INTEGRAL ARTICULATION OF WOOD BUILDING SYSTEMS

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ABSTRACT

This study focuses on the design and development of a built-up wooden post and beam system comprised of standard, readily available parts. The design attitude is based on the lessons that can be learned from vernacular architecture. Consequently, the question asked is how do the nature of materials and assembly affect the structural scheme and, ultimately, the entire building ensemble? The study is organized as follows:

INTRODUCTION : In which some theoretical aspects of the frame are considered
OVERVIEW : A general discussion of the built-up approach
ELEMENT : A discussion of the nature of wood as a building material
PRINCIPLE : The largest part of the work, in which structural principles are introduced and developed in detail
SCHEME : An exploration of how these principles can then be assembled into a building-scale scheme
SYSTEMS INTEGRATION : In which the structural assembly is considered in relation to other parts of the building ensemble

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I owe a great deal of thanks to Eric Dluhosch, my advisor. If there is so much as an ounce of truth in this work, it is because he patiently—yet insistently—demanded that I find it. I am deeply grateful. If, however, my effort falls short, the fault is my own.

There are many others to whom I am indebted. I believe, I hope, it appropriate to acknowledge that indebtedness by dedicating myself to the ongoing process of making a world as it should be.
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INTRODUCTION

This work focuses on a wood post and beam frame system. In his essay, "Chicago Frame," Colin Rowe asks why Frank Lloyd Wright never really employed the skeleton frame system, despite that it was the premier tectonic development of his formative time and place; a development which, Rowe points out, provisioned a major theme in twentieth century architecture. 1 It is a good question—the one that I would like to open this work with—for although the scale and the materials are somewhat different from those with which I am working, Rowe establishes in his examination both the functional and theoretical issues raised by the frame in modern architecture.

The introduction of the steel frame to the architects of Chicago in the latter part of the nineteenth century was timely. Chicago had been virtually leveled by the fire of 1871, but reconstruction was initially slow due in part to fear of further disaster. The development of the frame in the 1880's, and the earlier invention of the passenger lift, made safe, economic high-rise construction possible. Rebuilding was particularly intense during the 1880's and '90's in The Loop—the business section—"....where new building methods were tried out, with unusual boldness, to meet new needs." 2

"In Chicago" Louis Sullivan was later to write "....The future looked bright. The flag was in the breeze...." 3 But if the spirit was one of bold experimentation, it was a spirit based upon the extremely pragmatic attitude brought to their work by the men whose activities had made the city what it was. This attitude could be seen in the very founding of the city in 1830 when it "....became a city; not as in the time of Romulus, by the ploughing of a furrow, but with a mathematical and economic operation in the American tradition, the division of an area of half a square mile into small regular squares near the mouth of the river, and by their subsequent sale as separate sites. The network was such that it could be extended indefinitely and by successive additions...." 4

This is the attitude and the landscape out of which the first tall buildings arose, and in a sense the buildings were an
extension into the third dimension of what was already on the ground, for if the layout of the city was essentially an act of division, the construction of a skyscraper can be understood as an act of multiplication.\textsuperscript{5}

Wright denounced the Chicago skyscraper as a "mechanical device" and at least one critic maintains that "...it has always been judged harshly from the point of view of overall composition, since it is an indefinite device lacking both proportion and unity...."\textsuperscript{6} The fact remains, however, that in Chicago the tall building, and the frame that makes it possible, points "...to a new mental process which contains—for the moment in rough and embryonic outline—a new way of seeing architecture which must be judged according to new criteria."\textsuperscript{7}

This new criteria of twentieth century architecture is what Rowe seeks to establish in his essay, which was itself written in the early 1960's. His assessment of these buildings is of buildings 'as fact' and is at once both generous and critical.

For some ten years the architects of Chicago devoted themselves to the solution of typical problems of the frame; and, before the end of this time, they had achieved results which are still today unsurpassed for their elegance and economy. But, admiring these results and acknowledging this great achievement, one is still disposed to ask of these Chicago buildings whether they are indeed representative of a 'modern' architecture. Certainly the process of their design was as rational and as direct as that of any modern building is supposed to be. Certainly these buildings are lacking in both rhetoric and sentimental excess; but, also, there is about them a quality of rudimentary magnificence, a flavor at once more heroic and more brutal than is to be found in any building of the present day. These structures make no compromise with the observer; they are neither capricious nor urbane and they display an authenticity so complete that we are disposed to accept them as facts of nature, as geological manifestations rather than as architectural achievements.\textsuperscript{8}

It is precisely within the ipso-facto nature of these buildings that Rowe perceives an inherent limitation in design attitude and understanding.

....the architects of Chicago did not demand the frame; it was rather presented to them; and this simple fact may explain both the rapid and dispassionate manner in which
they contrived to rationalize the frame structure.... With a lack of stylistic prejudice and with a discretion which seem remarkable to us today, the Chicago architects projected on to their facades the neutral structure which they felt to be the reality of the frame behind; and if, as was the case with Sullivan's Wainwright Building in St. Louis and his Guaranty Building in Buffalo, it was considered aesthetically desirable that the frame should be modified, this process was rationalized in terms of the need for psychological expressiveness in the facade rather than in any need for internal spatial excitement. 9

From the perspective of the present, it is virtually inconceivable to think of the frame without thinking too of its spatial potential; we have long since come to understandings of the grid which permit a great deal of structural complexity. Rowe is careful to remind us, however, that in Chicago in the 1880's and '90's this was neither the case nor, in a sense, could it be.

With little occasion to use the frame for any other program than that of the office building, it is not surprising that the Chicago architects remained unaware of certain of its attributes,...they had limited themselves to producing buildings which should be no more than the logical instruments of investment. In other words, being in no position to make manifestos in the cause of rationalism, they were obliged--and within the strictest terms--to be as rational as they might. 10

In contrast to this, Wright had entirely different concerns, as well as a different approach. From the start Wright was "abnormally sensitive to the demands of an expressive space" and his early work in Oak Park displays an absolutely consistent spatial development. 11 Rowe suggests that it was not until later--after he had developed his understanding of spatial order, an order he was "compelled" to satisfy--that he was able to rationalize his spatial "...achievement in terms of generating structure." 12 Thus, a partial explanation of Wright's reluctance to use the frame can be found in the predominant understanding of it in contrast to his own pressing concerns.
However, Rowe contends that an argument based solely on the precept of a purely formal will is an incomplete answer at best. We must look to the progenitors of the International Style--specifically Le Corbusier and Mies van der Rohe--in order to fully grasp the situation; their understanding of the frame was fundamentally different from that of the Chicago architects, and the difference is manifested precisely at that critical juncture of space and structure.

