CONTINUING EDUCATION CENTER

TU VIENNA

MSc Program "Building Science & Technology"

Foam Structures: A Comparative Structural Efficiency Analysis Based on the Building Case "Watercube"

A master's thesis submitted for the degree of "Master of Science"

Supervisor: Arch.Dipl.-Ing.Dr.techn. Margit Pfeiffer-Rudy
Department of Structural Design and Timber Engineering

Nilufer Senses

Vienna, June 2007

0527085

CONTINUING EDUCATION CENTER

TU VIENNA

Affidavit

I, **Nilufer Senses**, hereby declare

1. That I am the sole author of the present Master Thesis <Foam Structures: A Comparative Structural Efficiency Analysis Based on the Building Case "Watercube"> and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. That I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

Vienna, June 2007

____

Signature

Acknowledgement

With my deepest gratitude, I want to thank my supervisor Arch.Dipl.-Ing.Dr.techn. Margit Pfeiffer-Rudy whose help, stimulating support and encouragement helped and guided me in all the step of this thesis.

I have furthermore to thank Dipl.-Ing. Stephan Jaksch for his stimulating help and support.

July 12, 2007

Abstract

Foam structure in macro-scale has arisen as a new type of large span building structure recently which is a product of cooperation of advanced structural design, radical architectural design approach, and computer and software technology, and efficiency of foam structure became an important question to answer which could help further structural improvements.

This study analyses efficiency of large span foam structure relative to conventional large span building structures with a parametric simulation method.

Space frames are a special case of conventional large span structures one compared with foam structures, because it satisfies criteria such as being lightweight and three-dimensional as foam structure. Analysis is based on the comparison of base cases of foam model and space frame model, which are developed on light of real projects the Water Cube and the Symbol Zone of Expo’70, based on the parameters structural depth, weight and displacement, and vertical and horizontal load cases. During the analysis structural behavior of base cases were simulated by using a special structural behavior simulation program.

It was found that foam model is more efficient than space frame model in terms of structural depth which is an important issue for large span building structures from both architectural and engineering point of view. Capability of spanning large distance with significantly less structural depth makes foam structure a preferable, new generation, steel structure for large spans. Moreover, the development process of base case foam model demonstrated the critical importance of geometrical design concerns of foam structure. Structural behavior simulations were exposed that structural optimization is one of the vitally important process of structural design of the foam structure.

Keywords: Foam, foam theory, foam structure, space frame, geometrical optimization, structural optimization, structural behavior simulation

Table of Contents

Table of Figures

List of Tables

1 Introduction

During the twentieth century, increasing use of information technologies enhanced creativity and productivity in many fields. The architectural design became much freer than it was in the past in terms of form, aesthetics and functionality. This innovative path launched the demand for and supply of new materials and structures in the construction and material industries. Nowadays, architects, engineers and researchers focus on developing new approaches to the architectural and structural design and on the most efficient use of materials in buildings and structures to get desired levels of aesthetics and quality. In this sense, nature remains a great source of inspiration, which includes the best examples of the efficient uses of materials in super-efficient structures with aesthetically sparkling ways in living organisms and in inorganic matter. Researches tend to understand the physics of such structures. Data are collected and interpreted to replicate the efficiency of nature in the architectural and structural designs.

Foam is one of the good examples of this type of adaptation. It is quite common in the nature i.e. sponge, honeycomb, cork, cancellous bone etc., and they have wide spread uses of micro- and macro-scales. For example, especially in the material industry, foamed constitution of the same material has proven to be much more efficient relative to the natural one in many respects (i.e. mechanical behavior, density and the quantity of material) to provide same conditions. Other micro-scale applications of foam, for instance metal, polymer and ceramic foams, have been used for many years in many branches of the industry including construction. Crash safety material of cycling helmets is polymer foam and the system works based on making use of the polymer foam constitution absorbing energy and the lightness of the foamed material.

The first macro-scale example of the foam structures appeared in 2003. The structure is the National Swimming Center of Beijing in China, which is also called “The Water Cube”. Arup and PTW designed an enormous large span building structure. It was a radical approach to the architectural and structural design and was inspired from the shape of bubbles in a continuous array. Architects have been based on Weaire-Phelan Theory, which sets the most efficient solution for the old mathematical problem on finding the shape of soap bubbles in a foam. Unconventionally, The Water Cube respects original architectural design despite its vast span structure. Usually, in such building structures, dimensions of structural elements connected to the span and loads are large. The major emphasis stands on the structure rather than the architectural design. In many cases, the structures also stiffened with tensile cables or cable nets which are far from following the architectural shape and boundaries. In the Water Cube, the structure consists of a network of steel tubular elements and it fills the space between architectural shape boundaries. The structure itself is part of the shape, architectural boundaries and architecture. The structure forms a unity together with architectural design as in organic or inorganic matter where structure follows shape and stays in the boundaries.

This study concentrates especially on the latter; the macro-scale application of foam in architecture and analyses structural efficiency with a comparative study. The first part presents foam theory and the types of foam. The second part discusses the Water Cube and Expo ’07, which are physical examples of the two structural types of comparative study, as case studies. The third part presents simulation models for foam and space frame structures and their development process. Furthermore, the fourth part compares the efficiency of these structures in large span buildings.

1.1 Foam Theory

Soap foam has been engaging scientists’ attention since the 1870’s. As in the Encyclopedia of Applied Physics[1] a foam is a coarse dispersion of gas in liquid or solid and the main question driving research on the soap foam is how to divide the space with minimum partitional area.

First in 1873, Belgian scientist Plateau observed soap bubbles and demonstrated the rules of soap foam constitution. After about 10 years, Sir William Thomson (Lord Kelvin), solved the problem of division of the space with minimum partitional area in the foam based on Plateau’s research. After Lord Kelvin’s contribution, the problem of division of space is called as Kelvin problem and soap bubbles became the core of involved researches.

Today, foam is an interdisciplinary subject of physics, mathematics, chemistry and engineering science. Physics is interested in shape, orientation and physics of liquid foam along with mechanical and material properties of solid foam. Nano-scale foam models, such as atomic packing models of molecules and material properties of solid foams are the subjects of chemistry.

[1] Encyclopedia of Applied Physics (1997). USA:WILEY-VCH Verlag GmbH. ISBN: 3 527 29306 X

1.1.1 Foam Types

There is a wide range of foam types by material, constitution, behavior etc. Nevertheless, they can be classified in two major groups as liquid and solid foams.

Liquid foams are created by air dispersion in a liquid. The properties of liquid content determine stability of the foam. Stable foams cannot be made by pure liquids. Additional substances, such as natural or synthetic soaps or proteins, are used as foam promoters to provide the stability of the foam.[2] There are two sub-types of liquid foams i.e. two-dimensional and three-dimensional foams, that are distinguished as wet and dry foams within each sub-category.

The two-dimensional foam could be made by squeezing the three-dimensional liquid foam between two glass plates. Honeycomb is the best example of the two-dimensional foams in the nature (Weaire and Hutzler, 1999). Two-dimensional liquid foams can be either in a wet or dry foam form. The two-dimensional wet foam consists of two-dimensional circular bubbles. Because of the high liquid fraction, this two-dimensional foam is called wet foam. When the liquid fraction of wet foam increases, the shapes of the foam bubbles approach to circle.

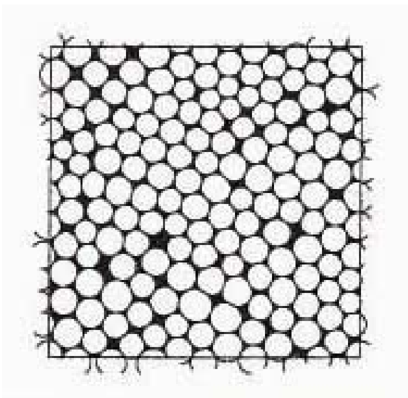


Figure 1: Computer simulation of two-dimensional wet foam
liquid fraction Φ_l=0.12

The two-dimensional dry foam is derived from two-dimensional wet foam by reducing the liquid fraction of the foam. Two-dimensional dry foam simply consists of polygons with arch edges

[2] The New Encyclopedia Britannica (1985). Chicago,USA: Encyclopedia Britannica,Inc. ISBN:0 85229 423 9

and different variations of polygons could be observed. Every three edges of the foam meet in a vertex at the Plateau 120˚ rule (see History of the Foam Theory, Weaire and Hutzler, 1999).

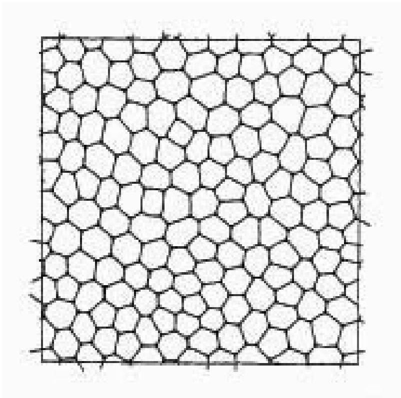


Figure 2: Computer simulation of two-dimensional dry foam liquid fraction Φ_l=0.02

The three-dimensional foam in liquid environment comprises almost spherical bubbles and this type of foam is called the three-dimensional wet foam. It has high liquid fraction like the two-dimensional wet foam. When the liquid fraction of wet foam decreases to a certain level, bubbles transform from spherical to polyhedral shape. The foam becomes a network of thin liquid films joining together with Plateau rules. In this case, it is called the three-dimensional dry foam (Garcia-Gonzales and Monnereau, 1999).

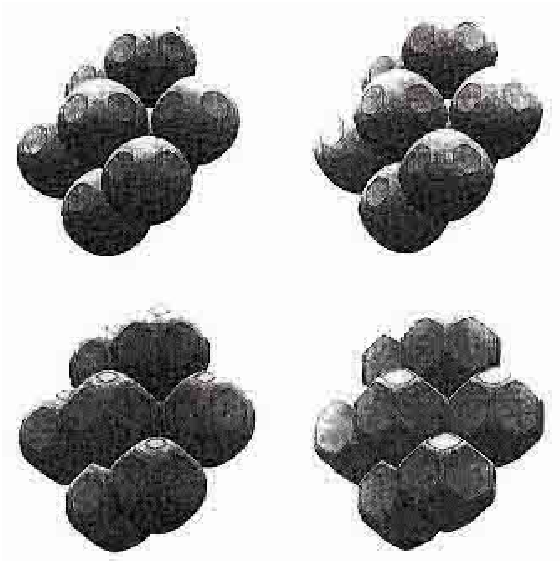


Figure 3: Transformation of the three-dimensional wet foam by decreasing liquid fraction

Solid foams are common constitutions in both nature and industry. Sponge, cancellous bone, cork are examples of natural solid foams. Industrial foams, or artificial foams, could be made of metal, polyurethane, ceramic or glass and they can be 100 times lighter than the equivalent solid material.

The typical manufacturing method of solid foams is rapid solidification of liquid foam. In the first step, the liquid is foamed with gas bubbles by using special chemical additives in the liquid material. This step is run under controlled temperature and pressure. The second step is solidifying the foamed material which is done by freezing the foamed liquid or through chemical reactions or decomposition.

A partition of solid foam is called a “cell”. Because solid foams are derived from liquid ones, the shapes of solid foam cells and liquid foam bubbles are similar. Basically, there are two types of cell in artificial foams. In the first case, the network of edges and faces still exist in the cells like foam bubbles and this type is called the closed cell foam. In the second case, the foam comprises only the network of edges without cell faces. This foam is called the open cell foam.

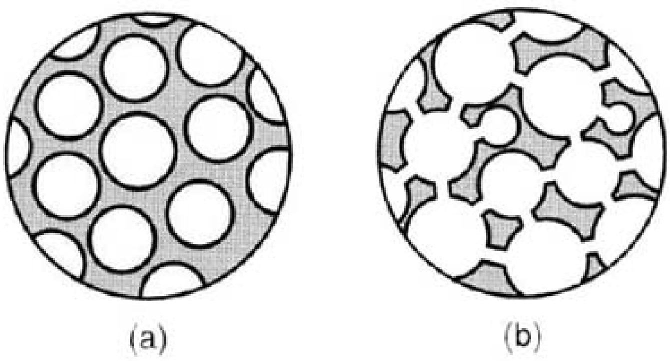


Figure 4: Closed cell foam (a) and opened cell foam (b)

The self-supporting constitution of opened cell foams are unlike closed cell foams but it is similar to that of dry foams. In closed cell foams, both cell edges and faces provide stiffness while the stiffness of opened cell foam derives only from the cell edges. Similarly, in dry foams, surface tension causes the liquid to be dragged in to the bubble edges and faces are covered by a thin membrane. Despite the fact that, bubbles (cells) of dry foam are closed, stiffness mostly arises from the bubble (cell) edges. In this sense, dry foams and opened cell foams are identical (Gibson and Ashby, 1997). On the other hand, theoretically, the edges of cells in an open cell foam must meet at the Plateau rules to provide stability. In other words, the process of manufacturing must be accomplished precisely in the right time. However, stopping the industrial process just in the right time and providing the Plateau rules in every vertice of the network of the solid foam is practically impossible. Therefore, the science behind the self-supporting behavior of opened cell foams is obscure (Weaire and Hutzler, 1999).

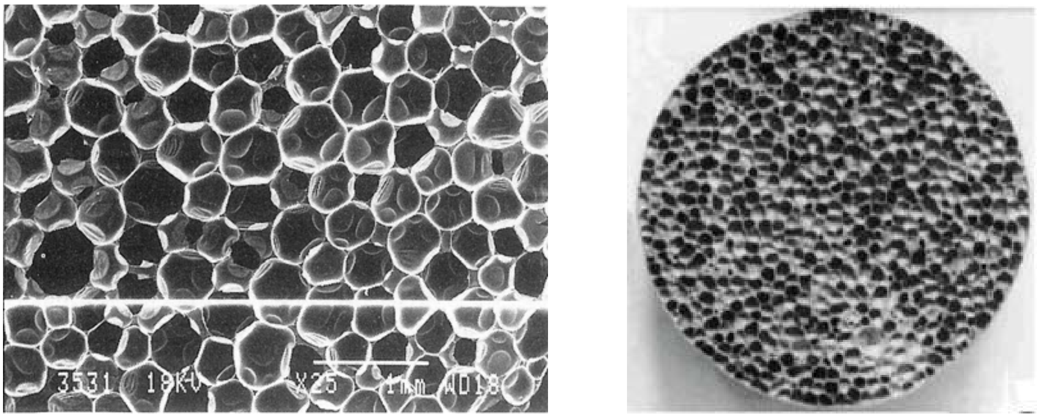


Figure 5: Polystrene foam (left) and aluminium foam (right), various shapes of cells

The mechanical behavior of solid foams depends on the cell type and the material. The solid foam could be elastomeric or ductile, which is capable of deforming plastically without fracturing or brittle (Gibson and Ashby, 1997).

1.1.2 History of The Foam Theory

Finding the shape of soap bubbles with minimum partitional area in a continuous array of soap bubbles is a mathematical problem since the late 18^{th} century.

Belgian physicist Joseph Antoine Ferdinand Plateau can be considered as the pioneer of research on foam. In 1873, Plateau published “Statique expérimentale et théorique des liquides soumis aux seules forces moléculaires” as a complete summary of his research. This work was based on the idea that foam is not ruled by chance. To demonstrate, he has observed soap bubbles and presented fundamental geometrical principles of foams under static conditions. These principles are named “Plateau rules” (Weaire and Hutzler, 1999).

