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Hōryūji Reconsidered

法隆寺の再検討

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Chapter Two

The Central Core Structural System: A Three-Dimensional Analysis of the Five-Story Pagoda of Hōryūji

Eric M. Field

It was long believed that the central wooden core of the five-story pagoda at Hōryūji—a continuous post reaching from ground to spire—was embedded into the ground at its base and served as a primary load-bearing member of the building's structure.[1] Indeed, the popular vision of the pagoda's form largely remains one of horizontal roofs hung from a single central trunk, and this vision inspired architects such as Frank Lloyd Wright (1867–1959) to imagine skyscrapers supported by rigid central cores in the model of the Japanese pagoda.

Upon discovery that the post at the Hōryūji pagoda as it stands today is in fact suspended several feet in the air, its base having rotted away with age, this prevailing theory was proven wrong. How could the pagoda be standing now, much less have survived centuries of significant earthquake activity, if what was thought to be its primary structure does not even touch the ground? The theory had to be rethought.

This paper presents an analysis of the five-story pagoda and its central core structural system that explains this discrepancy. Through three-dimensional computer graphics modeling and geometric analysis, the complete structural system and interlocking organization of the pagoda are considered, including the central core post. This analysis reveals the relationship of the central core to the rest of the pagoda's structure, and specifically what role the core post plays. The key findings are:

1. The central core post not only does not but *could not* carry the primary vertical load of the pagoda. Contrary to the prevailing diagram of the pagoda's structure, the core post's connection to the rest of the structure occurs above any surrounding elements and therefore cannot carry their load. Instead, the weight of the

core post is transferred to the surrounding structure and through it to the ground, inverting the long-held theory. This explains the rotted post's suspension above the ground.

2. Instead of the central core, it is the surrounding matrix and interlocking system of columns, cloud brackets, and horizontal cross-ties that serve as the pagoda's primary structure. These are the same elements that provide the spatial, formal, and occupiable shape of the pagoda and its roofs, and that carry and suspend the core post.
3. Though it does not carry vertical load, the central core post plays the critical structural role of bracing against lateral (horizontal) loads from wind, and especially from earthquake activity. As a continuous vertical post connected laterally to four of the five distinct stories, the core post acts as a "pin," or "key," holding the tall and narrow pagoda together during an earthquake. It is this innovation that has allowed this wooden pagoda to survive the centuries in an actively seismic region.
4. Because the core post acts laterally rather than vertically, the post does not need to touch the ground to serve its function. The rot and resulting suspension of the post is therefore not a problem. The pagoda remains as stable now as it ever has been. In fact, had the post been planted into the ground, the pagoda likely would not have survived as it has, and would have been torn apart from too rigid a connection to the shaking ground.

Structural Motifs: The Sympodial Model

Let us first consider the prevailing theory—the sympodial, or branching, structural model. A sympodial structure operates, quite literally, like a tree. There is a single apparent main axis, or stem—the sympodium—from which a series of recursively branching members extend outward to produce a complete structure. Each branching member carries a portion of the load successively back to the one central axis, or foot, of the structure (Fig. 2.1).

In this model, the weights at points spaced farther away from the center are successively brought back to the center as they move downward. The single point at the bottom holds the entire structure above it. This basic structural form is quite common throughout Eastern architecture, most notably in the iconic Chinese *dougong* systems (Fig. 2.2) used to support the outstretched roofs typical of traditional Chinese design. This tectonic of interlocking wooden blocks and bracket arms follows the sympodial diagram

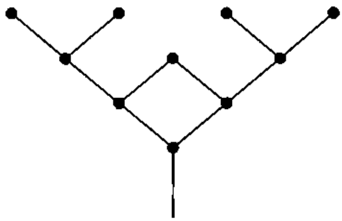

Fig. 2.1. (Left) Diagram of a sympodial structure.

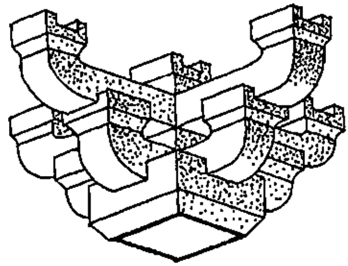

Fig. 2.2 (Right) The dougong (tou-kung) system (Liang Ssu-ch'eng, A Pictorial History Of Chinese Architecture, and The MIT Press, p.13, used by permission).

directly.

The proliferation of this model within East Asian design, combined with the simple presence of a central core post in many of these structures (including the five-story pagoda at Hōryūji) led many to extrapolate the central core post as an extension of the sympodial model. Following the analogy to a tree, the central post would operate as a trunk to which the branches of a pagoda's upper wooden structures would attach and transfer their loads (Fig. 2.3). This was the prevailing understanding of the five-story pagoda.

The analogy was powerful enough to convince Frank Lloyd Wright, who visited the pagoda and, with no other knowledge of the inner workings of its structure, surmised that the central core post was indeed the primary structural element and that the floors and roofs of the five individual stories were hung directly from it. Wright later used this inspiration to propose a series of rigid-core high-rise structures, working from the theory of an embedded rigid post that connected and carried a series of cantilevered floor plates.

Prior to the discovery of the rotted hanging post, this was the prevailing theory, and the analysis presented here began with its presumption. My intent was originally to analyze exactly how the system would have worked—how the wooden bracket system that supported the roofs was connected to the post and transferred loads to it, and how the entire assembly could hold itself together across centuries of earthquake activity. The constructed three-dimensional model instead revealed that the initial premise was wrong: the post did not support the structure vertically; it did not need to touch much less be embedded into the ground; and the entire sympodial model that had been presumed to hold the structure was in fact inverted.

