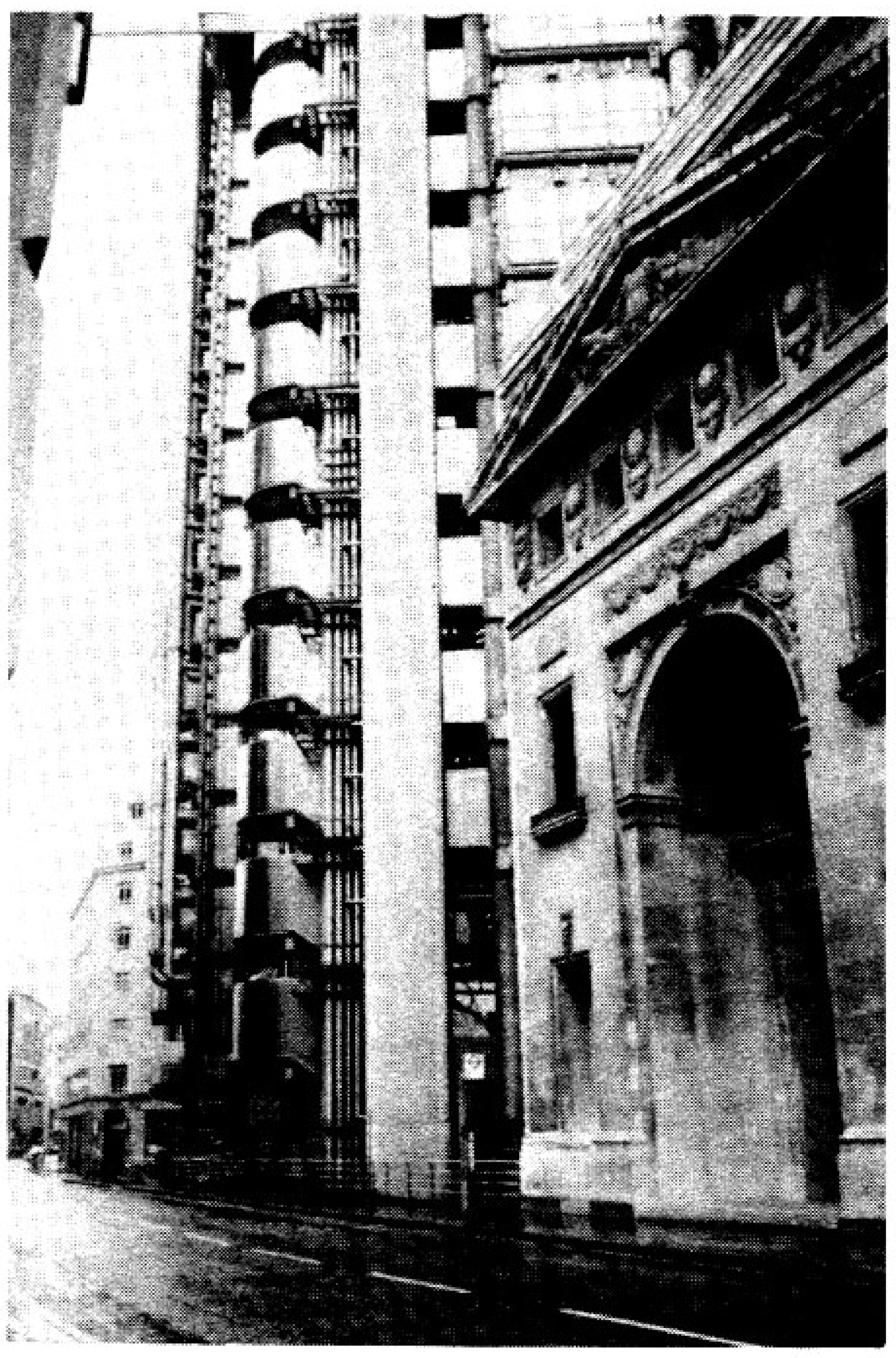
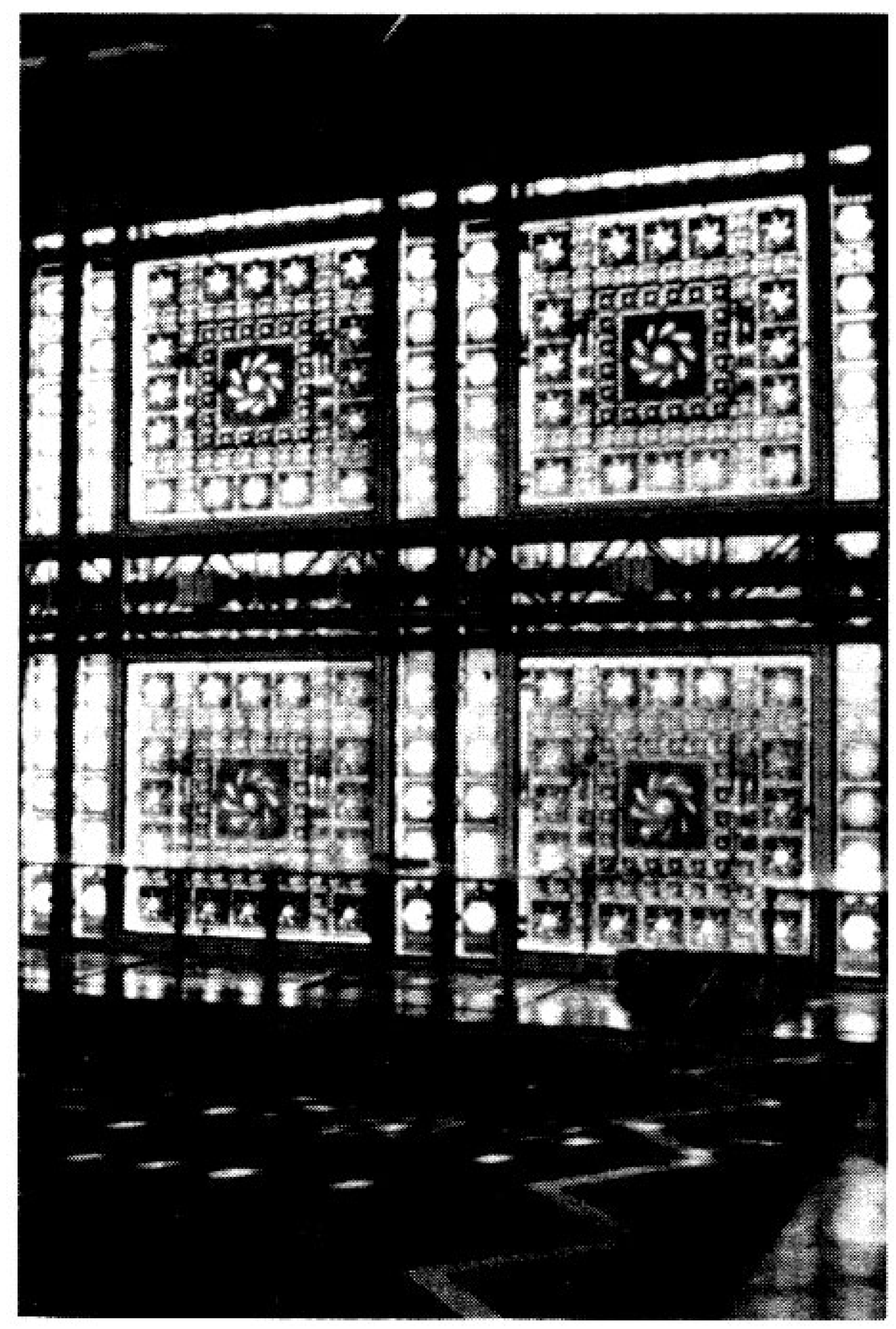
Design and Technological Innovation for the Environment