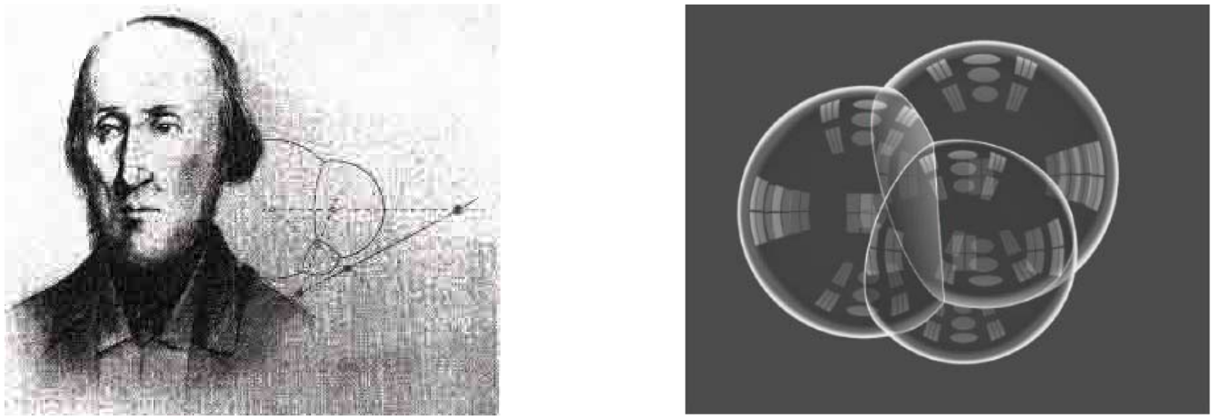


Figure 6: Joseph Antoine Ferdinand Plateau and the illustration of Plateau Rule: Three bubbles meet at angle of 120°

According to Plateau rules, soap bubbles, bubble clusters and soap films are supported on wires. These wires consist of bubble edges and vertices. Each bubble comprises three soap films and four bubble edges. Soap films meet at equal angle of 120˚ and bubble edges meet at tetrahedral angle of 109.47˚ in the vertices. Furthermore, all of the soap films are not flat and also the edges are not straight because it is not possible to meet only straight edges at the equal tetrahedral angle in the vertices. These geometrical principles provide the balance between surface tension forces of films and pressure differences of bubbles (Kraynık and Reinelt, 1996). Plateau's results encouraged subsequent researches about the problem of division of space with a minimum partitonal area.

Several years after Plateau's publishing, in 1887, Irish scientist Sir William Thomson (Lord Kelvin), inspired from Plateau's research, developed an ideal model of a foam (Weaire and Hutzler, 1999). It was a significant improvement, which inspired many new researches. His model, known as *Kelvin foam*, perfectly meets with Plateau's Rules.

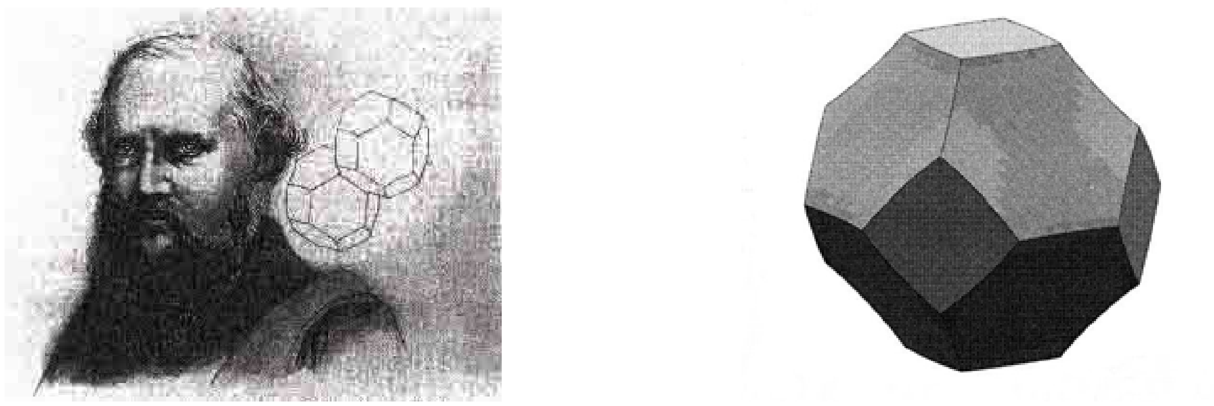


Figure 7: Sir William Thomson (Lord Kelvin) and Kelvin bubble

Kelvin foam comprises 14-sided polyhedral bubbles. Each polyhedral bubble consists of six flat square faces and eight non-planer hexagonal faces and the curvature of the edges are the same. As Plateau rules requires, bubbles meet at 120˚ angle, edges of the bubbles meet at 109, 47˚ angle and they are slightly curved in order to meet at Plateau's Rules. Moreover, the bubbles of foam are combined with the same orientation in which each square faces are perpendicular to the coordinate axis (Kraynık and Reinelt, 1996; Kose, 1995).

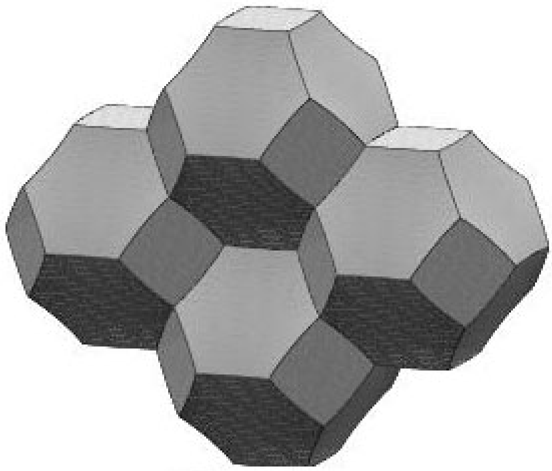


Figure 8: Orientation of Kelvin foam

Kelvin's ideal foam model was not scientifically verified. However, it remained as an optimal model of the problem of division of space for years. However, in 1946, results of the experimental research of American botanist Edwin Martzke caused doubts about Kelvin's model.

In Martzke's experiment, 2000 equal volume soap bubbles were made by using a syringe, one by one, in a cylindrical dish and it was repeated 16 times. 600 of 2000 soap bubbles, placed around the central axis of the cylinder, were observed with binocular dissecting microscope. Many of individual bubbles were captured and 40 drawings were made based on the photographs. As a result, many bubbles with the shape of 12, 13, 14 and 15 sided polyhedra and very few with the shape of 11, 16 and 17 sided polyhedra were detected. No exception of the Plateau Rules could be observed but Martzke couldn't find any single bubble with the shape of the Kelvin bubble. He asserted that this is the result of the perfect ordering and monodispersity of the Kelvin foam. And also, Martzke claimed that practically, it was not possible to make bubbles in perfect ordering. He explained that readjustments and slipping always occur and Kelvin bubble can only be observed if every equal volume bubble is put in its exact place (Kose, 1995).

Even though the Kelvin bubble couldn't be observed in Martzke's experimental research, its first photograph of Kelvin bubble was published in botanist John D. Dodd's research about 10 years after Martzke's experiment. Many years after, Weaire and Phelan and Darton observed the Kelvin bubble in soap foam and found that pentagonal face is a common face in soap foams, which does not exist in the Kelvin model.

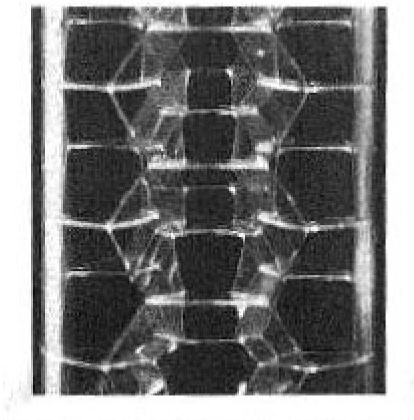


Figure 9: Picture of string of Kelvin bubble captured by Weaire and Phelan

Another foam model was developed by Robert Edward Williams in 1968. Williams bubble, which is called β-tetrakaidecahedron, was derived from the Kelvin bubble, which is also known as α-tetrakaidecahedron. The Kelvin bubble was deformed to Williams bubble by firstly, rotating the one common edge of the two hexagonal faces of the bubble 90˚at first and joining them to other edges again and then repeating the process with the same group of edges on the opposite side of the bubble (Williams,1968).

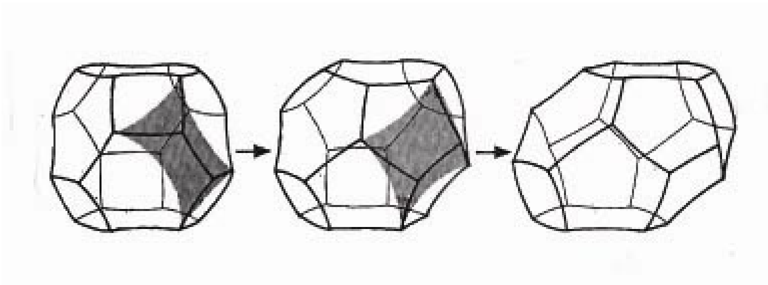


Figure 10: Transformation of the Kelvin bubble into Williams bubble

Williams' foam model consists of two tetrakaidecahedral bubbles. In fact, the bubbles have the same shape but different orientation. Each bubble comprises two flat quadrilateral faces, eight pentagonal faces and four hexagonal faces (Kraynık and Reinelt, 1996). Although Williams bubble contains pentagonal faces, the same number of faces, vertices and edges with the Kelvin bubble were retained, the Williams bubble consists of 14 faces, 24 vertices and 36 edges like Kelvin bubble. Because of both the pentagonal faces and the number of faces, Williams' model is highly satisfactory model in terms of Martzke's demonstration. However, the surface area of Williams bubble is 4% more than the Kelvin bubble (Williams, 1968). 30 years after, in 1996, Kraynık and Reinelt measured the surface area difference between Kelvin and Williams bubbles. It is found that the Williams bubble has just 0.581% more surface area than the Kelvin bubble (Kraynık and Reinelt, 1996).

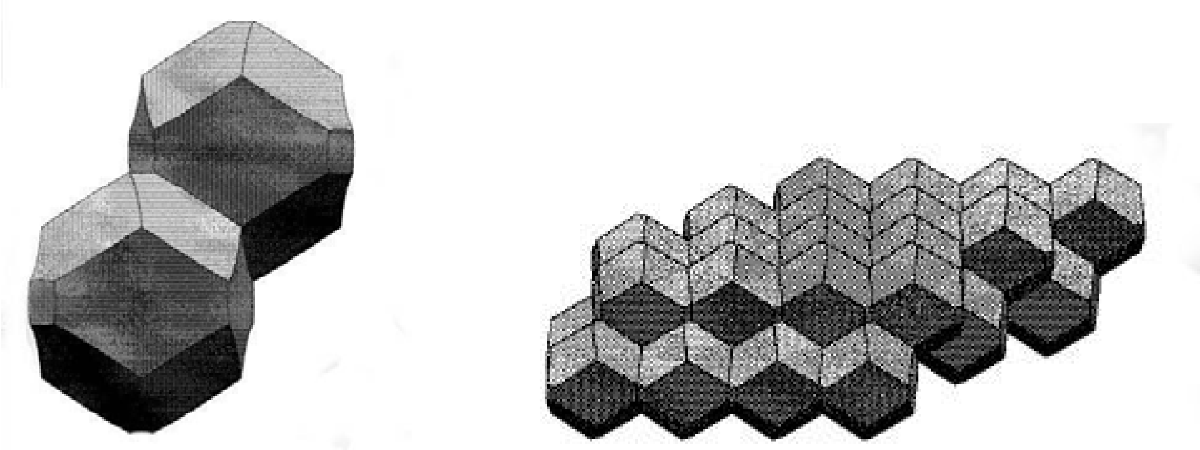


Figure 11: Williams bubble and orientation of bubbles

In 1993, a new optimal foam model published by Irish Physicists Denis Weaire and Robert Phelan from Trinity College of University of Dublin. Weaire-Phelan foam model had 0.3% less partitional area than Kelvin's model. Currently, Weaire-Phelan model remains as the optimal model of foam, which has the lowest partitional area ever.

1.1.3 Weaire-Phelan Model

The Weaire–Phelan foam model consists of two types of bubbles: One type is a 12-faced polyhedron composed of non-plan pentagonal faces and the other type is 14-faced polyhedra composed of two flat hexagonal faces and twelve non-plan pentagonal faces. Two 12-faced bubbles and six 14-faced bubbles, in total eight bubbles, constitute the Weaire-Phelan bubble cluster, which is the recursive unit of the foam (Kraynık and Reinelt, 1996).

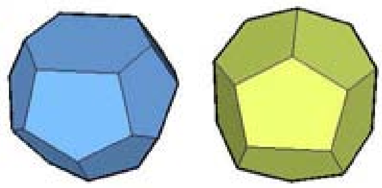


Figure 12: Weaire-Phelan bubbles: 14-faced polyhedron (blue) and 12-faced polyhedron (yellow)

In the orientation of Weaire-Phelan bubble cluster, 14-faced polyhedral bubbles constitute three perpendicular columns of the cluster and hexagonal faces separate bubbles of each column. 12-faced polyhedral bubbles fill the space between columns (Kraynık, 1996).

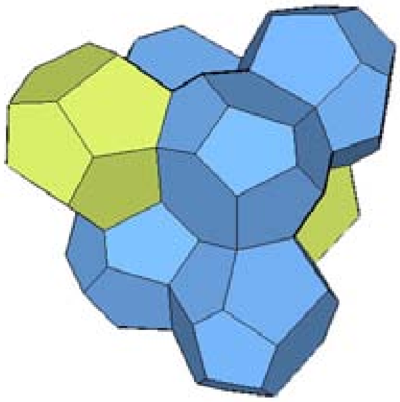


Figure 13: Orientation of Weaire-Phelan bubbles

The characteristics of the ideal bubble of Kelvin's problem were calculated and the results showed that the ideal bubble has 13.397 faces and each face has 5.104 sides. Weaire and Phelan improved their model with the least possible derivation from the ideal values. One type of Weaire-Phelan bubble is 14-faced and the faces have 5 or 6 sides, the second type bubble is 12-faced and each face has 5 sides (Weaire and Hutzler, 1999).

Weaire-Phelan model was improved based on computational analysis of some crystal structures. Although Kose claimed that Weaire-Phelan model was not proven experimentally (Kose, 1996), the picture of Weaire-Phelan bubble has been published in the book "The Physics of Foams" in 1999 (Weaire and Hutzler, 1999).

The picture below is captured during the experimental observation of Weaire-Phelan foam. It shows a fragment of the Weaire-Phelan model in the three-dimensional monodisperse foam and it has been matched by same perspective view of it's 3D computer based model (Weaire and Hutzler, 1999).

