When most people think of Frei Otto, they think of a structural engineer; but in fact, he is an architect. My first meeting with Otto occurred three years ago, on July 1, 1997, when I visited him at his atelier in the town of Warmbronn. I have had great respect for Otto ever since my first years in college: I will never forget the excitement I felt on my first encounter with his Munich Olympic Stadium and his multipurpose hall in Mannheim, Germany.

So when I needed a German collaborator for the Japan Pavilion at Expo 2000 in Hannover, the first name that occurred to me was Otto, even though I had not seen his work since the 1980s and I did not know if he was still practicing, much less whether he would cooperate on the project. Nevertheless, I sent him a letter with copies of my work and subsequently paid him a visit. Up until the moment we met I was still wondering what sort of cooperation I should ask him for; but he had already arranged to have paper tubes sent to his atelier, and when I arrived he was ready to start work immediately.

The main theme of the Hannover Expo 2000 concerned the environment, following the concept of sustainable development proposed at the 1992 U.N. Conference on Environment and Development in Rio de Janeiro. The Japan External Trade Organization (JETRO), the client and general producer for the Japan Pavilion at the Expo, had approached me with the idea of building the pavilion using paper architecture. The basic concept for the Japan Pavilion was a structure that would produce as little industrial waste as possible when dismantled. As design criteria for the materials and structure, Otto and I decided that it should be possible to recycle or reuse nearly all of the materials.

Otto agreed to cooperate as a consultant in the design of the Japan Pavilion, but we also needed the services of engineering consultants. Otto specified Buro Happold, the English firm founded by Ted Happold, former leader of the special structures group at Ove Arup, which handled the design of the grid shell structure at Otto's multipurpose hall in Mannheim. Although he is not well known in Japan, Happold is the person who brought Richard Rogers together with the young Renzo Piano for the Centre Georges Pompidou. The basic structural element, paper tubes, was developed under the leadership of Wim van de Camp, technical director at Sonoco Europa, who cooperated with me on the development of emergency refugee paper shelters in Africa. The paper tubes developed in Germany were to be more waterproof than those in Africa, and were to be recyclable.

FINDING STRUCTURE AND FORM

The first structural idea was a tunnel arch of paper tubes, similar to my Paper Dome in Gifu, Japan (1997–98). However, when I designed the Paper Dome, I was bothered by the high cost of the wood joints compared to inexpensive paper tubes. With this in mind, I had an idea to take advantage of one of the characteristics of paper tubes—they can be made to any length. I proposed a grid shell without joints to Otto. The tunnel arch would be about 74 meters long, 25 meters wide, and 16 meters high. The most critical factor was lateral strain along the length of the building. To address this factor, I chose a grid shell of three-
Shigeru Ban

dimensional curves instead of a simple arch. The curved shape, formed by indentations along the length and width of the structure, was stronger with respect to lateral strain.

Beginning in August 1997, staff from Buro Happold participated in our monthly meetings and a large model was constructed for every meeting to illustrate the topics discussed at the previous one. Otto’s daughter, an assistant at his atelier, was always present at our meetings. As the main exhibition hall began to take shape, she created models and began formal studies.

To determine the form, we adopted a building method in which straight paper tubes one meter in length would be connected in a grid by rotating joints. The grid would then be elevated, or pushed up, from below to form the grid shell. Since the final formal decision depended on the construction method, it took a long time to program software to output the shape. In the meantime, we used custom-ordered narrow tubes to create a 1:15 scale model of the push-up construction method, to measure the intersections of the paper tubes and create elevations and cross sections.

The site was a block divided into a grid, facing a main street on the short side and an intersecting street on the long side. If the main hall had been placed there, it would not have fit into the urban block. In terms of circulation, the structure required a space leading into the main hall. We decided to surround the main hall on three sides with large stairs and three-meter-high stages, using footing boards on the scaffolding of the structure. Corridors would be formed on the stages by columns of cantilevering 5-meter-long paper tubes, with their foundations weighted down by sandbags. These corridors would serve as waiting areas for visitors about to enter the pavilion, allowing them to experience the variations of light and shadow in the paper-tube columns.