But in order to arrive at an equation of the demands of space and structure, Le Corbusier and Mies van der Rohe had been led to postulate their functional independence, i.e., the independence of partitions from columns, so that unlike Wright's development--which may be said to proceed from a conviction as to the 'organic' unity of space and structure--the International Style may be seen to issue from an assumption of the separate existence of both according to distinct laws. Wright's structure creates space or is created by it; but in the International Style an autonomous structure perforates a freely abstracted space, acting as its punctuation rather than its defining form. There is thus in the International Style no fusion of space and structure, but each in the end remains

In the Millowners Association (LeCorbusier, 1954) the frame punctuates the space. It does not define it.
an identifiable component, and architecture is conceived, not as their confluence, but rather as their dialectical opposition, as a species of debate between them. 13

For the Chicago architects the use of the frame was determined by a rational approach toward a physical problem. There was no specifically architectural program. Rather, there were utilitarian demands placed upon these architects by the extremely pragmatic men of the Chicago business community. The Europeans, by contrast, approached the frame from a basically ideological point of view; it was, for them, "an essential idea before it was an altogether reasonable fact." 14

In Europe, where simple issues of utility could not assume such prominence, it was given a logical form only by the sustained volition of an architectural intelligentsia. And, for these avowed protagonists of revolution, the frame became something other than what it had been for Chicago. It became an answer not to the specific problem, office building, but to the universal problem, architecture.

Disposed to accept the frame as much for reasons of dogma as utility, the International Style was therefore led to envisage it as enforcing a system with which the architect was obliged to come to terms; and, for this reason, the exponents of the International Style felt themselves under the necessity of evolving an equation between the demands of space and the demands of the skeleton structure. In Chicago, a comparable obligation could not exist and, therefore, no comparable equation could be reached.

If Wright did not use the frame as perceived by the Chicago architects because it was too austere spatially, he could not use it as formulated by the Europeans, for their largely ideological approach led them to dialectical opposition, an approach which cannot be reconciled with "....the indivisible fusion of structure and space which Wright has designated 'organic'." 15 Rowe maintains that it was the essential idea or, with the Chicago architects, a lack of it, which disallowed the frame for Wright. Ultimately, he was too close to the "abrasiveness and constriction" of Chicago and unable--I would argue unwilling-- to "....invest it with the iconographical content which it later came to possess." 16
Ideas, Norberg-Schulz reminds us "...such as the relations between technics and form, or form and function, really are important." It is equally important to understand how those relations came about, and the effects that they have. A fascinating study could be made, for example, of the relationship between the ideological tenets of the progenitors of the International Style and the forms they generated. A question that would have to be dealt with immediately is how they formulated their architectural questions. "Very few present-day architects have a secure grip on this task. Most of them dispute the functional problems because they disagree on what is a desirable way of life, or because they fail to understand how a 'way of life' may be formulated or 'translated' into an architectural frame." In this respect Le Corbusier's machine for living or Mies van der Rohe's preoccupation with anonymity reminds us that "the actual situation, however, makes us understand that the solutions are still rather defective, not least because of the omission of fundamental environmental and symbolical factors."

We have noted that the dialectical approach toward space and structure which the internationals formulated was incompatible with Wright's demand for the "organic" integration of space and structure, a demand to which I adhere and upon which this work is based. Schulz notes the following:

Although the client's criticism of the architects and their products is imprecise and subjective, we should not call it irrelevant. It has sprung from concrete situations and shows better than any other symptom that our present-day architecture does not participate in a unified and naturally ordered environment.

Ideology is not a dirty word, despite that I have used it in a largely negative context. Ideology is not only inescapable, it reflects hopes and expectations for the future. Ideology must never lose sight of real-world conditions, even though those conditions are comprised of intangibles such as "symbolic factors" or "a desirable way of life."

This work focuses on how the frame can be deployed in a naturally unified and ordered way or, to use Wright's
In a Typical Japanese House Space and Structure "Fit."

terminology, how the organic integration of space and structure can be achieved.

"Real space exists solely by virtue of the material elements that bound it." Thus, structural rationale must be integrally linked to both materials and space. I believe that the finest understanding of this tenet can be made through the lessons that can be learned from "vernacular" architecture. The remainder of this introduction will be devoted to this.

The dictionary defines vernacular as follows:

- Using a language or dialect native to a region or country rather than a literary, cultured, or foreign language.
- Of, relating to, or characteristic of a period, place, or group.
- The idiom of a particular trade or profession.
- Of or relating to a common building style of a period or place.

When speaking of or referring to vernacular architecture, we may understand the following:

- Vernacular is precedent; it is the result of an "evolutionary" process within a folk culture, and is
intrinsically related to the time, the geography, the recourses and the weather of that culture. In speaking of the traditional wood buildings of Norway, Norberg-Schulz states, "the term 'wood culture' therefore means something more than the mere presence of wooden houses and artifacts. It implies that the inhabitants of the North have a deep emotional relationship to the material wood. It gives them a sense of belonging and security, and satisfies a need for 'home'." Vernacular architecture seems to be reassuring even to those who are not of the culture.

- Vernacular architecture is holistic in the sense that distinctions between life and work, or work and art, did not exist. It is therefore understandable.
- This consistency carries through into a "family" of building attitudes and solutions starting with a direct use of materials. Vernacular architecture is therefore experiential.

In his book, Notes on the Synthesis of Form, Christopher Alexander presents a systematic analysis of vernacular architecture. He tries to understand how folk cultures have consistently been able to develop and produce structures which satisfy the functional requirements of those cultures, whereas other design methodologies (Alexander hates "....the whole idea of design methods as a subject of study") fail to do so. I will outline his argument.