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Feasibility of Shells Made with Recycled Tires

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INTRODUCTION

It is estimated that over 100 million cubic feet of waste tires are generated in the US each year. The round hollow shape of tires prevents them from being densely packed. Their rubbery resilience prevents them from being crushed and compacted. As a result, used tires are not easily accommodated at landfill sites. Tires are made to be tough. High strength steel wire belts are impregnated with a durable synthetic rubber. The result is near indestructible. Because the synthetic rubber is thermosetting, tires cannot be melted down and reformed. Because of the high strength steel reinforcing, they are very difficult to chop or shred. Any attempt to breakdown a tire is costly in terms of energy expended in the process.

On the other hand, many building materials which have been used with no reservation in the past are now rising in price as the supply is stretched by demand. Expendable uses of wood for temporary shoring and formwork now has to be questioned in light of limited availability. It is no longer economic to expend wood in the process of forming a less expensive material like concrete. Building systems must be found that are erectable with minimal impact on the environment. These will be systems that do not drain choice resources as expendables.

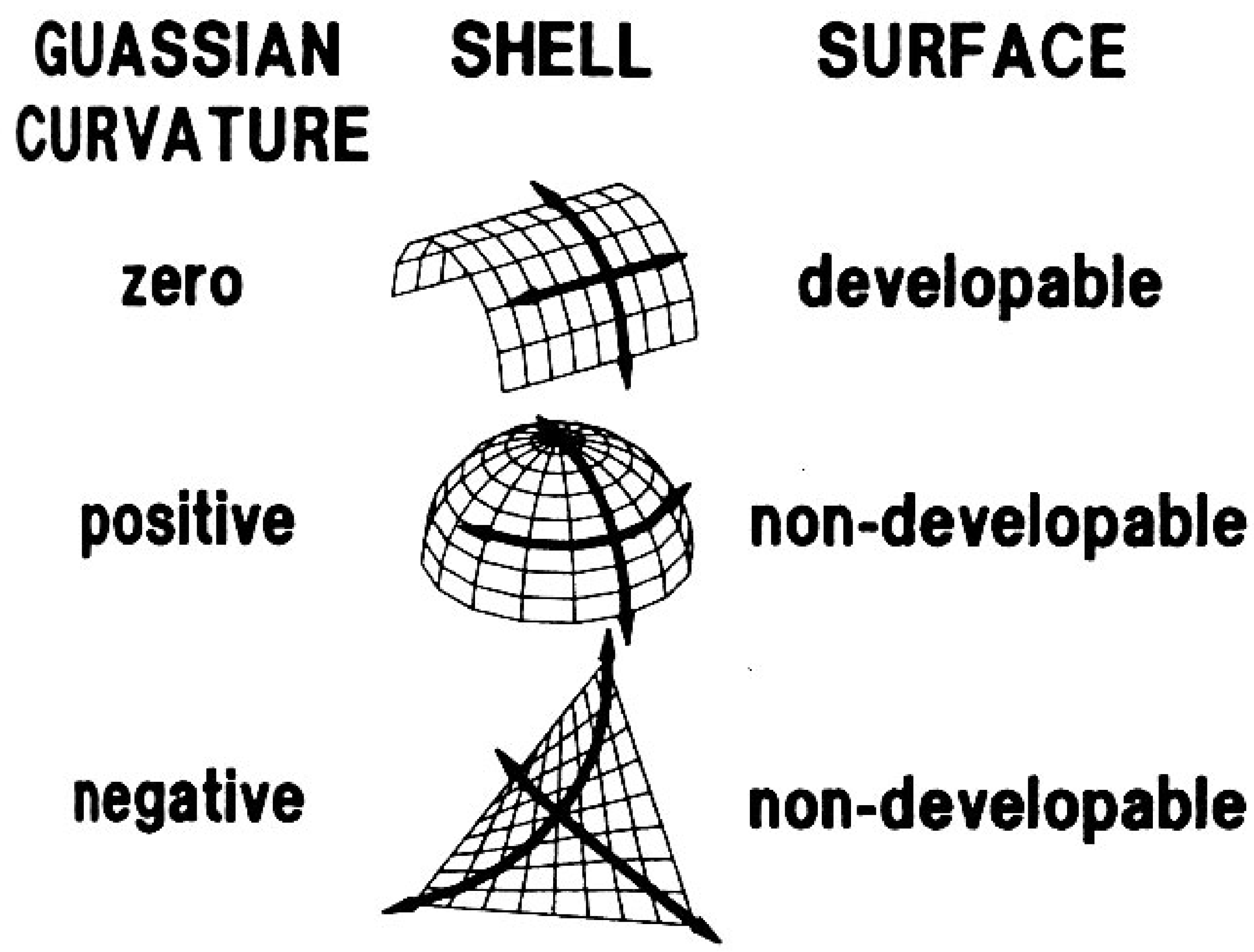
This work represents an initial feasibility study of new methods of construction using tires and concrete as a composite shell. If successful, an environmental burden could be used in place of a limited environmental resource. In this way the resource can be conserved and the burden can be made useful.

