Construction Economy Through Systems Building

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The systems buildings concept has been with us for more than 20 years. Eastern Europe and, of course, Russia has spent tens of billions of dollars on systems building. When I say building, I mean it in a general sense; it applies to bridges as well. In the United States, there are more than 200 companies that are becoming involved with systematized and industrialized construction. Systems building is, or could be, the solution to building needs. Many people, and I am among them, believe it is the solution to the problems that face us. I was involved for years in systems construction of housing and other structures and visited many countries that were supposed to be leaders in industrialized construction. Our firm is developing rapid transit systems for the Delaware River Authority through systems components. Nevertheless, we must acknowledge that there is no systems building as yet. There are no systems as we understand them. Actually, to compare what we have today to systems building is like comparing the Saturn Rocket with the Goddard Rocket. However, there is a tremendous activity in the area, and the bridge construction profession has to take a very thorough look at what should be done and what could be done.

I do not dispute the beauty of the bridges of Maillart and Leonhardt in Europe, but they are not systems bridges. We are not criticizing those bridges; however, through a systems type of approach we can build bridges cheaper. Because of my experience and exposure to the problems of rapid transit, industrialized bridges, and industrialized building components, I would like to share with you some thoughts on the problems of bridge construction costs.

Skyrocketing costs of construction demand that traditional construction methods be closely reevaluated for their applicability to present projects. Traditional methods of construction have served us well for many years and have been the mainstay of the construction industry. They are, however, primarily applicable to a set of economic conditions that are rapidly changing in our modern life. Our present and projected economic climate dictates optimization in the economy of construction. Too often engineers are called on to make significant innovations, if not breakthroughs, by using traditional tools and by working under the same set of circumstances that are applicable to conventional, routine designs. Often requirements for innovations occur in a company engaged in a panic program that has unrealistic deadlines. This forces the engineer to rely on handbook approaches. The job gets done, but the opportunity to save millions of dollars in the construction is lost.

What is needed are programs that permit advanced engineering studies at the very preliminary conception of a project idea to ensure that, during the final design phase, all possible cost-cutting innovations can be included. Such preliminary studies to foresee cost-cutting techniques during final design have proved their validity. However, development and realization of cost-cutting techniques require initiative and willingness on the part of both the engineer and the client. It must first be recognized that, because of the spiraling construction cost, drastic cost cutting must be done. This cannot be accomplished by the laborious savings of only construction materials through sophisticated analyses of standard conventional construction components. What is needed is a total design approach that considers the basic requirements of a project and results in an optimized design concept that is the most applicable, both functionally and economically. That is to say, the geometric form of the entire structure and its components should not be predetermined before the needs of the problem are studied. The geometric form and shape should be a result of such study.

Although drastic cost cutting is desirable, it must be done through the process of evolution rather than revolution. One evolutionary process, for example, consists of using a basic concept developed in other industries not related to the bridge industry and adjusting that component to a bridge.

When innovating cost-cutting solutions for construction are developed, the following major items must be emphasized:

1. Reduction in the number of skilled laborers as well as in their man-hours,
2. More efficient use of labor by moving it from the field to the assembly line under cover,
3. Simplicity of design details and construction assemblies,
4. Larger permissible tolerance of error in construction of the bridge, and
5. Determinacy of the design and construction program to ensure accuracy of the initial cost estimate of construction and its correspondence with final construction cost.

What must be flagged first is the word "simplicity." The military preassembled bridges of AVCO are erected kinetically on top of tanks through a series of hinges. Although they are beautiful and sophisticated, they are not simple. They are a piece of machinery. We in the construction industry have to come up with the simplest possible solutions. To design a simple detail, one might have to go through an extremely complex design process. In our firm, we have repeatedly found that the use of advanced design methodology is worthwhile. Unfortunately, too many of us think that simplicity in design means simplicity in thinking and simplicity on the drafting boards. It is just the other way around. Your thinking may be the most complex and and your design equipment may be the most complex, but they must be used, to produce a construction detail that is as simple as possible.

Not only are construction costs very high but also construction needs are great. The combination of construction costs and needs can bankrupt the nation. However, our biggest problem today is that the actual cost of completed construction is much higher than the estimated cost of construction made during design stages, and we cannot even predict how much higher. We think it is possible to achieve a close relation between initial estimated cost and final construction cost. It certainly should be a factor for anyone who considers preassembled bridges.