His premise is "....that every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context." The rightness of the form then depends on the degree to which it fits into the entire ensemble. He points out that one of the problems with characterizing the fit between form and context is that although it is experientially possible to identify specific misfits, "good" fit is far harder to recognize.
But it is only through the form that we can create order in the ensemble, for we have no control over the context.\textsuperscript{26} For those cultures that produce what I have called vernacular architecture, Alexander has chosen the term "unself-conscious" cultures, as opposed to self-conscious ones. He notes that the contrast implicit in the two opposing terms rarely exists in actuality, that there are always components of both processes in true operation, but that in terms of discussion the contrast is illuminating. The general features distinguishing the two cultural types are that in unself-conscious cultures there may be generally accepted procedures or remedies for building "failure," but there exist no conceptual, design, or architectural principles, as is the case in self-conscious cultures. In unself-conscious cultures architecture or design does not really exist as we understand it in that it is not conceived as such.\textsuperscript{27}

The difference can be seen clearly in the respective ways form making is learned. In the unself-conscious culture there are a limited number of forms, and those forms are made over and over again. Learning how to make form is simply a process of learning how to repeat familiar physical patterns. This is done largely through imitation by practice. "The most important feature of this kind of learning is that the rules are not made explicit, but are, as it were, revealed through the correction of mistakes."\textsuperscript{28} In self-conscious cultures, by comparison, form making is learned through the development and study of design principles. "....the unformulated precepts of tradition give way to clearly formulated concepts whose very formulation invites criticism and debate. Questions lead to unrest, architectural freedom to further self-consciousness, until it turns out that (for the moment anyway) the form makers' freedom has been dearly bought."\textsuperscript{29} For Alexander then, "with the invention of a teachable discipline called 'architecture', the old process of making form was adulterated and its chances of success destroyed."\textsuperscript{30} Remember that success and failure are determined not by theory, but by fit. In unself-conscious cultures the process of form making is
homeostatic (self organizing), and consistently well-fitting forms—even in the face of change—can be produced. In outline form, this process can be circumscribed as follows:

- There is a firmly set tradition for building, dictating how to do things, which is accepted by all builders. This tradition resists change.
- As noted, learning the form-making process is based on imitation, alternative approaches do not exist.
- The entire process takes place within the limitations of the materials, and the capacities of those materials, which are available.
- The individual who makes the form will also ultimately live in it. This leads to "...a special closeness of contact between man and form which leads to constant rearrangement of unsatisfactory detail, constant improvement." 31

It is this capacity for immediate adaption and improvement which allows for fit—or refit—to take place when conditions change. Alexander argues that the tendency toward equilibrium—that is to say good fit—is irreversible, and unself-conscious form makers can consistently produce well-fitting forms because the traditional process of form learning and form making offers the context for immediate adaption. "The direct response is the feedback of the process." 32

For our purposes, I will add the final note that change must not occur too quickly. "It must have time to happen. The process must be able to achieve its equilibrium before the next culture change upsets it again." 33

Unfortunately, this work cannot deal with form change as Alexander addresses the problem, except peripherally. What I wish to address, here and now, is form making. The important point to extract from Alexander's work is that good form making must deal immediately and directly with the materials and, obviously, the characteristics of the materials at hand. Alexander states the problem better than I:

The argument is based on the assumption that physical clarity cannot be achieved in a form until there is first
some programmatic clarity in the designer’s mind and actions; and that for this to be possible, in turn, the designer must first trace his design problem to its earliest functional origins and be able to find some sort of pattern in them.34

Perceiving the frame as a neutral structure (to return for the moment to Rowe) absolutely fails to do this because it absolutely subjugates the requirements of those who inhabit the structure to the rationale of the structure itself (a classic example of Marx’s theory of alienation). Ideology, on the other hand, obscures this tenet at best. And, if Wright did not employ the frame because he could not--for reasons discussed--formulate it organically, it is not because it is not possible. In designing or developing a building system, one of the "earliest functional origins" to be addressed is how the system goes together, for how it goes together, the details, will inform and affect the entire ensemble.
OVERVIEW

This work is concerned with the design and development of a built-up, or a sandwiched, post and beam system. The system is not new; I did not invent it. On the other hand, I have never seen its formal characteristics systematically developed. That is what I attempt here.

My initial, intuitive attraction to the built-up approach to post and beam grows out of a number of things, not the least of which being that I like post and beam. To my mind, it is both a structural principle and tectonic device par excellent. Four posts, for example, can be used to define a space within a room, or to articulate the corners. A row of posts can define the edge of a space while allowing visual, and in fact spatial, continuity to exist. Zones within spaces can be defined. Beams provide further spatial definition, while at the same time reminding and assuring that the structure is sound. As noted earlier, there can be a remarkable integration of structure and space. Most post and beam work is done the
same way it has been done, quite literally, for millennia. There are a number of problems with this.

- Traditional post and beam requires large members, which are becoming increasingly scarce and expensive. Put another way, it no longer truly responds to the materials available.

- Traditional post and beam depends on elaborate joinery. This system was developed before the advent of mechanical (metal) fasteners. Extensive mortise, tenon, and peg work is time consuming and therefore not economically viable. The situation is further exacerbated by the high level of skill necessary to do this kind of work, a skill level that is not commonly found among builders today.

- Traditional post and beam requires either heavy machinery or extensive manpower to erect. This can be problematic for smaller-scale structures.

The built-up post and beam approach alleviates many of these problems.
Perhaps the first thing to point out is that this system relies on mechanical fasteners such as nails and bolts. All fasteners employed are readily available. These fasteners greatly reduce the need for elaborate joinery, and speed up the construction process in comparison to traditional post and beam. I should point out that this system has been specifically designed to minimize and, in fact, eliminate the need for metal connectors such as plates and hangers. There are two reasons for this. First, reliance on metal connectors (which would largely have to be custom made) greatly reduces the ability of the system to withstand alteration or adaptation (read Change a.k.a. Alexander). This system is conceived as an additive, formally generative assembly which can be constructed from standard, readily available materials. To my mind, depending upon connectors is not only unnecessary, it compromises this goal. Second, I simply do not care for the aesthetics of metal connectors.
The three-layer sandwich approach makes highly interlocked joints possible. In a typical cross tee joint, for example, the center part (the core) of either the post or the beam can pass entirely through the joint, while the exterior parts (the sides) of the other can pass by on the outside (for a full discussion of how the system goes together, see both Assembly and Limited Construct). This interlocking approach is a powerful joining technique, while eliminating elaborate joinery as it is traditionally understood and practiced.

There are other practical advantages. As noted, the system is an assembly of parts. These parts, one at a time, do not weigh very much. For example, when I built a small frame network (see Limited Construct), I discovered that a twelve-foot long section of beam core weighed less than forty pounds. It was so light that it was more difficult to balance it with one hand than it was to actually lift it with one hand. Thus, the traditional problem of lifting heavy members into place is eliminated.

