CASTEEL

SPRING/1982

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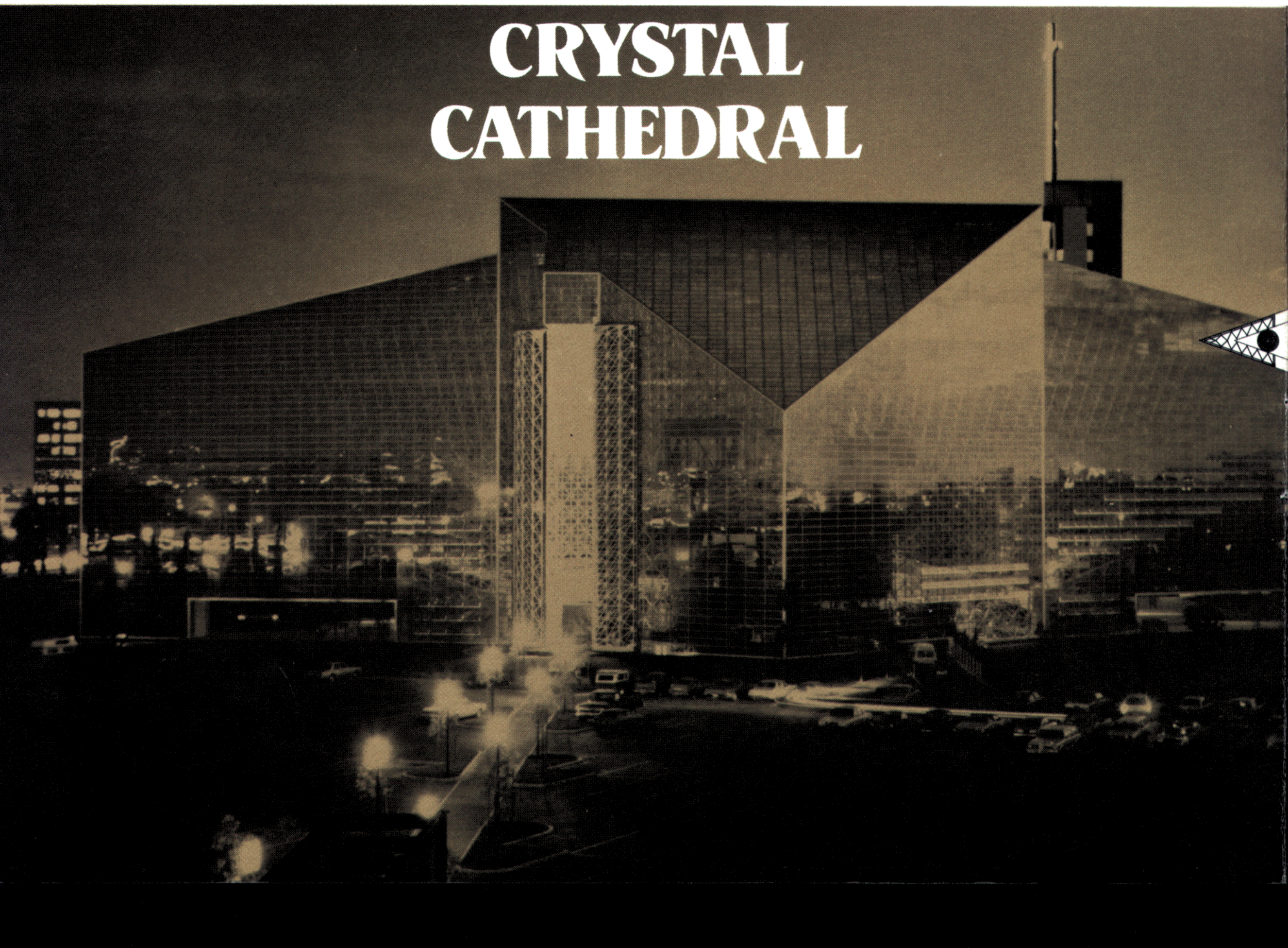
STEEL CASTINGS: NEW HEIGHTS IN CRYSTAL CATHEDRAL