CLASSIFICATION OF COMPOSITE SYSTEMS

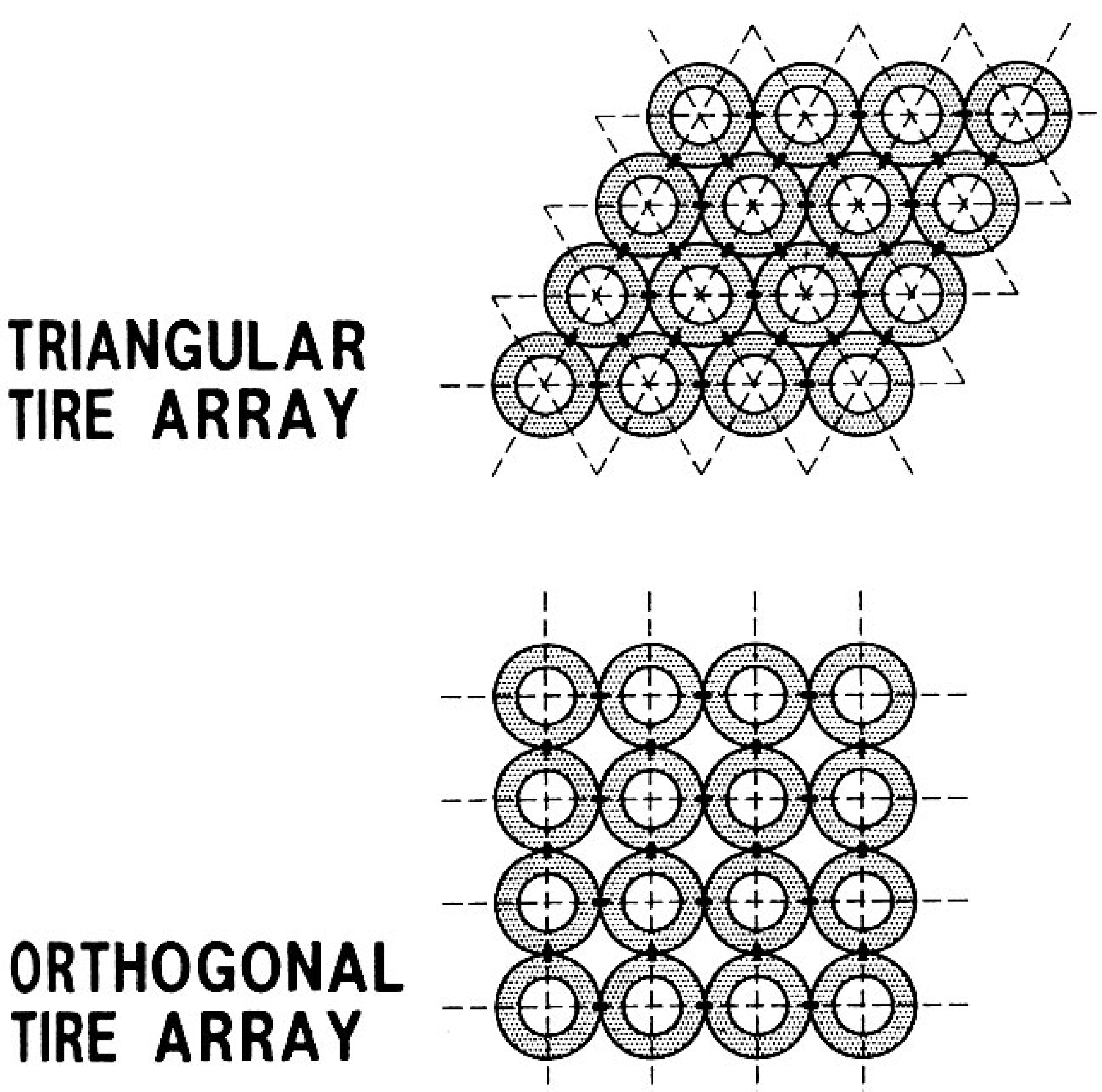
SHELL GEOMETRY. Shell structures are systems that resist loads by the geometry of the surface. In order to resist applied loads efficiently the surface needs a certain amount of curvature. In membrane theory (applicable to thin shell structures) the amount of stress in the shell due to a given load is inversely proportional to the curvature. In other words, the smaller the radius of curvature the smaller the stress in the surface. Of course, the trade-off here is that the smaller the radius of curvature, the less distance is spanned for the material used. Therefore, sufficient curvature is needed structurally, but too much will decrease the effectiveness of the shell as an architectural element. To further define a curved surface more than just the radius of curvature is needed. Gaussian surface classification is used to describe the type of curvature - zero for single, simple curvature, positive for double, complex curvature in the same direction, and negative for double, complex curvature in opposing directions. Figure 1. illustrates these surfaces.

TIRE ARRAYS. Since the object is to develop a shell structure, only tire arrays with tires oriented flat-wise are considered. The two arrays examined, triangular and orthogonal, are shown in Figure 2. The triangular array is more densely packed. Therefore, it would use more tires per area covered, and would be heavier. In the triangular array each tire connects with six others. In the orthogonal array each tire only connects with four others. There would, therefore, be less connectors in the orthogonal array. Also, it appears that the triangular surface is more ridged (higher shear modulus). Finally, the edge conditions are at 60 degrees on the triangular array, and 90 degrees on the orthogonal array.

CONNECTION DETAILS. In detailing the tire to tire connection it is necessary to determine what type of force the connections will transmit. If the tire array is to be a self supporting shell prior to the application of concrete then the connection would have to transmit compression, shear, flexure, and in some cases tension. If, on the other hand, the tire array is hung as a tensile net until after the application of the concrete, then the connection would only need to transmit tension. Figure 3. shows one connection which transmits tension, and four other connections which can transmit some degree of flexure. Connection A is a single 3/8 inch bolt used to simply link the tires at the point of contact. Due to the lack of rigidity of the open "C" cross section of the tire, a hinge quickly forms at the connection and limits stiffness. In connection B two bolts were used spaced at 4 inches apart to increase the flexural moment arm of the connection. In this