The skyrocketing cost of labor requires that the engineer and all others involved be attuned to the amount of man-hours required to assemble the components of a designed structure. As the engineer develops the details, he must be sensitive to the numerous hours that can be wasted in constructing complicated connections that require a high degree of precision and watchmaking operations. Innovative concepts must result in designs and construction details that minimize contingencies in preplanning field operations. The basic approach to cost cutting in construction must also consider the proper balance between policy and technology. There is a tendency to think that there is too much technology and that only policy will solve our problems. Within policy I include considerations, such as aesthetics and ecology. Of course policy should always be given due importance in any project. In modern society, however, technology always affects policy, and de-emphasis on technology could lead to misguided policy decisions. Therefore, we must maintain a proper respect for both the development and the application of technology to ensure that the adopted policy consists of all the tools available to effect maximum economy in construction. Any type of construction is a result of a compromise of many parameters. We sometimes find we have cornered ourselves because we emphasized one parameter more than the others.

We can develop innovative structural systems that will lead to economical construction by using the following available tools:

1. Modern methodology and analyses;
2. Lighter and more versatile materials;
3. Geometry of structural components and systems to obtain strength resistance;
4. Interdisciplinary approach to the design and solution of problems;
5. Industrialization (this, of course, was the prime purpose of this conference);
6. Extrapolation of proven concepts (for example, those in the aerospace industry) to innovations in construction designs; and
7. Modern fabrication and erection techniques.

I think that the bridge industry particularly should be more aware of and more flexible in accepting the experience of those in other fields of technology. We will not be able to lift ourselves by our own boot straps; we cannot improve by inbreeding. We have to learn from others and possibly involve other disciplines in the bridge construction industry. Some of these statements sound like cliches; nevertheless, they are worth consideration.

I think that we can make better use of available materials and tools than we have. It is the use of these tools in proper combination that is important. Someone has already stated that using modern analysis techniques on conventional structural components for the sole purpose of reducing material and weight will not result in significant cost cutting. Why should we not be building bridges at 20 percent of today's cost instead of reducing costs by 5 or 10 percent? The use of modern analyses and techniques on a new design concept that capitalizes on the efficient use of both the geometry and the lighter and more versatile materials can lead to drastic cost cutting. The new materials could be plastics, improved concrete, light-gauge steel, or any combination of these materials. As I said before, our purpose is evolution, a step-by-step progress. The engineering profession must recognize its role as one component of the entire scientific community and as one of the various talents required during design development. Input from other disciplines involved in a project must be considered to ensure an overall applicable solution.

I would like to discuss some specific projects involving preassembled construction. Both the projects and their engineering solutions are varied. Familiarity with varied projects can help solve some of the problems in systems bridges. I do not mean that we must apply the construction details to bridges but that, by knowing what has been done on structures other than bridges, we may more easily find solutions for problems related to preassembled bridges.

In the Delaware River Port Authority program, there have been about 66 systems developed. Most of them consist of components for uses such as subway linings, viaducts, bridges, stations, retaining walls, cuts, overpasses, and other related rapid transit structures. The systems components developed for the Delaware River Port Authority have the following characteristics, which I think should also be the key characteristics for preassembled bridges: ease of construction of connections, minimum amount of field labor, and savings in construction time. Most of the components are mass produced under a roof by traditional production techniques. Another important feature of the components is their interchangeability. For example, a retaining wall component serves also as an overpass component. Numerous elements may be nested during shipping, reducing site delivery cost. The universal use of these elements for various rapid transit facilities reduces the construction operation to repetitive operations and results in speed and economy. In most cases, the structural material for the component is concrete, except that the weight is less than it would be were components of traditional form. One of the reasons for this lighter weight is structural geometry. Concrete, however, is not the only material used in this program. A combination of concrete and light-gauge metal or plastic has proved to have great merit. Retaining wall and viaduct structures could be built out of the same components.

The figures discussed below show some preassembled structures that are being used today both in this country and in Europe.

Figure 1 shows a conoid element that is used for overpasses and retaining walls.