There has never before been a house of worship like the Crystal Cathedral in Garden Grove, California, near Los Angeles, and there may never be one like it again. Enclosing 3.5 million cubic feet of uninterrupted space, the cathedral is open to the light that fills the California skies, to congregants worshipping in their automobiles, and to the world through the broadcasting activities of its minister, Dr. Robert H. Schuller. How is it done? With mirrors, of course — over 10,600 panels of reflective, one-way glass. And with a steel truss system strong enough to stand up to an earthquake and airy enough to "disappear" into the sky beyond the glass. And with over 400 cast steel connectors at the points of highest stress and most complex geometries, to hold up the angled roof and keep the whole visionary structure from crashing to the ground.

The concept of the cathedral evolved through long discussions between Dr. Schuller, who had once been a "drive-in" preacher, and Philip Johnson of Johnson/Burgee Architects, one of the leading architectural firms in the country today. With a local congregation of 10,000, Dr. Schuller needed seating space for about 3,000 worshippers plus a way for him to be visible to drive-in congregants remaining in their automobiles. He also wanted a space that would come as little as possible "between your eyeball and the infinity of space," and would still have room for the lights and electronic equipment needed for radio and television productions.

What he got was a building in the shape of a four-pointed star, 207 feet wide, 415 long, and 128 feet high at its apex, totally enclosed in glass. With balconies in the three corners of the star that face the chancel, the total seating capacity is 2890. And when Dr. Schuller stands at his raised pulpit at the extreme western end of the chancel and begins his service, two 90-foot-high doors open to reveal him to the automobiles parked nearby.

More than any other feature, however, it's the soaring, swooping roof that transforms the vast space into a cathedral, a place clearly meant for worship. But it's also the roof that created some of the knottiest design and construction problems encountered.



Unique design based on truss system

Essentially, the Crystal Cathedral is a free-standing building in which a system of interconnected trusses constitutes both the walls and the roof. The truss was chosen as the basic structural element because it presents an open, lattice-like appearance and because it can be made to form an extremely strong structure. In fact, the cathedral was designed to withstand earthquakes of magnitude 8.0 on the Richter scale, as well as wind velocities of 100 mph.

A truss is normally made up of top and bottom chords connected together with inclined diagonals; the diagonals intersect with and connect to the chord members at "panel points." All loads are applied at the panel points. As designed by Severud, Perrone, Szegezdy, and Sturm, structural engineers for the project, the basic truss section for the Crystal Cathedral has two top and one bottom chord, with diagonals from the two top chords slanting to a common point at the bottom chord to form a triangular cross section. Adjacent truss sections share a common top chord member. Throughout the building, the apex of the triangle, where the diagonals meet, faces inward.

The basic truss width (distance between top chords) is five feet. For the wall, trusses were joined together before erection to form a 15-foot-wide wall truss subassembly; roof trusses are somewhat deeper than wall trusses and were not connected into subassemblies before erection. All in all, some 29,000 tube or solid bar sections were used to create 64 truss assemblies for the walls, 50 for the roof. All members of all trusses are painted white.

Why Cast Steel?

The cast steel advantages. Steel castings have many characteristics that offer advantages as compared with other metal-forming processes. For the Crystal Cathedral, the *specific* cast steel advantages were:

- Isotropic strength (equal in any direction)
- Ability to create complex shapes
- Economies of production

The user rewards. For the designer or engineer, the advantages of cast steel translate into specific design benefits. In the Crystal Cathedral, the specific benefits were:

- They allowed the realization of a unique, extraordinarily complicated design.
- Their ability to hold tight tolerances contributed to the remarkable rigidity of the structure.
- The unobtrusive spherical components harmonized with the overall aesthetics of the building.

