on them, to form a rough upside-down model of the building while he was working it out. The wires and strings naturally fell into parabolic curves and catenaries under the impact of pure tension — finding balance with the system of weights. When he turned the configuration discovered by the model upside down, it then formed a system of pure compression arches, one of the most natural ways of using mass material to form a building.[2]

Here the living process not only created space in a natural way, but also found positions for compression members that were congruent with the space. Later in the chapter, I shall describe a way that modern finite-element methods can be used in a still more sophisticated fashion, to supplement the use of a living process to elaborate and unfold a structural design. In the next few pages, I shall show, by example, how the unfolding of living structure can be made to work in other, larger situations, how it can actually be done, and why it will work properly only if one repeats the fundamental process again and again.

6 / THE GREAT HALL AT EISHIN

The essence of the problem lies in the process through which we understand solid and void as two balanced opposites.

To explain it, I give the following example of the Great Hall at Eishin (pages 102–110) where the process of working out the solid-void relationship took place in a large but rough-and-ready three-dimensional model. This rough model of the main hall itself, focusing on its interior, was built at a scale of 1:20. It was about 8 feet long, 4 feet wide, and some 2 feet high.[3]

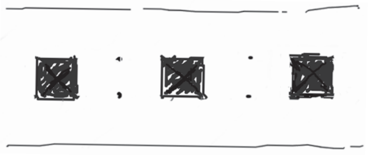
We began with the overall space, made in paper, getting its shape and feeling right — just as far as space and dimensions and light were concerned. This was done in paper. Then we began introducing columns. These solid wood columns, milled on our table saw, played an important role, since one of the first things to get clear was the size and scale of members that would create profound feeling in the space. After playing with different-sized pieces of wood we were able to determine that the best size for these columns (the one that made the strongest emotional impact) was a square section of about 1 meter by 1 meter: in the model this was a stick of wood 16 inches long, with a square cross section of about 2 inches by 2 inches. Having determined the column-size which had the most powerful depth of feeling, we made a number of them, and began standing them up in the space to get a clearer understanding of their *spacing* — the shape of the space between the columns. The space between the columns came to play a crucial role, and we finally settled on a space of two meters clear — i.e., the columns placed at three meters on center. This made the shape of the space between adjacent columns two meters by one meter in plan — a well-shaped rectangle, which had the capacity to form positive space, interlocked with the structure.

All the steps taken so far came from the fundamental process: making the shape, size, of the space, the shape and size of the columns, and shape and size of the space between the columns, making all these work as centers in their own right.

Having done all that, it began to dawn on us — just from looking at the model — that the overwhelming issue was the quality of light created in the space. The overall feeling showed itself mainly through the light that came into the Hall, and the way this subtle light was partially carried into the main space, lingering softly over the aisles. It also had to govern the structure. We then made a more solid model, capable of blocking light so that we weren't

First crude model, at 1:20 scale, of the Eishin Great Hall interior. You can see a certain quality of light beginning to appear, columns are massive, and the light is soft, created between the massive columns. It is the spacing of column and void, and the relation of the two, that makes the quality of light appear.

being fooled by the translucent quality of the light coming through the paper walls. We then focused on the size of openings. Surprisingly, it turned out that — once again following a living process — it was necessary that the hall be quite dark inside to preserve the wholeness of the interior. The hall could easily be damaged in its feeling, we found out, by too much light coming in. Under the impact of this observation, the emphasis began to shift to smaller windows and to the way the small openings were framed by the massive structure of the columns. Shortly after that we went on to the spacing and size and pattern of the beams.



The "solid" character of the space between the columns. In plan it is 1 meter by 2 meters. As a volume it is 1 meter by 2 meters by 7 meters high.

At each moment, as the work went forward, we were thinking primarily of making a system of centers which contributed to the emerging whole. These centers include the structural bays (vertically and horizontally), the columns, the beams, vaults, trusses, buttresses, braces, patterns of bays, foundations, piers, beams, ties and so on. At any state our model was in, one or another of these centers was in some sort of weakened state. As I kept on trying to intensify the structural system of the building as a whole, I was at the same time actively making one of these centers *more* of a center, a more powerfully *living* center. The process of making it more of a center (giving it more life) then also played a role structurally, at the same time that the elements and members helped the space.

When I started, all I knew was that there must be a number of columns. As I placed the columns, and as we watched the light develop in the 1: 20 model we had in our office, it became

Another interior model in our workshop. In this model we first began to see the quality of light, and the structure, clearly.

An early view of the Eishin Great Hall interior, as built in 1985. The quality of light, dimly visible in the model, was now fully achieved. Christopher Alexander with Ingrid King, Hajo Neis, Gary Black.

clear that the building was most powerful, had most life in its columns, when the columns were very big, and the space between the columns rather small. So, I put a rhythm of this kind — big columns, small spaces — into the building. Of course this rhythm was useful structurally.

From an elementary point of view we might have said, "But we do not need this much structure. There could be less material. The columns could be smaller, or further apart." But if we take this step, then the life of the building evaporates. So I kept the big columns, and the close spacing, because that is where the life comes from, and asked myself instead: How can I get the most structural efficiency out of *this* pattern of columns?

We considered the possibility they might be hollow. Then we considered them as elements of a moment-resisting frame. We were looking for a pattern which made the best structural use of this beautiful arrangement for columns. We never allowed the simple-minded pure-efficiency argument to dictate, since this would have killed the structure. The simple efficiency argument has no more sense, in structure, than allowing *any* single aspect of the building to rule. For example, the pure plumbing economy argument in an apartment building says all bathrooms and kitchens must be in the same relative position. Obviously, we do not give way to such a silly argument, since it will certainly kill the life of the building. In the same spirit, when designing structure we must recognize that our job is to take the pattern of columns which has the maximum life, and to extract from this maximum life a more intense pattern still, which develops great structural strength and benefits from the life to create a further *structural* life.

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7 / A NEW KIND OF ENGINEERING DESIGN PROCESS BASED ON FINITE ELEMENT ANALYSIS

A finite element model is a form of computer simulation in which the differential movement of the elements of a given structure can be determined, based on the loads it experiences. This has become the most powerful — and easiest — way of finding out what really happens to a structure. It allows you to make rapid tests to see how the various elements of the structure move, in relation to one another. This in turn allows one to correct the structure, test it again, modify again, until the structure becomes well-behaved.[4]

I first began to make experiments with finite element analysis in 1973, analyzing the shells of the Etna Street cottage and the wood-concrete combinations of our United Nations houses in Peru. The conventional use of finite-element analysis, standard in engineering practice both then and now, normally uses the analysis to size members in an overall configuration of members, when the configuration itself has already been achieved by intuitive design or guesswork.

It occurred to me that one could, with the advent of computers, do something more useful and far more creative with finite-element analysis, namely: To obtain the design *itself*, that is to say, the best *configuration* of members, not merely the best sizes of members in a given configuration. One could very quickly examine a sequence of different configurations, each time obtaining the overall forces, tension, compression, bending moments and shear, in the members, observing the badly behaved zones in the structure, and then inserting, or deleting members, or re-sizing them, to improve the behavior, then testing the finite-element program again, obtaining new forces and so on, thus moving rapidly through a sequence of different configurations — hence different designs. After a small number of iterations, which can be examined in a day or two, one is able to arrive at a "best" configuration which has good behavior as a whole. This technique became standard in all