Current Developments in Analysis, Design, and Engineering of Lightweight Structures

Bharath Gowda, Structural Consultant,* e-mail: gowda_bharath@yahoo.com

The intent of this paper is to present an overview of some current developments in Analysis, Design and Engineering of Lightweight Structures. In specific this paper would address space frame structures, tensioned fabric structures and glass structures (with a focus on earthquake resistant design). After a brief introduction to historic analysis and design, each of these categories of above-mentioned structures will be discussed with a project example.

Introduction

The story of lightweight structures, space frames, suspension bridges, in fact all inventions and developments in light weight technology begin with that wondrous natural enigma - the spider's web. The modern lightweight structure's evolution from the invention of the space frame by Alexander Graham Bell (1900), and its popularization by Buckminister Fuller (1960), to the tensioned structure technology first used in ship rigging , primitve tents, and suspension bridges, and later applied to cover large span roofs by Matthew Nowicki (State Fair Arena at Raleigh, U.S.A 1950) and popularized by Fri Otto (Munich Stadium 1972), to the first large airtight space frame structure - the Bio Sphere (1990) - built by Pierce Structure; and from the earliest large glass structure - the Crystal Palace in Europe (1850) - built by Engineer/Horticulturalist Joseph Paxton, to the high transparency structures (cablenet) invented and designed by Engineer Schlaich, to the complex and earthquake resistant glass structure of the T-30 umbrella (2000) and San Jose Civic Center (2004)) by Advanced Structures Inc. is testimony to the technical inventiveness of the human intelligence . This presentation is about the story of this remarkable engineering account.

Analysis of lightweight structures is complex and involves rigorous mathematics. Historically designers used physical modeling to analyze and design lightweight structures. However, in recent years, with the advent of high speed computers, engineers use computers to analyze and design lightweight structures. Computer based methods for analysis of nonlinear structures can broadly be classified into two sections either Implicit or explicit methods.

Common Implicit method is basically application of stiffness matrix method with the formation of structural overall tangent stiffness matrix to account for non-linearity, and solve incrementally until convergence is obtained utilizing Newton-Raphson algorithm. Development of these methods is traced to England/Germany. Most common explicit method is the Dynamic Relaxation method where the conditions of equilibrium and compatibility are decoupled until equilibrium. Origin of this method is traced to England.

Space frame Structures

Space frame system for the Cloud structure at Fashion Show Mall in Las Vegas [2]

The cloud structure is an articulated entrance portal to the existing Fashion Show Mall. The main body of the structure has an ellipsoid shape that is 478 feet long, 160 feet wide, and up to 20 feet thick. The main body of the structure sits between 90 and 120 feet off of the ground level. It slopes 12 degrees in the transverse direction and 4 degrees in the longitudinal direction and its two support columns are set approximately 250 feet apart and approximately 16 feet off of its center longitudinal axis [figure 1].

The purpose of the Cloud sign structure is to be an urban marker and accentuate the presence of the shopping center among the nearby casinos. The sign structure in not merely symbolic feature but functional. The cloud sign will provide shade from the sun during the day for a food court below, and by night the structure would act as a large reflective display medium for the projection of images and advertisements.

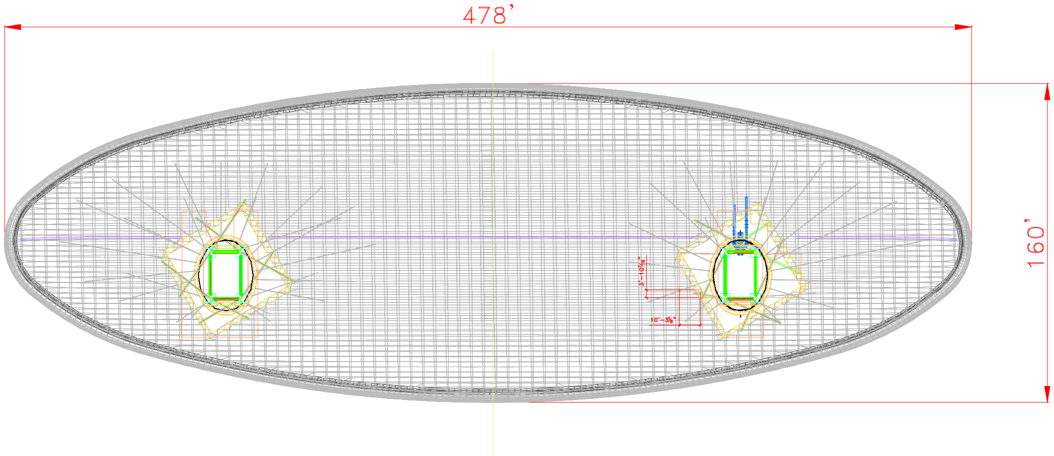


Figure 1. Cloud plan view

Advanced Structures Inc was subcontracted to design the entire structure, and provide fabrication for the space frame and cable elements. During the project the cladding and cladding support framing was modified, and ultimately reengineered by the fabricator of these element.