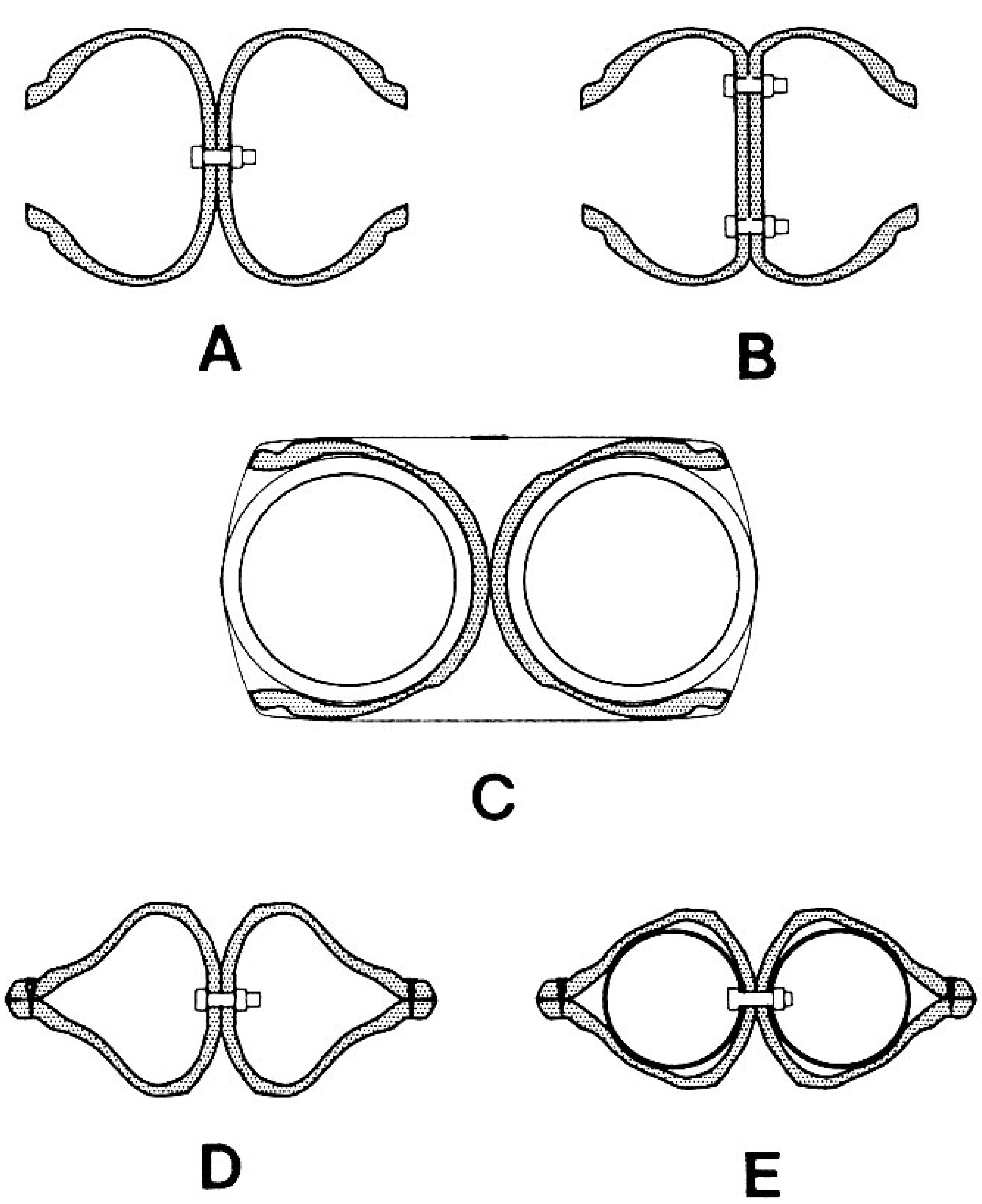


1. Categories of overall shell geometry.



2. Tire arrays.

case as well, the tire itself collapsed at the connection and would not transmit much flexure. Connection C uses a 6 inch long by 6 inch diameter ridged pipe inserted inside both tires at the contact points to prevent the tires from collapsing. This insert was held in place by banding. It provided a stiffer connection but would involve significant additional expense. Connection D attaches the center beads from each side together, changing the unstable "C" cross section of the tire to a closed stable triangle. This provided more stiffness without adding extra parts to the connection. Finally, connection E combined the idea of an stiffening insert with the closed bead approach of connection D. Since the bead is closed a smaller 4 inch diameter insert, which is less expensive, is used.