Fill embankments are quite expensive with today's labor cost; they are a carry-over from the past when labor costs were lower. Figure 2 shows an attempt to replace all embankments with open-latticed structures. This structure is not a viaduct; it has functions entirely different from a viaduct. Elements are interchangeable. The railroad station and the structure that replaces the fill consist of the same elements. An important feature is that the structural elements are telescopic, giving the contractor an opportunity to use identical elements irrespective of the ground elevation. Telescoping is accomplished through the serrated detail.

Figure 3 shows a preassembled viaduct truss. The Bailey bridge has served well, but its trouble is a lack of homogeneity and the indeterminacy of deflections. The particular truss shown in Figure 3 consists of modular portions of truss components where shear resistance is supplied through post-tensioning in the field. In this manner one does get a homogeneous continuous structure that can be analyzed as if it were monolithic, and its behavior can be predicted.

Figure 4 shows an attempt to have a continuous prestressed viaduct that consists of individual pretensioned units. It has a vertical stem connection rather than a conventional top and bottom flange connection. We find that this is a much more economical type of connection, and it permits that previously mentioned margin of error to the contractor.

Figure 5 shows what we call a super-perlin. It is one-half of a complete structural unit with 2 legs and only half a flange. This way it becomes very versatile for use in many applications. Figure 6, for example, shows it being used for a subway station.

Figure 7 shows some more studies for replacing fills in embankments. Consideration of the impact and rolling effect of trains is of prime importance. Because there is quite a bit of information avialable on the behavior and response of structures, it is possible to design preassembled systems for impact loads.

Figure 8 shows a stretched membrane to be used in railroad stations. Railroad stations built by the use of conventional techniques are costly. Actually, railroad stations do not have to be heavy; they could be light, preassembled, brought to the site, and erected rapidly.

Figure 9 shows a system for preassembled floating units to support a STOL airport on water; stability is provided through buoyancy. The idea is for the preassembled units to be brought to the site and anchored into the water bed.

Figure 10 shows the availability of a wide range of materials today. The top line shows a material that has a strength of 3 million psi with modulus of elasticity of 100 million psi. In other words, this material is 100 times stronger than steel but has only 3 times its modulus of elasticity. Obviously, high-strength materials have tremendous advantages and are being more frequently used. However, because the modulus of elasticity is relatively low, structures built with such materials will be too flexible for practical use. We must, therefore, devise different forms for structures; namely, let geometry of structure, rather than quantity of material, resist deformations.

Figures 11 and 12 show the versatility available in the space industry. A mat used for helicopter landing is also used to cover shelters. Skin or membrane structures have tremendous advantages because of their geometry. This hyperbolic paraboloid could be built out of identical strips that in turn could be mass produced and assembled in the field by unskilled labor.

Figures 13, 14, and 15 show the American Airlines hangars in San Francisco and Los Angeles. They were erected on the ground and lifted up and thereby saved about 60 percent of weight, saved time in construction, and enhanced the aesthetics. Skin structures can be built out of almost any material: aluminum, steel, or thin concrete. The hangars in San Francisco and Los Angeles can stand 15 percent error in welds.

Figure 1.

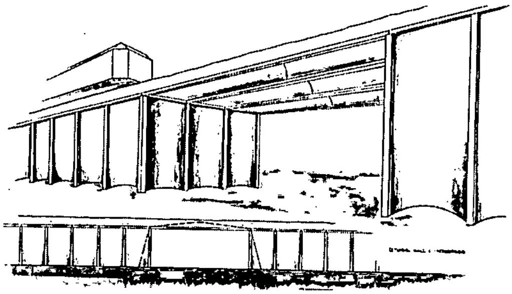


Figure 2.

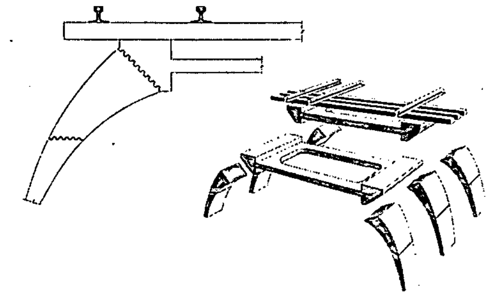


Figure 3.