Otto and I had serious disagreements with Buro Happold about the joints between the paper tubes and about how to secure internal and external strength. We wanted to finish the entire structure using methods that were as low-tech as possible, so we argued for simple joints of fabric or metal tape. As the intersection between two paper tubes was pushed up to form the three-dimensional grid, an angle would open and a suitable amount of tension would be applied. Furthermore, since the paper tubes themselves would rotate to form a gentle S-curve, the joint needed to allow for three-dimensional movement. Tape was the appropriate solution.

Otto proposed a fixed timber frame of ladder arches and intersecting rafters that would lend strength to the paper-tube grid shell, allow the roof membrane to be attached, and be used during construction and maintenance. Buro Happold proposed metal joints into which bracing cables would be inserted at diagonal angles to tension the paper-tube grid while allowing the paper tubes to move in three dimensions.

As we developed the paper membrane and honeycomb structure, we also worked on developing the membrane material for the roof. The PVC used in conventional membranes cannot be recycled and gives off dioxins when burned. Therefore, we had to develop a membrane material that could be recycled along with the paper tubes when the pavilion was dismantled. We consulted the research and development
departments at several large paper manufacturers, but were told that it was impossible to develop a paper membrane with the necessary waterproof and fireproof properties. By chance, however, we discovered a waterproof bag used by a courier service. The R&D department at the bag's manufacturer, Oji Seitai Co., told us that such a membrane might be possible. It was the first positive response we had received thus far. We asked Oji to prepare samples and had them tested for strength and usability.

The main hall of the Japan Pavilion was a single-story structure, so the paper tubes and membrane were required to meet Germany's B2-grade fireproof requirements. The paper tubes used in this project cleared the B2 requirements in a single try, without any fire-resistant coating. However, it was not easy to achieve the proper balance between strength, waterproofing, and fireproofing in the paper membranes. After preparing samples and repeating the tests ten times, we finally succeeded in achieving the required strength and performance by using fireproof paper with glass-fiber reinforcement and a laminated fireproof film of polyethylene. For strength, we used a ladder and rafter timber frame with three-meter intervals, to which battens were stapled and the paper membrane affixed with waterproofing tape.

For the two nearly semicircular end walls we used timber arches that clamped to the ends of the paper-tube grid shell, achieving the required planar strength by pulling cables at a 60-degree angle from the foundation, as in a tennis racquet. The foundation did not rely on concrete. Instead, it consisted of boxes made of steel framework and footing boards filled with sand for easy use after dismantling.

STRUCTURAL AND CONSTRUCTION PROBLEMS

Preliminary strength tests of the paper tubes were carried out by Buro Happold at Bath University, with official tests for strength, water resistance, and durability carried out later at Dortmund University in Germany. At our meeting in January 1999, when the tests were proceeding, the basic structural design firmed up, and calculations underway, Buro Happold suddenly pointed out a major structural defect. There was an unexpectedly large amount of creep in the paper tubes, which made it impossible to guarantee an adequate safety ratio for the grid shell. Buro Happold proposed several ideas as countermeasures, but at this point it was impossible to make any major changes to the form or function of the pavilion or any changes that would significantly increase costs. The paper tubes were being tested, so their size could not be changed. Although it detracted from the purity of the paper tube architecture, we decided to combine the grid shell with timber arches. This was achieved by eliminating all of the joints and bracing cables in Buro Happold's original proposal for the grid shell and enlarging the sections of the timber rafters, originally designed as a frame for the membrane and scaffolding for construction work. Structural purity is important, but we were developing a new type of structure using new methods and new materials in a limited time-frame.

