my projects in CES from 1969 onward. Several brilliant and helpful engineers were involved in these experiments, including James Axley in the 70s, Gary Black in the 80s, and John Hewitt in the 90s.[5]

Thus, instead of merely using the finite element analysis to detail sizes and stiffness of members, the method is able to give us the far more exciting unknown *configuration*, the global organization and design.

In the next section I shall show how detailed structural engineering, too, can be done by the repetition of the fundamental process, using finite-element models that allow a novel and essential approach to member design. We can make a (computer) model of a rough sketch design, apply forces to it (as if the forces were coming on in the real world). Within seconds, the finite element model shows us forces, deformations, stresses, and so on, in every element of the sketch structure. So, we see in the computer which elements take the most force, which ones deform, how the whole configuration stretches, bends, twists and deforms. This allows us to change the design, experiment, see the effects, improve it on the basis of the feedback we are getting. Just as a cardboard model of a building volume on a site gives us excellent feedback about its spatial life within the larger configuration — so the finite element computer model gives us almost instant feedback about the good, or bad, behavior of the structure when forces are applied to it. We are able to correct the structure within minutes, making different elements stiffer, or less stiff, or larger, smaller, differently connected and so on. Then we run the program again, and watch to see how the structure behaves. If the behavior gets better, we have done something useful. If it gets worse, we go back, and try again. Within a few hours it is possible to make many, many iterations of this kind. With care, we may then allow a beautiful and efficient structure to develop.

8 / USING THE FUNDAMENTAL PROCESS TO GET THE DESIGN OF A CONCRETE TRUSS

I shall now describe the detailed working through of one particular structural element in a building. This example comes from the Julian Street Inn, in California (pages 120–31).

At an early stage in its evolution, I reached the idea of a long building, wrapped around the site, with two courtyards in it like donut holes. It was the client's liking for this idea that got us the job (Book 2, pages 283–97).

One notices, right away, that latent in this structure is the center formed by the volume between the two courtyards. You feel this latent center even in the roughest sketch. So now, this center between the courtyards begs for attention. It is a latent center of considerable power.

At the next stage in the evolution of the design, we allowed this center to develop, to strengthen. It became a dining hall. This did not emerge as an "idea" or a "concept." It appeared, organically, in a step by step process, by applying the fundamental process to the building layout as a whole.

At a later stage, this dining hall got bigger, that is, higher. Again the center, having been established, was latent. It was not yet strong enough, and volumetrically, it did not fully take its share of the load or reach the capacity which

The two courtyards showing the dining hall, marked with an X, as the key latent center in the whole configuration this center had for life and intensity. Then the building got higher and formed a more powerful center at the heart of the building complex.

Inside this higher building volume, we used the fundamental process repeatedly to get the detailed engineering structure itself. The hall, a single room, 30 feet wide and 50 feet long, was intended to seat about 100 people. We decided to make beautiful exposed concrete trusses to mark the inside of the hall and to intensify its character.

Before our work on the trusses themselves began, the following things had already been fixed: the shape, length, and width of the building; the height of the building; the slope of the roof; the pattern of movement in and out at the two ends; the movement onto the garden terraces. These decisions themselves had already been fixed by the same methods.

Looking back at the process of designing the trusses themselves, I can identify some twenty distinct stages.[6]

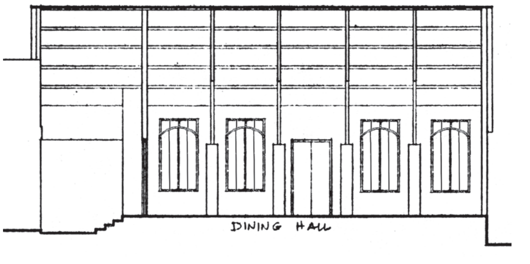
1. *Overall feeling of the dining hall.*
We had a general global feeling in the building of concrete and wood in combination. The building was heavily dominated by concrete and plaster surfaces, with wood beams and ceilings in the main rooms. In order to make the dining hall harmonious, it felt as if use of concrete, not wood, in the trusses, with wood on the floor, would make the thing most harmonious — but with a real delicacy of feeling in the truss itself — something like a Gothic tracery, but floral, and related to the forces with a kind of free delicacy which had not been seen before in a concrete member.

