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ABSTRACT

Air structures can be erected quickly, cover large areas, cost substantially less than conventional buildings, and use less natural resources. Air structures are economically utilized for many facilities, such as athletic fields, swimming pools, high schools, day care centers, and college campuses. The literature on air structures covered in this review consists of materials on technical information, costs, specific uses, advantages and disadvantages of air structures, and a look at some of the future uses. (Author)

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Air Structures

Mary Lou Finne

Mounting construction costs, fluctuating student enrollments, and unsuccessful school budget elections are forcing school administrators who have building needs to explore contemporary, flexible, facility design alternatives available at costs below those of traditional structures.

One of these alternatives, air structures, has been economically utilized for many facilities, such as athletic fields, swimming pools, high schools, day care centers, and college campuses. Often referred to as "bubbles," air structures are enclosures fabricated from flexible, essentially airtight materials supported and stabilized through air pressure.

There are three basic types of air structures. In air supported structures the entire enclosed space is maintained at a pressure higher than ambient atmospheric pressure. Variations include utilization of a second membrane layer and/or addition of cable reinforcements to reduce primary stresses in the structural envelope. Air inflated structures do not have pressurized interiors but use air inflated elements that act as columns, beams or arches to support the membrane. Cable reinforcements can also be utilized in air supported and air inflated structures. Hybrid air structures combine elements of the first two types or use them with other structure supports.

Air structures can be erected quickly, cover large areas, cost substantially less than conventional buildings, and use less natural resources. Those designed without permanent foundations are adaptable to changing needs, can be moved easily from location to location, and have a minimal effect on the terrain where they are used.

The literature on air structures consists, for the most part, of technical state-of-the-art reports, case studies of particular schools using air structures, and overviews of various advantages and disadvantages of air structures.

This review cites reports covering almost a ten-year time span. Because the technology of air structures has advanced very rapidly, some of the problems cited in earlier literature have been partially or completely solved at the time of later studies. Some references are not discussed in the text but are annotated in the bibliography. Readers are advised to compare earlier references with later accounts to obtain an up-to-date view of air structure development.

TECHNICAL INFORMATION

An entire issue of *Building Research* ("Air Structures" 1972) is devoted to reports from a 1971 international, interdisciplinary Air Structures Forum, cosponsored by twenty corporations. Intended as a compilation of the latest developments in the field, the report includes twelve short "design criteria" papers dealing with engineering, materials, wide-span structures, inflation and environmental systems, heating and air conditioning, thermal transmission, solar energy control, environmental control, large area covers, space subdivisions, and local code requirements.

The technical articles are followed by nine case studies of air structure utilization, including Antioch College's branch campus in Columbia, Maryland, and the field house at Milligan College in Johnson City, Tennessee.

In an address to the group, Walter W. Bird, who is known as the "father" of air structures in the United States, traces the history of air structure development (Bird 1972). Although patents had been obtained on air-structure ideas as far back as 1917, the first practical application came in the mid-1940s at the Cornell Aeronautical Laboratory, a research facility in Buffalo, New York. This first air structure was a radar dome conceived and developed to meet the need for a thin, nonmetallic protective covering for radar stations.

Commercial applications of air structures began about 1956 when warehouses and pool enclosures were designed and constructed. Because of the lack of recognized design standards and regulations, of building code specifications, and of construction expertise, many of the early structures gave unsatisfactory service.

Two years after the 1971 initial forum on air structures, the Building Research Institute in cooperation with the Educational Facilities Laboratories, Inc. (EFL) and Antioch College conducted a three-day national technical conference on "Air Structures in Education," partially held inside the 180-foot-square air structure at Antioch College.

The purpose of the meeting was to gather the world's leading architects, engineers, educators, and others for presentations of the very latest developments in air structures, particularly as related to the field of education, and to discuss educational opportunities, economics, technological developments, and the feasibility for future use of air structures.

Some of the papers presented at the meeting are included in the April/June 1973 issue of *Building Research* ("Air Structures in Education" 1973). Featured are actual or planned facilities at Antioch College, the University of Wisconsin, Charles Wright Academy, and the Delta Winter Club.

In an address to this conference, Walter Bird stated that the air structure has developed through significant stages, gaining acceptance at each stage, but often for far different reasons (Bird 1973). The first stage was military applications, followed by conventional standard air structures (the "bubbles"), exhibition structures, and, now, permanent building applications.