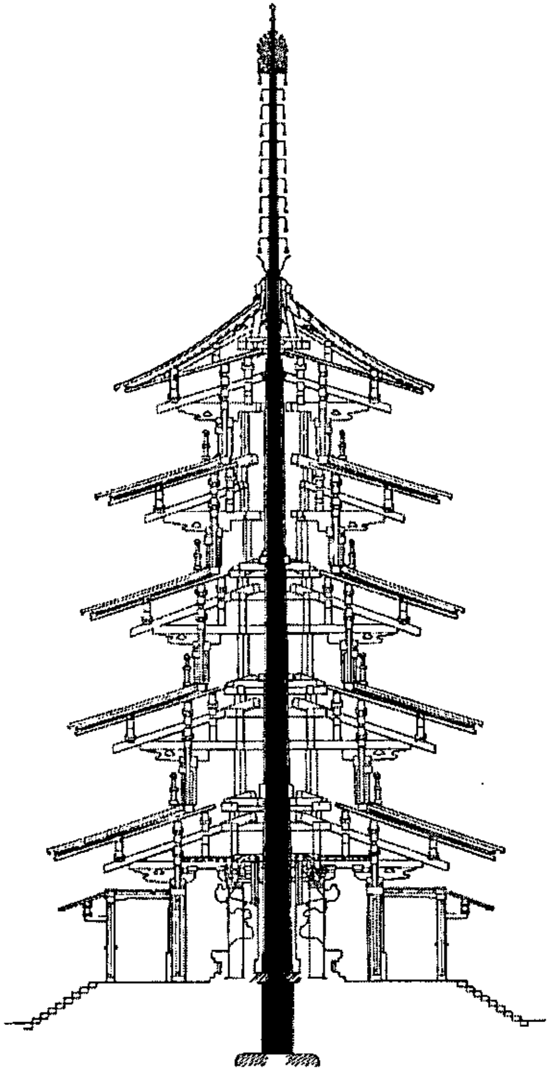

Fig. 2.3. The initial hypothesis and starting point of analysis. The central core post runs continuously through the pagoda and was presumed buried into the ground at its base—as was customary—for stability, much like the trunk and root of a tree. Other elements would connect to the post like branches. Discovery of the rotted and suspended post called this presumption into question.

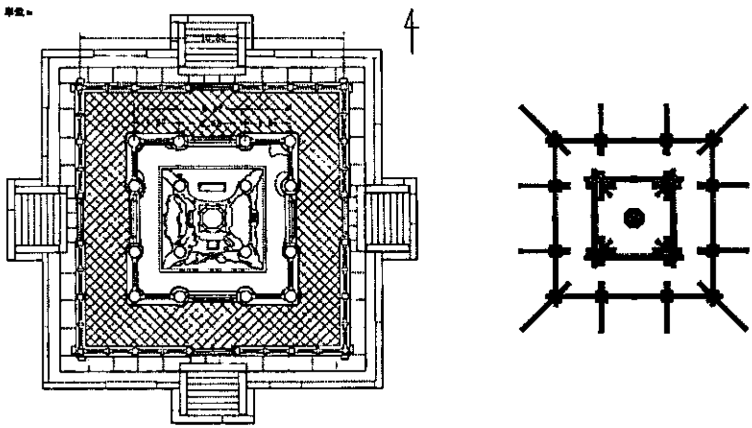

Fig. 2.4. Plan diagram (Kuno and Suzuki 1966, p.165) with computer model.

Analyzing the Structure

With the aid of three-dimensional geometric computer modeling, the assembly sequence and structure of the pagoda were considered in detail. The analysis began from measured diagrams of the pagoda's wooden structural members in both plan and section (Fig. 2.4). The measurements and proportional relationships indicated in these drawings and associated texts were taken as givens for the purpose of this study.

Through computer modeling, the analysis constructed each member of the pagoda in a fully three-dimensional representation, extrapolating both plan and section information to construct the model and arranging each member spatially in a manner consistent with the drawings. The patterns of each member's arrangement then began to provide clues to the structural arrangements and functions of each of the wooden members. We will now walk through the analytical sequence.

The Formal and Structural Elements of the Pagoda

The pagoda's architectural structure consists of three primary systems of components: an outer structure, the core post, and a locking bracket and tie system that connects the two others together. All three systems interlock to create a larger complete system, though we will investigate them separately for sake of clarity.

The outer structure provides the primary formal arrangement, look, and physical enclosure of the pagoda. Its components include columns along the

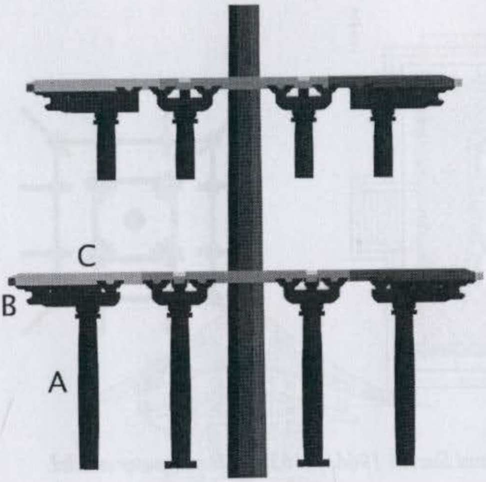

Fig. 2.5. (Left) Column (A), cloud bracket (B), and tie beam (C) on the first and second stories. Through the center is the core post of the pagoda, shown for reference.