Figure 2. Cloud under construction

The cloud project is one of the first large-scale cable supported space frame projects in the United States at approximately 60,000 square feet of covered area on each face. There were numerous difficult engineering issues to solve on this problem, with the eccentric cable supported nature of the design. Despite the design difficulty, ASI provided a workable solution for the framing that allowed an efficient space frame solution that resolved the ellipsoid varied depth shape and still resolved the forces at hand.

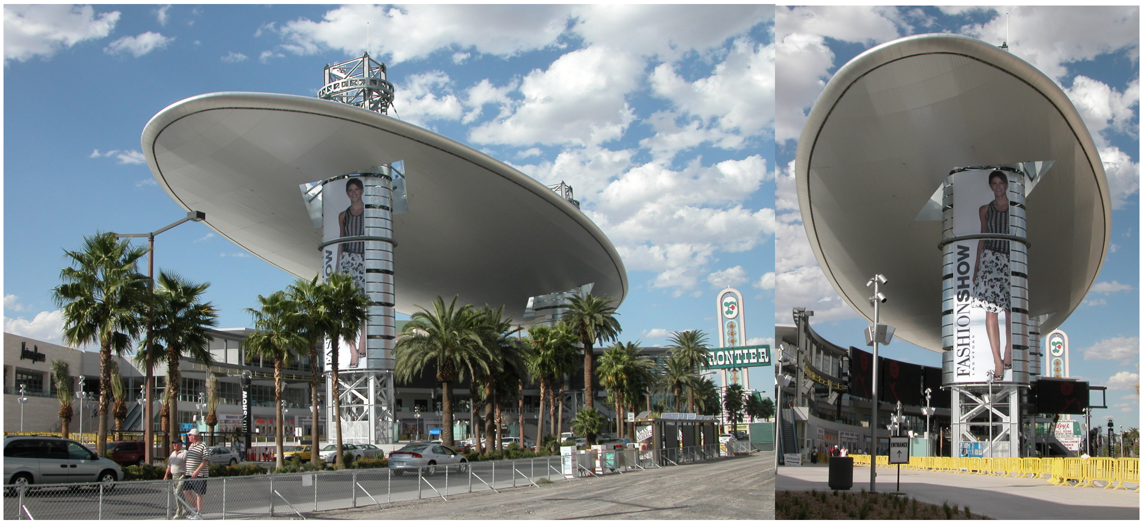


Figure 3. Cloud fully built

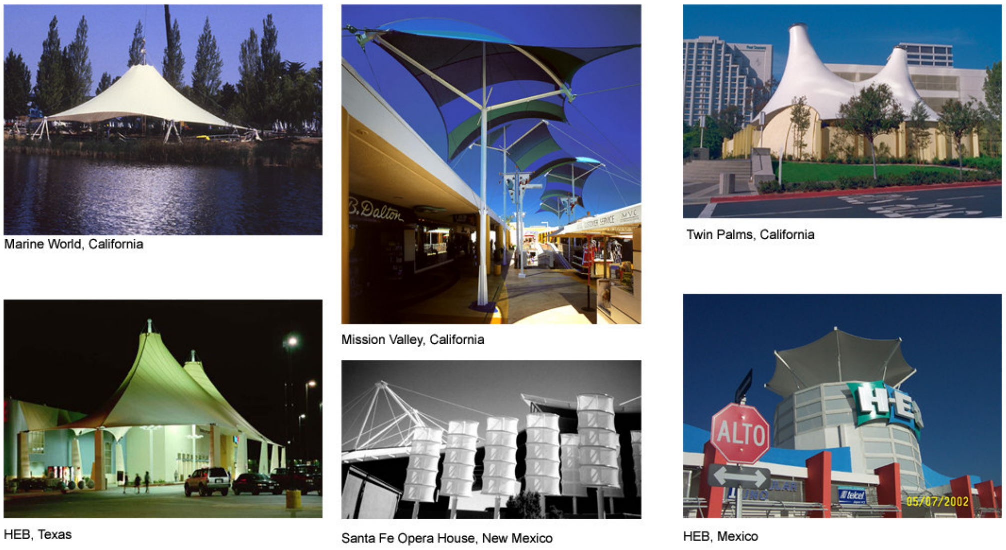
Figure 4. Cloud after cladding installation

The final result is a mammoth sized, sleek looking, shade and sign structure that provides visual impact for both the day and night times. The Owner is extremely pleased with the final structure, and is using it to its full potential.