Within each truss, the diagonals are connected to the panel points through a gusset plate: a flat plate of metal welded to the chord. But gusset plates can accommodate only a limited number of members, and chords can accommodate only a limited number of gusset plates at a panel point. However, where the wall trusses meet the roof trusses, a typical situation is for eight

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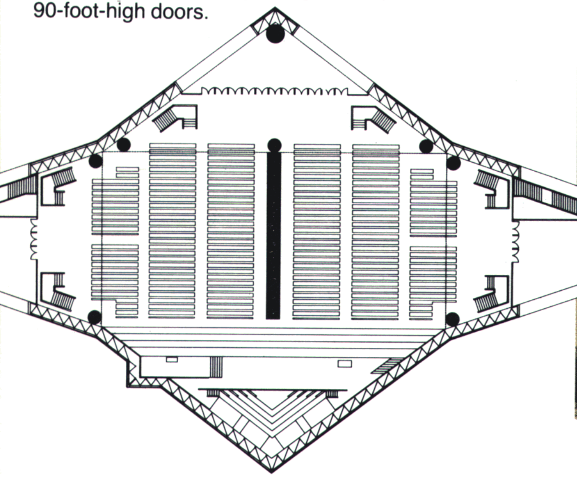
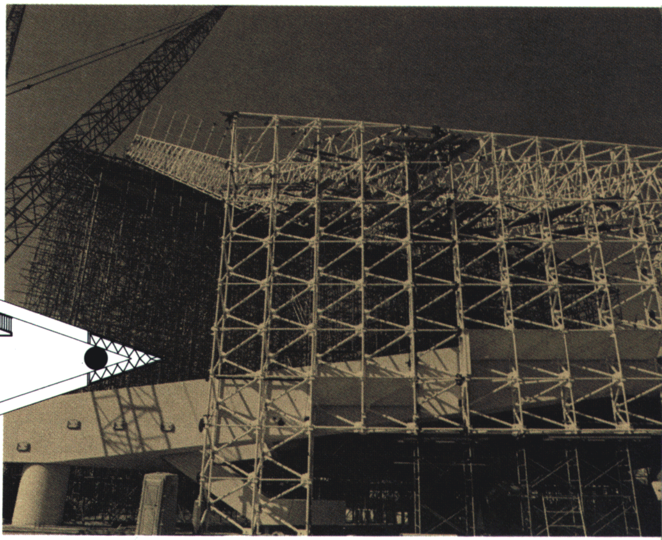
Plan view of cathedral. The chancel occupies bottom triangle; the right-angle "bump" is location of 90-foot-high doors.





During construction, the balconies went up first, and the walls were built around them.

Incorporating the publication **8 PLUS**

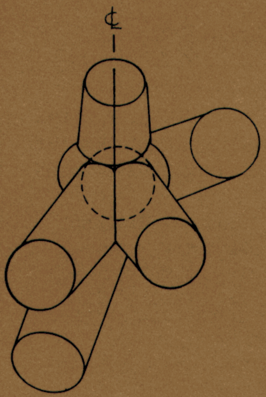
CASTEEL

Spring/1982 **Vol. 16 No. 1**

Cover. In Garden Grove, California, the Crystal Cathedral waits for worshipers. Steel castings support the cathedral roof, which caps a volume of over 3 million cubic feet.

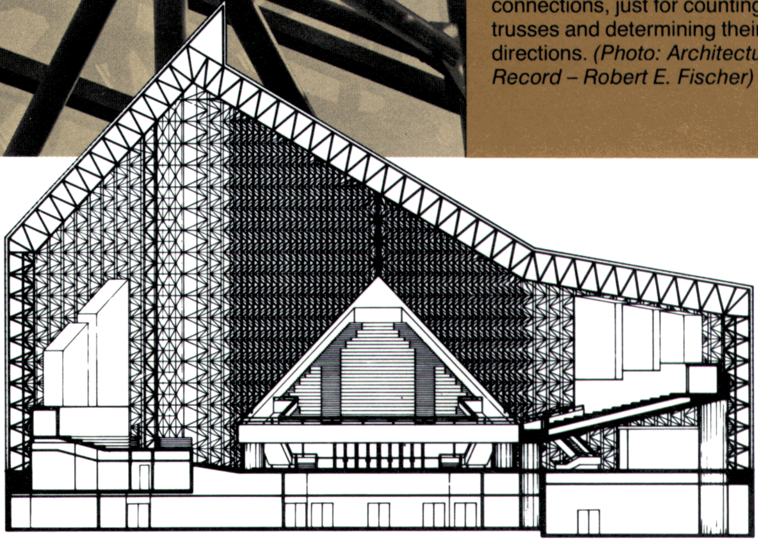
Published by the Steel Founders' Society of America, Cast Metals Federation Building, 455 State Street, Des Plaines, Illinois 60016. Contents prepared by Harold Schor Associates, Inc. 21 E. 40th St., New York, NY 10016. Publication editors will be granted permission to reprint material on request.