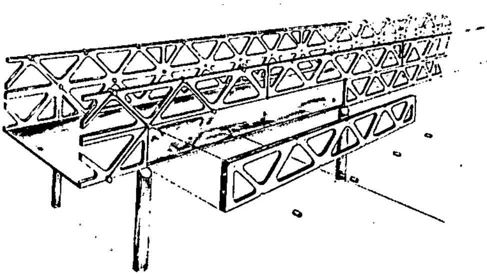
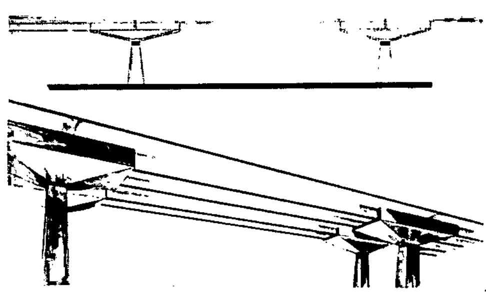


Figure 4.



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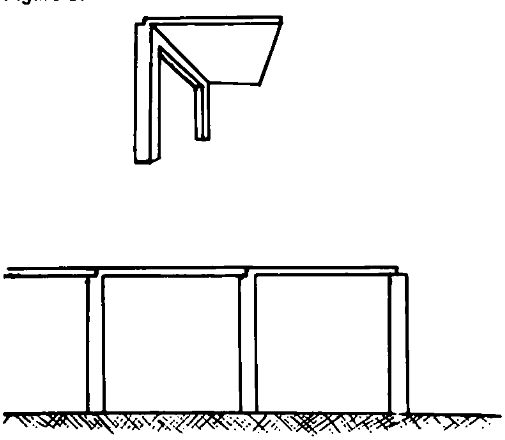

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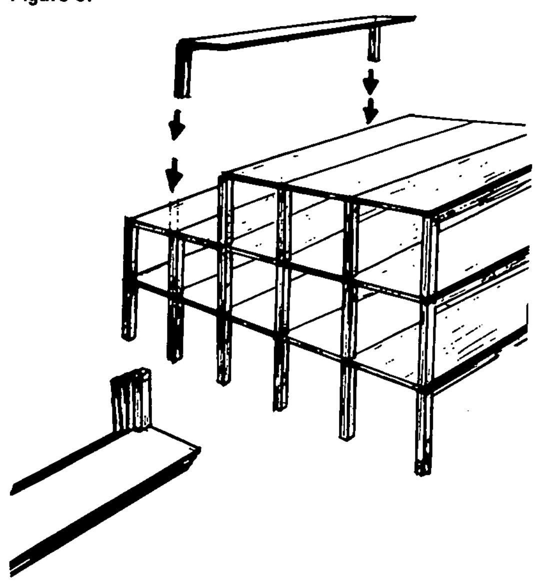

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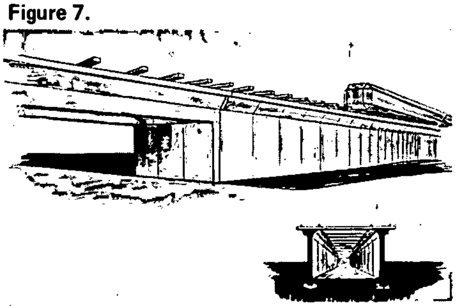

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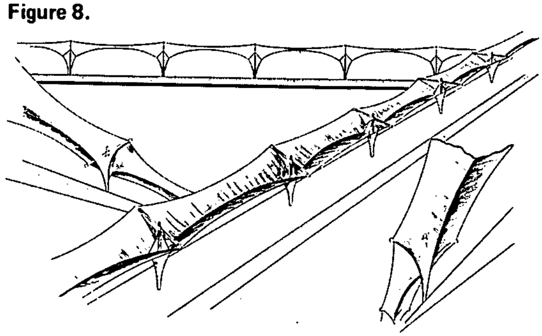

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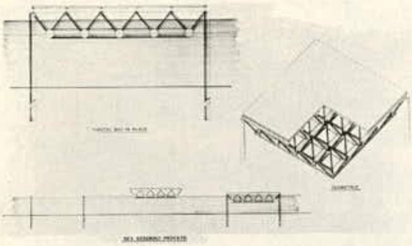
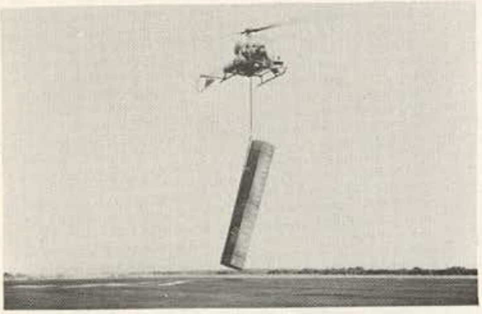


Figure 10.