What we had in mind here was a unique type of truss, not previously attempted.

2. *Decision to use gunite.*
It was our intention to make these trusses by shooting them in the air, in gunite, a high-strength dry, air-shot concrete technique I had perfected several years earlier in the Martinez building, where I had developed the ability to make very finely detailed designs in concrete, without the use of the expensive pressure-resistant forms needed for poured concrete work. Gary and I were greatly interested in the fact that the flexibility of forming concrete in this way would allow us to achieve an optimum design from the point of view of the tracery of the truss, and make it delicate and strong at the same time.

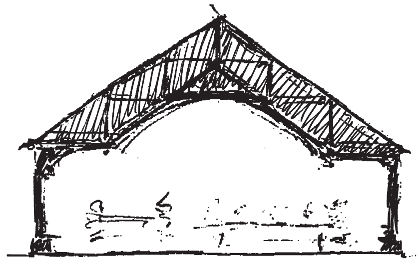
3. *Spacing of the trusses.*
The next thing we did was to settle the number of structural bays.

To get this result we started with a certain wholeness — the wholeness of the exterior wall of the building — and then intensified that wholeness by making the windows as strong as possible as centers. By looking at the building volume and thinking about window shape, we decided that there were going to be five structural bays. This came from looking at the exterior and interior walls, from the point of view of making beautiful windows, and seeing that the bays needed to be about 10 feet on center. This meant that there would have to be either 4 or 6 trusses (depending on whether we used them at the end walls, or not).



3. Early interior section giving the feeling of the interior, and from which we then derived the decision to use five 10'-bays

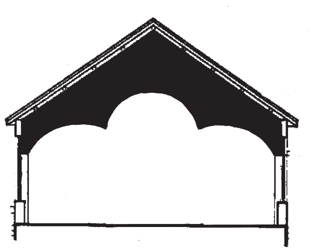
4. *Overall outline of the truss envelope.*
The next thing we did was to get a sense of the most desirable overall shape for the truss, that is, the envelope for the truss along its lower boundary, not including internal structural members. We were concerned here with the effect of the truss on the space and feeling of the dining hall. In order to study it, we first made a series of sketches of possible shapes.



4a. Early idea of the truss envelope showing cross-sectional shape with main arch and two half arches

From these drawings alone, it was difficult to find out which shape was best. It was almost impossible to tell what effect the different truss shapes would have on the three-dimensional space of the interior. One couldn't foresee clearly to what extent the under side of the trusses, spaced ten feet apart, would create a "ceiling" with the right feeling.

Since the three-dimensional effect was going to be the main thing one would experience in the building, we decided to make simple paper models and to compare them directly.



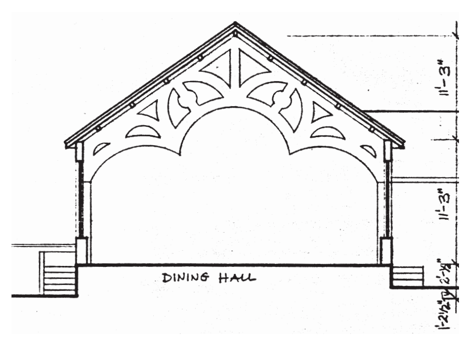
4b. Our final definition of the truss envelope, showing cross-sectional shape with main arch and two half arches

We made paper models of thirteen different shapes. The variables in these models was the perimeter of the truss underside: that part which would later form the virtual "ceiling." We included versions with a flat chord, a single arch, three equal arches, a large arch with two smaller half arches on either side. In each case, we had a full sequence of six truss outlines made of paper by xeroxing and cutting with scissors, over the base model of the hall itself.