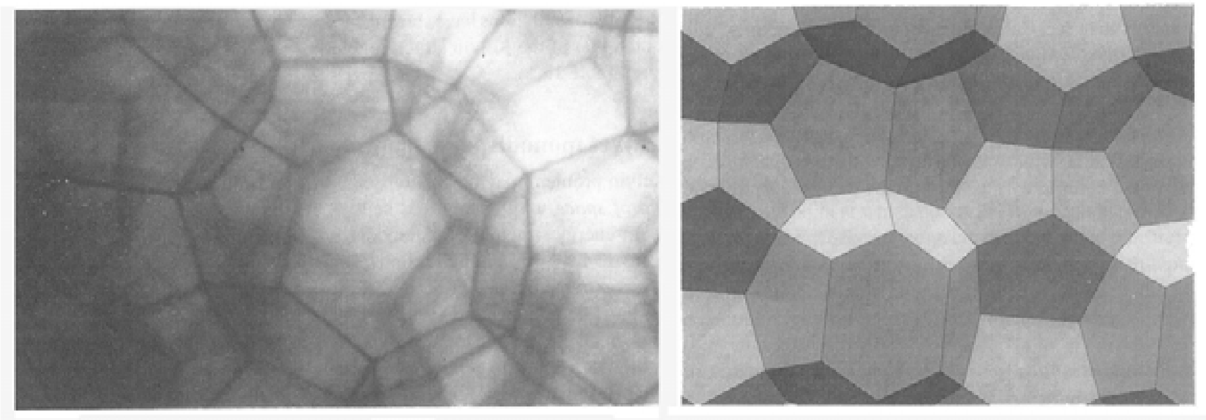


Figure 14: Experimental observation of the Weaire-Phelan bubble matched by it's 3D computer based model

Energy levels of the demonstrated models of Kelvin's problem i.e. Weaire-Phelan model (A15), Frank-Kasper phase (C15), Kelvin model (bcc) is compared in Table 1. Dry foam energy is given by,

$$E_{surface}=A\ .\ \gamma_{\mathrm{surface}}$$

where γ is the surface tension and the *A* the surface area. In each case, surface tension is γ=1 and volume of cells is unity (Weaire and Hutzler, 1999). Results, given in per cell, show that Weaire-Phelan model has the lowest dry foam energy.

STRUCTURE	DRY FOAM ENERGY
simple cubic	6.00000
fcc	5.34539
bcc	5.30628
C15	5.32421
A15	5.28834

Table 1: Comparison of dry foam energy levels of demonstrated models

In the above table, simple cubic, fcc and bcc denotes the three basic packing types: simple cubic cubic packing, face centered cubic packing (fcc) and body centered cubic packing (bcc). The Kelvin model is bcc packing.

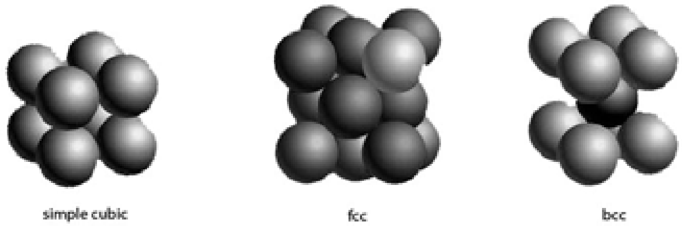


Figure 15: Packing types of foam models

1.2 Natural Foams

Natural solid foams are either inorganic or organic. Natural sponge is a well known example of organic solid foam. Cancellous bone is natural solid foam, which has an organic constitution.

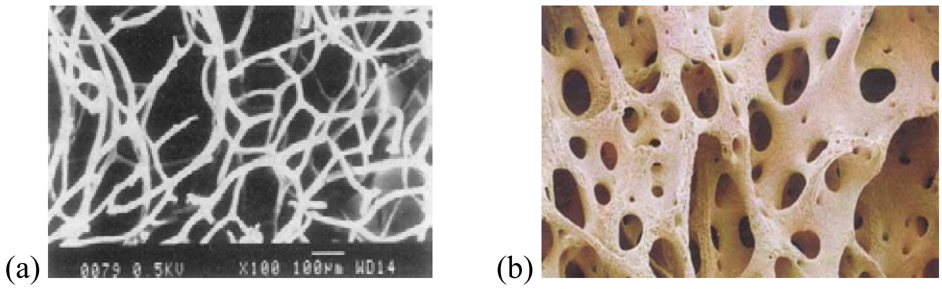


Figure 16: Natural solid foams: (a) sponge, (b) cancellous bone

Cork Oak, as natural organic solid foam, is widely used in wine industry as a cork stopper. It has a highly anisotropic constitution. The pictures below shows the anisotropy of cork oak.

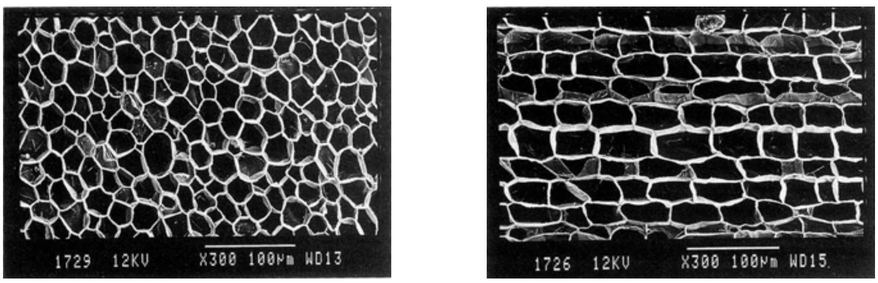


Figure 17: Cork is an anisotropic natural foam and its anisotropy is shown in two different directions

1.3 **Artificial Foams**

Artificial foams are man-made foams. They are widely being used in many fields of the industry because foamed materials have many superior features compared to natural constitution of that material. Metal, polymer, ceramic and glass foam are the most common and well-known examples of foam in the industry. On the other hand, some of artificial foams are the part of ever day life; they are organic and delicious.

1.3.1 Organic Foams

Either liquid of solid, artificial organic foams are a part of everyday life. The whipped cream on top of coffee, marshmallow filling of snack, maringue or bread.



The foam promoters, in most of foodstuffs, are proteins. Proteins such as egg white and gelatin are used as stabilizer of the foam of wiped cream, marshmallow or meringue. Beer and champagne foam are other common examples of artificial organic foams.

1.3.2 Metal Foams

Metal foam is a low-density material. It has an excellent performance in mechanical, electrical, thermal and acoustic applications (Körner and Singer, 1999). A well-known mechanical use of metal foam is lightweight sandwich construction. The material of sandwich cores must be stiff, strong and light as much as possible and metal foam has sufficient properties for such core applications. For instance, aluminum foams are widely used in the automotive industry because of their low density and relatively high rigidity. They are efficient materials, especially for sandwich panels. Besides, compressive strain tests show that aluminum core sandwich panels give better results than steel systems and steel plus aluminum systems (Körner and Singer, 1999; Baumgärtner, Gers and Seeliger, 1999). Besides its mechanical properties, the aluminum foam is a good acoustic damper and thermal insulator and a good material for high impact energy absorption and applications of buoyancy.

Solid foams are good sound absorbers. Their cellular constitution causes an energy loss in sound waves with friction during the gas flow within cells. Therefore, metal foams are highly efficient materials for acoustic damping applications, as well as the other artificial foams (Körner and Singer, 1999).

Metal foams have high thermal conductivity despite their cellular constitution. Their high thermal conductivity combined with large internal surface make metal foams efficient materials for heat exchangers (Körner and Singer, 1999).

Consequently, metal foams possess properties of both cellular solids and metals. Hence, they have a unique property combination. For instance, metal foams are stiff and lightweight or stiff and highly thermal conductive. They are efficient materials especially for applications in which more than one functions is required e.g. high stiffness and acoustic damping, high stiffness and fire resistance, or thermal stability and acoustic damping.

1.3.3 Polymer Foams

Polymer foams are widely used in many applications of aerospace and maritime industry, as well as the medical field. They have uniquely combined properties: lightweight, high flexibility and mechanically strength. It is not possible to find this combination in natural materials.

Basically, there are two types of polymers in terms of their constitution. Simple polymers are homogenous and they have similar density and strength in every direction. Complex polymers are not homogenous. Their production process lets different properties on the surface and in interior. Complex polymers are suitable for multi-layered applications where each layer has differentiated function i.e. multi-functional façade systems, which comprise a very strong transparent film that is water-repellent and self-cleaning surface (Hensel, Menges, and Weinstock, 2006).

Thermal conductivity of polymer foam is low which makes them good thermal insulation materials. Insulation of refrigerators is a good example of the thermal application of polymer foam. In the refrigerator insulation, according to the design life of the machine, mostly PHEN (phenolic foam), EPS (expended polystyrene) and PP (polypropylene) are used (Gibson and Ashby, 1997).

Moreover, closed-cell polymer foam is used in buoyancy applications because they have the lowest density comparison to the other solid foams. On the other hand, opened cell foam is used for filtration. For example, dust filters in air-conditioners, air-cooled electronics and face masks are made of polymer foams. Another well-known example of polymer applications is cycle helmet. Cycle helmet is an energy-absorbing system. Between inner and outer shell, commonly EPS is used as an omni-directional energy absorber (Gibson and Ashby, 1997).

1.3.4 Ceramic, Glass and Artificial Liquid Foams

Ceramic is very light material. It's compressive strength is equivalent to metal but in some cases, it can be even higher. The weakness of ceramic is its lack of tensile strength (Hensel, Menges and Weinstock, 2006). Because of that ceramic and ceramic foams are not preferred in mechanical uses. Nevertheless, ceramic foam is good thermal insulation material especially for very high temperature applications. Furthermore, it is used in filtration of liquid metals (Gibson and Ashby, 1997).

Glass foam is good thermal insulator for high temperature applications. Moreover, a glass foam type, called "bio-glass" is used for bone regeneration in medical field (Gibson and Ashby, 1997; Hensel, Menges and Weinstock, 2006).

The greatest use of artificial liquid foams is fire-fighting applications which benefits from the bubble constitution (low density and stability of fire-fighting foam). Fire-fighting foam forms a blanket on the top of burning materials and acts as an oxygen blocker. Furthermore, artificial liquid foams are used for ore segregation, coal cleaning and oil recovery (Weaire and Hutzler, 1999).

2 Case Studies

In this part, the Water Cube and the Symbol Zone of the Expo'70, which are the two physical examples of two structural types of comparative study, will be discussed and analyzed. Deep understanding of foam structure of the Water Cube and space frame structure of the Symbol Zone is aimed to be achieved with these case studies.

2.1 The Water Cube

The Water Cube is the one of the most inspiring projects of recent years. It is huge and radically different from conventional large span building structures. Because of its foam structure, it constitutes the point of interest of this study.

2.1.1 Context

The Water Cube rises as a monument of future buildings. It represents current technology and gives an inspiring impression of future buildings. As a product of advanced structural engineering and architecture along with a radical design approach, it is one of the most significant buildings in recent years.

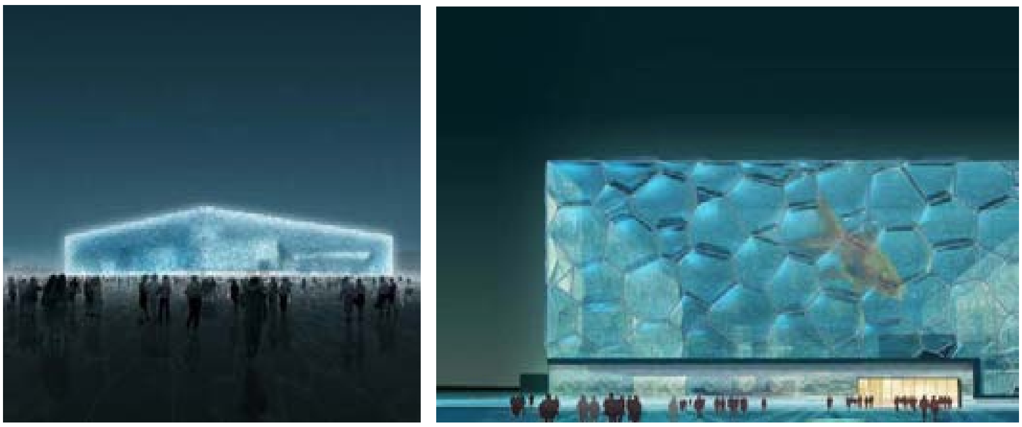


Figure 18: Perspective and façade view of the Water Cube

First of all, the Water Cube is the first and unique example of foam structures at extremely large scale. There are also other projects referred with the name having a bubble or foam such as Bubble High Rise which is a concept project for Berlin designed by SMO Architecture & Arup London in 2002.

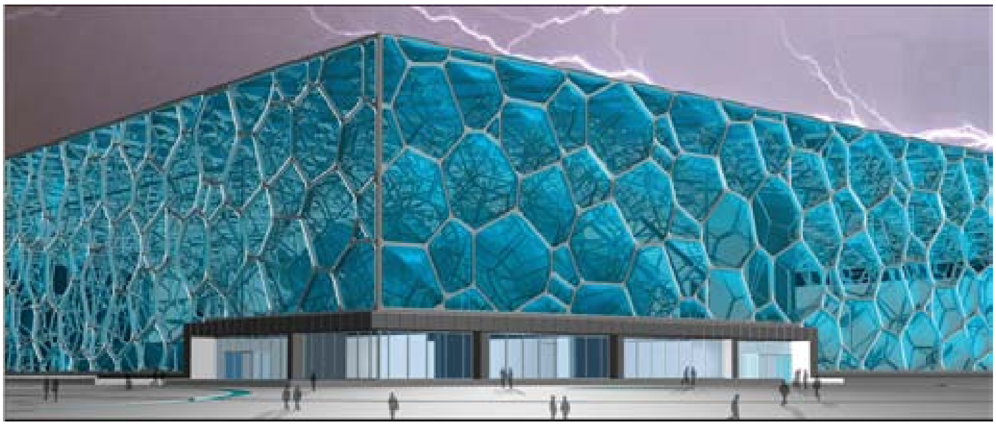


Figure 19: Perspective view of the Water Cube

But the structure of the building reminds one of two-dimensional wet foam, which consists of circular bubbles, and it is a highly idealized structural interpretation of foam constitutions in nature existing mostly in three dimensions as a structure of matter.

Figure 20: Bubble High Rise concept project

Secondly, the design approach of the Water Cube is radically different from the conventional design approach. Space filling structural constitution in nature constitutes the origin of new design approach of the Water Cube. In the conventional approach, architectural design is mostly adopted to structural boundaries, in other words, the load-bearing structure dominates the building especially in the design of high-rise or large span buildings. But the new design approach of the Water Cube accepts the structure as an element of architectural design. This approach is inspired by nature.