MATERIAL	TENSILE STRENGTH, X10^6 psi	MODULUS OF ELASTICITY, X10^6 psi
Graphite whiskers	3.0-3.5	98
Silicon carbide whiskers	3.0	100
Alumina whiskers	2.2	76
Iron whiskers	1.9	28
Silica fibers	1.0-3.0	10
Carbon steel wire	0.6	30
Boron filaments	0.5	55
Stainless steel wire	0.5	29
Tungsten wire	0.4	50
Beryllium wire	0.2	45

Figure 11.



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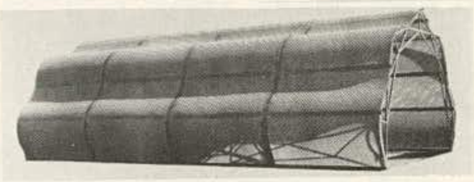
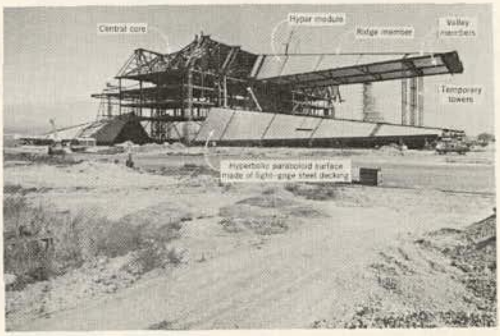


Figure 13.

Figure 14.



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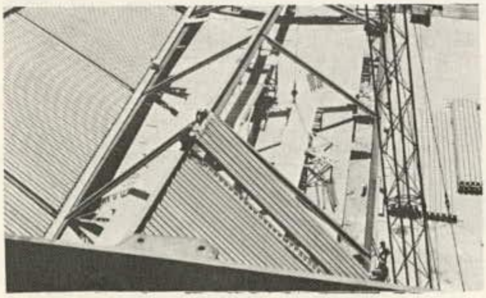


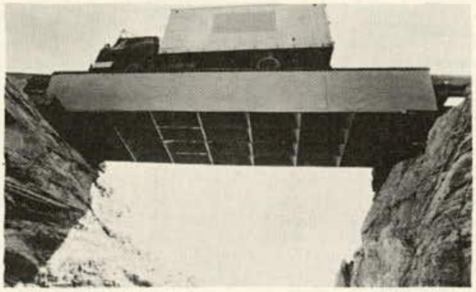
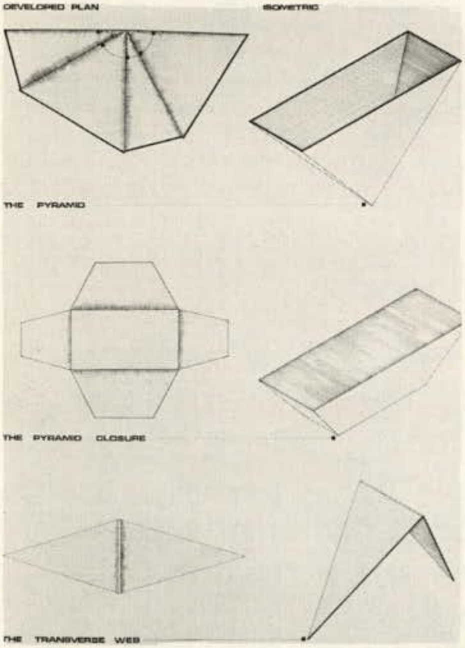


Figure 16.

Figure 17.