Tensioned Structures [3]

Introduction

Tension fabric structures are one of the most exciting and rapidly developing technologies in the building industry today. Material advances in coated woven textiles combined with design and numerical techniques for developing membrane structures have yielded a new building form for permanent architectural applications (see figure 5). Among them are complete architectural fabric enclosures for buildings, airport terminals, restaurants, and other public spaces: large span structures such as stadiums, arena enclosures and retractable membrane systems for covering indoor and outdoor spaces.


Marine World, California

Mission Valley, California

Twin Palms, California

HEB, Texas

Santa Fe Opera House, New Mexico

HEB, Mexico

Figure 5- Examples of Membrane Forms

Perhaps the most exciting aspects of fabric structures are the remarkable variety of anticlastic forms that can be realized. These include hyperbolic shapes, saddles, cones, domes, vaults, and waved and plate types. The choices are endless. The range of forms is augmented through the use of support and restraint elements such as cables, masts, trusses, and rigid nodes. Cable-membrane structures are referred to as “form active systems” since the form being derived from the direct relationship between force and cable structures. This concept may be referred to as **"form follows force".**

Design of Tension Fabric Structures

The design of tension fabric structures begins with a form conceived by the designer. A drawing or a physical model usually represents this form. The designer’s form provides basic concept and support conditions which allow an engineer to find the true shape of the structure. (It is interesting to note the concept of form finding and not form giving).

The engineer usually employs the following approaches for form finding:

Qualitatively - through physical modeling historically used by designers like Frei Otto to analyze and design membrane structures. Physical modeling involves creating a scaled model made of materials, which depict the actual structure (e.g. textile cloth for the fabric, wire for edge cables etc.). If the structural properties of the material of the model are known this model can also be a structural testing model for load analysis. The great advantage of the physical modeling method is the explanation of the physical behavior of the actual structure.

Quantitatively - Using mathematical tools. Mathematics does not explain physical behavior; it only describes it. However, in recent years, with the help of powerful computers, engineers can easily solve nonlinear equations and track out complex trajectories that cannot be drawn. Mathematical descriptions are now so efficient that powerful computers can easily and fully conceive and explain membrane structure behavior. Computer simulation of the structure has become a valuable tool to help the designer find realistic shapes.

The design of membrane structures regardless of the methods used has three steps:

1) Form-finding or Initial geometry formulation
2) Engineering analysis and membrane design
3) Patterning

Glass Structures [4]

Point supported glazing system for the San Jose Civic Center Rotunda.

The Rotunda serves as the focal point of the new San Jose Civic Center, The Rotunda is a large cylindrical structure (90 feet in diameter and 40 feet high) topped by a dome (90 diameter and 50 feet high), clad mostly in glass. The primary structure consists of a set of steel ribs filled with concrete, which are arranged on a radial grid. Horizontal cable trusses span between the ribs to hold the point supported glazing system. Each truss consists of one pre tensioned cable front and back, separated by spreaders. A set of pre tensioned cables runs vertically to stabilize the trusses and carry gravity loads. (See Figure 6).