There is also considerable flexibility in terms of assembly sequence, and where the assembly takes place, that has not been present in traditional post and beam construction. For example, in traditional post and beam, individual frame segments are built on the ground. The assembly is then tilted into place. This is so because fitting a beam with two tenoned ends into two posts with mortises to receive it is, at best, a difficult operation to perform in mid air. The sandwich system can also be largely built on the ground and hoisted as per traditional methods. However, it can also be erected in place in a manner similar to steel skeleton construction, the difference being that heavy lifting machinery is not necessary.

I would like to point out the interactive nature of this system. In a sense, my study of it, the development of its characteristics, has been an ongoing conversation; I have studied it but, more importantly, it has spoken to me. The process then has been one of discerning what the inherent characteristics of the system are, rather than
Complex Japanese Joinery
"inventing" a system to meet a given set of requirements. If requirements are met, it is due to the formal tectonic and structural nature of the system, and not the other way around; it is not idiosyncratic.

This is an important point to make because we have to remember who will be building with it. If, in order to be viable, a system must be assembled from readily available parts, it must also be construct-able within the confines of the tools available to builders, and the level of skill those builders possess. In this sense, the sandwich frame system has true potential for carpenter vernacular. It does not require special tools, and the method of assembly is consistent with building practices and skills generally found today. Finally, the logic of the system is understandable and therefore replicable, yet it contains rich potential for variation.

The next sections of this work are devoted to developing the various aspects of the system. Amine Klam has developed the following categories: Structural Element, Structural Principle, and Structural Scheme.² I have chosen to borrow his terms and use them here, for all architectural concepts represent relationships between material, structure, and space. "...real space is always more than a mere by-product of abstract space, just as the reality of an object perceived always transcends the moment of its perception."³

The categories may be understood as follows:

- **Structural Element** represents the inherent properties of the material; size, shape, and other physical characteristics.
- **Structural Principle** leads us to the consideration of the structural role that a group of elements play in defining space based on configuration geometry.
- **Structural Scheme** can be understood to be the configurational combinations of statically congruent principles.
ELEMENT: WOOD

Wood is an organic material; it grows. It is porous and has grain. It is one-directional. It will decay. Wood "breathes" and it will expand and contract. It is a renewable resource. As a building material, it has these further characteristics:

- Wood is light in weight.
- Wood is strong. It works both in tension and compression. Pound for pound, some construction-grade woods are stronger than some steels.
- Wood is easily worked.
- Wood is easily fastened with staples, glue, nails, screws, bolts, and other connectors.
- Because of its porous nature, wood lends itself well to preservative treatment. Further, wood can be maintained.
- Wood structures can be easily repaired, altered, or added to.
- Wood combines well with other materials.\(^1\)

Wood as Fabric
As an architectural material, the following considerations must also be noted:

- Construction technique and scale should be directly related to the inherent nature, including the limitations, of the material.
- A similar relationship should exist when fitting the individual pieces to each other.
- The inbred consistency of wood in terms of color, texture, grain, and gloss should also contribute to the overall aesthetic.\(^2\)

In speaking of Japanese vernacular houses, in which wood is the dominant material, Engel notes that "whereas architectural form in the West is conceived as something given to a material and therefore remains attributive, in Japan form evolved from the material itself and is essentially its own substance." \(^3\) Thus, for Engel, material is the primary generator of what he calls "fabric." It is worth quoting him in detail.

Fabric in building is the material which, when assembled with others into an organism, constitutes
architecture. Dominance of one fabric in the organism can characterize the building and may even become the distinctive feature of an architectural region or period.

Fabric in building is in close interdependence with construction. Some materials forbid certain construction systems just as others may stimulate them. Disclosure of fabric’s inherent possibilities, therefore, effects architectural advance.

Fabric in building is apt to disclose national traits and standards of civilization. Identical materials have been differently employed by different peoples and thus distinctly reflect the skill, taste, and thought of their builders.

Fabric in building possesses an innate quality, i.e., a characteristic substance that determines proportion, scale, and expression of fabric, as these in turn influence the entire building structure. Interdependence of material consistency and architectural expression, therefore, is a legality to which building and its design are subjected.

Fabric in building is the total of many materials, each with its own distinct qualities. Harmonious composition of these properties is architectural design, while mere restriction in number of materials employed has no architectural importance.
Fabric in building depends on natural resources. Abundance of particular natural materials can stimulate the growth of architectural features just as lack of all ordinary materials can instigate the development of new products.

Fabric in building is but one component in the entirety of forces that constitute architectural creation. Subordination of all component elements to an encompassing architectural idea is an important principle that establishes unity in building.

Fabric in building, then, embodies an innate order of architecture. Its principles have been the determining factors of early architecture everywhere; they were for some time neglected and are newly interpreted in contemporary architecture.  

Virtually all construction lumber in the United States is based on the American stick-frame system. It is this commercially available material upon which the structural system developed here is founded. Under this system, readily available lumber has the following characteristics:

- Sizing: Lumber sizes are nominal. The 2" x 4", for example, measures 1 1/2" x 3 1/2". A 2" x 6" measures
1 1/2" x 5 1/2". The larger pieces, the 2" x 8", 2" x 10", and 2" x 12", are 7 1/4", 9 1/4", and 11 1/4" respectively.

- Seasoning: All wood is dried. Virtually all wood is kiln dried. "Green" wood (fresh cut) will contain from 30% to 300% more moisture than it will after drying. While drying, wood shrinks. Kiln drying is performed to quickly reduce the moisture content to an appropriate level (usually around 10%), and thereby stabilize the wood for proper and consistent dimensioning. This is the theory. In fact, individual pieces can vary considerably. The 1 1/2" width is usually dependable, but the depths in 2" x 8" to 2" x 12" sizes can vary as much as 1/2". This must be taken into account both in design and construction.

- Grading: Construction lumber is graded according to species, overall quality, structural capacity, etc. The structural characteristics of all construction grade lumber have been thoroughly determined. It is therefore easy to size and otherwise calculate all structural requirements.
The two most common structural species used are hemlock and fir. These two woods are extremely similar in terms of structural characteristics, overall quality, and appearance.

Practically speaking, however, there is considerable variation in lumber as it is available out of a lumber yard. Knots, splits, checks and warping are often present to some degree. Where wood is exposed, as in this system, this must be taken into account. On smaller projects wood can be selected; on larger ones minimum standards must be specified. The built-up nature of the structural system developed here eliminates the need for "perfect" lumber, because only one side of each individual piece is exposed.