A Magazine of
Steel Founders' Society of America



Typical Cast Steel Connector

Eleven tubes and bars converge on this single point – and on the cast steel connector that handles many of them. Even people who lived with the job month after month had a hard time visualizing situations such as this, where several truss assemblies come together. John Muller, project manager for the structural engineers, recalls that he and his associates spent weeks getting used to the overall cathedral shape – and even then they had to create special drawings for the connections, just for counting trusses and determining their directions. *(Photo: Architectural Record – Robert E. Fischer)*



Section through cathedral shows soaring roof line, plus rear balcony and far side balcony. The angled structures at the left represent giant organ pipes.

separate members to converge on a single point from five directions, and this is too many for gusset plates alone. Some supplementary connecting method had to be found.

Two methods were examined. One was to weld a block of metal to the chord, with edges and faces machined away at angles that would mate with the incoming members. But analysis showed this to be cumbersome, expensive, and hard to control. The method selected was the use of a cast steel ball, with projections (termed nibs) emerging from it to meet with the tubes or bars.

Cast steel connectors: economical solution to a tough support problem

The cast steel connector provided many advantages. One was assured strength: the sphere is inherently a strong structural shape, and cast steel is isotropic, or equally strong in all directions. No matter from what direction the load was coming, the cast steel sphere would be able to carry it. Another advantage was economy: no metal-forming process is as economical or efficient as casting for creating complex configurations and geometries. Nor was there any problem maintaining the angles required on the nibs, since the casting process can produce components to the most exacting tolerances.

In its unique way, however, the building threatened to add considerably to the connector cost. Because of the constantly changing roof slope and wall directions, there are very few right angles where truss assemblies meet each other, and there is also no such thing as a "standard" truss. The trusses fall into dozens of different types, and the connectors into still more types. At the beginning of the job it was thought that as many as 60 separate connector configurations would be required, but this turned out to be too low; 18 additional configurations were added later, to accommodate the 90-foot-high doors and the clerestory.

Normally, components are produced from drawings, but to develop 78 separate and complete casting drawings, connector by connector, nib by nib, would have added substantially to the cost. The problem was sidestepped by utilizing another advantage of the casting process: the ability to produce precision components without detailed production drawings. Every casting is made from a pattern, and it is sometimes easier to start with the pattern itself than with a drawing. This was the case with the cathedral connectors: together, the foundry and the engineers developed the required patterns directly. The patterns were checked carefully, and actual casting proceeded with a high degree of confidence.

The cast steel grade used for the connectors was ASTM A148, grade 80-50, a high-strength

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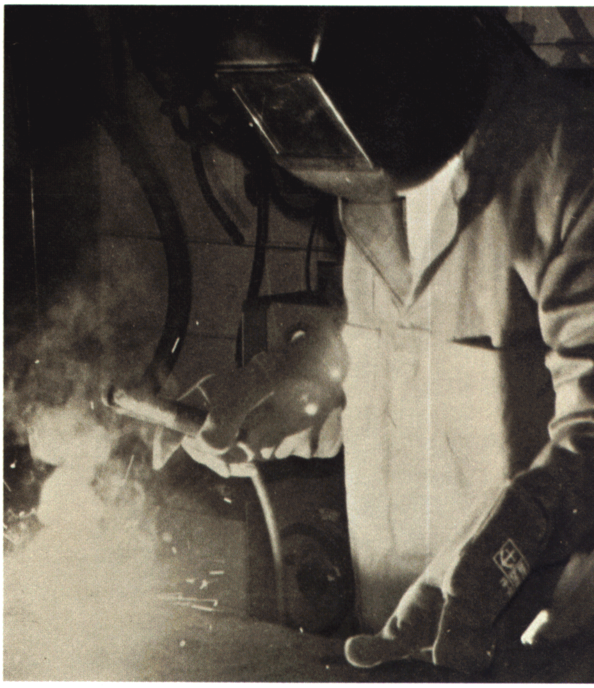
Weldability tests prove cast steel superior to wrought