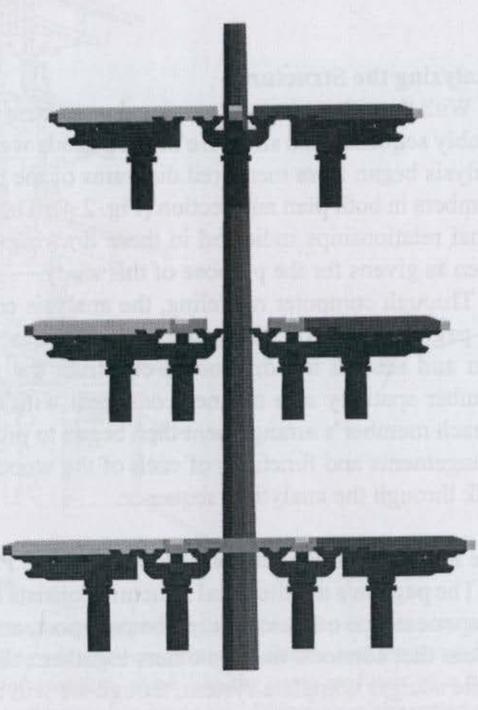

Fig. 2.6. (Right) Columns, cloud brackets, and tie beams at stories three through five. At the fourth and fifth stories, the crossing tie beams break continuity at the core. At story five, the number of columns reduces to three on a side.

perimeter of the outer walls, cloud brackets, the walls themselves, and all of the roof members. The components of this system repeat in a well-defined order for each of the five stories and are applied with only slight variation—mostly for diminution—between stories. In what follows I discuss only the framing components and their relationships, not the materials that infill between them to provide for weather enclosure and surface finishes.

The system of framing components begins with the most apparent and well recognized—the column and cloud bracket (Fig. 2.5). At the first story, twelve regular columns (A) form a square perimeter 6.42 meters wide center-to-center (see Fig. 2.4 for a plan diagram of the column condition). On top of each column sits a cloud bracket (B). On the face columns (the two middle columns on each side), the cloud bracket is oriented perpendicularly to the face of the pagoda. On the four corner columns, the cloud bracket extends out to the corners at a 45-degree angle (again see Fig. 2.4).

At each story there is a third element—a tie beam (see Fig. 2.5, C)—crossing horizontally over the cloud brackets and connecting them. The tie beam sets into the *dou* of each cloud bracket to hold and align the system together. Other than a proportional reduction in the overall perimeter width (and associated reduction in inter-column spacing) to account for diminution, and a similar reduction in vertical height of the columns from the lower to upper stories, this basic pattern repeats itself and becomes the primary organizing structure for each story of the pagoda (see Figs. 2.5, 2.6). The only significant differences in the repetition occur at the upper stories. At story four, the tie beams break and do not pass fully across the centerline of the pagoda (Fig. 2.6). At story five the pattern reduces to three columns on a side, eight in total, and again the tie beams are broken at the core.

If we look at this condition in three dimensions (Fig. 2.7), this arrangement becomes clearer and an additional fact is revealed. Not only are the tie beams broken at the fourth and fifth stories—each tie beam only responding to one quadrant or corner of the pagoda rather than to a full story—but at the lower stories also, the tie beams intersect in an open box that fully surrounds the core. At no point do the tie beams, or any of the columns or cloud brackets, come into contact (or anywhere near contact) with the central core post. This significant gap begins to call into question the hypothesis of a rigid core post branching outward in which the critical elements are hung from, or at least attached to, the post.

Now that the organizing system and measure are in place, we can introduce additional elements to build up the outer structural system. First we add a series of lower tie beams (D) to each of stories two through five (Figs. 2.8, 2.9). These elements are similar to the tie beams already discussed,

Fig. 2.7. Columns, brackets, and tie beams seen in a three-dimensional view of a partial second through fifth stories. Notice how in each case, the column-bracket-beam assembly is completely independent of the central core post. In fact these top three stories show three unique conditions where the assembly specifically avoids touching the post.

except that they occur at the base of the columns for each story and are the element on which the columns rest. The lower tie beams, like their upper counterparts, also form a perimeter box around the pagoda's core (see Fig. 2.9) and keep their distance from the core post.

The next layer of elements, a stacked multi-element rectangular box structure, constructs a wall perimeter on top of the upper tie beams and fills in much of the space between the upper and lower tie beams of each inter-story. The wall perimeter structure is an interlocking series of horizontal beams (Fig. 2.10, element E) that provides an enclosing envelope above the columns. Its construction includes the beams and interstitial *dou*-blocks, all box-jointed to intersect with one another and with the top of the tie beams, which in turn rest on the cloud brackets and columns below them (see Fig. 2.10). This perimeter frame is ultimately in-filled, as is the space between the columns from lower to upper tie beams, to achieve a weather-enclosed building. The infill materials are not shown or discussed further in this analysis.

To complete the outer structure, we can now add two roof layers—a lower (Fig. 2.11, element F) and an upper (Fig. 2.12, element G)—that intersect with the elements already in place and complete the connection of

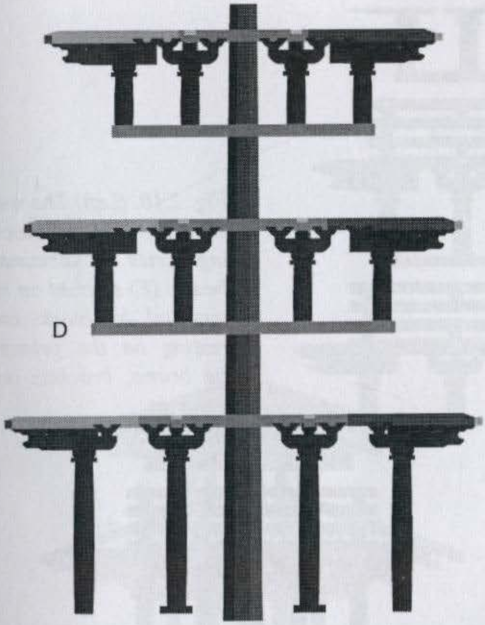

Fig. 2.8. (Left) Lower tie beams (D) span underneath the bases of the columns.