CONFRONTATION WITH HANNOVER CITY AUTHORITY

Problems arose one after the other. Over the course of the year, we had consulted repeatedly with our proof engineer in Cologne, Stefan Polonyi, to verify the structural concepts as we proceeded with the design work. In August, however, the Hannover city authority suddenly ordered us to dismiss Polonyi and replace him with a local engineer. As their reason for doing so, the city cited a letter that our local architect had submitted as part of our paperwork, stating that we had obtained Professor Polonyi's "involvement" in the design work. The city objected to the word "involvement," arguing that the proof engineer should be a neutral third party. We proposed a compromise under which Polonyi would work together with the engineer nominated by the city, but this was summarily rejected.
There were essential differences between our original design concept and the concept that emerged under the new engineer. First, since the Japan Pavilion was a temporary structure, we assumed that conditions such as wind load and ground friction coefficients could be alleviated. Now we were obliged to meet the same conditions as those applied to permanent buildings. The paper-tube grid shell, ladders, and rafters were originally designed to be loosely connected and mobile. Now the entire structure was to be rigid. Although we submitted additional test results and calculations, these did not resolve the basic issue. Second, in order to create a structure that was primarily dependent on conventional materials such as wood and steel, we were obliged to enlarge the section of the rafters and add unnecessary steel reinforcement. Although it delayed the construction permit by four months, we submitted the required additional tests and calculations, hoping to avoid additional reinforcement as much as possible. Finally, an incredible restriction was placed on the push-up construction method, limiting it to two centimeters per day instead of the planned twenty centimeters. This made it impossible to meet the May opening schedule. Faced with this final, impossible demand, we made the heartbreaking decision to accept all of the city's requirements.

This was not the end of the story, however. Although the roof and paper membranes had already cleared the fire standard tests, it was widely reported that the Japan Pavilion would be made out of paper. On the pretext that the pavilion might become a target for terrorists, we were required to replace the roof and paper membranes with conventional PVC membranes rated at B1, one grade higher on the fireproof scale. We could not accept abandoning the paper membrane developed especially for this project, so we placed a transparent PVC membrane above the paper membrane. Though we now had a double membrane, the PVC membrane was at least transparent, allowing natural light to filter through the paper.

After all of these compromises, the pavilion began to go up at the end of January. In view of the construction delays and the additional structural reinforcements, the contractor and client decided to abandon the paper-tube corridors around the main hall. Ironically, the city and Expo authorities reacted to this by trying to convince the client that the corridors were important elements of the structure and should be reinstated. They even offered to issue an immediate construction permit for the paper-tube corridors, which were still untouched at that point. In the end, the corridors could not be revived.

AFTERWORD

Although the completed main hall was marked by many compromises from the viewpoint of structural purity, we were proud that it was spatially satisfactory. I was surprised by the city's reluctance to recognize new structures and new materials, and above all by its unwillingness to listen to an authority of Otto's stature and achievements. Nevertheless, I learned a great deal through our collaboration. Without Otto's cooperation, a structural advance such as paper architecture would have been impossible. Otto and I agreed that this project was only the first step in a continuing collaboration, and that we ought to work together in the future. And in fact, we did: our subsequent cooperation was on the design of the Uno Chiyo Memorial Museum projected for the city of Iwakuni, Japan.
Shigeru Ban has used paper, an inherently weak material, in the form of tubes, honeycomb panels, and membranes to construct dozens of structures over the past two decades, from exhibition installations and temporary shelters to monumental pavilions.

Ban challenges the assumed relationship between the strength and sustainability of a material and the corresponding strength and sustainability of a structure. For him, these factors depend on the building technique and on how much one knows about the inherent qualities of the chosen materials.