3. Five connection details investigated.

MATERIAL PROPERTIES OF TIRES

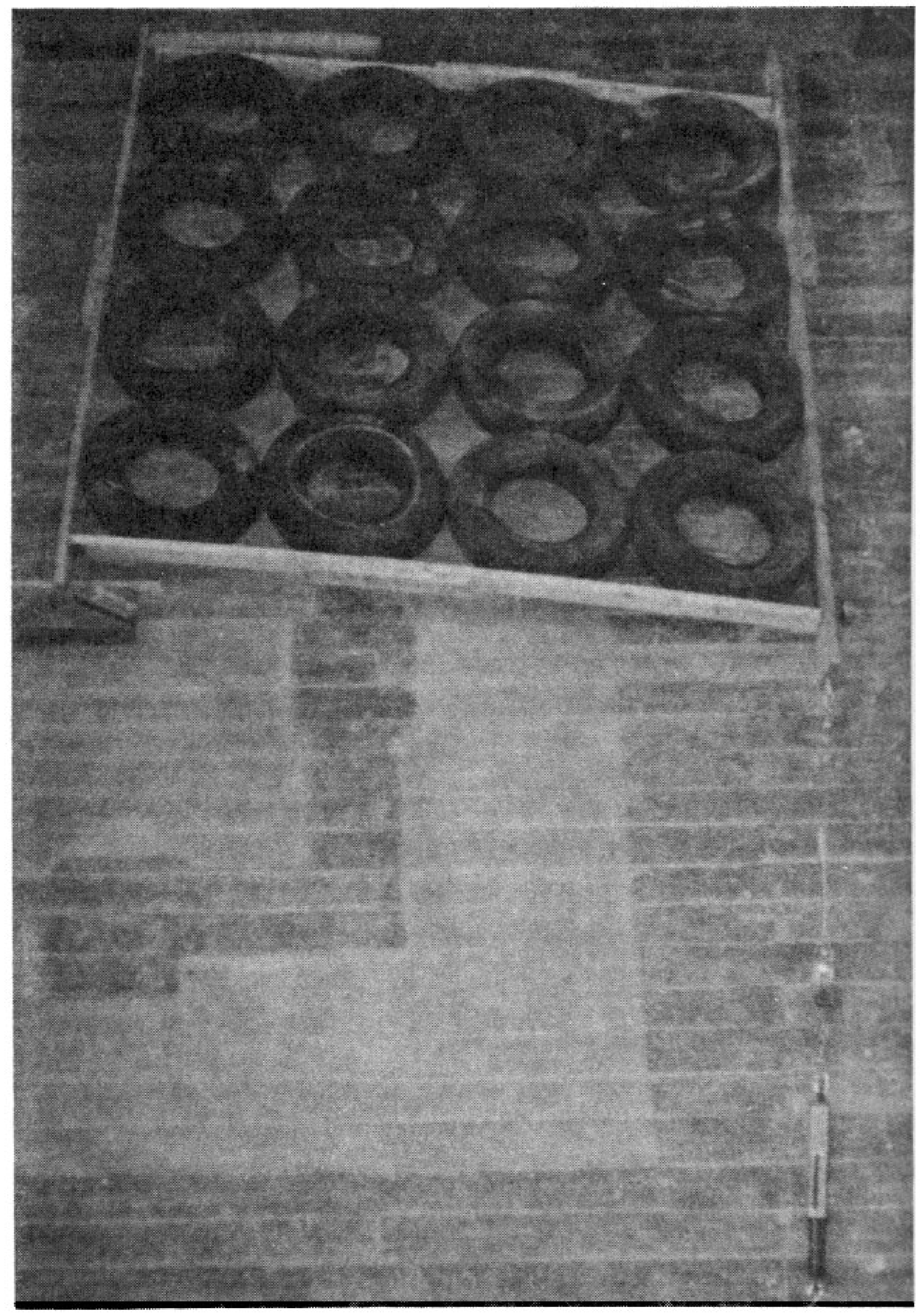
To determine the suitability of tires in forming different shell surfaces, specific information is needed concerning the behavior of tires and surfaces made from tires. In as mush as tires are designed and analyzed for an entirely different application (as pneumatic elements used individually, etc.) there is no information available on how they would behave when connected to form a surface. Even the array and method of connecting tires will effect how they perform as a system. Therefore, to get information regarding the behavior and stiffness of the system it is necessary to test the system in as complete a form as possible to the final design.

Two measures of behavior that would be particularly useful in analyzing the system are a shear modulus and a flexure modulus. The shear modulus gives a gauge of the in plane (in the surface) stiffness, while the flexure modulus gives a gauge of the out of plane stiffness. Beyond these measurable quantities it is helpful in getting a "feel" for the material to work through some basic tests.

SHEAR MODULUS. It was decided to arrange the tires flatwise to best cover surface area and orthogonally to allow more flexibility in achieving non-developable shapes. The non-developable surfaces discussed above (non-zero Gaussian curvature) can be obtained from a flat surface if sufficient angular rotation is possible in the plane of the surface. What happens is that the material distorts enough to push and stretch into the new shape. The flat orthogonal pattern can more easily accommodate this initial distortion than a geometrically more ridged triangular pattern. With this approach, once the final shape is attained further distortion (or un-distortion) must be prevented. This would be accomplished by actually casting the shell inside (and/or around) the tires.