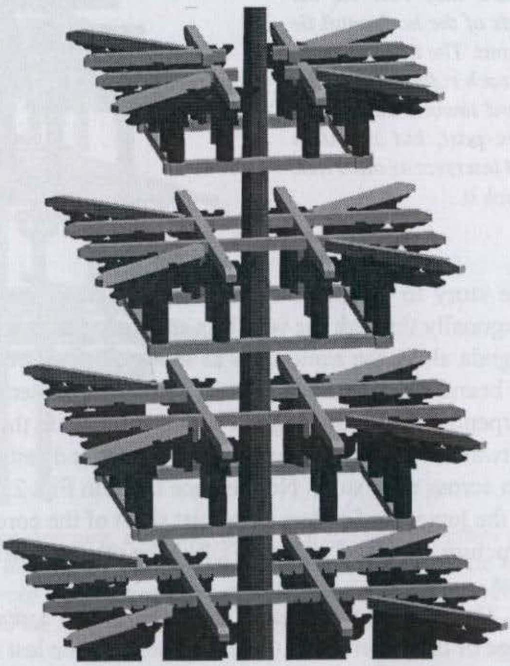

Fig. 2.9. (Right) The lower tie beam elements are at the perimeter, providing a base element for the columns to bear onto. These tie beams, like the upper ones, completely surround yet never touch the core post. The assembly remains independent of the post.

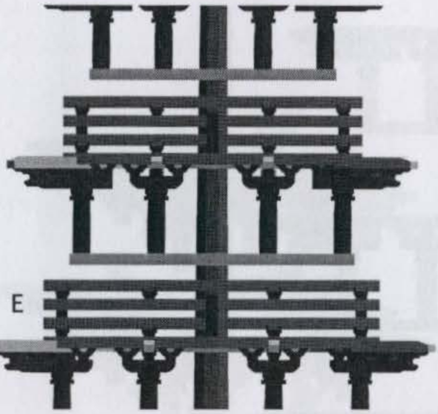

Fig. 2.10. (Left) The wall elements: an interlocking series of horizontal beams (E) stacked on interstitial dou-blocks and resting on the primary tie beams, brackets and columns.

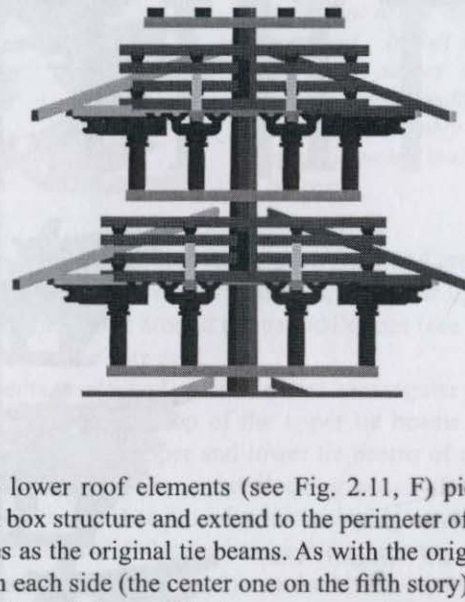

Fig. 2.11. (Right) Lower roof rafters (F, diagonal) intersect through the wall box and extend outward to the edges and corners where they rest on the ends of the horizontal tie beams. The topmost point of each rafter extends inward toward the central core post, but still does not intersect or otherwise touch it.

one story to the next. The lower roof elements (see Fig. 2.11, F) pierce diagonally through the wall box structure and extend to the perimeter of the pagoda along the same lines as the original tie beams. As with the original tie beams, the center two on each side (the center one on the fifth story) are perpendicular to the pagoda's wall face while the corner members extend outward at a 45-degree angle, matching—and resting on—the tie beams that run across each story. Notice once more in Fig. 2.11 how the topmost point of the lower roof rafters stops just short of the core post inside the pagoda's structure. The roof rafters (F), like the other elements, do not touch the core post.

The upper roof rafter (G) then sits atop a *dou*-block at the outermost edge of the lower rafter (F) and slides into the last remaining space between