Ban refers to paper as "evolved wood," implying that wood and paper share certain similarities—the most obvious being that one is the source for the other. Paper's multistep manufacturing process begins with wood pulp saturated in water. Paper tubes, the form of paper most associated with Ban, actually begin with rolls of recycled paper. These are cut into strips, saturated with glue, and wound spirally around a short metal rod that creates the hollow core of the tube. The tube can be made in any diameter, thickness, and length, depending on its use. And used tubes can be recycled, creating an endless reincarnation cycle.

Ban was attracted to paper tubes because they are inexpensive, easily replaceable, low-tech, retain their natural color, and produce virtually no waste. He began using them as a structural material on a modest scale in 1986 for an exhibition on the furniture and glass of Alvar Aalto. Three years later, he used paper tubes again, as display panels and space dividers for an exhibition on the work of architect and designer Emilio Ambasz. The tubes could be disassembled for travel and reduced material waste.

In 1989 Ban also built his first paper-tube structure, Paper Arbor, an outdoor pavilion at the World Design Expo in Nagoya, Japan. At the close of the six-month Expo, the pavilion was dismantled and the strength of the paper tubes tested. Despite harsh weather conditions, the tubes' compressive strength had actually increased as a result of the hardening of the glue and moderate exposure to ultraviolet rays. Paper Arbor was followed in 1990 by two additional temporary structures, the Odawara Pavilion and East Gate. Ban used steel columns to support the roof of the Pavilion, with paper tubes included on the exterior and interior to withstand wind loads.

Ban constructed his first permanent paper-tube structure, Library of a Poet, in 1991; two years later the use of paper tubes was authorized in Japan under the Building Standard law. Over the next few years, no situation proved to be as challenging or appropriate for paper tubes as the temporary houses that Ban built for victims of earthquakes in Japan, Turkey, and India, and the paper shelters built for Rwandan refugees. As Ban explained, "Anyone who participates in the construction of a paper log house in that situation could not find himself spiritually untouched. Moreover, it is different to construct temporary housing with one's own labor as opposed to simply purchasing ready-made accommodations. Even if the paper log houses themselves were pulled down
after several years, they will remain in the minds of the people who built and lived in them.”

These projects involved close collaboration with structural engineer Gengo Matsui, who influenced Ban’s thoughts about tectonics and structure and taught him how materials react under different conditions and tests—for tension, compression, bending, and condensation, among other stresses. Despite years of testing, different combinations of materials often require reevaluation. For example, Ban tested the wood joints that connected the paper tubes when he built his Paper Dome, and they were acceptable. Yet several years later, when designing the Boathouse at the Centre d’Interpretation du Canal de Bourgogne, Ban was able to eliminate the wood joint by using die-cast aluminum joint.

Ban’s largest paper tube structure to date, the Japan Pavilion at Expo 2000 in Hannover, Germany, required similar testing. However, late in the design process the Pavilion team was forced to make changes that resulted in a hybrid structure of wood arches and paper tubes. Although this detracted from the purity of the paper-tube architecture, the work of Ban and his team was extremely groundbreaking. Ban’s experience in Hannover inspired him to construct a pure paper-tube structure for a temporary outdoor installation at The Museum of Modern Art in New York. Whereas in Hannover wooden arches were incorporated to withstand deformation of the cardboard-tube grid shell, Ban substituted cardboard trusses at MoMA. Finally, in the Nemunoki Children’s Art Museum, which utilizes paper honeycomb panels for a lattice roof, Ban made a relatively weak material stronger by interlocking two facing honeycomb panels to form a grid core.

It is the very simplicity and banality of paper that Ban cites in describing the material’s power and beauty. Ban retains the paper tube’s humble character, enhancing its underlying qualities to create a solid structural material. Whether he is transforming tubes into monumental columns or majestic roof structures, he has forever changed our notion of the weakness, durability, and ephemeral nature of paper.

LEFT: Alvar Aalto exhibition, Axis Gallery, Tokyo, Japan, 1986
RIGHT: Paper Arbor, PTS-01, World Design Expo, Nagoya, Aichi, Japan, 1989