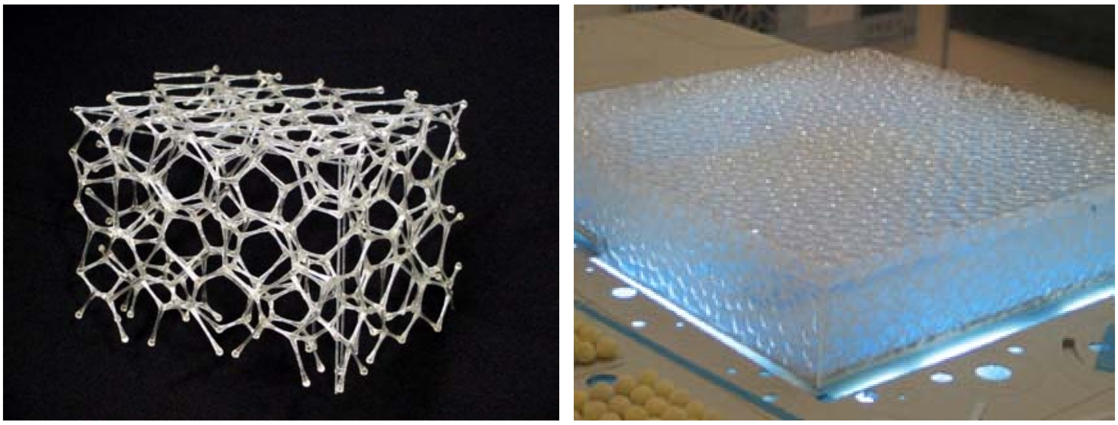


Figure 21: Rapid prototype models of the Water Cube structure

Structures in nature are part of matters that are homogenously or heterogeneously spread within composition of the matter such as cancellous bone. The foam structure of cancellous bone, is also the tissue of the bone; it exactly fills the space within bone boundaries instead of grown as outer or separate support. The object itself is also the structure.

Thirdly, conventional building structures are composed of beam, column, and slab elements, etc. All these elements have different cross-sections, dimensions and most importantly different functions from each other. While columns are vertical load transmitters of load-bearing system, slabs and beams are the horizontal load transmitters. But the elements of the Water Cube structure are all the same. Unlike conventional structures, there is neither column nor beam in the Water Cube.

Figure 22: Inner perspective views of the Water Cube

Moreover, behind the highly random appearance of the Water Cube, it is simply a recursive structure like other space frame structures. The recursive module of the structure is a bubble cluster which is designed based on the physical-mathematical model of the most efficient subdivision of space into equal volume cells (what would the shape of soap bubbles in continuous bubble array foam be), which is the Weaire-Phelan model. The overall structure is composed of thousands of bubble clusters.

On the other hand, beside its structural constitution, the Water Cube is also a new type of large span building structure. With the largest clear span of 140 m x 120 m, the Water Cube could be considered as a competitive structure of large span, compared to other large span building structures such as the space frame.

Consequently, the Water Cube is a good example of macro-scale foam structure in terms of architectural and structural design. Furthermore, the idea of using the most efficient soap bubble model, which is Weaire-Phelan model, as a basis for the design is a significant approach regarding the geometric efficiency. Moreover, the structure as a space filling large span building structure constitutes a convenient statement for comparative efficiency analysis of foam structures because there are other large span building structures in space filling structures category such as a space frame.

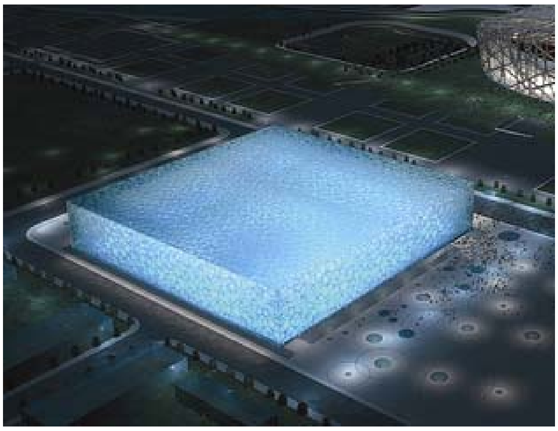
The geometrical and structural constitutions of the Water Cube structure are the focus of this case study. Understanding the structural constitution behind its random and relatively complicated appearance and, more importantly, discovering the transition from the theoretical foam model to the real macro-scale foam structure is the aim of this case study.

2.1.2 Strategy

The case study will be represented in two parts. The structural constitution of the Water Cube in terms of structural dimensions, dimensions of elements, joints, load-bearing system, cladding and other properties of the structure in the first part will be focused on. This analysis will provide deep understanding of the Water Cube structure and it will expose many key considerations of the transition from theoretical phase to structural phase such as the relation between the types of joints, stability and shape of the basic recursive units.

In the second part, following the same way used in modeling of the Water Cube, a new foam structure will be modeled based on the case of Water Cube. In this way, the same transition from the theory to structural design will be passed through and regularities and/or irregularities, the complexity level of the Water Cube structure and assumptions of the transition will be exposed. Furthermore, the new foam structure model will be used in the parametric comparison analysis.

National Swimming Center, Beijing "The Water Cube"



Location	Beijing,China
Function	swimming/aquatic center of Beijing Olympics 2008
Status	under construction
Project Information	
Client	Beijing State-Owned Assets Management Co.Ltd.
Owner	People's Government of Beijing Municipality
Design	Ove Arup&Partners Ltd., CSCEC Shenzhen Design Institute
Architecture	PTW Architects
Engineering	Ove Arup&Partners Ltd.
Contractor	China State Construction&Engineering Corporation
Begin Date	End of 2003
Finish Date	October,2007
Scope	
Construction Area	79 532 m2
Construction Cost	100 M $
Technical Information	
Structural Type	Large Span Polyhedral Space Frame
Structural Material	Steel
Architectural Volume	177 m x 177 m x 31 m = 971 199 m3
Longest Clear Span Volume	140 m x 120 m x 31 m = 520 800 m3

2.1.3 Description of the Project

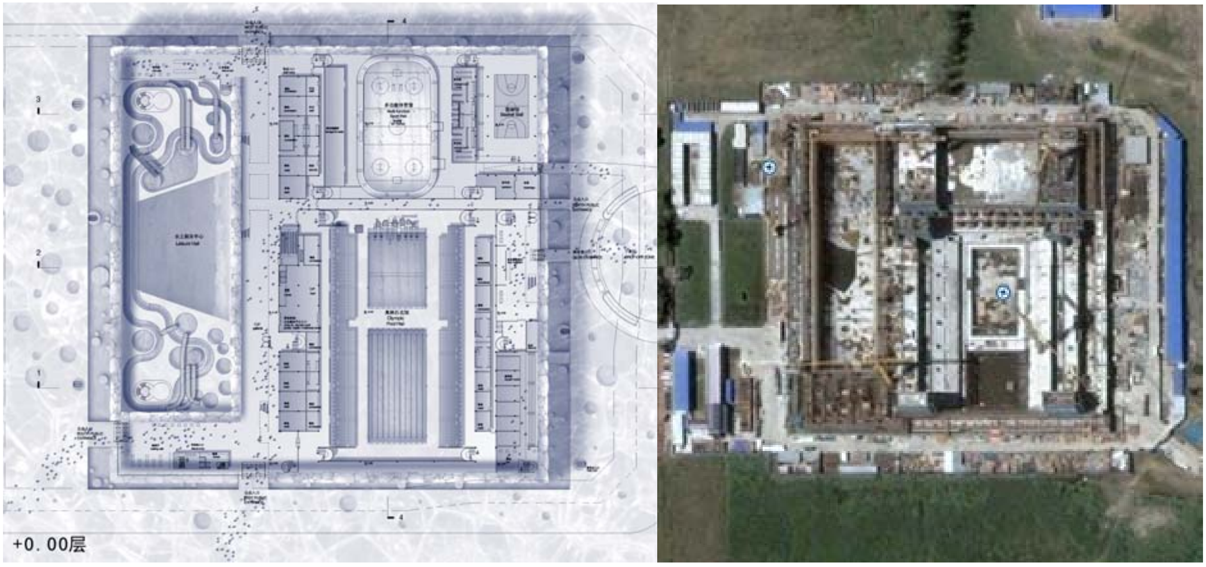


Figure 23: Floor plan at ± 0.00 and bird's eye view of the Water Cube

The Water Cube is 177 m wide, 177 m long and 31m high. It is a large span foam structure which is also called a polyhedral space frame. Even though, its random appearance, the Water Cube is a recursive structure. The basic recursive unit of the structure is a bubble cluster which is designed based on Weaire-Phelan model. A bubble cluster consists of eight bubbles. There are two types of bubbles in the cluster, in other words, the structure is composed of the recursive orientation of only two different bubbles.

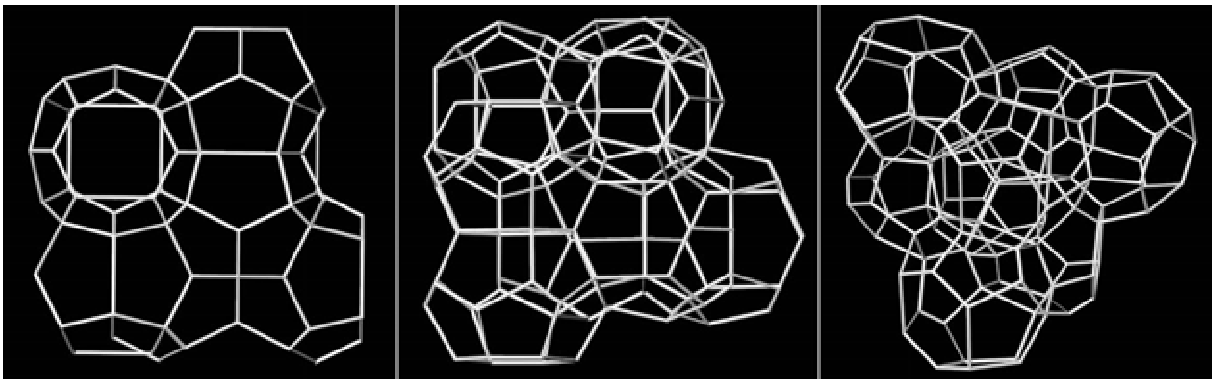


Figure 24: Top, front, and perspective view of the Water Cube structure module: bubble cluster

2.1.4 Load-Bearing System

In the Water Cube structure, the same foam structure is used in both walls and the roof. The structural system consists of bubble clusters which are made up by steel tubular members. There is neither a column nor a beam in the entire structural system. While foam structure in the roof transmits loads horizontally, the same foam structure in the walls transmits loads vertically.

Largest clear span of the structure is 140 m x 120 m. Structural dept of the outer walls is 3.6 m and structural depth of the roof is 7.2 m. Basically, the structure consists of three parts (Structural Engineer (1) 2004; Arup 2006; Architecture and Urbanism 2005):

1. Outer flat web frame
2. Inner flat web frame
3. Inner foam structure

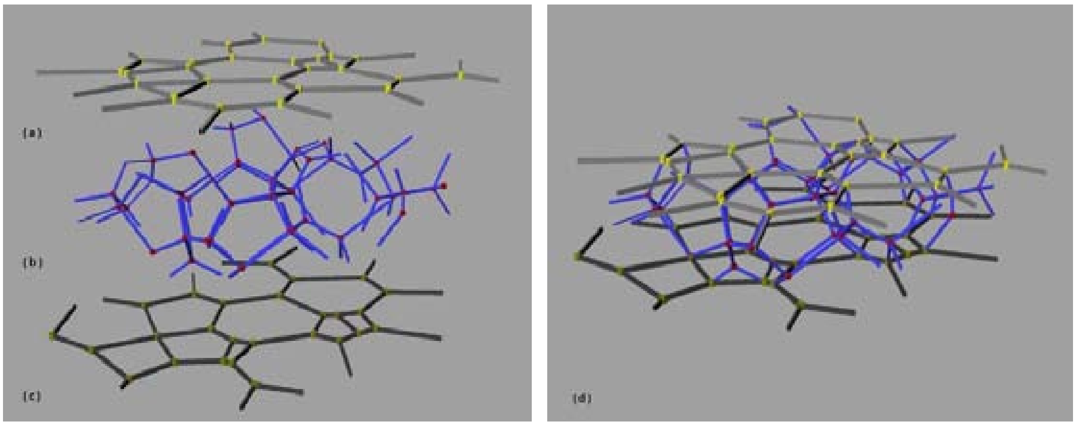


Figure 25: (a) outer web frame, (b) foam structure, (c) inner web frame, (d) the Water Cube structure

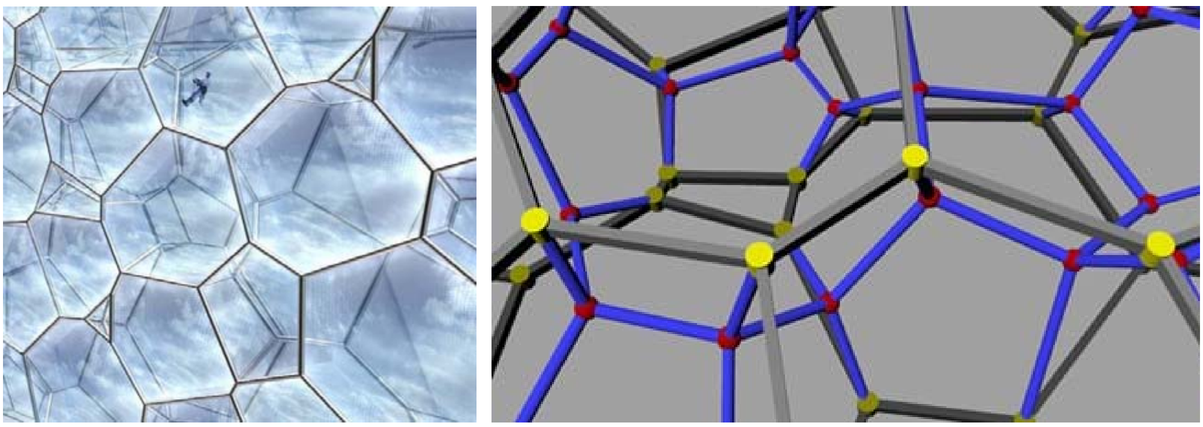


Figure 26: Perspective views of structural system: outer and inner frame and inner structure

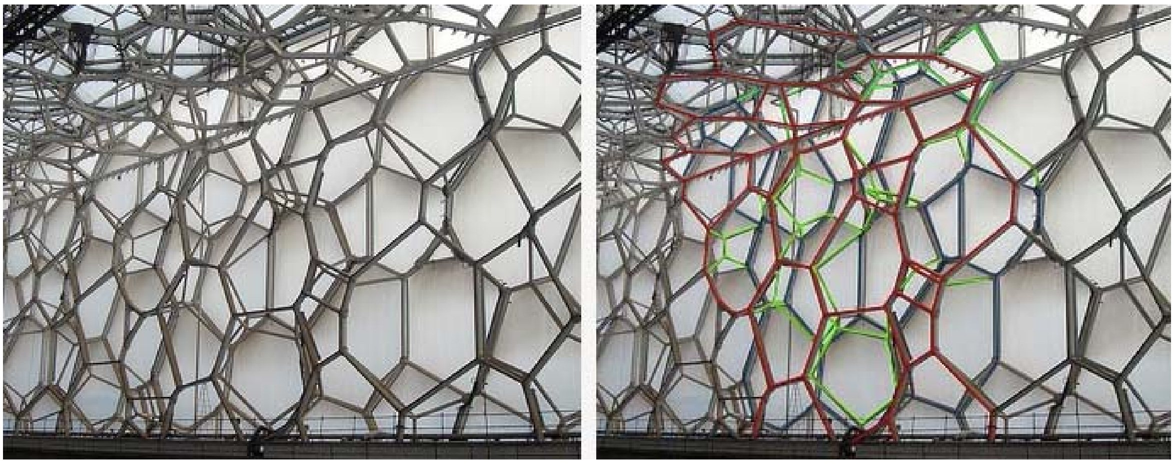


Figure 27: The Water Cube structure: Red represents inner web, blue represents outer web and green is foam structure

The outer frame and inner frames are composed of rectangular steel hollows in many different dimensions. The web frames provide the perfect prismatic shape of the structure and they could be also considered as the cutting planes of foam structure (Arup 2006; Architecture and Urbanism 2005).