When we had them, Gary and I sat in the basement and held them up to our eyes, one by one, independently comparing them. We classified them as beautiful in feeling, so-so, and no good. Only three of them were in the top group for both of us. Of these, after several days of careful thought, we finally chose the one which consistently seemed to score highest on the mirror test: a main arch with two half arches.

5. *First sketch of tracery.*

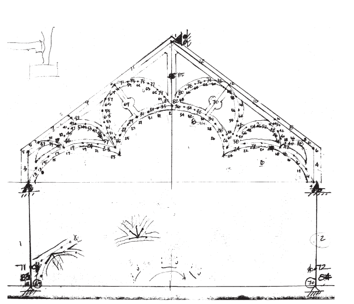
We wanted to see next, what it would be like looking "through" the tracery of an open lattice



5. Sketch of conventional triangulated truss with curved members

truss, and if this would help us choose which one had the best shape.

At my request, Gary made a rough sketch of curved tracery, following a conventional triangulated format, with curved members, and we made a model with holes cut in the trusses to see the effect of tracery. Although we didn't like the



6. Finite element model of first curved truss tracery yet, it gave us enough confidence so that we did fix the lower chord, and its three-arched truss envelope as the final shape of the one we were going to keep.

We knew that its interior tracery was not beautiful yet, and I knew it was far from acceptable for the project — especially judging it on the mirror-of-the-self criterion. However, by this stage, we had in principle consolidated our decision to try and make a truss with beautiful geometrical tracery, using curved members, and not obviously based on simple truss design. From this point of view, the free form of the first curved tracery was something to start with, even though it was not beautiful. As it turned out, it was not well-behaved structurally either.

9 / GOING ON WITH THE UNFOLDING PROCESS FOR THE TRUSS: FINITE ELEMENT ANALYSIS

6. *First finite element model.*

Of course we had no idea whether this first tracery would be well-behaved structurally. We therefore made a first finite element model to find out how the forces went. We could immediately see some very bad behavior. The forces were several times over limits in several places, huge shears at the base, and moments too big in some of the curves.

7. *First scissors truss.*

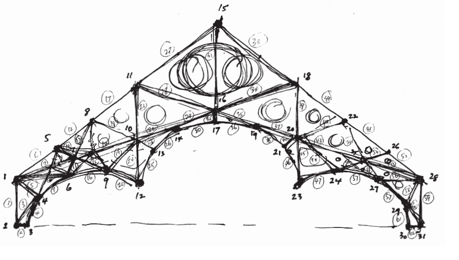
At this stage I decided to go back to structural behavior, and started by trying to define the most efficient truss which was consistent with the three arch profile we had chosen.

It seemed to me most likely that the arches could be made to work by placing a tension member in the position typical in a classic scissors truss. I sketched this out in rough, and one of our apprentices built a miniature one in concrete, one inch thick, with a span of 3 feet. It was not appealing. The apparent simplicity of the structural lines, when given width, made a mishmash of shapes which was inconsistent, geometrically, with the beauty of the three-arch form. (Two minor points about its ugliness: The sharp points where the arches meet, and its lack of three-dimensional relief — like a slab of chocolate. These problems were solved later.)

I then decided, myself, to test a series of computer models, in rapid succession, and started an intensive ten-day session of uninterrupted computer work, to try and find a solution which was both beautiful and structurally efficient.

8. *Second scissors truss.*

In spite of the ugliness of the first scissors truss, I did not give it up right away. Before going ahead, I still wanted to find out what kind of



8. Second scissors truss sketch and its nodes

truss would be structurally efficient for the three-arch envelope we had chosen for the truss. Since the first scissors truss was ugly geometrically, I did not even take time to test it in the computer, and instead decided to try sketching a second scissors truss, and ran a finite-element model to determine its behavior.

I drew what seemed like a perfect triangulation of the curvilinear shape above the three-arch bottom chord (see drawing above). In this drawing, I tried to make all the triangles as neat and similar as possible with good angles, and