There are other approaches as well. Yellow pine, for example, is a viable option. It is not generally available "out of the yard," but is easily ordered. Yellow pine tends to be superior in overall quality to hemlock or fir. It is visually quite attractive. It is more expensive than yard lumber, but not
excessively so. Other woods such as oak and "architectural" 
grade fir are also within the realm of possibilities, but are not 
considered here.

COMPOSITE WOOD PRODUCTS

Composite wood products such as plywood or oriented 
strand board are employed in this system, notably in the box 
beam. Although it is a structural part of the system, it is not a 
formal element in that its characteristics are not developed as a 
visibly articulated part of the whole. Therefore, only the 
structural characteristics will be briefly noted. Composite 
boards are:

- Stable
- Extremely consistent
- Light weight
- Very strong
- Laterally resistant
- Easily worked

Composite boards would be used in these additional 
applications:

- As part of the envelope wall to resist lateral loads.
- As part of a floor system to create a floor diaphragm.
- As roof sheathing for the same reason.
- As roof trusses or, more properly, as wood I-Beams for a 
  number of reasons (see Roof-to-Frame).
STRUCTURAL PRINCIPLES: Configurations

The structural principles developed and worked with here are those of simple trabeation; the post and lintel, the cantilever, the point load, and triangulation. In the section on Scheme, these principles will be treated in an additive, generative way to create spatial configurations.
Post and Lintel

Triangulation

The Cantilever

Point Load
ASSEMBLY

The sandwich approach can be applied toward any number of wood sizes, but a few factors must be taken into account. In order for proper connection to take place in the two directions, the post core must be square. Concomitantly, the beam core must be the same width as the post. For this work I selected a 4 x 4 for the post core, with 2 x 6's for the post sides. Other sizes could be used (such as a 6 x 6 core with, say, 2 x 8 sides), but the 4 x 4/2 x 6 assembly corresponds well with the ubiquitous 2 x 4 and has the structural capacity to sustain great loads. It is also large enough to be visually believable.

Selecting a beam configuration was somewhat more problematic. Within the confines of the 4" width, any number of depths and configurations are possible. Illustrated are a number, though by no means all, of those possibilities. For this work I selected a hollow "box beam" core 8 1/2" deep. It is constructed of two pieces of 1/2"
SOME POSSIBLE BEAM CONFIGURATIONS
composite board on either side of 2 x 3 flanges with stiffeners at regular intervals. The beam sides are 2 x 10's. I might have chosen a smaller configuration, but I wanted a beam hefty enough to enable at least some point loading. I further want to allow the possibilities of the cantilever. Although the system has not been formally engineered, I have reasonable assurance that this beam can carry 320 p.l.f. over 18', and further, that carrying that load, it can cantilever up to 4' beyond its last post and still support the weight of a standard wood frame envelope.

Note that both the post and the beam assemblies selected are used throughout this work.

The following set of drawings shows the sequential assembly of a typical post and beam configuration. Note that the drawing sequence does not necessarily reflect the order in which the assembly is actually built. For example, in actual construction it would be more realistic to attach the beam sides before the post sides.

Beam side lengths:

The longer beam sides overhang the post support 1/3 to 1/4 of the span, at a point where the bending moment approaches zero.

Beam core lengths:

The beam cores span the posts center to center.
FRAME ASSEMBLY: BOX BEAM TO POST CORE

1. Box Beam Parts

   Note that the box beam would normally be assembled on the ground and lifted into place. In this illustration (consistent with the entire work), the configuration is that of 2 x 3 flanges with stiffeners placed at regular intervals, and two 1/2" plywood webs

2. Post core

3. Beam seats
FRAME ASSEMBLY: ASSEMBLED BOX BEAM

1. Assembled box beam

2. Beam seats in place
FRAME ASSEMBLY: POST SIDES TO POST CORE

1. Box beam in place

2. Post sides. Note that the tops of the post sides are rabbeted. This is to articulate the joint, as well as to minimize the effect of possible misfit.
ASSEMBLY: BEAM SIDES TO BEAM CORE

1. Post sides in place

2. Beam sides
ASSEMBLY: BEAM CAP TO BEAM

1. Beam sides in place

2. Beam caps
FRAME ASSEMBLY: FULLY ASSEMBLED FRAME
Generic Joints
The joints illustrated are called "generic" because they satisfy all of the basic post and beam situations. In the drawings these joints are further broken down according to whether the post core is continual or the beam core is continual. Not all possible joints are drawn; some are redundant. Others are—though technically feasible—not viable, given the alternatives. The joints illustrated satisfy all potential situations within the generic category.
The generating factors in forming the design of the joints are as follows: as noted, dimensional variation is to be expected among the various lumber sizes. To account for this, wherever possible, all wood-to-wood contact either overlaps or passes. Thus, in the beam assembly the tops of the beam sides and beam core are flush and even, but at the bottom the beam core has 3/4" less depth than the sides. This articulates the difference between the two. It further creates a "track" inside of which may go the triangulating pieces. This is likewise the case for the posts. The beam cap, a standard 2" x 8", is 3/4" wider than the beam and when positioned over the rest of the beam, protrudes beyond it, creating a lip on either side. This kind of attitude minimizes high-tolerance joining.

I employ the passing connection in these joints, and I should explain what it means to me. Wood may be a natural "organic" material, but by the time it reaches the
job site, it has been cut, shipped, shaped, dried, sized, planed, inspected, graded, stamped and shipped again. Wood, as we use it, is clearly a product, then, of the machine. It seems to me that if we wish to understand methods of articulation, we should take the machine factor into account, especially given that, once on the site, the material is shaped again by machines in the form of carpenter power tools. To this understanding we must also add the understanding of the scheme, as well as the elements in the scheme, as an additive, generative system. If we understand that the element could move past a specific joint, we can say so by allowing the element to do so. This is the possibility created by a sandwiched, overlapped system which, by definition, will not be found in a single in-line system such as traditional post and beam. In traditional post and beam, only one member (either the post or the beam) can move past the other, not both.