Bird considers this fourth stage the most important in the development of air structures. In discussing durability of fabric structures and cost advantages, he mentions a new material (Teflon-glass) that is expected to provide a service life of twenty years or more.

Bird stresses the importance of architects working closely, in the early design stage, with fabricators fully familiar with all aspects of air structures. This should be done to avoid designs that cannot be supported by available materials or fabrication techniques and to take full advantage of available experience to assure successful performance.

COSTS

Construction-cost estimates for air structures vary between $4 and $6.60 per square foot depending on the type and size of the structure and the materials used ("Lightweight Structures for Education" 1973, Valerio and others 1973, Ontario Department of Education 1972, and Geiger 1972).

When compared to the $20-$40 per square foot cost of new permanent construction ("Lightweight Structures for Education" 1973), it is apparent that low cost is one of the most compelling reasons for considering air structures.

Bird (1973) cautions against attempts to cut too many costs in the design and construction of air structures. "There is no such thing as a good, cheap air structure. It may be good, or it may be cheap, but not both. However, a good air structure can be economically designed without sacrificing quality....The low cost of conventional, standard air structures is possible only because of standard designs, standard patterning, and production fabrication procedures."

To obtain reliable data on the relative costs of alternative enclosure systems over various periods of time, the Educational Facilities Laboratories, Inc. (EFL) sponsored a study in which the costs of air structures and six other distinct types of readily available structures were analyzed and compared (Koppes 1969). Costs, including the charges for financing, operation, and maintenance as well as the initial costs, are compared for three alternative annual terms of use over periods of five, ten, and twenty years.

Detailed cost calculations for each of twelve variations of appropriate structures are presented and summarized in both tabular and graph form. Also included are recommendations about the essential features of the "ideal" structure for each alternative term of use and time period.

USES

In addition to providing cover for permanent facilities, air structures are suitable for emergency short-notice shelters, for experimentation, and for growth ("Trend 10 . . ." 1972). Air structures can be quickly and economically erected to meet sudden enrollment surges that call for emergency housing, or they can serve as transition shelters until growth is enough to justify a permanent facility.

These structures can be experimentally used for open plan schools, with far less initial investment than conventional schools, minimal upkeep, virtually equal comfort and function, and an anticipated usage of ten or more years.

The ideal facility for lifetime sports is described as a membrane structure encapsulating space with three intramural fields, and facilities for ice hockey and swimming ("P. Richard Theibert on Facilities . . ." 1971). Large clear span areas can accommodate major events like football games, then be converted for multipurpose activities under the same shelter.

Some of the uses of air structures are cited in a Canadian journal, *School Progress* ("A Scoop of the Sky" 1971). Because Sweden's climate is similar to that of Canada, an inflatable used for a daycare center erected in Sweden in 1970 is of particular interest to Canadians. In comparison to conventional buildings, the installation, called "The Plastic Flat," is credited as being highly suitable for children because it provides a fun, unconventional atmosphere without limitations of space.

ADVANTAGES AND DISADVANTAGES

Valerio, Davies, and Stanton (1973) describe conventional buildings as "overweight, overfed, and dumb." Conventional buildings are overfed in the sense that they consume an enormous amount of time and resources during planning and construction. Conventional buildings are overweight because of the rigid heavy materials that are difficult to move, assemble, and destruct. Conventional buildings are dumb because components must be lifted into place in lengthy, costly, and involved processes under the constant monitoring of humans.

On the other hand, air structures consume minimal resources, are lightweight and portable, and have memories tailored into the fabric requiring only air pressure to erect them.

Another advantage cited by these authors is that large areas can be enclosed without internal supports.

An article in *Nation's Schools* ("Bubble, Bubble: Less Cost, Minimum Trouble" 1970) indicates mixed reactions to the use of air structures for inexpensive athletic facilities during the last ten years.

The merits of air structures are cited as being economy, rapid construction (three to ten days), coverage of large areas, ease of maintenance, and versatility. Problems mentioned include vandalism, wind problems, snow, maintenance of air pressure, acoustics, and lighting. The advantages of the bubble—lightness and movability—make it susceptible to damage, especially around the seams where the fabrics are most vulnerable. Some school users have found their bubbles knifed or torn.