Figure 28: Picture of roof nodes during the assembly of the structure

Inner structure is designed based on the Weaire-Phelan foam model. There are around 4000 bubbles in the entire structure and the width of the bubbles is about 7.5 m. Inner structure is made up of circular steel hollows in various dimensions. Each steel circular hollow is welded to ball-shaped node joints. Therefore, all connections of the inner structure are rigid (Arup 2006).

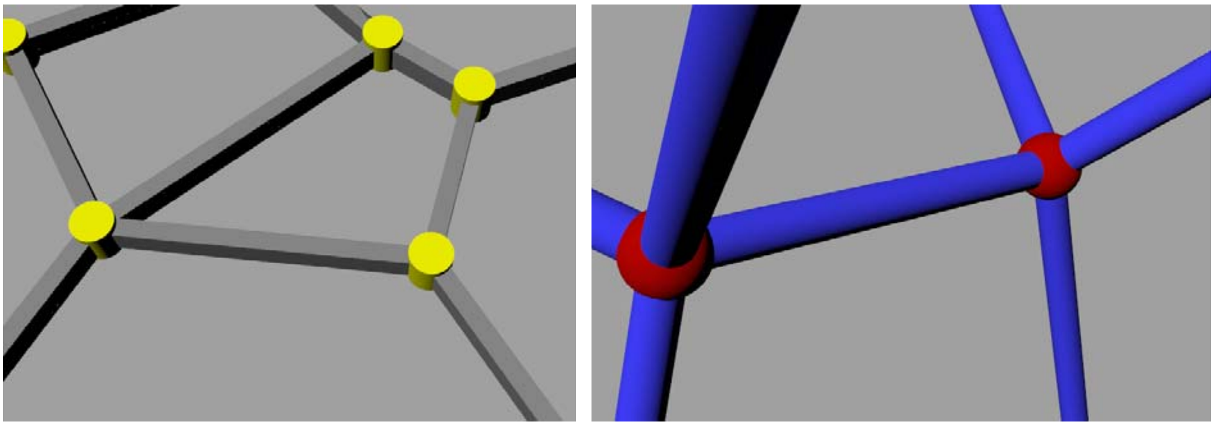


Figure 29: Simplified model of web joints and foam structure joints

There are 22 000 steel members, 12 000 nodes and 190 loading conditions in the structure. 6500 tones of steel is used in the construction. The dimensions of every single member is tried to be kept as small as possible to minimize the steel tonnage, because dead load (self weight) is critical for such large span buildings like the Water Cube (Arup 2006 ; Chriss Bosse 2007). To increase dead load increase the structural deformation therefore dead load of large span buildings is tried to be kept as small as possible.

The substructure of the Water Cube is a reinforced concrete conventional structure (Structural Engineer (1) 2004).

Figure 30: Reinforcement substructure of the Water Cube

2.1.5 Cladding and Greenhouse Effect

The Water Cube is clad with ETFE foil cushions inside and outside. ETFE (Ethyl Tetra Fluoro Ethylene) is fluorocarbon based polymer. Thickness of ETFE foil used in the Water Cube is 2 mm and the largest area clad with ETFE is 9 m wide (Arup 2006; Structural Engineer (1) 2004).

Compared to glass, ETFE has better insulation properties. Furthermore, ETFE foil has a light transparency of approximately 94-97 percent of total light and a property of transmission of 83-87 percent UV lights which are better properties than glass properties (Architen 2007). Therefore, in the Water Cube, the heating and illumination system is designed and programmed to benefit from natural light and solar energy and in this way, for instance, 30 percent reduction in energy consumption and up to 55 percent saving in lighting energy are achieved in the leisure pool hall. Pools and interior spaces are heated by the energy trapped by the building which stands for 20 percent of the total solar energy falling on the building and this energy would be equivalent to the absorbed energy if the entire roof was covered in photovoltaic panels (Arup 2006).

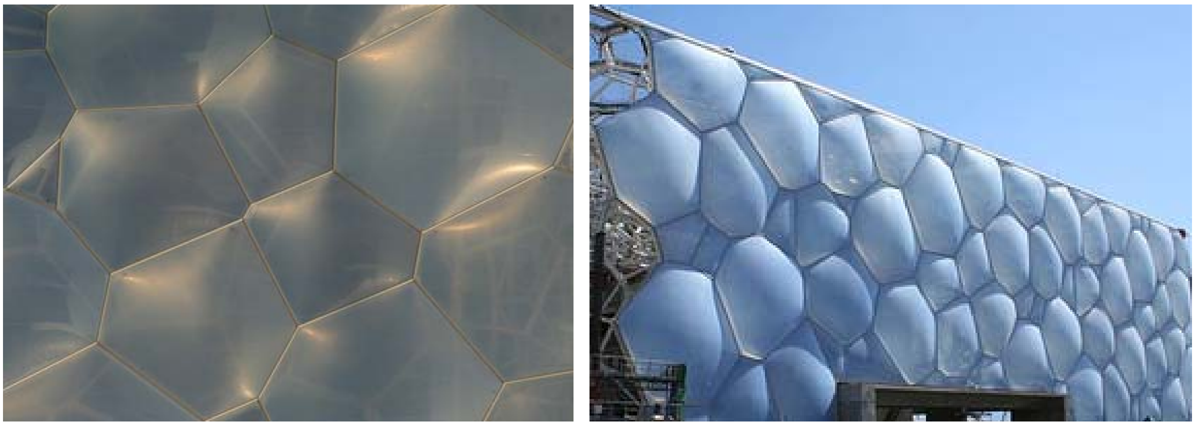


Figure 31: ETFE cushions

Above all, ETFE foil weighs only 2 to 3.5 kg/m2 which is just 1% of a glass panel with an equivalent-size. This is one of the most important reasons of choosing ETFE as cladding of the Water Cube façade. Because in total 100 000 m^2 area from inside and outside is clad with ETFE and this is a huge area. If the façade area was clad with other alternative material such as laminated glass, the cladding would highly increase the dead load of the structure and this would not be an optimal and efficient structural solution for the Water cube.

Moreover, ETFE is tough recyclable material, its durability is more than 20 years. It is highly resistant to the weathering effects of sunlight (Arup 2006).

Figure 32: ETFE cladding of the Water Cube

2.1.6 Structural Optimization and Seismic Design

Structural optimization means determining the structural design variables in the best possible way to achieve the highest structural performance with given constraints. There are many optimization types. For instance, size optimization is about sizing the structure and cross-section area and thickness of the members are the variables of size optimization. Shape optimization is about finding the shape of the structure which provides the highest performance to structure. Accordingly, shape boundaries are the variables of this optimization. And topology optimization is about the distribution of a given amount of material in specified structural domain.

Structures in nature are great examples of optimized structures. Every structure in nature is optimized in terms of its material, size, shape or topology. For instance, in natural structures there is a perfect material distribution related to the stress level of that structural area. That is, topology optimization (material distribution) achieves higher structural performance with less material. For example, the cross-section of the stem of palm tree continuously changes along the stem, and this creates anisotropic properties which provide different stiffness and elasticity values along the stem's length and hence the stem could resist dynamic and unpredictable loads (Hensel, Menges and Weinstock, 2006).

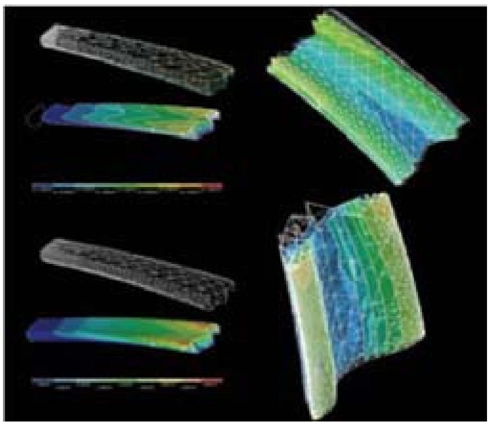


Figure 33: The analysis of the bending stress of a palm stem. Each color represents different bending stresses at different cross-sections

Structural optimization is an important issue for industrial structures in order to provide high structural performance and efficiency. Therefore, optimization process constituted significant part of structural design process of the Water Cube. The Water Cube structure is optimized based on the principle of minimizing the structural weight without scarifying strength. During the optimization process, 22 000 steel members with 190 different load combinations were checked at five points based on 13 certain equations in the Chinese Structural Code (Structural Engineer 2006). Special software was developed by Arup which is able to carry out optimization, structural analysis and design (Arup 2006).

Three main optimization cases were run during the structural design process of the Water Cube. The first is “strong wall and weak roof” optimization. In this optimization the control stress levels of wall members are lower than the control stress levels of roof members. The second is the section type optimization and instead of using standard sections with a longitudinal stiffener, compact sections are adapted to the structure and plastic properties of compact sections are utilized in the seismic design process.

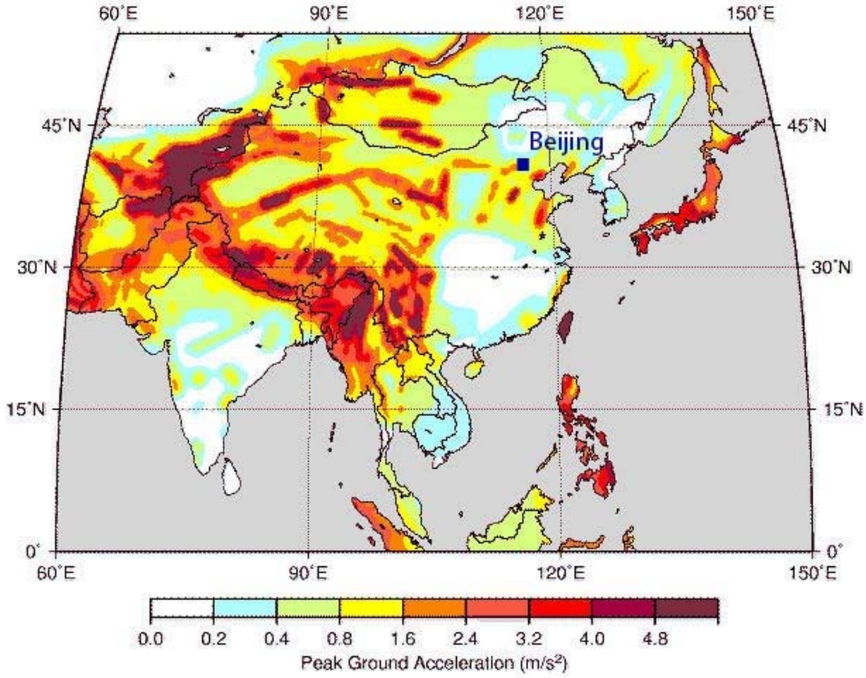


Figure 34: Asia Seismic Hazard Map

According to Global Seismic Hazard Map, Beijing is in medium-high risk seismic area. One of the biggest earthquakes of the world in the 20^{th} century occurred in 1976 in Tangshan Shi, which is just about 200 km away from Beijing with the magnitude of 7.5. Therefore, fulfilling the seismic requirements of Beijing was an important issue in the design process. Arup for the first time in the world did inelastic-cross section buckling analysis by using a special technique developed by themselves and the Water Cube seismic design was accomplished by adopting the final solution of the analysis to compact sections which have plastic behavior under level three seismic loading of Beijing. The third optimization case is hybrid optimization of geometric constitution in which the bending stresses of the members near the boundary of the walls and the large span roof are decreased (Fu and Gu, 2005; Arup 2006).

2.2 **Expo'70 "The Symbol Zone"**

In many resources, the Symbol Zone of the Expo'70 is given one of the good examples of large span space frame structures. Furthermore, it has many common futures with the foam structure of the Water Cube. The common features of the both projects; the Water Cube and the Symbol Zone will be exposed and the deep understanding of space frame structure of the Symbol Zone will be provided in the this case study.

2.2.1 Context

Space grid structures are three-dimensional, space-filling and large span building structures. They are characterized by their large, column-free and two-way spanning structural span. Other conventional large span building structures i.e. frame and truss structures are called one-way spanning and their longitudinal span is significantly larger than the latitudinal one. The larger span is supported by many columns and the column-free span is only in one direction.

Figure 35: Bird's eye view of Expo'70 "The Symbol Zone"

The structure of the Symbol Zone of Expo'70 in Osaka, Japan is pointed as a significant application of space grid structures because of its large span, efficient structural constitution, assembly and construction (Chilton, 2000). Large span space grid steel structure of the Symbol Zone is also an excellent example for comparative efficiency analysis of the space-filling foam structure due to the many reasons.

First of all, Symbol Zone structure as a space grid system is two-way spanning structure like the Water Cube foam structure. The largest clear span of the structure which is supported on only four columns is 108 m by 75.6 m and it is large enough to compared to the largest span of the Water Cube which is 140 m by 120 m. Moreover, both structures are made up by steel tubular members.

Secondly, the structure is based on the repetition of one of the most common space grid units of half-octahedron, which is simply a standard space frame system. At this point, it is important to have a common and uncomplicated example of space grid systems for the comparative efficiency analysis of the foam structure because comparison of the foam structure, as a new one, with a standard, well-known space grid structure demonstrates more concrete results in terms of structural efficiency than compared to a foam structure with a special space grid system.

Thirdly, the cladding of the Symbol Zone structure is polyester film membrane cushions which are 1.5 mm and 1.25 mm thick. This is a highly lightweight material for cladding like the ETFE, the Water Cube cladding. Polyester film membrane was the equivalent material of ETFE in 70's. Over the years, with technological developments, ETFE has replaced polyester film membranes in the construction industry.

Consequently, the large span space grid steel structure of Symbol Zone of Expo'70 is a convenient and successful structural example for the comparative efficiency analysis of the large span foam structure, though it is an old example, because of their familiarities about span, structural members, composition and cladding.

2.2.2 Strategy

The case study will consist of two parts. In the first part, the structure will be analyzed in terms of structural members, joints, the material, the load-bearing system, the assembly technology and the construction method etc. starting from the basic recursive unit to the entire structure. This analysis will help to discover the common, similar and different features of the space-filling foam structure and the half-octahedron space grid structure. Further more, other special features of the structure will be explored. And also the structure will be observed in terms of structural optimization, and other design considerations.

In the second part, geometrical constitution of the structure will be focused on. The regularities or irregularities of the structure will be exposed. And the structure will be modeled for the parametric simulation analysis. Modeling step will provide a deep understanding of the geometric constitution of the structure.