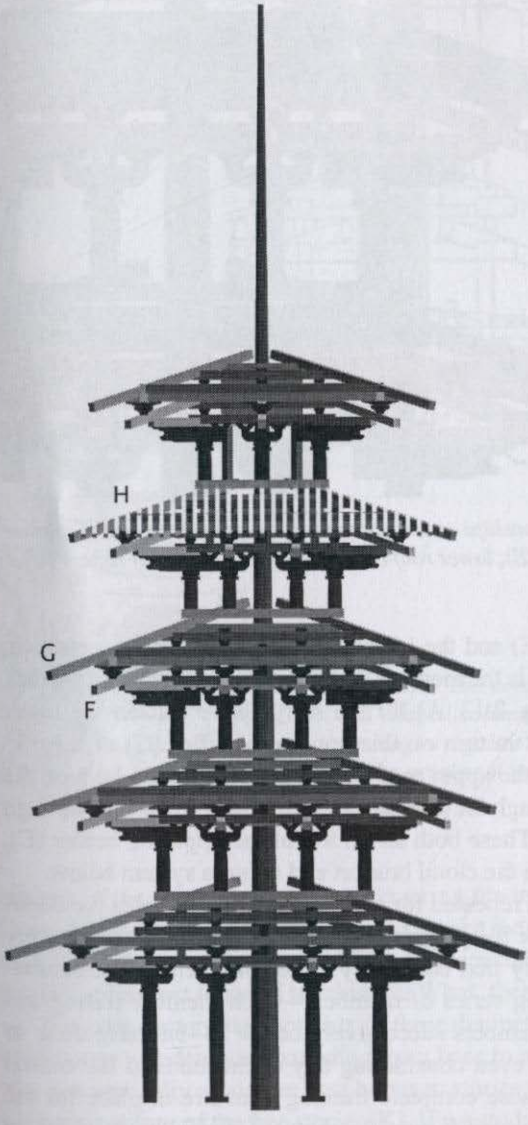

Fig. 2.12. The complete outer structure, including lower and upper roof rafters (F and G). The fourth story in this image also shows roof battens (H), which are the substrate for final weatherproof roofing surface materials. Note that while several elements completely surround the core, not one element of the structure shown here yet touches it directly.

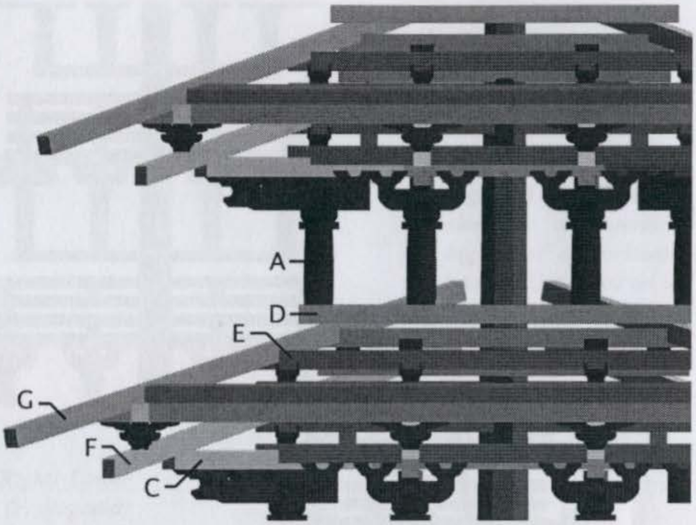

Fig. 2.13. Component relationships among columns (A), upper tie beams (C), lower tie beams (D), the wall box (E), lower roof rafters (F), and upper roof rafters (G).

the top of the wall box (E) and the lower tie beam (D) of the floor above. This upper roof rafter (G) is the member that finally ties the stories together, because the columns (Fig. 2.13, A) for the story above rest on the lower tie beams (D), which rest in turn on this upper roof rafter (G) of the current story. The weight of the upper roof rafter (G) bears in turn both on the lower roof rafters (F) through the *dou*-block and on the wall box (E) through its box-joint connection. These both sit on top of the upper tie beams (C), which distribute load onto the cloud bracket and column system below.

Taken all together and repeated for each story, this completes the dominant architectural form for the pagoda. With the completed outer structure in place, we have not only tied each story to the one below it structurally, through an interlocking series of members—each member resting and bearing its load on the members successively below it—but have done so without ever touching or even considering any connections to the central core post. With an otherwise complete framing structure in place for the five-story pagoda, we now need to consider the core post in greater detail to determine its role in the framing system.

The Core Post

Thus far, we have analyzed elements building up around the outer pe-

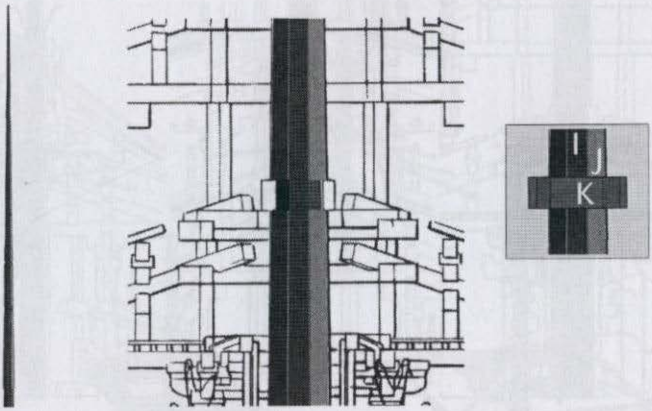

Fig. 2.14. (Above) The core post elements: the continuous wooden post (I), batten rails (J), and locking bracket (K).

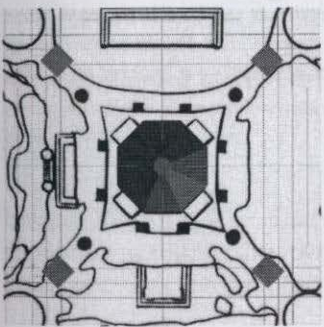

Fig. 2.15. The core post is a tapering octagonal shaped column. Batten strips (the drawn rectangles against the outer diagonal corners of the octagonal post) run vertically along the octagonal post.

rimeter of the pagoda without ever entering the important central zone. We know that the central post is there, and we see the other elements in relation to it, but nothing has yet touched it. In fact, several elements display explicit modifications just to avoid touching it. What, then, is its role?