In this test a four foot by four foot square test panel was made by attaching the tires by single 3/8 inch bolts at points of contact as shown in Figure 6. The test panel was intended to represent a typical square from a larger surface. For the sake of consistency all the same size tires were used (195/75R14). To model the restraint that would be provided by the surrounding tires, boards were attached to the edges and hinges placed at each corner. The frame was then loaded on one edge and restrained on the opposite edge. Load was applied in 50 pound increments up to 500 pounds with a winch. Each incremental load was measured with a spring gauge and the deformation was measured with a ruler. Using the equation G=tau/gamma for the shear modulus, a value of about 7.0 PSI was found. This value may at first seem very low, but it should be realized that most of the element is air. The area taken for the stress is the full 7 inch depth of the tires times the 100 inch length of the square panel.

Another useful datum that was observed in this test was the maximum angular distortion for the tire system. Figure 4. shows the test panel at 5 degrees rack. At this point the individual tires are beginning to deform out of plane. For this reason 5 degrees was taken as a working maximum that the tires could be subjected to in forming a non-developable surface from a flat pattern.



4. Shear modulus test at 5 degree rack.

FLEXURE MODULUS. At this time the testing necessary to determine a flexure modulus has not been completed. However, initial tests were performed while working with the different connection details. Using each connection design, free standing arches were attempted. It was quickly realized that, even when using a catenary shaped arch, the connections required some degree of flexural rigidity. Tires are fairly heavy and not very ridged, which makes for a rather problematic compression structure. With stiffer connections, as show by C, D, or E in Figure 2, an arch could be made to stand. Even with the stiffer connections temporary shoring would certainly be needed until the concrete was in place.

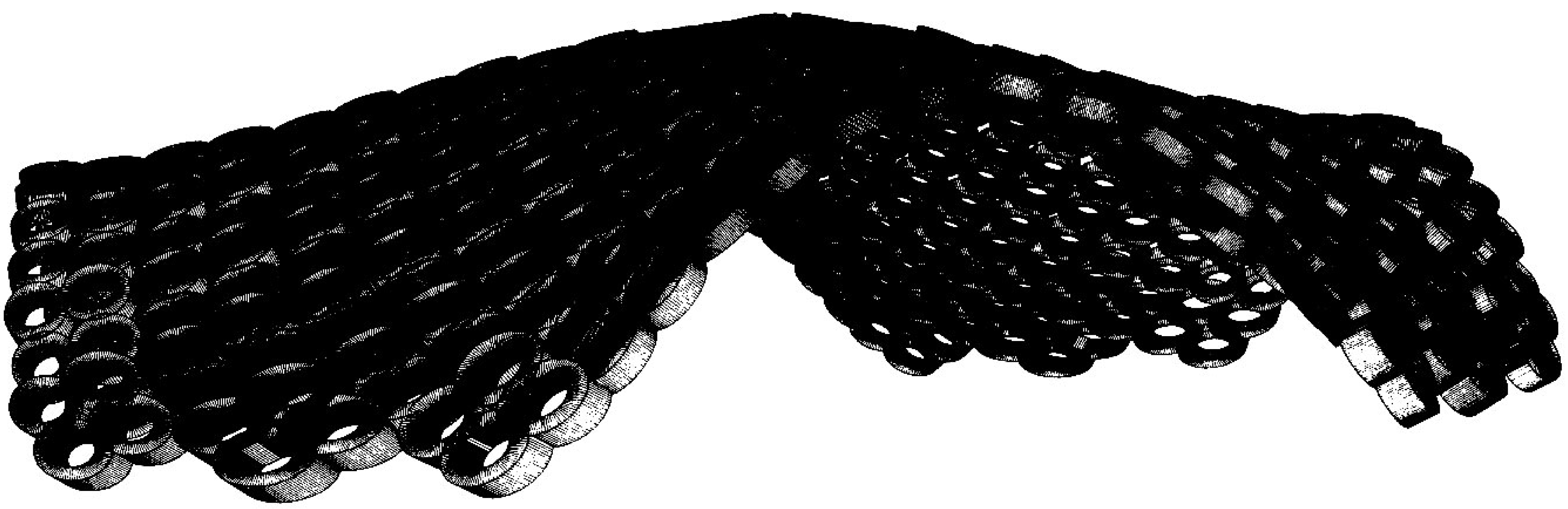
CONSTRUCTION METHODS

After working with the tires two general approaches to construction of the shells seem possible. The first would use the tires as a compression shell that would subsequently be rigidified with concrete. With this approach some degree of temporary shoring would be needed. The second approach would use the tires as a tensile net which would be rigidified by concrete and placed inverted as a precast compression panel in a frame. This method does not require any shoring for the shell but does require another system, the frame, which would support the panels. In both of these approaches the shell could be made either solid with the tires embedded or sandwiched between two layers of concrete, or the shell could be made perforated by casting only the ring of the tire full of concrete. In the latter case the tire beads would have to be brought together as in connection D of Figure 2. and a concrete slurry pumped or funnelled through a hole punched in the sidewall of the tire. Fabric or lightweight roofing could be used to cover the shell and seal it against the weather but still remain translucent. Examples of these two approaches are shown in Figures 5. and 6.