An article in *Progressive Architecture* ("With a Little Help From My Friends" 1971) stresses that the freedom of the individual to determine his immediate environment can be reflected in architecture. Domes and inflatables are the forms nearest to annihilation of the "edifice complex."

A *CEFP Journal* Special Report ("Trend 10 . . ." 1972) considers "there can be little doubt that inflatables are rapidly becoming both an asset and trend in the educational program."

An Ontario Department of Education (1972) publication summarizes current information and identifies some of the benefits and the problems involved in the use of air structures.

The advantages listed include low initial cost; speed and ease of erection, handling, and repair; portability; adaptability for temporary functions; unobstructed space with high ceilings; integrated heating, ventilating, and air-pressure systems; and maximum utilization of daylight illumination.

Disadvantages listed seem to be correlated with the fact that air structures are the product of a recent and rapidly developing technology. Difficulties that other authorities claim are in the process of being solved are short life of the fabric envelope; thermal, light, and sound problems; and uncertain performance over long-term periods.

SIGNIFICANT EXAMPLES

Several structures have been covered in the literature from drawing board stage through completion. The scope, dimensions, materials, and costs of these structures, as cited in the articles, have changed with time. In most cases the planned size and amenities of the structures have decreased and the costs have increased.

An early publication (Robertson 1964) describes the air structures at The Forman School of Litchfield, Connecticut. The first bubble erected in 1961 on the campus of this secondary school pioneered the use of air structures for school sports, and a later second bubble incorporated solutions to problems posed by the first.

The school's experiences with bubble-covered play space in solving site, lighting, and heating problems are considered a significant contribution to the research and development work that has perfected air structures.

An air structure that has received extensive coverage in the literature is the Milligan College field house. According to an article in the July 1973 issue of *American School & University* ("Lightweight Structures for Education"), the roof of the air-supported field house was scheduled for inflation the last week of August 1973. The low-profile building will be cable-restrained and column-free with lower and upper floors and mezzanine levels on the sides.

Additional description of the field house at the planning stage is available in "Advanced Encapsulated Fieldhouse" (1971).

The story of a three-year experiment in education and architecture, involving a hundred or more people and resulting in the construction of the Antioch College air structure, is told by the architect for the project (Ekstrom 1973).

The Antioch bubble at Columbia, Maryland, serves as a base for students on work-study leave from the main campus ("Lightweight Structures for Education" 1973). The bubble is a translucent vinyl material covering 32,400 square feet, with faculty and administrative offices, classrooms, and seminars inside assembled from lightweight, movable materials such as geodesic domes. The bubble provides an inexpensive semipermanent campus easily adaptable to many different educational programs.

According to the same article, at LaVerne College, outside Los Angeles, September 1973 completion was scheduled for two cone-shaped structures housing a two-story student center and a drama lab. These structures, consisting of Teflon-coated fiberglass supported by a network of cables, are not technically air structures. However, the buildings are cited in many articles about air structures and Bird lists them among his design of air structures.

The upper level of the student center includes basketball and volleyball courts; the lower level has a campus radio station, photographic darkroom, and media room. The drama lab contains a theater with seating for 245 people, a rehearsal room, and scene shops.

The technical aspects of the LaVerne structures are described in the May-June 1973 *CEFP Journal* ("A 'Scoop of the Sky' for LaVerne College"). LaVerne's innovative president said that there were two reasons for the permanent lightweight structure approach to the college's problems: cost, and a need for the college to remain flexible in an educationally fluid decade. The new concept for encapsulating space fits in with the freedom and adaptability of the LaVerne curriculum.

FUTURE USES

Valerio, Davies, and Stanton (1973) say that designers are in the experimental stage of constructing a completely self-sustaining environment in which the membrane will serve as structure, enclosure, and anchorage, control light and thermal transmission, and collect solar energy.

Geiger (1972) in a technical article forecasts future developments that may include a "thermal roof" to serve as a solar collector and thermal radiator, which would permit climate control. The article contains a structural analysis of the latest developments in air structures from new fabrics to new uses.

Projections of future uses include encapsulating whole communities to provide environmental protection in the far north or pollution protection in other locations ("Air Fare" 1972).

Three prototype structures preceded the present structure at Antioch College, which is considered Prototype IV. The design of Prototype V, powered by the sun and the wind, is to be the result of all the experience gained in the building of the previous models (Ekstrom 1973).

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