Expo'70, Osaka "The Symbol Zone"		
Location	Osaka,Japan	
Function	Festival Zone of the World Exposition in 1970	
Status	Not exist	
Project Information		
Client	The World Expo'70	
Design	Kenzo Tange (Design of the Festival Square)	
Architecture	Tomoo Fukuda, Koji Kamiya	
Engineering	Yoshikatsu Tsuboi	
Finish Date	1969	
Scope		
Construction Area	~32 000 m2	
Construction Cost		
Technical Information		
Structural Type	Large Span Half-Octahedronal Space Frame	
Structural Material	Steel	
Total Structural Weight	6000 tones	
Architectural Volume	291.6 m x 108 m x 30 m= 944 784 m3	
Longest Clear Span Volume	108 m x 75.6 m x 30 m = 244 944 m3	

2.2.3 Description of the Project

The space grid roof structure of the Symbol Zone of Expo'70 is 291.6 m long and 108 m wide. The structure is supported on six columns at 30 m above the ground. The lattice structure of the roof continues along the columns. The maximum structural span in the longitudinal direction is 75.6 m and in the latitudinal direction is 108 m. It has two 108 m spans in longitudinal direction. Furthermore, the roof structure has 37.8 m cantilevers in each side of the longitudinal direction and 16.2 m cantilevers in each side of latitudinal direction. The structural depth of the roof is 7.637 m (Chilton, 2000).

Figure 36: The roof structure of the Symbol Zone supported on six columns

Moreover, one of the main spans of the roof has a diameter of about 54 m circular opening which is around the Tower of the Sun designed by Japanese artist Okamoto Taro. The roof structure was a part of the Festival Plaza which was designed by Kenzo Tange. After Expo'70, the exposition site was converted to "Expo Memorial Park". Today, Tower of the Sun is still there but the roof structure was demolished.

Figure 37: Expo site and Festival Plaza, Tower of the Sun in 1970

Figure 38: Expo site and Expo’70 Festival Plaza area+ Tower of the Sun today

2.2.4 Load-Bearing System

The structural constitution is based on repetition. The basic recursive unit is the half-octahedron constructed only by using steel circular hollows. The basis of the half-octahedron is 10.8 m by 10.8 m square. The height of the unit 7.637 m and entire structure is composed of one row of these units; hence, the structural dept is the same with the height of the recursive unit. The diameter of the chords is 500 mm and the diameter of the diagonals is 350 mm. The thicknesses of the members are varied from 7.9 mm to 30 mm depending on the forces the member has to resist (Chilton, 2000).

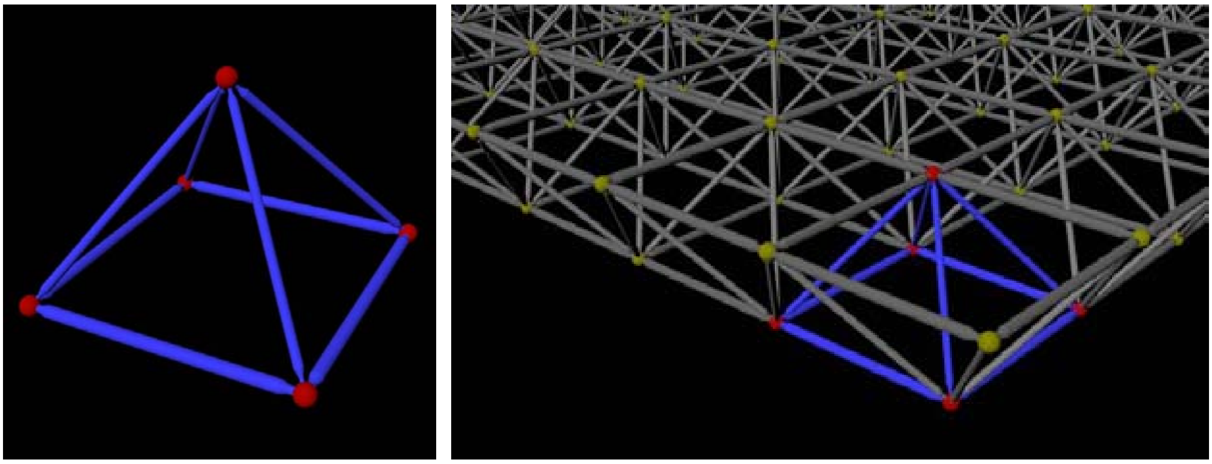


Figure 39: The recursive unit of the structure: Half-octahedron and the entire structure

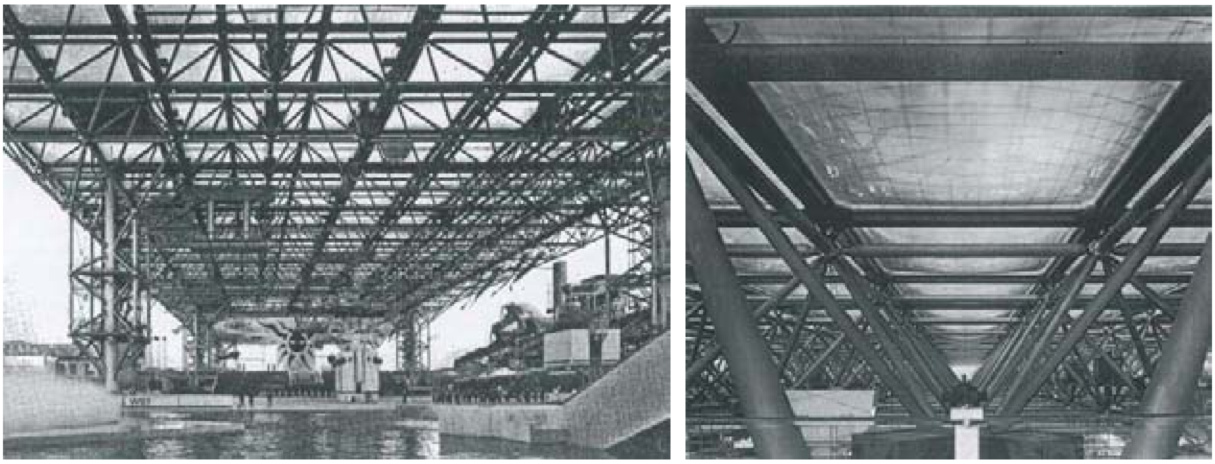


Figure 40: Space grid structure and it's half-octahedron repeating units

Lattice structure of the roof continues along the columns. There is a big tubular steel post with the diameter of 1.8 m in the center. Chords and diagonals of the lattice structure are joined to this post. And all the columns have the same structural constitution.

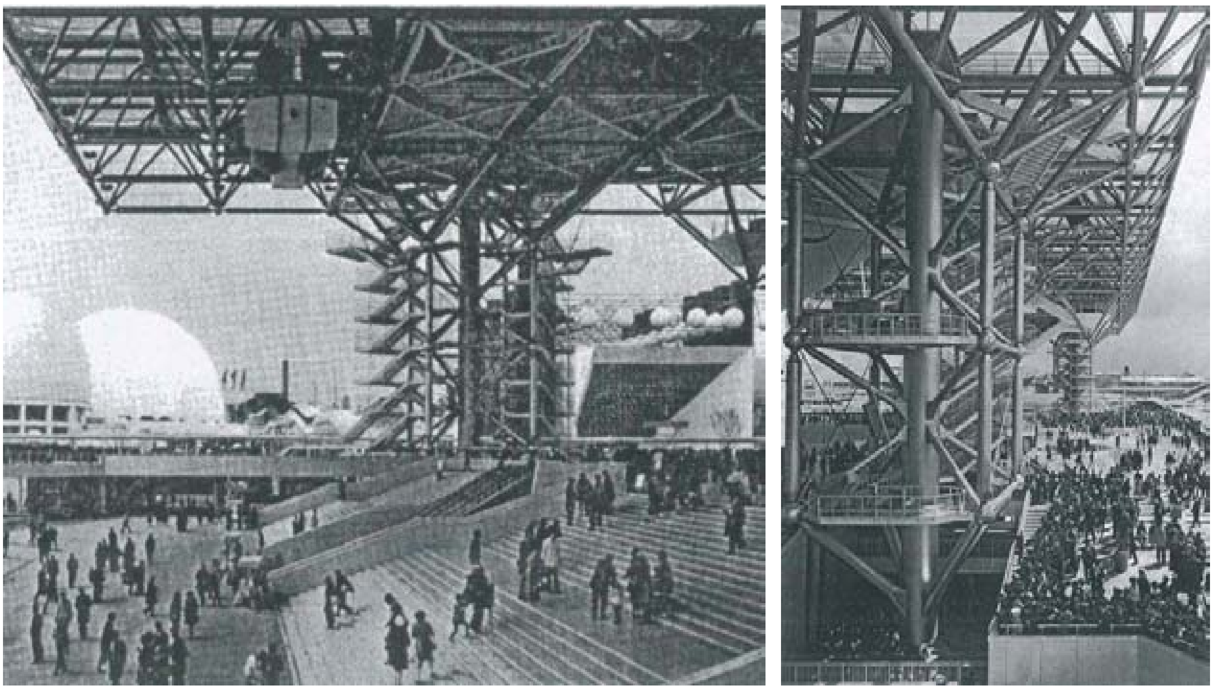


Figure 41: The lattice structural constitution of columns

Each hollow member of the roof structure has conical end pieces in the node joints. Steel chords and diagonals are joined to the steel spherical nodes by 70-188 mm diameter high-tensile steel bolts. The spherical nodes are cast steel members and their diameter varies from 800 mm to 1000 mm. The entire structure consists of 2272 hollow members and 639 nodes in total (Chilton, 2000).

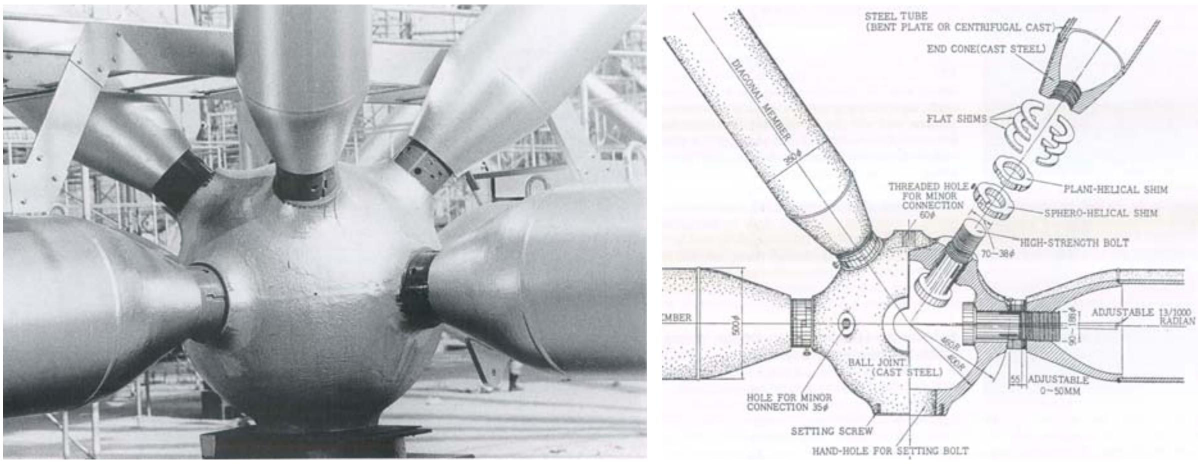


Figure 42: Ball joint of space grid structure of the "Symbol Zone" and detailed explanation of the joint

2.2.5 Cladding

The roof cladding of the "Symbol Zone" is the translucent polyester film membrane cushion. The translucent film membrane is 0.25 mm thick. Both upper and lower skins of cushions are multi-layered. The upper skin has 6 layers and lower skin has 5 layers of film membrane. Additionally, a special ultraviolet-resistant film was used in upper skin of the cushions. It reflects 60% of total UV lights. Each cushion is 9.9 m by 9.9 m and there are totally 243 cushions in the entire structure. Currently, the polyester film membrane was replaced with the ETFE film membrane which is highly translucent (Chilton, 2000; Detail 1970).

Figure 43: Translucent cladding of the roof: Polyester film cushions

3 Development of Simulation Model Cases

In this section, a comparative efficiency analysis of two base cases, namely foam and space frame models, will be handled. Base cases will be built up in the light of structural principles of the Water Cube and the Symbol Zone of Expo'70. The comparative efficiency analysis will be made based on these base cases.

Before the comparative analysis, there is a two-step preliminary procedure to match base and real cases. The first step is to model the load-bearing systems of each one of the base cases for the simulation program. Loads of buildings are borne, distributed and transferred by load-bearing structure. In this sense, load-bearing structure is the skeleton of a building and columns, beams, slabs and cables are its principal members. Load- bearing system model is the simplified representation of the physical load-bearing structure. For instance, columns or beams are represented by lines; slabs, deep beams or membranes are represented by planes. The second step is to choose a common clear span for efficiency comparison. Hence, the largest clear span of the Water Cube, 140 m by 120 m is selected. In order to achieve the same span, either some basic modeling tools will be used such as scaling and stretching or some changes will be made i.e. adding or deleting some units.

Once adequate base case models, which have the same structural principles with the real structures are developed, comparative efficiency analysis will be made.

3.1 Definition of Parameters

Before starting, it is convenient to define some structural terms principally used in parametric simulation analyses of this research.

Maximum Allowable Stresses (kN/m^2): These are the maximum allowable compression, tension and shear stress values of the structural material. Each material has different maximum allowable stresses. For instance, maximum allowable stresses of hot rolled steel are different from cold rolled steel. In the simulation program BUILD which will be used in this research, "fc" refers to maximum allowable stresses.

Maximum Stresses (kN/m^2): These are the maximum stresses (compression, tension, shear) occurring in the structure. In the program BUILD, "sigma" refers to maximum stresses in the structure.

Results of simulations are represented as relative stress value which is the ratio of sigma/fc in BUILD. Maximum stresses in the structure shouldn't be greater than maximum allowable stresses. Therefore, relative stress should be less than 1.

Sigma (occured stresses) / fc (max.allowable stresses) < 1

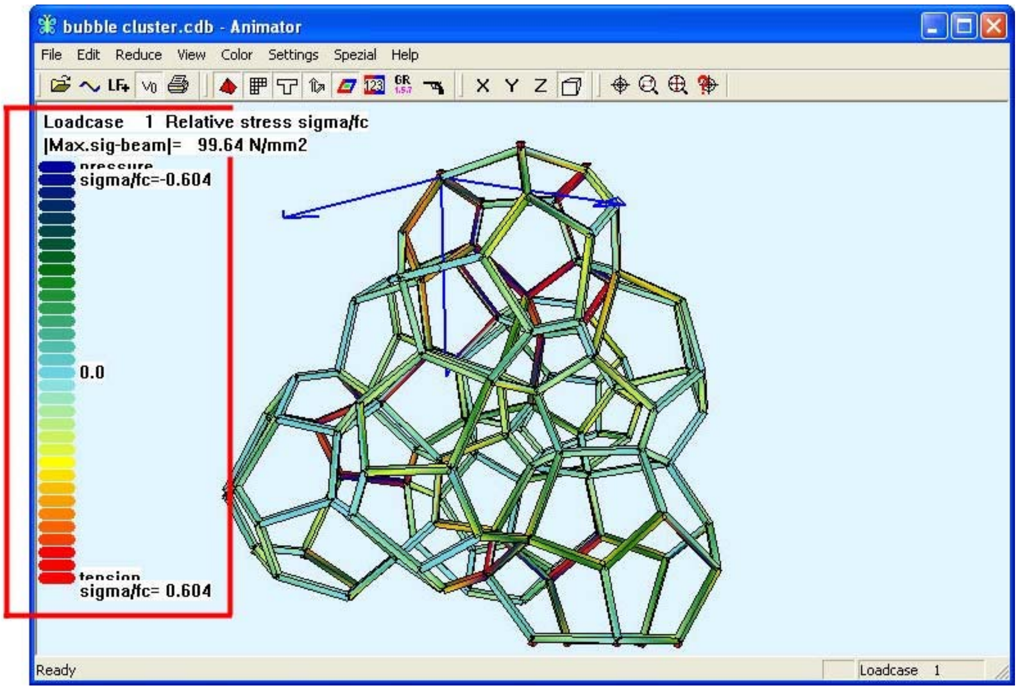


Figure 44: Results of simulation is represented on the left hand site of animator window of BUILD

The result of the simulation is represented with colors. In the color range on the left hand side, each color represents a certain relative stress value. In top and bottom of the colour range, maximum relative compression and tension stresses in the structure are given. Other colors represent relative stress values between the maximums. And the relative stress of each member is shown with a certain color from range on model depending on the stresses occurred in that member. In this way, the members which have the maximum stress could be easily detected.