A functional consideration in terms of cut and fit has to do with how various other pieces abut each other. For example, where the post side meets the beam side, it was decided to rabbet the post side just enough to create a visible reveal. This is
an easily and quickly performed operation. This creates a visual aesthetic out of a butt joint that would otherwise be problematic if it were anything less than a perfect fit. In terms of a hierarchy of decision making, if a butt joint could be used rather than a notch, it was. If a two-sided notch could be used rather than a three-sided notch, it was. There is no more complex joinery than a three-sided notch in this system.
OTHER JOINTS

The "other" joints are those designed to satisfy more or less specific conditions. I am sure that I have not thought of all possible conditions.
Cross Directional Joint
TRIANGULATION

Triangulation is treated in a separate category, primarily because, within the system as I have chosen to work with it, it is conceived largely as a secondary, auxiliary configuration. I feel obliged to point out, however, that in fact (and apart from the roof which is treated separately), triangulation could become a major systemic element. The small scale triangulation that I picture here, for example, could grow well beyond mere bracing to become a primary structural and tectonic device. That kind of understanding, however exciting, is beyond the limits of the system as I have chosen to focus on it.
Directional Bracing
Cross Directional Bracing
A LIMITED CONSTRUCT

Although I built a one-half scale model of one of the joints, it was not a satisfactory exercise. It was large enough to show the individual pieces, the smallest of which, full scale, is only two by four by twelve inches. The problem is with the fasteners. A built representation is clearly the ideal format in which to address how to fasten elements together. I decided that full-scale is the only way to accurately do this. My decision was further prompted by the knowledge that the real-scale construction process would be more informative.

I do not know what to call what I chose to build. I called it a clothesline, but my neighbor says that a hammock belongs there. I chose to sink my post cores directly into concrete. This would not be standard practice for building, but was fine for this exercise.

The fasteners are a highly visible element of the system and their contribution to the overall aesthetics should be understood. To me, this means recognizing their structural role and establishing an appropriately proportional pattern. I tried a number of patterns and have since thought of a few more. I will discuss these in relation to the photographs. Only one bolt size was necessary. I consider this advantageous.

Photo 1 shows the fasteners used that are visible. In keeping with the entire attitude of the system, they are off-the-shelf items; 12 penny nails, 3/8" by 3" bolts, washers and lock-washers. Theoretically, thru-bolt fastening would be ideal. Practically, however, this is impossible. On-site boring is a functional reality and it is not possible to hand guide a perfectly aligned hole through 6 1/2" of material. Consequently, I opted for lag bolts. A 3" bolt allows for ample penetration, but falls just short of center. This allows for bolting from both sides. Although perfect alignment is not possible, interference is.

I spray painted the bolts black because I do not like the look of galvanized metal against wood. In actual construction I would use slightly different fasteners which, although accessible, are not as readily available. All exposed nails would be of wrought iron. Also, I would not use bolts with hexagonal heads.
I associate them with machinery. I would use square headed bolts. Finally, I would buy fasteners that were blued. To me, this is an attractive contrast to wood.

Photo 2 shows a beam seat in place. Note that the holes are pre-drilled. Photo 3 shows how a piece is positioned and tacked into place. A finish nail is placed close to the pre-drilled hole, but angled away from it. When bolted down, the washer will cover and hide the nail, yet the nail does not interfere with tapping into the post or beam core. All built-up elements which are exposed can be constructed in this manner.

Photo 4 shows a partially built beam core in place. In actuality, the entire beam core is built on the ground and then lifted into position, but for purposes of illustration, I chose to include this shot. It is worth noting that this particular beam core, when finished, at twelve feet in length, still weighed only forty pounds. Note in Photo 5 that the bottom edge of the oriented strand board has been painted black. This is because it will be exposed.
In Photo 6 the beam sides and top have been bolted into place and a second beam core has been positioned. Note that this beam is cross-directional. Remember too that the actual configuration of the beam core is optional depending, among other things, on load bearing requirements. Whereas for the first beam core I chose to use two by threes sandwiched between two pieces of 1/2" oriented strand board, glued and nailed, for the second beam I selected the simple two-by-four option. I did this just to explore the options.

Photos seven and eight show a completed post-to-beam joint with diagonal bracing. The end cap in photo eight serves the structural role of keeping the beam in proper alignment. Although it is not visible in the picture, the end cap is bolted to the beam. The end cap also covers and protects the beam core.

In Photo 7 the bolt pattern on the beam is two feet on center, vertically aligned. On the other side of the beam (Photo 8) I tried a sixteen-inch on-center alternating pattern. Taken at absolute face value, I like them equally well, but I tend to lean toward the two-foot pattern because its use throughout a
building would reinforce and accentuate the two-foot module (see section on scheme).

Photo 9 is a somewhat misleading detail of brace-to-post. The nails are set away from the edge of the post side to minimize splitting, and they are slightly angled into the brace. There is ample penetration.

Photo 10 is a head-on shot of post, beam, brace, and brace seats. Note the exposed black edges of the oriented strand board. Note too the joint in the two by three of the beam core. This should and can be avoided. The lumber yard I bought from only had eight footers, but they are usually available in lengths up to sixteen feet.

Photo 11 shows the cross-directional beam-to-post joint. A beam seat is not necessary in this situation, as the beam sides can rest directly on the post sides, which have been notched to accommodate, as seen in Photo 12. Photo twelve also indicates a possible bolt pattern for the posts, in this case a sixteen-inch on-center alternating pattern. In retrospect,
I believe that a similar alternating pattern using twelve-inch centers should be tried.

Photos 13, 14, and 15 show what is possibly my favorite joint, for it indicates the potential for systemic articulation. Unfortunately, as it is built, it is also the most problematic; I had to build it in order to see how it should be built. Although in this situation the cross-directional beam sits directly on top of the directional beam which, in turn, is directly over the post, it need not do so. A beam-over-beam situation can exist independently of where the post is. I wish that I had set the post in two feet in order to exemplify this. Be that as it may, the highly built interlocking nature of the system can be clearly seen.

There exists in this joint as I built it an even more significant error which I must point out. If the top beam can sit anywhere along the line of the bottom beam, it should behave that way, and it should look that way. This joint does neither. When I built it, I placed the top beam core directly on top of the bottom beam core without taking account of the thickness of

Photo 4
either the bottom beam cap or the top beam sides. This can best be seen in Photo 13, where I had to do extensive notching in order to make the joint work at all. Although I specifically wish to minimize the amount of notching necessary from the point of view of the labor involved, that is only a superficial explanation. All other things being equal, a notched joint indicates that the connection must take place at that point, for it is inherently captured. The way to properly indicate that the top beam could in fact rest anywhere along the line of the bottom one would be to place completely built beam on top of completely built beam and then do the joining through the use of connectors. The beam thus becomes located through application instead of being captured, and the optional nature of the connection can be read.