The core post system consists of three distinct elements (Fig. 2.14): the continuous wooden post extending from base to spire (I); strapping battens that run vertically along the post between stories (J); and a locking bracket occurring at four of the five stories (K). If we study the drawings, the system here becomes clearer. The post runs the full height of the pagoda, and along its length are four batten rails (see Fig. 2.14, J)—thin wooden boards affixed to the side of the rising post. The post is not circular in cross section but, rather, a tapering octagon (Fig. 2.15). The octagon provides eight tapering

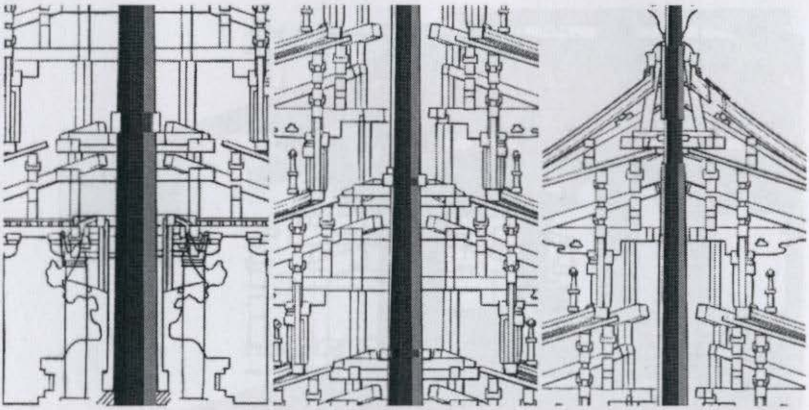

Fig. 2.16. The battens break at four distinct connection points along the length of the core post. At each of these points, a bracket (seen in the drawing behind) locks against the post and between the battens. The bracket simply sets against the post, and the battens lock it in place. This connection occurs at stories one through three (left and middle images) and at story five (right image). The fourth story (top of middle and again bottom of rightmost image) does not contain a bracket or a connection.

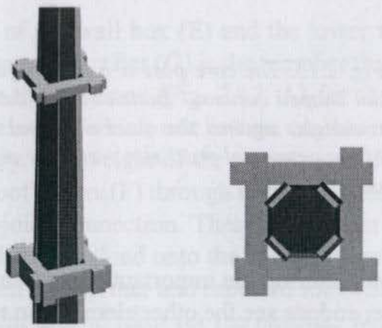

Fig. 2.17. Detail of the core post, battens, and locking bracket in axonometric and plan views.

surfaces, four of which (toward the outward corners) have battens running their length. At a given point within each story (with the notable exception of the fourth story), the battens break and there is a special point of connection where the post interacts with surrounding structures (Fig. 2.16). At each of these points a square bracket (see Fig. 2.14, K) is inserted to box the post on four sides, just touching the post's outer surface. The bracket only sandwiches the post; it does not penetrate it, nor does it appear either to be counter-set into the post or to accept an outward boss from the post into the

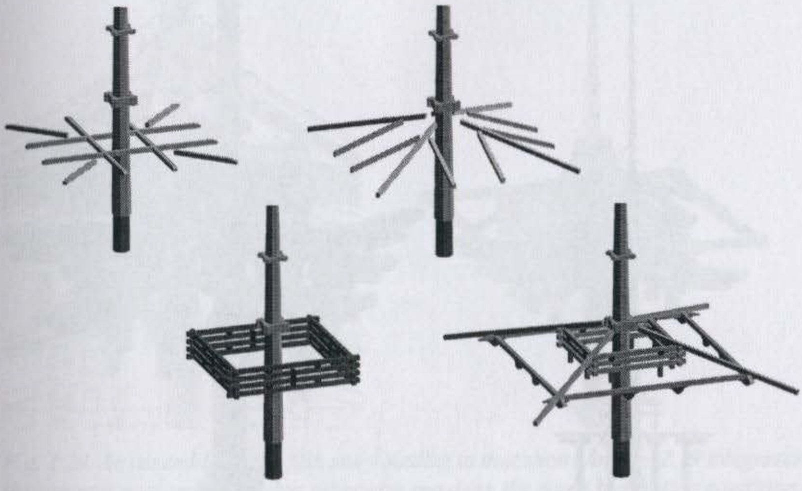

Fig. 2.18. Elements of the outer structure, each viewed independently in three dimensions. Each element surrounds the core post without connecting to it, and each occurs below the bracket.

bracket (Fig. 2.17). The surface of the post appears smooth, with the bracket simply set against it; thus the purpose of the battens is to butt against the brackets at their ends and prevent the bracket from sliding up or down.

Putting It All Together: The Final System

The locking bracket located at four of the five stories of the pagoda gives us a first hint that the core post does indeed connect to the rest of the structure, but thus far the completed outer structure assembly exists without regard to the core post or to this bracket connection specifically. The columns and cloud brackets, tie beams, box-wall enclosure, and upper and lower rafter elements all surround the post at a distance. Some come near to it, almost touching, but none actually touches the post or allows for the critical point of connection that we have been looking for (Fig. 2.18).

Considering the initial hypothesis, an even more unexpected discovery is that the locking bracket just described always occurs *above* the surrounding structural elements for a given story. Such placement works precisely against an approach that would bear the weight of these members downward—*onto* the bracket and core post—to the ground. Trying to justify this

