory quality control. Using industrial component assembly techniques, the designer can better control tolerance requirements for field erection. This control is a result of totally independent units. The two units are prototypes, thus reducing special conditions to a minimum. The chord and diagonal struts consist of standard rolled structural shapes. These struts are assembled in triangulated and frame units as illustrated on the drawings. All unit connections are welded in the factory. The joint connectors consisting of bolt and plate assemblies are punched in the factory and the bolt stubs and shear studs are welded there also.

Tolerance, an enemy to prefabricated unit systems is recognized, controlled, and provided for in the joint design. Due to the number of units required to complete one bay the tolerance control between these units has to be considered. Using factory fabricated units, the designer decreases field assembly work and thus minimizes this problem. Respecting the fact that all tolerance can not be controlled or eliminated, the joint plates and their complimentary shear studs are tapered to provide for slight gains and losses.

All design statements are shadowed with the advantage of continuous frame design. The resulting continuity is most advantageous to this type of structural system. This continuity provides internal
stability and in turn reduces the maximum moment at mid-span. The top concrete also provides stability to the space truss while assisting with the design in absorbing compressive stresses.

The weight of the individual units is limited to the lifting capacity of two men. This design prerequisite allows for transportation and erection without the mandatory use of a crane. Then the component units can be easily handled and stacked until needed. Suggested maximum weight is 140 pounds per structural unit or a design parameter of 8 pounds per square foot in place. The physical size of the unit should be within the horizontal expanse of a man's arms (approximately six feet).

The span-depth ratio of this design solution is much greater than conventionally one and two way structural systems. The load distribution is similar to a flat slab with the advantage of the additional depth of the truss. Unfortunately optimal structural is rarely realized due to mechanical requirements for the building. The amount of area required for air handling systems normally exceeds the minimum depth as required for structural design of this type of space truss system.

Column conditions are presented in a later chapter. Their integration with and their impact on the space truss shall then be
COLUMNS SUPPORTS

The vertical support of the space truss slab poses a difficult problem. This investigation deals only with internal column supports. The main problem is the distribution of this reaction force at the column capital to the space truss. Since the system incorporates units of prototype design, the designer must strive to approach maximum operating efficiency for these units. Contact points between the column and space truss should be clustered to distribute this force to as many bearing points as possible.

The column or column clusters should be integrated into the design and operation of the lower chord of the structural grid. This integration coincides with partition flexibility and modular ceiling treatments. When column clusters are used they may double in function as mechanical shafts provided that adequate fire protection is supplied.

Sample column supporting systems are illustrated on drawing #5. These suggestions represent various methods of supporting the space truss slab.
UPPER CHORD REQUIREMENTS

The flooring system must be capable of spanning the upper chord grid system. Design analysis for this flooring section must include a constant distributed load plus recognition of a maximum partition load; in addition to normal dead load consideration. Respect for the composite loading condition must be dealt with and this analysis often determines the thickness of the slab beyond gravity loading carrying requirements. Location of construction and expansion joints should follow normal construction procedures for flat slabs.

The position of the upper chord grid network usually follows positioning of the the lower chord to facilitate plan and ceiling conditions below. Thus, the upper chord is one half module removed due to the triangulated shape of the space truss members.

Continuity in the upper chord is essential to resist inherent compressive stresses. The composite design solution using the steel struts in the top chord plus the continuous concrete offers the best design solution to this problem. To facilitate adequate bond between these two dissimilar materials, shear studs are supplied to transfer shear stresses and link these materials together. These structural shear connectors must be fixed to the upper chord steel so that they penetrate into the concrete and
tie the material together to resist compressive stresses.

Since light weight concrete or a similar continuous material placed in a similar way shall be employed on the top surface of the space truss, formwork for this material has to be included. This forming unit must be capable of spanning between two parallel top chords without requiring additional support or shoring. The framing unit in addition need be capable of supporting a man's weight during the construction period. The edge condition of this element must compliment the interior edge of the frame and triangulated units in order to provide a continuous water tight seal. Intermediate joints may be closed and sealed with rubber gaskets. This gasket closure may be cut to provide mechanical passageways to the slab above. Suggested solutions are presented on drawings #2, #3, and #4.

The above solutions suggest permanent form work which is the most efficient. Temporary and reuseable framing units could be employed, but this operation appears to be unnecessary.

Precast structural flooring panels may be placed into the grid of the upper chord. If this method is used the joints between adjacent panels have to be filled with a material similar to that of the panel units. The main disadvantage of this solution is
the resulting lack of continuity for the compressive stresses.
The principle advantage of this solution is that it is generally
a dry process and thus eliminates wet trades from this operation.