NOTES ON PRODUCTION

This system seems to be preternaturally disposed toward production, which is slightly embarrassing; I did not develop the system for production technique. Even in this small
building exercise, for example, I was able to pre-cut, drill, and rabbet all the post sides. In production this would be obvious, leaving the bottom ends long to be cut to length on site.

Beam cores can, and in fact should, be pre-assembled; a significant amount of load-bearing capacity of the beam is dependent upon the care with which it is nailed or screwed and glued together to create a structural unit. It would be easy to account for on-site fitting by leaving one end long--omitting the end stiffener during assembly--and installing it on site after the beam has been cut to length.

The beam sides could be pre-drilled and cut to length on site. This would require attention, however. The actual position of the sides have to be keyed according to the bolt pattern in reference to the grid. Both ends of the sides would therefore have to be cut.

All of the smaller pieces such as beam seats and end caps can, of course, be pre-cut and drilled.
Generally speaking, an entire framework can be viewed as a "kit of parts" and prepared largely off site, understanding the on-site process is one of assembly. The question is one of degree. My own tendency would be to search for the balance between quality control and the ability to make on-site decisions.
SCHEME: THE FRAME

As a structural scheme, the regulated grid has the following characteristics:

- It is orthogonal.
- It is additive.
- It is directional.
- It establishes a common ratio throughout a building to which all parts are related.
- Since the frame defines largely repetitive, modular units of space, it can be added to, subtracted from, and layered, and still maintain its organizational characteristics.
- The frame can be altered (such as in the tartan grid) to accommodate specific dimensional requirements.
- Within its field, spaces can occur either as isolated events, or as repetitions of the inherent grid.¹
An immediate issue raised by the frame is that of measure. Engel, who defined "fabric" for us, does an equally admirable job with measure.

**Definition**

Measure in building is the order that controls the scale, proportion, and form of the building. It relates the parts to the whole and in turn makes the whole dependent on its parts.

Measure in building means standard. The standard of man’s body was the earliest measure. Incorporation of various standard units of the body into one system by relating them in simple ratios effected the first measure system.

Measure in building precedes construction. Before man could build, he had to conceive of measuring. Measuring is one of man’s first intellectual achievements. It distinguished man’s house from the animal’s den.

Measure in building is the essential means by which man brings building into precise relationship with himself. Measure is the element which humanizes man’s environment.

Measure in building thus is manifestation of culture. For standard of culture is determined by
the variety and depth of emotional intercommunication of man and man-made environment, i.e., by the degree of human measure in his environment.

Measure in building also contains measures of aesthetics, fabric, and technique and thus constitutes in itself a compromise between these frequently opposite forces. The character of this compromise reflects the purpose of a building.

Measure in building manifests the skill, taste, and thought of builders. Ancient cultures possessed an elaborate order of measure that determined building. This order was based primarily on visual aesthetic principles.

Measure in building, then, is the instrument by which man masters the basic fabric of building. Thus, it is his "measure" to organize the elements of building into an entirety and to create the human environment called architecture.  

With the scheme of the frame we can therefore understand no less than three "scales" within the realm of measure: the building scale, the scale at which habitation takes place, and the scale of the bay, which is the unifier.
The bay size is not only related to the size of the building and actual habitation; it is further dictated by the capabilities and limitations of the materials used, as well as by market size. In the United States most small-scale buildings are regulated by the ubiquitous 4' x 8' size in which sheet goods such as composite boards are available. For this work I selected a standard bay size of 8' x 12'. This size responds to market size. The material has more than enough capacity to span the 12' length. This bay size also reflects the size of a small, though habitable, room. The organizational capability of the bay, and of the frame, should therefore be understood in relation to the scale at which habitation takes place. For this work I selected a module of two-foot square.

In smaller scale buildings the bay size need not be quite as rigid as we might have been led to believe thus far. In traditional Japanese house construction, for example, the basic module is both added to and subtracted from in order to "fit" with the plan. This understanding
must be approached with caution. The frame is a scheme with powerful organizational capabilities. Altering the scheme must be justified in terms of a rationalized plan. Illustrated are various options available.

Three different regular grid configurations
The Cantilever

Point Load

Altering the grid: Note that variations occur along the line of the frame.
FRAME TO GROUND

There are three basic foundation types suitable for this system: slab-on-grade, pier, and foundation wall. Combinations are possible. They must all meet the general requirements of holding a building up, but those requirements are not dealt with here.
Slab-on-Grade

Slab on grade offers interesting possibilities. Plumbing and heating pipes can be set directly into the floor, saving space and creating an extremely stable thermal environment. In cold weather climates, it can act as an integrated passive solar collector. When other systems are planted in it, the structure can become difficult to alter or add on to. On the other hand, slab-on-grade can be extended beyond the building envelope, extending the limits of the "built" form.
Pier

For reasons more emotional than anything, I like the idea of pier foundations. The idea of a column connecting with a pier which has come up out of the ground to meet it appeals to me. Piers provide an excellent base for a column which has to get up high. Piers are economical. In warm climates, floors over piers are naturally ventilated and cooled.
Foundation Wall

Foundation walls are common. They are especially good on hilly terrain, where a three-sided foundation, with the fourth side open, can be used. An important point is that the foundation wall should be directed by the frame, not by the envelope.
FOOTING CRAWL SPACE
Two floor-to-frame approaches are illustrated; floor joist/diaphragm and secondary beam/plank. For most (by no means all) situations the floor joist situation is preferable. There are three reasons for this. First, a floor joist can be cantilevered beyond its last supporting beam, which may be necessary in order to separate the envelope from the frame. Second, it provides the depth necessary to accommodate mechanical systems between floors. Third, as a constructed diaphragm with skin coverings on top (floor) and bottom (ceiling), it becomes clearly distinguishable from the frame and secondary to it. To repeat, I can think of any number of conditions in which a secondary beam/plank approach would be desirable.
Secondary Beam to Primary Beam over which planking may be placed.
Floor joists cantilevered beyond their supporting beam.

This is necessary in this direction in order to separate the envelope from the frame.

Floor joist approach. Note the ease with which level changes can occur.
Assembled floor diaphragms
The individual frames can be tied together either by cross-directional beams or by floors.
ENVELOPE-TO-FRAME

The configurations developed in the section on Floor-to-Frame indicate that, in fact, the envelope will rarely meet the frame, except where the frame pokes through the envelope at right angles to it. In general, I can think of very few situations in which it would be desirable for the envelope and the frame to be in line and to have to meet; the possibility for misfit (to recall Alexander) is too high. With this in mind, the possibilities illustrated are offered.