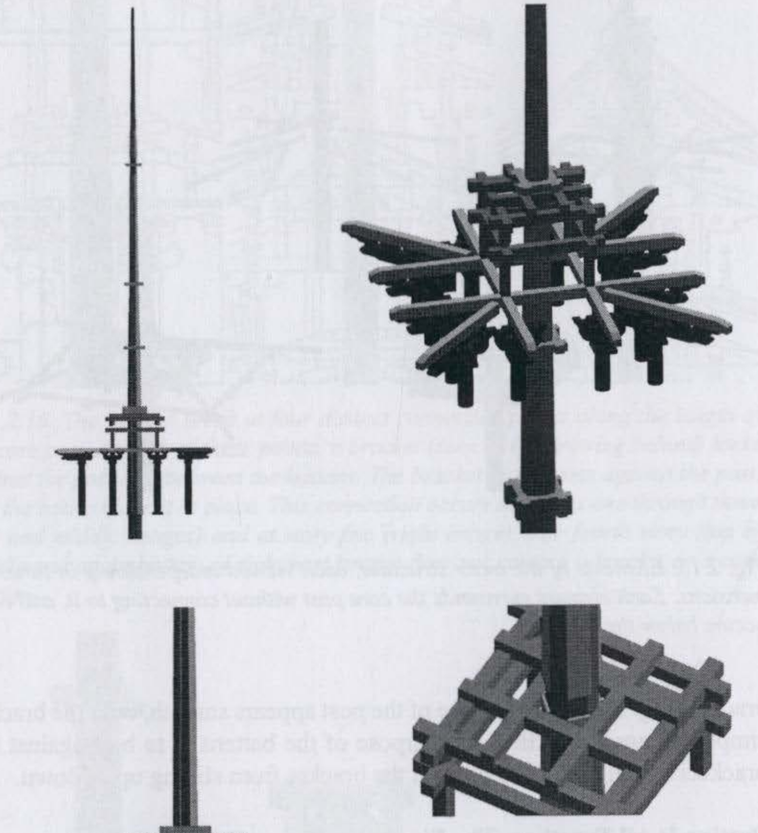

Fig. 2.19. The inner structural system. A frame structure hooks into the underside of the core post's locking bracket and connects back to the original tie beams of the outer structure.

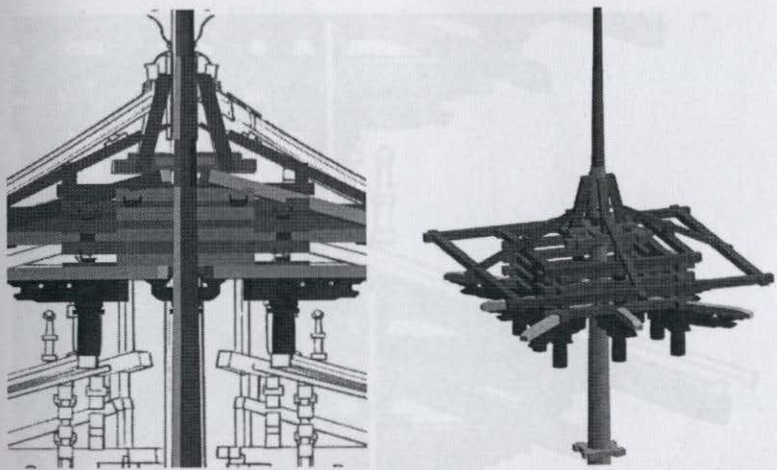

Fig. 2.20. An assembly on the fifth story similar to that shown in Fig. 2.19 integrates the topmost roof and spire, but otherwise provides the same bracketing condition. The fourth story, which does not have the bracket and locking framework, can also be seen in the drawing behind. The core post is not a single solid unit but two separate posts joined together. The fourth story is where this joining occurs, and therefore there is no bracket at this location.

finding to the original sympodial diagram of Fig. 2.1, the foot of the diagram here would be above the elements, not below them, inverting what we would expect from a downward-bearing structural approach. In other words, the sympodial diagram turns upside-down.

This discrepancy is resolved through one final system that ties everything together (Fig. 2.19). At each of the four bracketed stories, an additional framing structure is built within the open core space. This new frame is built around the core post and against the locking bracket's lower surface, but connects directly to the original set of horizontal tie beams and lower rafters of the primary outer structure (see Figs. 2.19 and 2.20). This frame is the element that finally locks the core post back to the outer structure's post-and-lintel, direct-bearing assembly. It occurs *below* the locking bracket on the post and *above* the tie beams of the post and lintel. Being effectively above the surrounding structure, it does not—and cannot—transfer loads from the outer structure (which includes the extending roof system) inward and downward *to* the central core. The bracket is too high to do so, and the connection pattern moves upward rather than downward. Instead, any downward loads that would be carried by this frame would be moving *from*

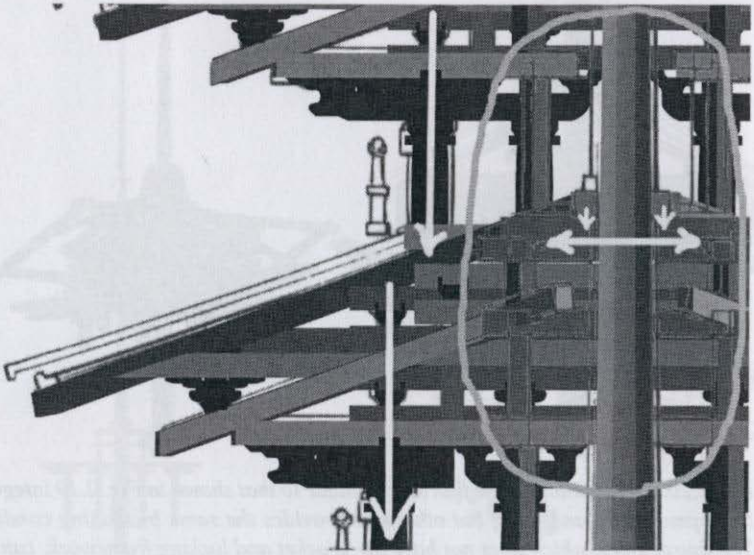

Fig. 2.21. The central core post provides lateral rather than vertical stability for the pagoda. Vertical load bearing is carried by the outer post-and-lintel structural system.

the core post and locking bracket through the frame to the tie beam and primary structure below. Thus this final component is not working to carry bearing loads. It can only be, instead, a brace to lock the post against the outer structure and triangulate the other two systems together (Plate 9).