Steel Founders' research reveals higher underbead cracking resistance.

Welds in cast steel are stronger and less likely to crack than welds in equivalent grades of wrought steel, according to a study recently performed at the University of Tennessee. Funded by the Steel Founders' Society of America, the study proved that cast steels are significantly more resistant to "underbead" cracking than are wrought steels of comparable composition and hardenability. The researchers said that differences in microscopic "inclusions" in cast and wrought steels probably account for the difference in crack resistance.

Underbead cracks pose hidden dangers

Underbead or cold cracking (see Fig 1) can occur in any metal weld. These cracks are especially troublesome because they are not detectable by surface inspection and can only be found using expensive non-destructive tests. The cracks arise after the weld has cooled and need not result from loading; in fact, underbead cracks have formed spontaneously as much as a week after welding has been completed. The cracking mechanism has not yet been fully explained.



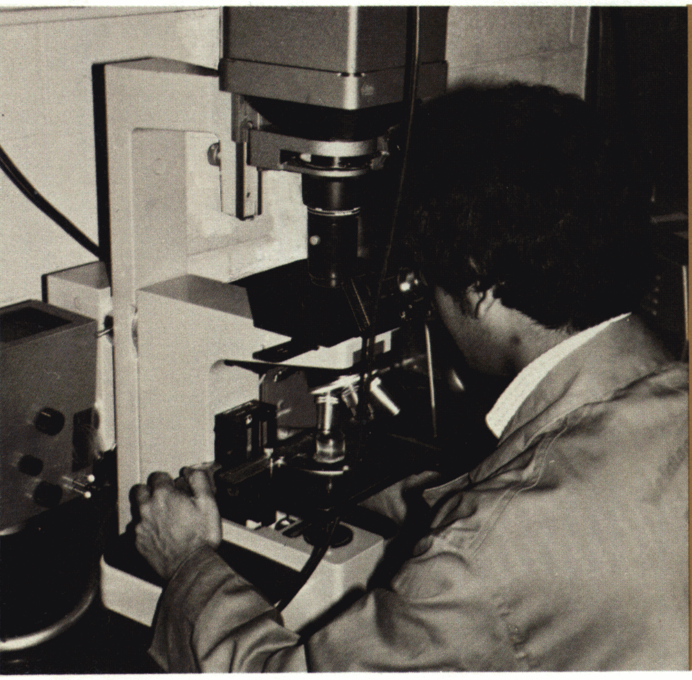
Welding of sample for underbead cracking test

The problem has become more severe as component applications have become more strenuous and as the effects of failure have become more dangerous or expensive. As a result, the need for reliable data on crack resistance, or weldability, has become more pressing. However, no such data existed for cast steels, and weldability data for wrought steels appeared to be questionable. The University of Tennessee program was designed to provide completely reliable data for common grades of cast steel and, where possible, their wrought equivalents.

Cast steel wins in underbead and hydrogen sensitivity tests

The program had three major goals. One was to analyze the effect on crack susceptibility of weld preheating as well as post-weld "holds" — keeping the welding zone at an elevated temperature after welding is completed. The second was to see whether it was possible to predict weldability from hardenability formulas. The third goal was to compare the weldability of cast and wrought steels.