The flooring system must also assist in sound isolation and
provide fireproofing for the network of steel structure below.
The flooring surface itself should be waterproof and of a material
and finish that offers long term maintenance efficiency.

LOWER CHORD REQUIREMENTS

The physical and mechanical functions of the lower chord ceiling
system determines its configuration. This chapter is devoted
to these required functions, and design solutions are presented
to illustrate these functions on drawings #2, #3, #4, and #5.

Functional requirements include successful integration of the
following elements into the expression and operation of the
ceiling system; 1) lighting unit, 2) air handling diffusers,
3) fire protection, 4) acoustic qualities, 5) special mechanical
equipment, 6) provision for partition alignment and fastening,
and 7) attachment to the space frame with connectors that permit
removal.

Every ceiling element must facilitate a lighting unit. This unit
must compliment the desired aesthetic and functional requirements of the ceiling design. The light design must respect occupancy requirements and the expression of the structural system. Ventilation paths must be supplied to provide an escape for the heat generated by the lamp. The cover or shade has to be removable for periodical servicing and maintenance operations.

Supply and/or return diffusers for air handling systems have to be integrated into the expression of the ceiling. While every ceiling element does not require this mechanical service, provision for this equipment should be included in all elements. This provision accommodates flexibility in plan and occupancy requirements. Since light fixtures shall occur in every ceiling element, the air diffuser must be designed to operate with the lighting unit. In fire rated installations, special fire dampers are required to impede the spread of a fire through the duct system. The resulting negative triangulated areas in the space truss as formed by the ceiling units provides a distribution path for all mechanical services in two directions without structural interference.

The ceiling unit and all included equipment shall be fire rated when project requirements demand this. The material selected to perform this operation should be cast, moulded, or pressed into
a reinforcing shell for handling and erection. This back-up shell provides for easy attachment to the steel frame, and in addition accommodates removal without destruction.

The material selected to form the ceiling element should have acoustic qualities. This material must absorb the designed amount of sound and not allow for any sound transmission. If the sound is permitted to pass through the ceiling it may re-enter the space from an adjacent ceiling element. This type of sound transmission requires partitions that extend to the bottom of the slab above, thus destroying the inherent uninterrupted mechanical space as provided by the space truss. Only a portion of the ceiling element may have to be acoustically treated to provide the required absorption area.

The functional design of the ceiling should also be flexible to accommodate additional mechanical systems inclusive of exhaust, fire-sprinkler, and audio equipment. This multi-functional element is the terminal for most mechanical services delivered to the enclosed space, and thus it should accommodate all service systems with maximum operating efficiency.

The joint between the ceiling elements must also be multi-functional. This joint must first secure adjacent ceiling elements and then
provide a ground for prototype partition attachment. This attachment detail must be flexible to accommodate and permit change in plan requirements. The joint design must respect construction tolerances and simultaneously stabilize each element. Sample joint details are illustrated on drawings #2, #3, #4, and #5.

The ceiling element may be positioned during erection of the space truss components or placed later. Anchor clips to fix the ceiling element into position should be provided on the angle struts of the triangulated structural units. These clips should bond the angle struts to the reinforcing shell of the ceiling element. Slotted holes positioned normal to each other should be provided in the shell and in the angle clips. The only field operation is to screw the clip angle to the reinforcing shell.

Incorporating the above functional requirements, the designer must refine a ceiling element that expresses the structural system above and coincides with the plan module below.

This structural system offers a two directional square grid in the upper and lower plane chords. The principle function of the lower grid is to seat and terminate wall partitions. The position of this grid should always compliment the plan module and never require subdivision to facilitate internal operations. The location
of the column supports should also compliment both the ceiling grid and the plan module.

This chapter to now has emphasized the design and functional use of ceiling units. The designer may elect to eliminate this element and completely expose this structural framing network. Revealing the raw mechanical services and their respective functions could prove to be visually most exciting. This solution is adaptable to low rise structures, partially enclosed structures, pavilions, and buildings where the space truss slab constitutes the roof structure.

EDGE CONDITIONS

The design of an edge or terminal condition for the space truss slab has been purposely omitted from this thesis presentation. Recognition of this terminal condition has been considered. The facade should reflect the internal operation of the structure, and not mask or camouflage this internal structural network. In detail this statement should encompass the net expression of all contributing systems and their respective functions. The initial design parameters should incorporate facilities to perform and implement the design of this edge condition. These parameters should stimulate and structure the complete internal and external organization and operation of the structure.
FLEXIBILITY AND GROWTH

Flexibility normally suggests internal reorganization due to operational changes. The space truss slab may accommodate horizontal flexibility in several capacities. Mechanical systems can be repositioned and wall partitions can be relocated to blend with changing requirements. The only limitation is compliance with the existing module.