In addition to how the envelope is physically integrated into the entire building scheme there is a second topic that should be discussed, that being the functions that the envelope perform. Clearly, the envelope is the point at which the exterior environment stops and the interior environment begins. The envelope must keep out rain, snow, etc., but the subject I want to focus on is thermal control. This discussion may seem to run a little
afield from the frame, but the fact is that a frame system which allows for the separation of envelope from structure does, in fact, affect our understanding of and approach toward the envelope, and can ultimately affect the ways in which we can order or control the interior environment. In the section on Frame-to-Ground I noted that a slab-on-grade situation creates an integrated opportunity for a passive solar system. I mentioned it only in passing, for this work concentrates on the frame and not the entire ensemble. However, if we are to take Alexander seriously, we must pay heed to how an element in the ensemble—in this case the frame—affects the entire ensemble.

One of the lessons we have learned in the last twenty-five years or so is that we absolutely must learn to reduce our energy consumption. In terms of building, this means that we must reduce our reliance on energy consuming mechanical support systems such as those necessary for heating and cooling. With this in mind, let me outline two different building scenarios.

Assume a building 20'square with a standard stick-frame, load-bearing envelope—2 x 4 studs, 16" o.c. (For the sake of
clarity I am eliminating openings such as windows and doors. The roof will be dealt with later.) The R-value for standard fiberglass insulation for this wall depth is 11. But the structure itself takes up 15% of the total wall area. Factoring an R-value of 3.5 for the structure, the average R-value of the wall drops down to less than 9.9. Another problem—even worse—is that there are two vertical seams every 16", one on either side of each stud. Unless all the insulation is perfectly installed, there will be a great deal of heat loss. According to the ASHREA Fundamentals Handbook a 4% void in the insulation will result in a 15% loss of heat.¹

Now take the same building, but this time the envelope does not have to be structural. A 5 1/2" non-structural panel has a constant R-value of 23.² Its actual performance will be even higher than indicated for there are no voids.
For this reason I would take a serious look at a panel approach in conjunction with this frame for the envelope. A second serious advantage is that assembly is extremely fast.
ROOF-TO-FRAME

For this work I chose to concentrate on the flat roof configuration. On an intuitive level it seems that the flat roof is an extremely viable option, especially where environmental factors are concerned.

As noted in the section on Envelope-to-Frame, voids in insulation create tremendous heat loss. In a roof the consequences can be dire; a 4% void in insulation will result in a 50% loss of heat. In addition, an R-factor of 50 is not unreasonable in climates such as those found in New England. For walls the added expense of the panel option is not unreasonable, for the cost can be justified in terms of the speed with which it can be installed in comparison to stick framing. Panels are harder to justify for roof situations.

There is a further complication based on what I believe to be an incomplete understanding in recent years of how a roof should function. In warm weather the amount of heat generated on the roof cover can be considerable. This heat will push down through the roof, heating the living spaces below, and thereby necessitating mechanical cooling. In winter, on the other hand, enough heat from within the building can escape through the roof to create an undesirable freeze-thaw situation. What is needed is an air space between the insulation and the roof cover to dissipate heat transfer. This air space must be at least 3 1/2" deep. In a pitch roof configuration this space must be built as an additional element, adding expense. In a flat roof configuration this is not the case. Further, a flat roof allows for the installation of loose or blown insulation as an alternative to fiberglass. Loose insulation eliminates the problem of voids. However, loose insulation requires considerable depth to achieve the required R-value. Therefore, the solution offered here is as follows: The roof structure is comprised of plywood I-beams no less than 16" deep. This allows for insulation of a proper depth, as well as air space. It can span considerable distance with
relatively fewer members. On top of this is installed a cross-directional 2x network. This ties the entire roof together and enables cross ventilation.
Plywood I-Beams on Frame
2x Assembly Tying Roof Together
Air Space

R-50 Insulation - Loose Fill

Extensive Soffit Venting
In this type of assembly, stick frame interior partitions are a reasonable option. Stick frame is not unlike masonry construction in that it gains its true definition only as an assembled whole. Unlike masonry, however, it does not have its own surface definition; consequently, its definition is obtained by the surface which is applied to it. In this section I assume wallboard. Thus, a stick frame partition wall becomes a planar element. The problem I have chosen to address is how you can accept the "fact" of a planar element while still recognizing that its structural elements (the studs) are a part of the larger family of elements that also comprise the structure. As illustrated, I have decided to attack the problem at the edges. In fact, the problem could be addressed at openings (holes in walls) as well.
Interior Partition Walls: Articulated Corners and Baseboard
MECHANICAL SYSTEMS

Because the envelope is assumed to be a panel system, it is assumed that all mechanical systems are to be run within interior partition walls. Diagramatically, this may be represented as illustrated.

Lateral Pattern

Radial Pattern
ADDENDUM

Virtually all of the joints developed in this work have the beam cap-to-post connection shown in the detail to the left. Eric (my advisor) has objected to this detail, but I am capable of obstinacy. He was finally able to state his case in a way that I could hear it, to wit, that the system is far too straightforward and robust to suddenly become questionably finicky. He is, of course, right. Unfortunately, the constraints of time have not allowed me to correct the drawings. An alternate solution, with apologies, is offered on the next page.
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3. Rowe, p. 91

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16. ibid p. 108

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The best analysis of Wright’s spatial development I have seen is in Brooks’ article "Wright and the Destruction of the Box" in *Writings on Wright*, H. Allen Brooks, Cambridge MA: MIT Press, 1983, pp. 175-188.
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2 Amine Klam
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2 Heinrich Engel
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3 ibid

4 ibid p. 29

5 Feirer & Hutchings, pp. 65-75
FOOTNOTES: SCHEME

1. Francis D.K. Ching  
   *Architecture: Form, Space and Order*  
   New York, NY, Van Nostrand Reinhold 1979, pp. 238-239

2. Heinrich Engel  

FOOTNOTES: ROOF-TO-FRAME

1. Fine Homebuilding Magazine  
   October/November 1989, p. 36

2. This figure is based on a recent article in Fine Homebuilding, which I recall but cannot cite.

FOOTNOTES: ENVELOPE-TO-FRAME

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   New York, NY; Stewart, Tabori & Chang 1987  
   p. 138