Tests were run on cast and wrought 8630 steel and on eight cast grades of manganese-silicon steel, plus four equivalent wrought grades. Cracking was evaluated using the Battelle underbead cracking test (Fig 2), in which welds are laid down on samples and the sample is sectioned through the weld to expose the cracks. Also performed were hydrogen sensitivity tests, developed at the University of Tennessee, in which samples containing welds are bent until they crack (Fig 3).



Metallurgical examination for cracking

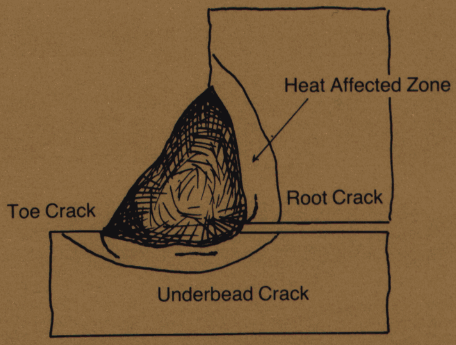


FIG. 1 – UNDERBEAD CRACK

In the test procedure, baseline data were obtained at 32 F. Samples were then preheated to 100 F and the extent of cracking was checked. Grades that did not crack were eliminated; the others were preheated to 200 F and checked again. The process of elimination continued, at increasing preheat temperatures, until the most susceptible grade did not crack. Post-weld hold tests were similar, using temperatures of 100 F and 200 F for periods up to two hours. (These samples had been welded at preheat temperatures of 100 F.)

The results proved conclusively that the cast grades had better crack resistance than their wrought equivalents. Under all preheat and post-weld conditions, higher temperatures were needed to prevent underbead cracking in wrought than in cast steels. For example, in the Battelle tests, preheating at 200 F halted cracking of cast 8630; the comparable temperature for wrought 8630 was 350 F. In the hydrogen sensitivity tests, four cast grades were superior to their wrought equivalents, with the fifth grade being equal. Thus, preheating at 300 F halted cracking of cast 8630, while preheating at 700 F was required for the wrought 8630.

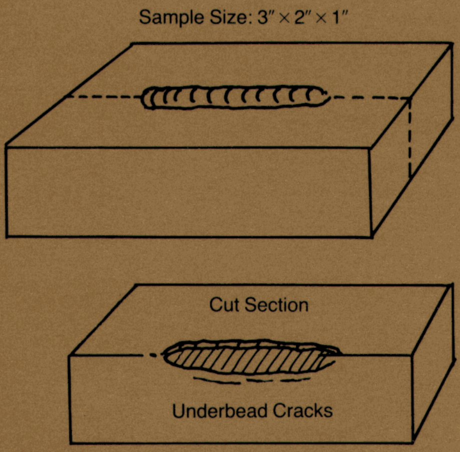


FIG. 2 – BATELLE UNDERBEAD CRACKING TEST

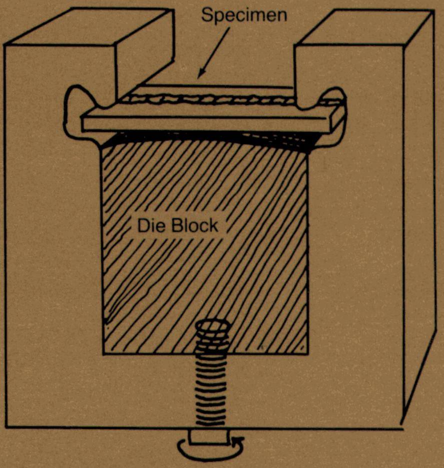


FIG. 3 – HYDROGEN SENSITIVITY TEST SETUP

The cast steel superiority gives the designer two options. First, for a given set of welding conditions he can obtain tougher welds with cast steel than with wrought steel. Or, he can realize significant cost benefits by using lower preheat and/or post-weld temperatures to obtain crack-resistant joints.

More benefits for the designer: weldability prediction

The goal of predicting weldability from hardenability formulas was also achieved. Hardenability is a direct function of the amount of carbon and other elements in the metal; hardenability formulas assign a factor to the constituents and express the result in terms of a "carbon equivalent" content. The study showed that two formulas have good predictive powers: one for Mn-Si steels, the other for 8630. The study also showed a strong correlation between specific hardenability ranges and the specific preheat temperature required to prevent cracking. When the results are complete they will allow the designer to specify, with confidence, the preheat temperatures that will eliminate underbead cracks.