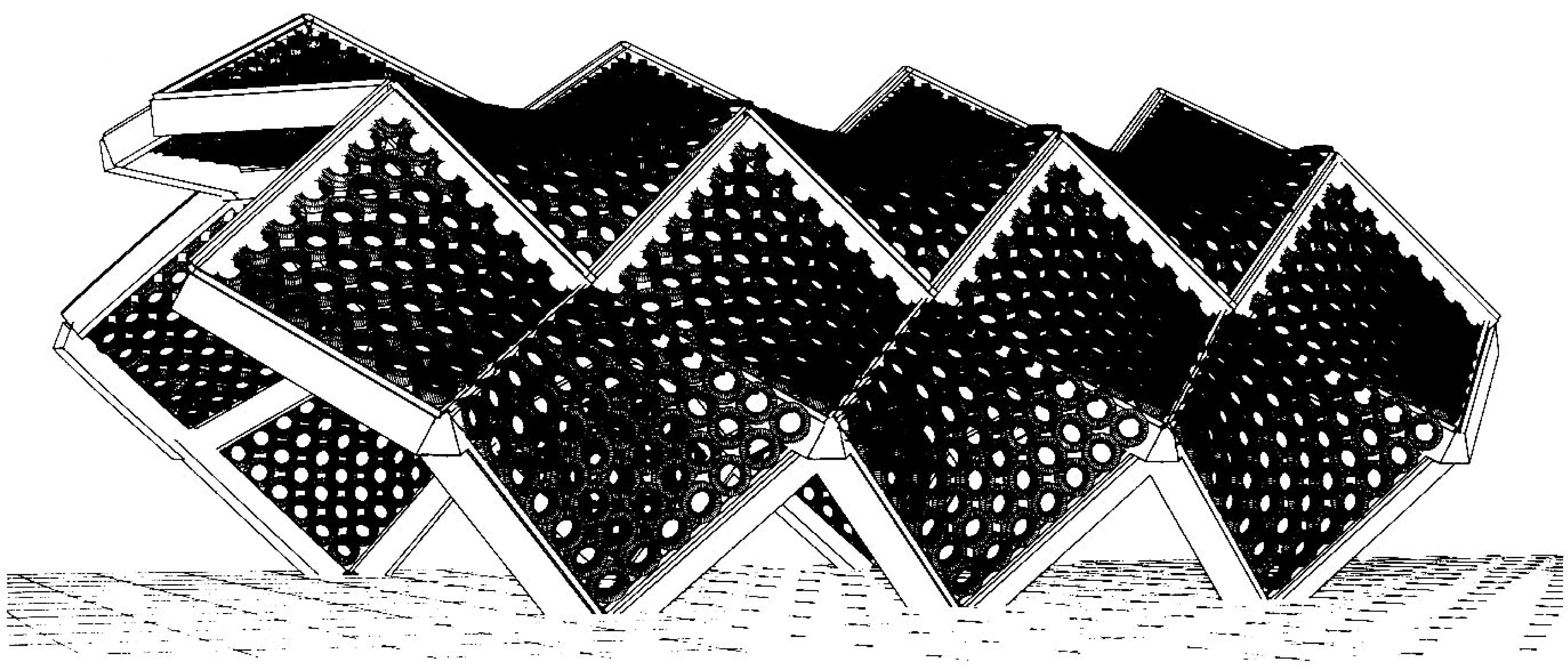
CONCLUSIONS AND RECOMMENDATIONS

From the work done thus far the concept of tires used with concrete to form composite shells looks feasible. Of the two general construction methods discussed the tensile net approach seems the most promising. It offers the following advantages:

1. The tire array can hang in a stable geometry with no shoring except for a frame.
2. Catenary shapes would occur naturally without formwork.
3. There is no danger that the tire array might buckle before the concrete is applied.
4. A large shell can be designed as a panelized set of smaller shells and prefabricated.



5. Cross-barrel vault design using compression arch approach.



6. Ribbed vault design using tensile net approach.

5. With prefabrication better quality control of the concrete would be easier.
6. More precise overall dimensions would be easier to maintain since the ribs would position the shell panels.

It is recommended that further testing, analysis and the construction of a prototype be carried out. First, further material properties are needed for the specific connections. This would include stress/strain behavior and ultimate strength data. Also testing needs to include the clamped closed position of the ring design. Finally material properties are needed for the composite shells including concrete and continuous reinforcement.

With the more detailed material properties a finite element computer model should be constructed to determine the amount and position of continuous reinforcement.

Several possible shell geometries have been developed based on work done thus far. Figures 5. and 6. show two of these designs. Based on more detailed stress analysis, one of these geometries should be refined and a prototype built in order to field test the construction technique.

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