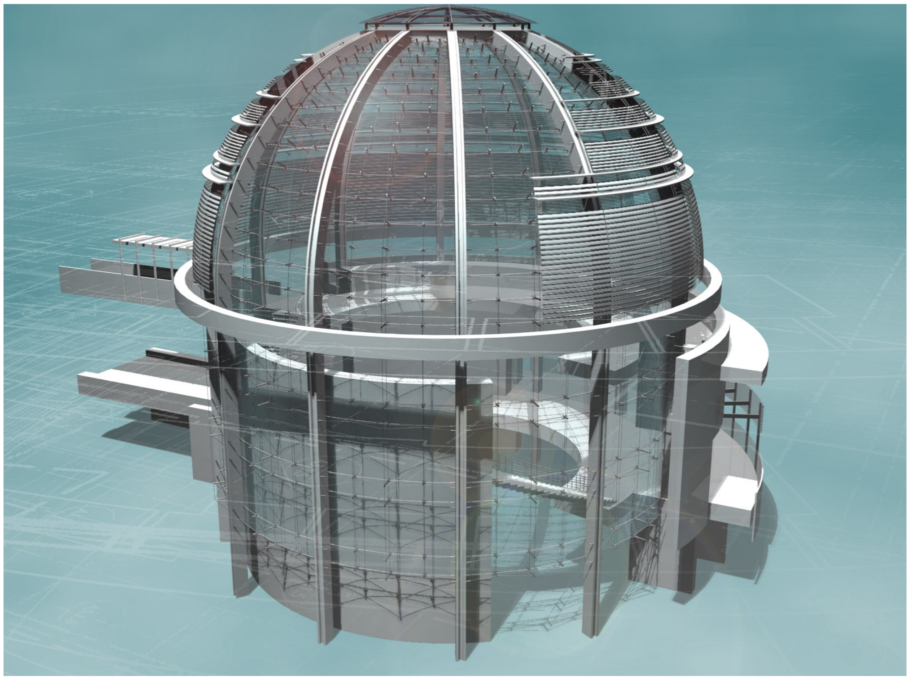


Figure 6 San Jose Civic Center Rotunda Rendering

Design Criteria

The project specification requires that the cladding system be designed according to the 2001 California Building Code. Hence the design Criteria is based on the California Building Code (CBC). The code requires that the cladding system be designed to withstand a maximum inelastic drift of 2 -2 ½ % of the height of the building. The code also requires that the cladding system for glass panels and glass panel joints accommodate movements of the structure based upon the elastic and inelastic displacement of the support structure.

CBC states that calculated story drifts using DeltaM shall not exceed 0.025 times the story height for structures having a fundamental period of less than 0.7 second. For structures having a fundamental period of 0.7 second or greater, the calculated story drift shall not exceed 0.020 times the story height. The maximum inelastic response displacement, Dm shall be computed as follows:

$$Dm=0.7\ R\ Ds$$

Where, R denotes the numerical coefficient representative of the inert over strength and global ductility of lateral force-resisting systems. Ds denotes Elastic Response Displacement. It should be noted that Ds and R, are both values that are characteristic of the support building and are critical information that should be defined for the design of the Cladding System. Although it would be beneficial for the design of the cladding system to have the actual calculated values for Ds and R from the Building Engineer, cladding designers usually do not have this information during cladding design and end up designing for the code maximum.

Current Code Philosophy and Implementation

The goal of the California Building Code is to prevent

- Non-structural damage in frequent, minor ground shaking
- Structural damage and minimize non-structural damage in occasional moderate ground shaking
- Collapse or serious damage in rare major ground shaking

Above all, the code aims to preserve life safety under all but the worst cases. The elastic level seismic drift requirements correspond to demand due to frequent, minor ground motion. The inelastic seismic drift requirements establish a performance level corresponding to stronger and less frequent events.

The implementation of code philosophy in the design of cladding systems presents some issues particularly, the code's view that exterior panel and panel joints must accommodate movements of the support building structure based upon Dm of the support building structure. Note here that the code only states "accommodate" and it is left to the design team to use an appropriate definition of accommodate questions and concerns remain in the interpretation of accommodate and the specific performance required of the cladding system.

ASI came up with an interpretation of the code definition of accommodate based on engineering judgment as:

- Under elastic deformation, no damage or disengagement of the frame, snap of members or glazing gaskets, breakage of metal panels or glass panels shall occur
- Under inelastic deformation, deformation or damage of framing members, and/or breakage of glass may occur defined only as cracking or spilling. System anchorage may deform, but catastrophic failure cannot occur (glass panels or fittings falling out or off of assembly), nor shall any damage or broken materials fall off from the wall (pieces of glass in excess of one square feet, glass fitting, falling off assembly)

Application of Code Requirements

The code is not necessarily an accurate predictor of the forces and deformations that structures will experience during earthquakes. In general, the inelastic deformation limit of 0.02*h is considered to be a conservatively large displacement. Buildings may be designed for less when justified by an appropriate engineering analysis. In the case of the San Jose Civic Center Rotunda, the Project Specification clearly states that the cladding be designed to the code maximum 0.02*h.

In a seismic event, we expect the structure to deform significantly less than the .02*h required by the project specification. Per the building code, inelastic deformation, Dm, can be calculated based on the elastic deformation

Ds using the following formula: Dm=0.7*R*Ds where R is a coefficient representing the stiffness of the lateral force resisting system. By using an R-value for a moment resistant frame of 4.5, and the specified elastic deformation limit of 0.004*h, Dm is given as 0.0126*h. By comparison, we have designed the system for 0.02*h. This represents an increase of more than 58%.