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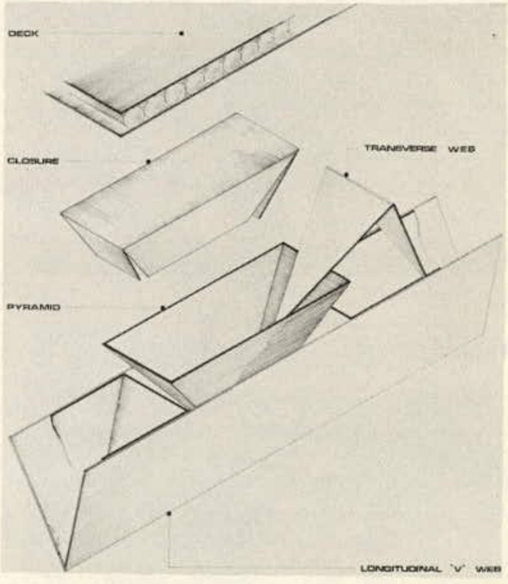

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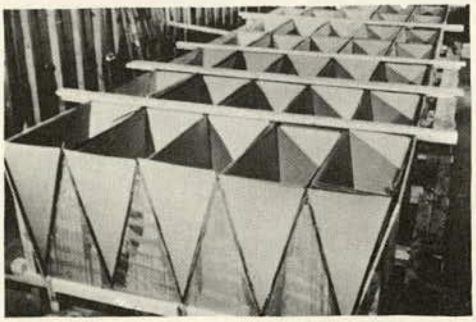
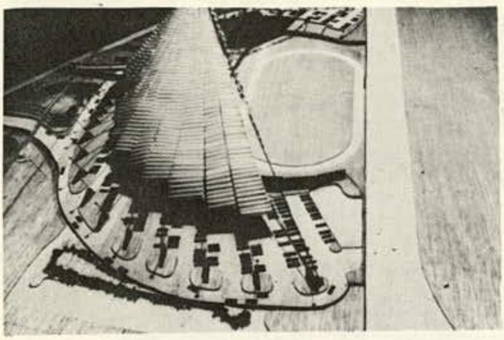


Figure 20.

Figure 21.

Figure 22.



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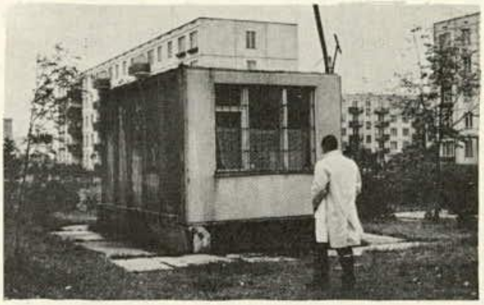


Figure 24.

Figure 25.

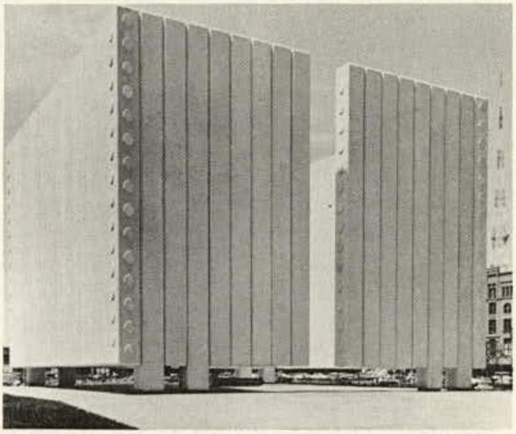
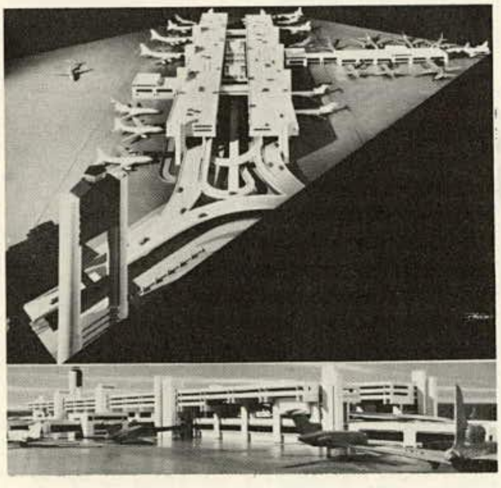


Figure 26.