Structural Loads: Forces that structure is subject to. There are many types of structural loads such as dead load, live load, wind load, snow load, earthquake loads, thermal loads etc. Load cases are defined as load combinations and they are used for structural analysis.

Load-Bearing Structure: All load-bearing system members of a physical building which bear, distribute and transfer loads of building.

Load-Bearing System Model: Simplified representation of a load-bearing structure.

Structural Depth: The distance between upper and lower or inner and outer layers of the member of load-bearing structure.

Dead Load (Structural Weight): Self-weight of the structure.

$$\textit{Structural Weight}(kN) = \textit{density of structural material } (kN/m^3) \times \textit{Volume of material used in structure } (m^3)$$

Architectural Volume: The space left between structural boundaries that are used for functions and installations of the building.

Clear Span: The clear distance between axes of vertical members of load-bearing system.

3.2 Foam Structure

The Water Cube structure seems highly random and complicated. But in fact, it is based on the repetition of the same structural unit which is the Weaire-Phelan bubble cluster. The cluster is composed of only two different polyhedral bubbles; hence the Water Cube random structure consists of only two different bubbles. So, the question is "How the random appearance could be provided?" In the modeling process, hundreds of bubble clusters are combined based on the Weaire-Phelan model, then rotated and sliced. The rotation and slicing provides the random appearance to the structure. But, in fact if the façade is observed carefully, it can be seen that the structure is not random; it is still the repetition of certain geometries but eye perceives it as a random structure at first sight.

3.2.1 Weaire-Phelan Bubbles

The Weaire-Phelan foam model is composed of two types of bubbles that are 12-faced bubble and 14-faced bubble. 12-faced bubble consists of pentagonal faces while 14-faced bubble consists of two hexagonal and twelve pentagonal faces. In the theory, the edges of the bubbles are slightly curved but it is assumed that all the edges are straight in application because the curvatures are so small as to be ignored and inconvenient for space frame structure applications.

The Weaire-Phelan bubbles could easily be modeled with special programs such as "Surface Evolver" which is a program for modeling liquid surfaces. Actually, the Weaire-Phelan model exists in the program as a data file.

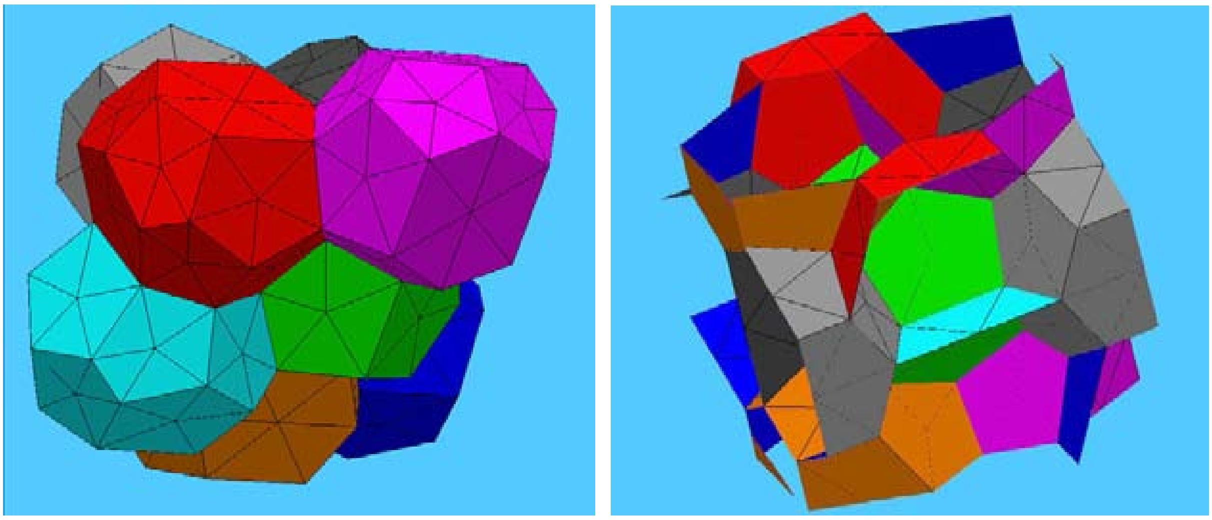


Figure 45: Weaire-Phelan bubble cluster and sliced cluster which are modeled in Surface Evolver

Another way of modeling Weaire-Phelan bubbles is using the coordinate list of the bubbles' vertices (steel pillow 2007). The coordinates of the Weaire-Phelan bubbles are given below.

12-FACED POLYHEDRA

3.1498	0	6.2996
-3.1498	0	6.2996
4.1997	4.1997	4.1997
0	6.2996	3.1498
-4.1997	4.1997	4.1997
-4.1997	-4.1997	4.1997
0	-6.2996	3.1498
4.1997	-4.1997	4.1997
6.2996	3.1498	0
-6.2996	3.1498	0
-6.2996	-3.1498	0
6.2996	-3.1498	0
4.1997	4.1997	-4.1997
0	6.2996	-3.1498
-4.1997	4.1997	-4.1997
-4.1997	-4.1997	-4.1997
0	-6.2996	-3.1498
4.1997	-4.1997	-4.1997
3.1498	0	-6.2996
-3.1498	0	-6.2996

14-FACED POLYHEDRA

3.14980	3.70039	5
-3.14980	3.70039	5
-5	0	5
-3.14980	-3.70039	5
3.14980	-3.70039	5
5	0	5
4.19974	5.80026	0.80026
-4.19974	5.80026	0.80026
-6.85020	0	1.29961
-4.19974	-5.80026	0.80026
4.19974	-5.80026	0.80026
6.85020	0	1.29961
5.80026	4.19974	-0.80026
0	6.85020	-1.29961
-5.80026	4.19974	-0.80026
-5.80026	-4.19974	-0.80026
0	-6.85020	-1.29961
5.80026	-4.19974	-0.80026
3.70039	3.14980	-5
0	5	-5
-3.70039	3.14980	-5
-3.70039	-3.14980	-5
0	-5	-5
3.70039	-3.14980	-5

First of all, the bubbles were modeled as wire frames based on the coordinates given above, and then they converted to solid bubbles. Because slicing the solid objects is easier and more precise than slicing wire frame shapes. Secondly, two 12-faced and six 14-faced bubbles are combined in order to have a recursive unit of the Water Cube structure which is the Weaire-Phelan bubble cluster.

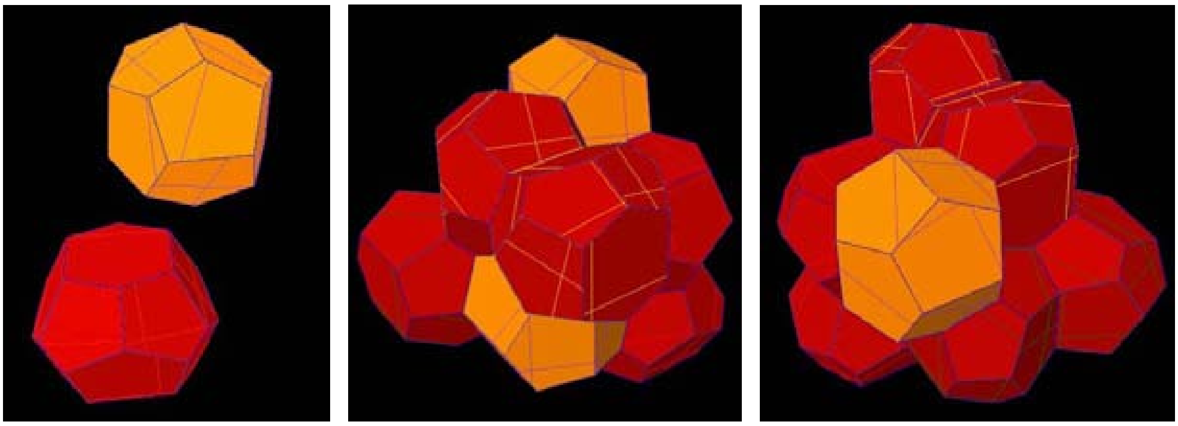


Figure 46: Weaire-Phelan bubbles and bubble cluster

3.2.2 Overall Structure

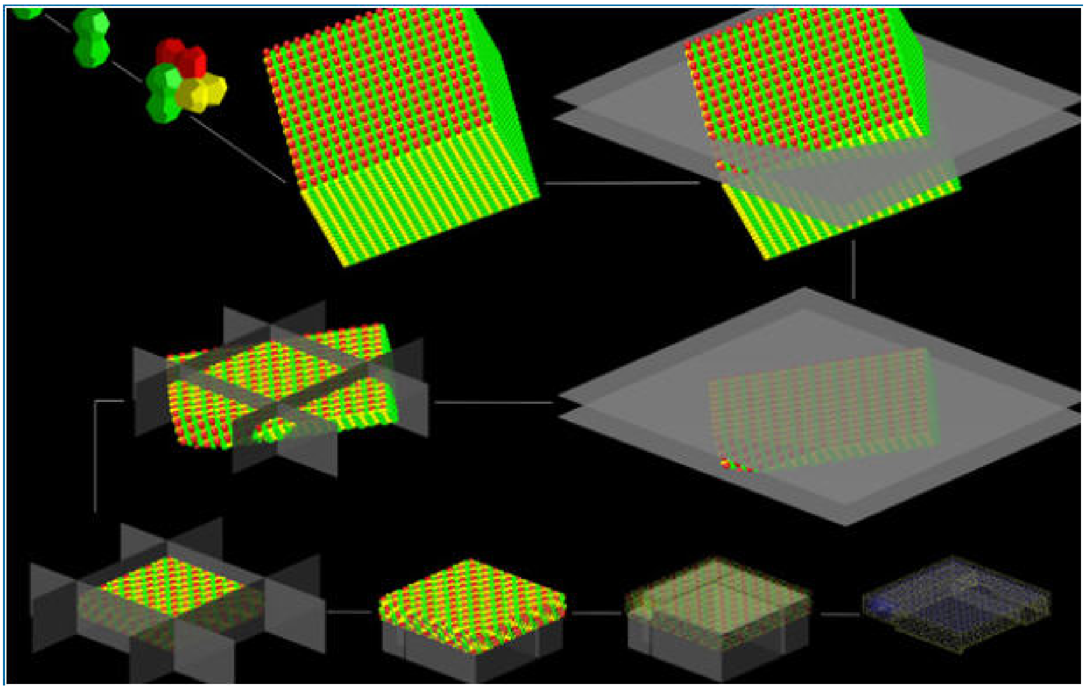


Figure 47: Schematic illustration of geometry modeling process of the Water Cube

The modeling process of the Water Cube structure consists of five steps. In the first step, hundreds of bubble clusters, which are the basic recursive units of the entire structure, are combined based on the orientation rules of the Weaire-Phelan model. Secondly, the prism constituted by hundreds of bubble clusters is rotated around prescribed axes. Thirdly, by slicing of the rotated prism with prescribed horizontal and vertical planes, the basic shape of the Water cube is reached (Arup 2006). In the fourth step, the sliced prism is also sliced from inside based on the proportions of the building. In the last step, the solid constitution of the model is converted to a wire frame and finally the structural model of the Water cube is achieved.

Based on the research by Weijiang Yu and Yang Zhao, the dimensions of bubbles, the axes and angles of rotation and the position of the slicing planes are important parameters of the geometry modeling and geometric optimization of polyhedral space frame structures. They demonstrated geometrical optimization rules for polyhedral space frames. Moreover, they asserted that geometric constitution of polyhedral space frame structures determines the basic dimensions of the building (Yu and Zhao, 2005).

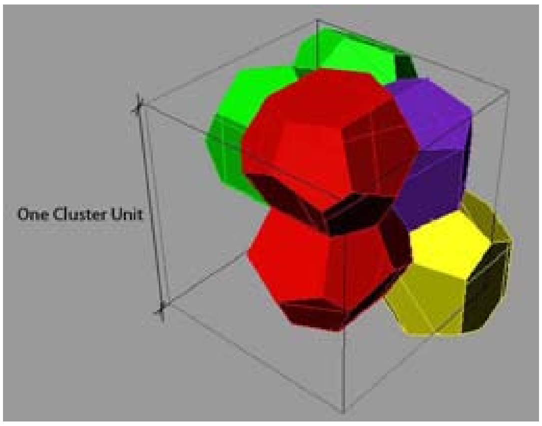
3.2.3 Simplifying and Developing the Base Case Foam Model

The geometric modeling process of the Water Cube is not complicated but high computer power is needed to be able to do that. After the first trial of modeling, it has been seen that the computer power currently possessed could not cope with this geometry modeling process. Therefore, simplifications were to be made. Furthermore, simplifications might make the simulation analysis less complicated.

First of all, the proportions of the Water Cube were determined. Structural depth of the roof is referred as X. Then the proportions of the other dimension to the roof depth were determined it gave these results:

BUILDING PART	LENGHT/DEPTH	ASSUMPTION 1
WALLS	3.6 m	X/2
ROOF	7.2 m	X
ARTCHITECTURAL BOUNDARIES	177m	~25X
	177 m	~25X
	31 m	~4X
LARGEST CLEAR SPAN	140 m	~20X
	120 m	~16X

Secondly, the density of the bubble constitution of the structure was reduced in order to achieve the new, less dense foam structure and another simplification was done. It was assumed that the roof is the half bubble cluster depth; in other words, 7.2 m assumed as 1/2 bubble cluster unit (BCU).