The design range of elastic behavior is from 0.00*h to 0.004*h. Deformation beyond 0.004*h is considered to be inelastic. Note here that for the 110' tall building the design inelastic range is 4.8"–24". This means that the code predicts a net maximum displacement at the top of the building of two feet. This must be accommodated by incremental deformations of joints between glass panels over the entire height of the building.

Rotunda Seismic Behavior

In our code based analysis the building ribs are displaced by a distance of .02*h to a maximum of 24" at the top of the building. The inelastic displacement of 24" over the building height will include large displacements (geometric non-linearity) and material yielding (material non-linearity). Under these conditions the true deflected shape of the structure is complex and hard to predict. For purposes of analysis we assume a simple linear deflected shape. We also assume that the geometry of each frame element will not significantly change during inelastic deformation. The horizontal cable trusses translate with the ribs, and the wall system accommodates the drift at each horizontal joint by shearing or shingling of silicone joint, and at the spider connection a slotted hole in the spider allows the glass bolt to translate, accommodating seismic movement while minimizing in-plane loads to the glass.

Mockup test

A full-scale mockup test (see figure 7), representing a portion of the dome, was conducted for the Rotunda with all the finalize components of the system. A proof test was performed by laterally displacing the wall by 7.2 inches (.02*h) each way for a total of 3 cycles, returning to its original position after each cycle. The system passes the test without any damage to components.

Figure 7 Mockup Testing

Project Application

After successful testing of the mock-up, actual manufacturing of the components for the project application started and later these components were used to erected and assembled the Rotonda at site (see figure 8). The project was completed, and is already in use.

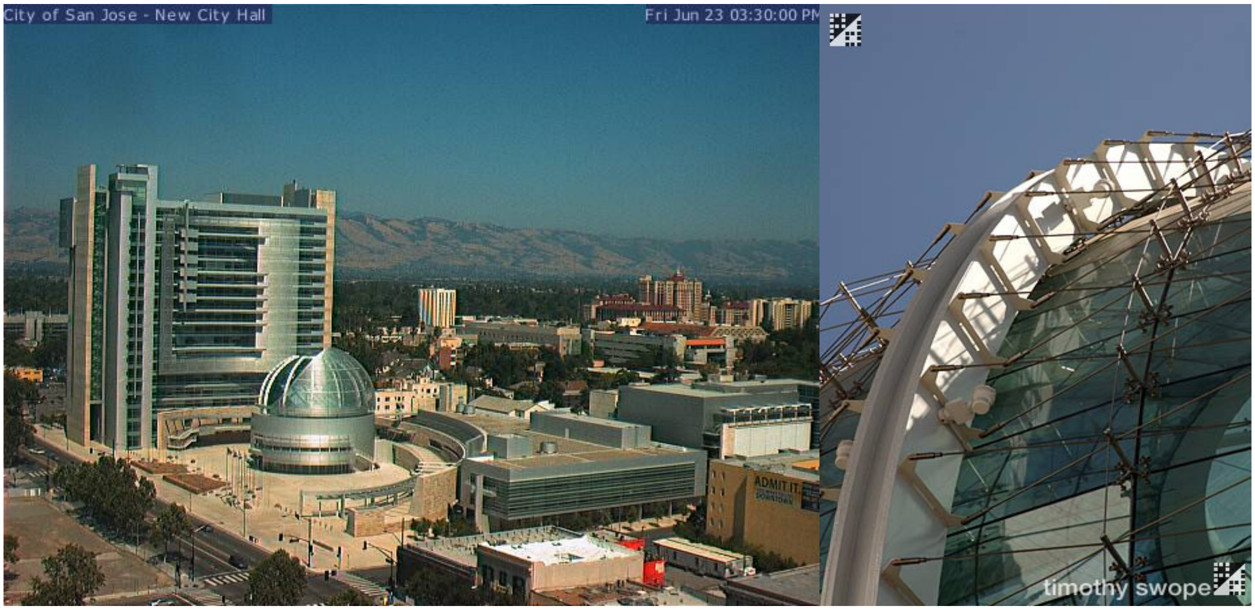


Figure 8 Site location

Final remarks

Lightweight structures are a developing technology, which gives architects and engineers the ability to experiment with forms and create exciting solutions to conventional design problems. Due to the variety of alternate design solutions to Lightweight structures that can be quickly achieved utilizing computers; computer methods would further enhance and develop engineering and design of lightweight structures.

References:

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