In almost every sample, cracking began at an inclusion — a microscopic non-metallic particle in the steel; and the study turned up substantial evidence that type of inclusion plays a major role in crack resistance. Inclusions in cast steel tend to be spherical; however, when steel is rolled, hammered, or otherwise wrought, the inclusions become elongated, almost needle-shaped. It is at the points of these needles that cracks seem to originate most readily. In contrast, the spherical inclusions of cast steel are much less favorable sites for crack initiation.

This study was conducted by the Welding Research and Engineering group of the University of Tennessee at Knoxville. The Steel Founders' Society of America, for whom the study was performed, has recently authorized a Phase II program to investigate more deeply the causes of underbead cracking and methods of increasing crack resistance.

CRYSTAL CATHEDRAL

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structural steel. Chemical composition is 0.20/0.25 C, 0.05 P (max), and 0.06 S (max). Minimum mechanical characteristics are 80,000 psi tensile strength, 50,000 psi yield strength, 35% reduction of area, and 22% elongation in 2 inches. All connectors were magnetic particle inspected; connectors destined for tension loading were also inspected by radiography. Altogether, 447 steel castings were required, 293 for tension loading and 154 for compression loading.

Building goes up — and stays there

In a sense, the Crystal Cathedral is four separate structures: three balconies and a shell. Each balcony is essentially free-standing, with post-tensioned concrete beams supported on three or four concrete columns. The balconies are connected to the walls in the horizontal direction only: slotted vertical holes allow the balconies and walls to move up and down independently of each other. This has the effect of stiffening the walls laterally without adding to the load on the trusses.

Erection of the structure was the responsibility of the Pittsburgh-Des Moines Corporation (PDM), which also fabricated the truss members. The average chord is three inches in diameter, although chords up to 4½ inches are used. Depending on the loading, some are solid and some are hollow.