The Real Function of the Core

The original hypothesis is thus disproved: the central core post cannot act as the primary load bearer for the pagoda structure because its connections to that structure occur in the wrong location to support vertical weight-bearing loads. The core post and bracket system does, however, exhibit characteristics of an equally important structural role—lateral stability (Fig. 2.21)—and this is the primary purpose of the core post.

The most significant characteristic of the central core post is that it spans and connects more than one floor. Though the post is not fully continuous from base to spire and the fourth-story locking bracket is conspicuously missing, the two posts that comprise the full core—one from the base to the fourth story, and a second from the fourth story to the tip of the spire—each span at least two structural stories of the pagoda. By spanning and connect-

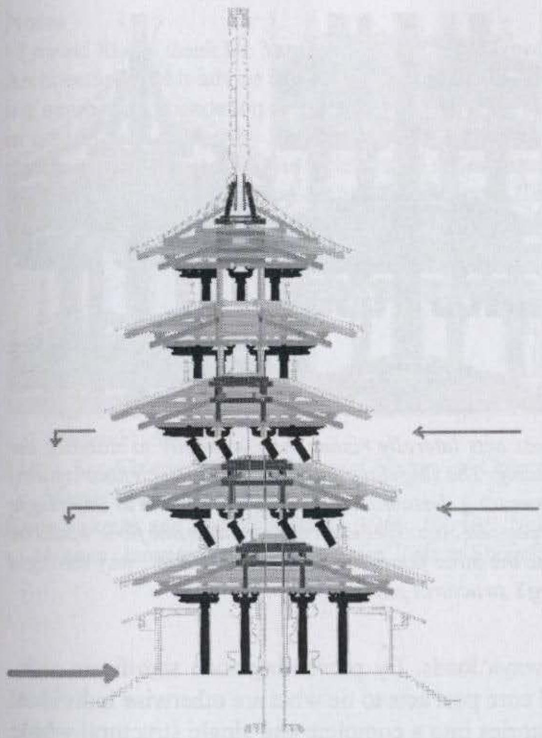

Fig. 2.22. Without the core post to brace against lateral (sideways) forces, the top-heavy roof assembly of each story could shift sideways and topple the pagoda under high winds or even mild to moderate earthquakes.

ing multiple stories, the critical function of the core post is to brace the actions of any one story against those of the others. The core post's rigid body acts quite simply as a pin, with each story being braced not only sideways against the rigid core but also against the stories above and below it—and in fact against the entire structure, through the core. Movement in one story is countered by lack of movement in another, using the core post's length to solidify the whole.

As already established, the outer post-and-lintel structure carries all vertical loads, slowly stepping outward, but this structure is not stable on its own against lateral movement (Fig. 2.22). The individual columns of the post-and-lintel structure on each story are simply set on the cross-beams below them. These connections, though pinned or box-jointed, are relatively weak except for vertical bearing. A significant sideways force, such as that typical of high winds or of earthquake conditions, would put considerable strain on the connections, creating moment (rotation or pivoting) conditions at their base. The top-heavy roof structure of each story could easily topple

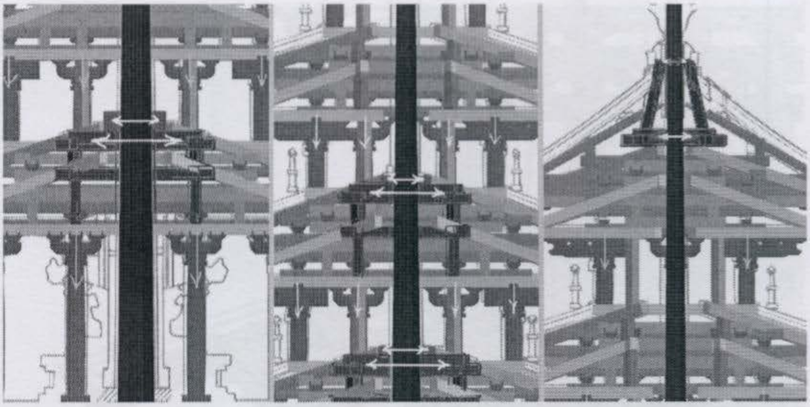

Fig. 2.23. The rigid core post acts laterally rather than vertically to stabilize the tall and narrow pagoda building. The singular rigid form braces each floor against each of the other floors, preventing destabilizing lateral movements at any single point along the height of the pagoda. Any significant movement in one floor would be transferred and distributed to the other floors for stabilization. In this way the rigid core post acts as the building's structural pin.

under great enough sideways loads. By preventing such significant sideways motions, the central core post acts to tie what are otherwise individual and structurally distinct stories into a complete and single structural whole (Fig. 2.23 and Plate 10).

Finally, if we accept the findings of this study—namely, that the central core post only operates to pin the structure laterally and does not bear any of the building's weight to the ground—then it does not matter in the least that the wooden post was discovered rotted away at its base, and thus suspended in the air above the ground (Plate 11) and above the vault of sacred objects below. In a now thoroughly inverted sympodial condition, not only the weight of the pagoda but the weight of the post as well are carried by the surrounding outer structure. The post could be suspended nearly a full story above the ground and still serve its most important function. It is this single and simple innovation of Japanese design that enabled such a tall and narrow structure to survive the centuries despite its location in an actively seismic zone.

Notes

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