Vertical flexibility can be achieved by removing the modular structural units at required locations. The bolted connectors may be disassembled to permit removal of these units. Additional framing may be required to transmit the surrounding forces without interrupting the continuity of the structural system.

Growth, an external increase in the physical plant, may be accommodated equally well. Additional modular units may be added in bays or individually to form cantilevers. Disruption of existing framing should not be necessary during this growth period.

ERECTON

The conventional methods for assembling and erecting segmented systems incorporates temporary shoring and scaffolding. This erection procedure offers certain inherent advantages and disadvantages. The principle advantage is that the complete system
can be formed without the assistance of a crane or similar lifting vehicle, provided the individual segments are movable be one or two men. The disadvantages are many and a few of the obvious ones shall be mentioned here. Construction of a temporary working surface (scaffolding) is very costly, monofunctional, time consuming, and an inconvenience and obstruction to other construction operations. These disadvantages suggest an erection procedure free of temporary formwork.

The individual units may be assembled in place without scaffolding and without additional equipment by using 'erection connectors'. These connectors should facilitate temporary positioning during erection and allow for continuous development. This temporary positioning provides a working platform for final joint connections. This procedure could commence about an internal column support and continue to mid-span. The erection stresses would be minimal, and the resulting deflection of very little consequence. The main disadvantage of this solution is time involved and the multiplication of slight tolerance errors.

The use of an 'erection table' may solve all erection problems without using heavy hoisting equipment. This table is illustrated on drawing #5. This multi-functional device performs the following functions: 1) offers an assembly surface and platform at bench
height, 2) telescopes vertically to position a cluster of ground assembled units, 3) provides a working surface at the final elevation of the space truss units for securing to adjacent joinery, and 4) moves horizontally to the next desired location. This 'erection table' would have to be custom built, but its capacity and operating efficiency would be self-rewarding.

The contractor may elect to assemble a large portion of the space truss and raise this unit to a final position with a crane. This preassembled unit may form an entire bay of a beam like unit to span between vertical supports or other beams. The important fact here is that the frame units must not be subjected to stresses foreign to inplace stresses. However, this procedure is very fast and the floor surface below may be used for the assembly area. The principle drawback is the use of a crane for the erection of initially small light weight structural units.

An alternative method to the above solution is to use the columns as lifting towers. The previously erected columns would be subjected to only a slight impact stress at the moment of lift-off. In this procedure the column unit must compliment the space frame design and be integrated into the network of structural components at its capital. This requirement is necessary to facilitate immediate joinery to the space frame upon final
positioning.

The designer must select the erection procedure to be employed, and design his system to meet these requirements. The design refinement of the structural units suggests an erection operation of equal simplicity. Use of the 'erection table' best completes this obligation.
STRUCTURAL CALCULATIONS

(1) 40 foot square bay

(2) 60 foot square bay

This bay has been extracted from a multiple bay framing system, and the gravity loading conditions are as follows:

<table>
<thead>
<tr>
<th>Dead Load</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>space truss</td>
<td>8# / sq. ft.</td>
<td></td>
</tr>
<tr>
<td>concrete slab</td>
<td>30# / sq. ft.</td>
<td></td>
</tr>
<tr>
<td>ceiling element</td>
<td>4# / sq. ft.</td>
<td></td>
</tr>
<tr>
<td>mechanical equipment</td>
<td>5# / sq. ft.</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>47# / sq. ft.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Live Load</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>per occupancy</td>
<td>100# / sq. ft.</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>100# / sq. ft.</td>
<td></td>
</tr>
</tbody>
</table>

(1) 40 foot square bay:

DIAGONAL AT COLUMN CLUSTER

\[
\begin{align*}
\text{TOTAL BAY AREA} & = 40' \times 40' = 1600 \text{ sq. ft.} \\
\text{LOAD / #} & = 150' \times 147' \\
\text{TOTAL WEIGHT} & = 1600' \times 150' = 240,000' \\
\text{EACH COLUMN CLUSTER SUPPORTS} & = 240,000' / 4 = 60,000' \\
\end{align*}
\]

Load is distributed to three diagonals.
LOAD ON EACH DIAGONAL: 60,000#/3 = 20,000#

FORCE IN ONE DIAGONAL: 20,000 / 1.3 / 2.5 = 12,200#

SINCE EACH DIAGONAL AT COLUMN CLUSTER CONSISTS OF TWO ANGULAR STRUTS, EACH STRUT CARRIES 41,200#/2 = 20,600#

USING ALLOWABLE STRESS = 30,000, THE CROSS SECTIONAL AREA REQUIRED = \[
\frac{20,600}{30,000}
\] .69"