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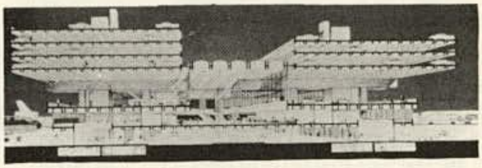
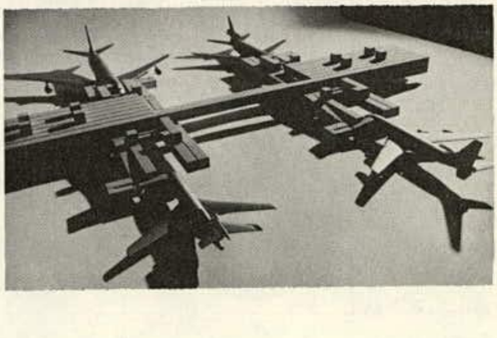


Figure 28.



The reason is that the strength of the welds in a given area depends on the "statistical" average strength of hundreds of welds rather than on an individual weld. In conventional trusses and structures today, theoretically if one of the connections fails, the whole structure collapses.

Figures 16 through 20 show a bridge constructed out of paper. A bridge constructed out of paper with the conventional slab and beam approach would weigh as much as concrete. In this case, however, a "molecular" approach was used, i.e., geometry of each molecule (a 4-ft hollow pyramid), its skin resistance, and statistical average strength. The weight of the bridge was reduced to 20 percent of that of concrete, and dead load was only a fraction of live load. Paper as a material is just an example. One could use the same approach with many other materials. The bridge was transported by helicopter and dropped into place. One can see the egg-crate appearance underneath and, instead of welding, glue was applied to the surfaces. Notice the deck of the bridge, which is hollow and is built out of paper tubes.

In my opinion, we do not correlate building concepts to foundation conditions. I believe that we have to adjust the shape of structures to the foundations in the same way that we have to adjust the shape of our structures to the materials and labor. For example, maybe we should permit a building or a bridge to sag or permit larger settlements in the foundations. In such cases, the concepts of the buildings should be such that the buildings can accommodate themselves to distortions without affecting their functions. Successful solutions in this direction have been achieved.

Figure 21 shows a preassembled stadium. It has an 800-ft span and consists of identical hyperbolic paraboloid units, which are connected together creating a lightweight steel shell. Figure 22 shows a preassembled stadium for Saudi Arabia; it consists of cables and inflated tubes manufactured in the United States. The cables are wound on reels and all components are packed tightly and shipped for erection by relatively unskilled labor. Figures 23 and 24 show an example of systems buildings in Russia. The boxes are stacked one on top of the other. A typical feature of a systems building is that every component has many inserts so that the component is integrated into the whole building rather than serving only a structural function. Figure 25 shows the Kennedy Memorial in Dallas. Its main structural feature is that it consists of identical elements. Vertical elements are put together and post-tensioned to create the interesting shape of the Memorial, which is eccentric.

In the United States we are in urgent search for systems, be they for buildings or bridges. We have tried to import European systems buildings. I think that one has to evaluate whether we should be importing European systems at all. What is right for us? I think that, even though we may not produce systems overnight, we will gradually develop them, step by step, as each step becomes profitable.

Today in the United States, when we use precast concrete structures, we try to integrate functions instead of building the way we used to build—which is like an onion-peel structure, i.e., a frame covered with insulation and then with something else. We are trying today to integrate the structure, the mechanical features, and the finish, all in one mass-produced unit. Integrated modular components, i.e., building components that serve simultaneously structural, architectural, and mechanical functions and are repetitive could contribute vastly to cost cutting.

Figures 26 and 27 show a 90 million dollar terminal in Boston, with attached roads, bridges, and overpasses, and a parking garage for 3,000 cars on top of the terminal. Compare this project with a possible future project of a novel geometric concept, shown in Figure 28, that utilized modern technology, both in material and manufacturing techniques. The concept consists of extruded pipes of synthetic materials. People move within tubes. A passenger has the feeling that he is getting into an airplane without going through a large open terminal. The estimated cost of this terminal is $7 million, as compared to $90 million.

This is the reason why I am optimistic about the future and why I think we will be able to cut construction costs drastically. The Delaware River Port Authority study has shown, as have other studies, that drastic cost-cutting techniques are possible. To achieve this advantage will require that every field of technology be utilized. As new techniques are applied, the change in construction methods should be gradual and evolutionary.