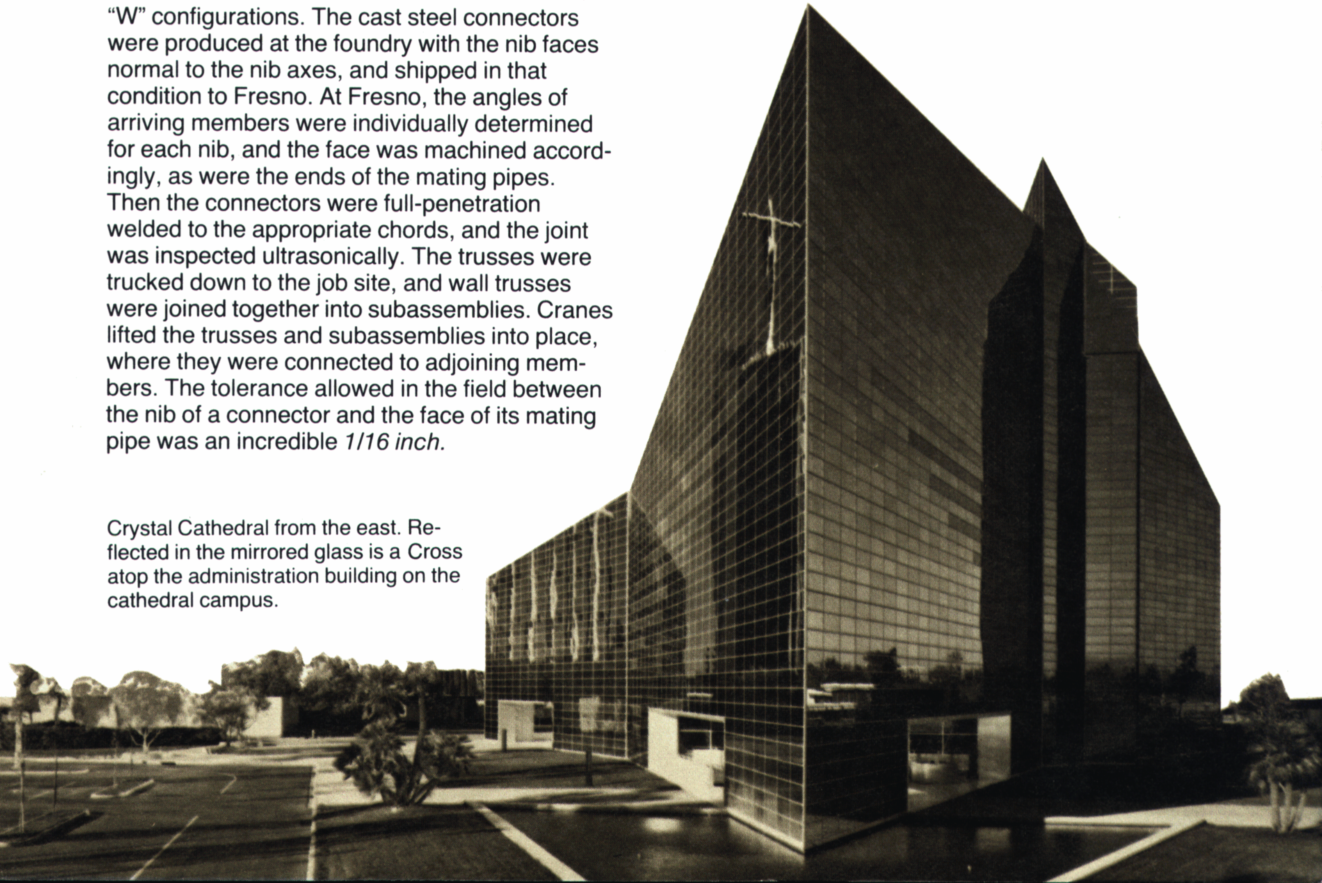
The building was erected on an assembly line basis, except that this assembly line was nearly 250 miles long. Truss elements were produced in Fresno and formed into trusses with "M" and "W" configurations. The cast steel connectors were produced at the foundry with the nib faces normal to the nib axes, and shipped in that condition to Fresno. At Fresno, the angles of arriving members were individually determined for each nib, and the face was machined accordingly, as were the ends of the mating pipes. Then the connectors were full-penetration welded to the appropriate chords, and the joint was inspected ultrasonically. The trusses were trucked down to the job site, and wall trusses were joined together into subassemblies. Cranes lifted the trusses and subassemblies into place, where they were connected to adjoining members. The tolerance allowed in the field between the nib of a connector and the face of its mating pipe was an incredible *1/16 inch.*

How solid is the resultant structure? It had been expected that once the shoring was removed there would be a deflection of 3-4 inches at the center, which is relatively small for the spans involved. In fact, however, a check at the doors and similar locations where problems usually show up revealed no deflection at all: no sag, no distortion, no warping. As far as the erector's instruments indicated, the cathedral was absolutely rigid.

Cathedral features natural cooling

In the Crystal Cathedral, the entire above-ground area is devoted to worship: offices, rehearsal studios, and similar areas are below grade. Only these rooms are air conditioned mechanically; the cathedral proper is cooled by natural ventilation. Over 550 glass panels are mounted on movable frames, motor-operated, and are opened or closed depending on the weather. The system works well except on hot, windless days; however, Dr. Schuller "would rather have it a little warm than consume extra oil just for a little comfort." Heating is available for both above- and below-grade areas.

Glazing consists of an equal number of ¼-inch and ⅜-inch panels, randomly dispersed. The reason is that the use of panels of a single thickness could cause the phenomenon known as "coincidence dip," in which certain musical notes seem to disappear. As it is, the structure has a long reverberation time, which affects the clarity of the choral works but provides the quality and resonance that have for centuries been associated with great cathedrals.



Crystal Cathedral from the east. Reflected in the mirrored glass is a Cross atop the administration building on the cathedral campus.