CHORD STRUT AT MID-SPAN

\[E/\text{M AT MID-SPAN} = 120,000 \cdot 10 = 1,200,000\] **
AVERAGE M/LIN. FOOT = \( \frac{11}{40} \times 1,200,000 \cdot 40 = 30,000 \)

CORRECTION COEFFICIENT FOR EQUILIBRAL DISTRIBUTION  
\( 30,000 \cdot 1.25 = 37,500 \) *

---

EACH CHORD CARRIES A 5' PATH  
\( 37,500 \cdot 5 = 187,500 \) *

DEPTH OF TRUSS = 2.5'

FORCE IN BOTTOM CHORD =  
\( 187,500 / 2.5 = 75,000 \) *

SECTONAL AREA REQUIRED =  
\( 75,000 / 30,000 = 2.5 \) **

SINCE EVERY CHORD CONSISTS OF TWO PARALLEL STRUTS, EACH STRUT HAS A SECTONAL AREA = 1.25 **

---

(2) 60 foot square bay

**DIAGONAL AT COLUMN CLUSTER**

TOTAL BAY AREA = 60' x 60' = 3600

TOTAL WEIGHT = 3600 \( \cdot 160 \cdot \frac{1}{4} \cdot 540,000 \) *

EACH COLUMN CLUSTER SUPPORTS = 540,000 \( / 4 \cdot 135,000 \) *

LOAD ON EACH DIAGONAL AT COLUMN = 135,000 \( \cdot 3 = 45,000 \) **

FORCE IN ONE DIAGONAL = 45,000 \( / 1.2 \cdot 4.6 \cdot 3 \cdot 82.75 \) **

SINCE EACH DIAGONAL IN THIS REGION CONSISTS OF TWO PARALLEL STRUTS, EACH STRUT CARRIES = 82.750 \( / 2 \cdot 41.375 \) **
SECTIONAL AREA REQUIRED FOR EACH STRUT:

\[ 41.375 / 30,000 \times 138^\circ \]

CHORD STRUT AT MID-SPAN:

\[ \varepsilon \text{ at mid-span} \times 270,000 \times 15 \times 405,000 \]

AVERAGE M/LIN. FOOT \[ \varepsilon \text{m/60} = 4,050,000/60 = 67,500 \]

CORRECTION COEFFICIENT FOR EMPIRICAL DISTRIBUTION

\[ 67,500 \times 1.25 = 84,400 \]

EACH CHORD CARRIES A 5' PATH \[ 84,400 \times 5 = 422,000 \]

DEPTH OF TRUSS \[ 3.0' \]

FORCE IN BOTTOM CHORD \[ 422,000 / 3' = 141,000 \]

SINCE ALL CHORD MEMBERS CONSIST OF TWO STRUTS,

EACH STRUT CARRIES \[ 141,000 / 2 = 70,500 \]

SECTIONAL AREA REQUIRED FOR EACH STRUT:

\[ 70,500 \times 1/30,000 \times 15 = 2.35^\circ \]
GRAPHICAL EXPLANATION

The following photographs of presentation drawings (sheets #1 thru #5) and models supplement the text of this thesis. Details and design solutions for any one particular component may be modified to compliment any component system. The drawings are referenced from the text to illustrate particular design solutions.
To view original plates, please see pocket in back of book.
BIBLIOGRAPHY

BOOKS

Hall, Arthur D.
A Methodology for System Engineering

Asimow, Morris.
Introduction to Design

Salvadori, Mario and Heller, Robert.
Structure in Architecture

Kinney, J. Sterling.
Indeterminate Structural Analysis

Hauf, Harold D. and Pfisterer, Henry A.
Design of Steel Buildings

Siegel, Curt.
Structure and Form in Modern Architecture

American Institute of Steel Construction.
Manual of Steel Construction

Lin, T.Y.
Design of Prestressed Concrete Structures

American Concrete Institute.
Manual of Standard Practice for Detailing Reinforced Concrete Structures
Detroit: American Concrete Institute, 1957.
BIBLIOGRAPHY

MAGAZINES AND BROCHURES

Purves, Edmund R.
"The Architect and the Superman Myth"
Architectural Forum

United States Steel.
Hot Rolled Steel Shapes and Plates

Teng, Wayne and Sbarounis, John A. and Gaus, Michael P.
"Engineering Problems of an All-Welded Two-Way Truss System"
The Welding Journal
June, 1958. 565-569.

Fenestra.
Composite Floor System
1964.

Leitzinger, Joseph L.
"Using Components for Wood Shell Design"
Architectural and Engineering News
Vol 5 No 4 April, 1963. 34-40

Fernandez, Manuel A.
"Structural Innovations: Aluminum"
Architectural and Engineering News
Vol 5 No 4 April, 1963. 31.