BUILDING PART	LENGHT/DEPTH	ASSUMPTION 1	ASSUMPTION 2
WALLS	3.6 m	X/2	1/4 BCU
ROOF	7.2 m	X	1/2 BCU
ARTCHITECTURAL BOUNDARIES	177m	~25X	12½ BCU
	177 m	~25X	12½ BCU
	31 m	~4X	2 BCU
LARGEST CLEAR SPAN	140 m	~20X	10 BCU
	120 m	~16X	8 BCU

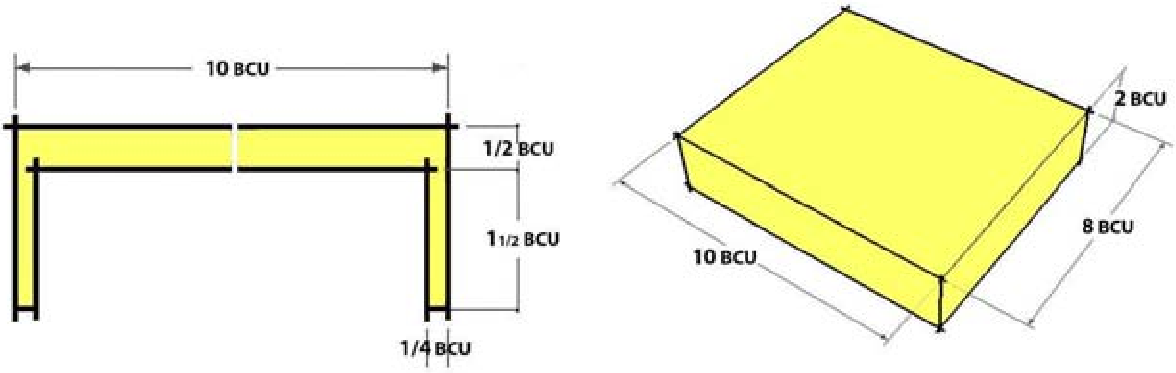


Figure 48: Dimension of the base case foam model

With these simplifications, the bubble density of base case foam model was reduced around 35% compared to the Water Cube structure. The reduction could be calculated roughly this way: There are 12 rows of red bubbles in the Water Cube structure. In the simplified base case, there are 8. This is equal to approximately 35% reduction.

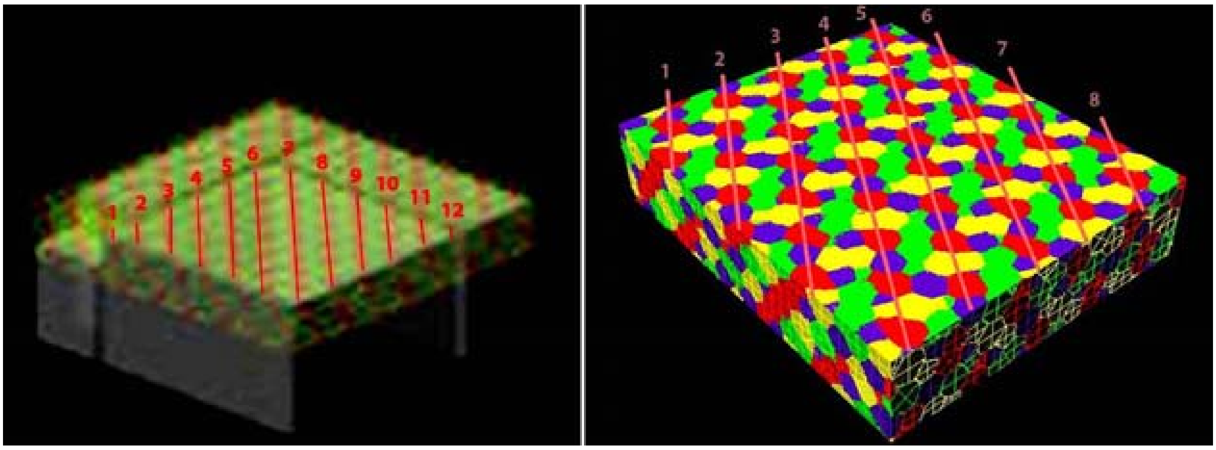


Figure 49: Comparison of bubble densities of the Water Cube and base case foam model

During the modeling of the base case foam model, the five step modeling process of the Water Cube was followed. Angles of the slicing planes are approximately found based on the schematic illustration in Figure 3.

First of all, because of the technical difficulties, some simplifications were done again. The hundreds of bubble clusters in Figure 3 were represented by squares. Each square represented one bubble cluster and squares were tiled just in the way the bubble clusters had been tiled.

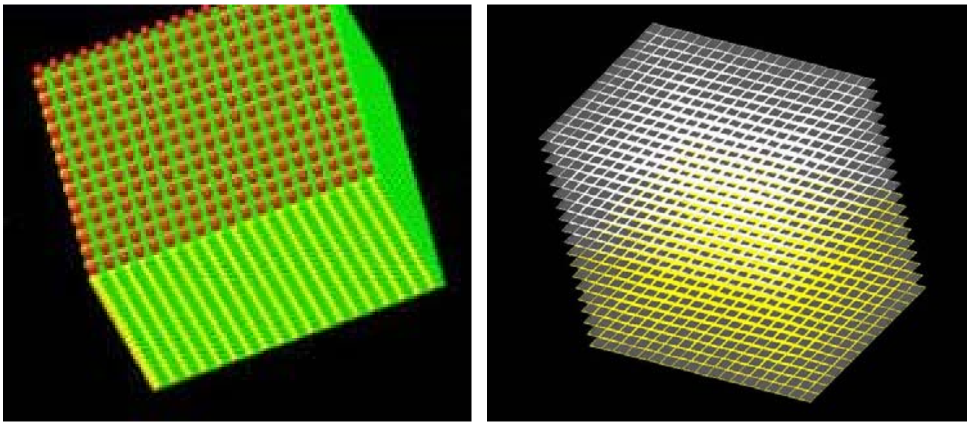


Figure 50: Solid bubble prism and it's simplified representation during the base case structure modeling

Secondly, the places of the two horizontal slicing planes were detected approximately based on the schematic illustration.

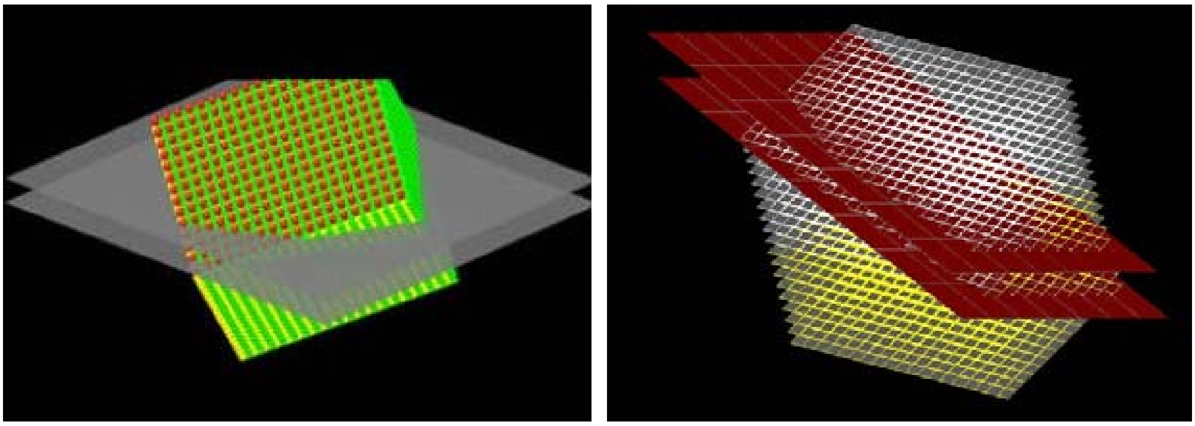


Figure 51: Horizontal slicing planes and their representation in simplified model

Then the squares which are not between the horizontal slicing planes were deleted.

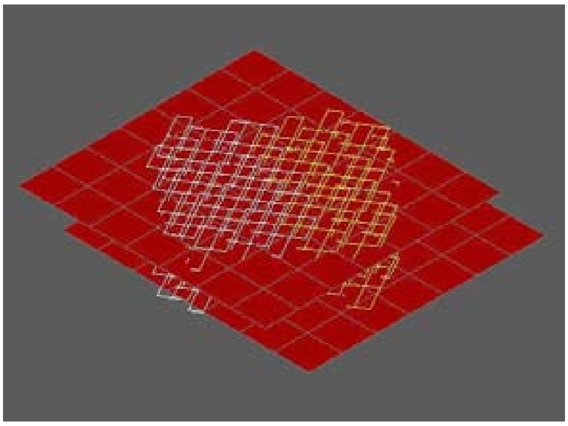


Figure 52: Deletion of the squares which are not in the horizontal borders

Thirdly, the vertical slicing planes were drawn and the squares which are not in the area bordered by vertical planes were deleted.

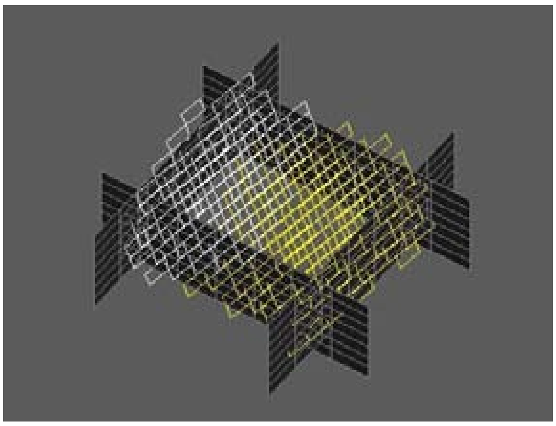


Figure 53: Deletion of the squares which are not in vertical borders

And finally, each square replaced with a Weaire-Phelan bubble cluster. Afterwards, horizontal and vertical planes were used again to slice the solid bubbles.

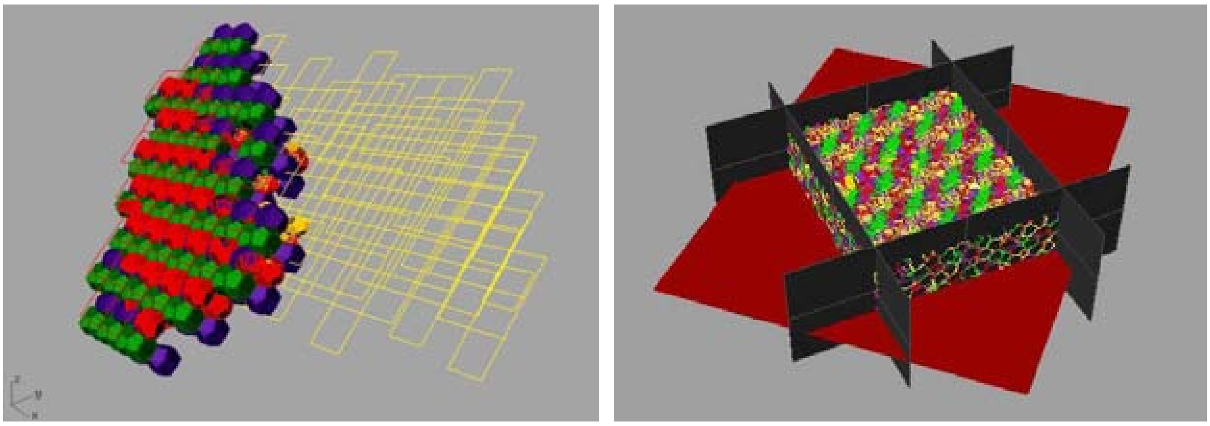


Figure 54: Left: Replacing bubble clusters with squares. Right: Slicing bubbles with vertical and horizontal planes

In the next step, the sliced model which has a perfect prismatic shape was sliced from inside based on previously defined proportions. Finally, solid bubbles of the model should be converted to wire frame bubbles which consist of only edges for the simulation process. Therefore, each edge of the solid bubbles in the model was drawn one by one in order to achieve the load-bearing system model (Figure 55) and the load-bearing system model was scaled into its original dimensions which are 140 m x 120 m x 31.

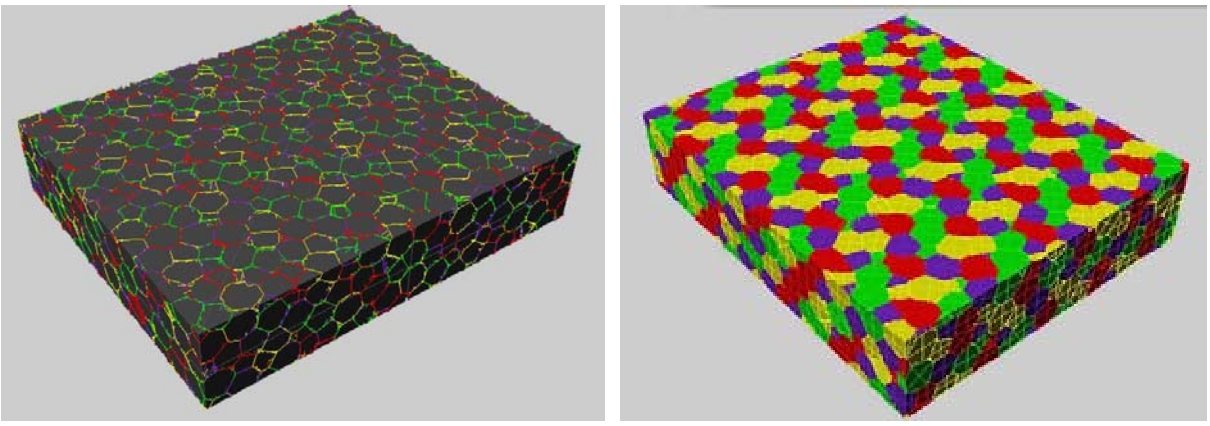


Figure 55: The model consists of sliced solid bubbles

Finally, the wire frame model of the base case foam model was exported from Rhino as .dwg file which is an AutoCad file format. When the file opened in AutoCad, it was ready to use in the simulation program. The wire frame model is the load-bearing system model of the base case foam model.

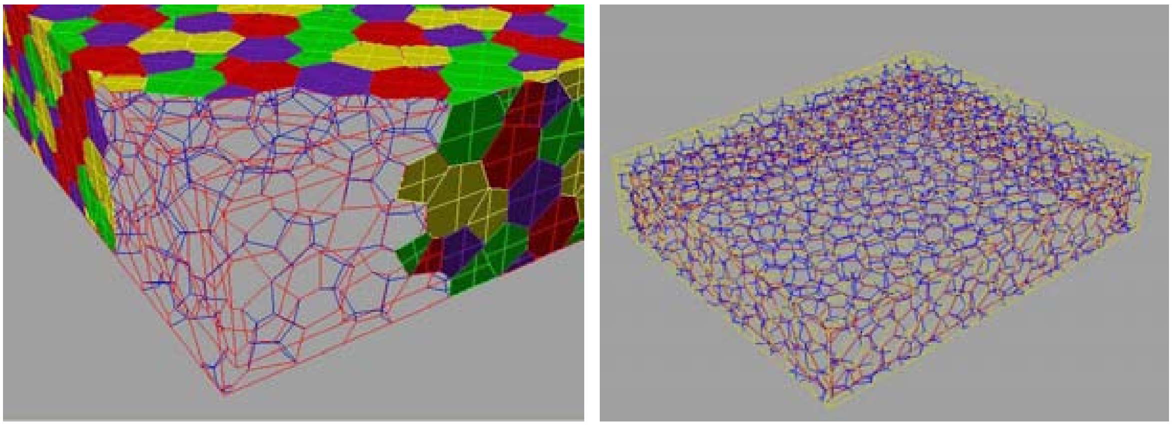


Figure 56: Converting solid bubbles to wire frame bubbles

The load-bearing system model of base case foam model in AutoCad is composed of only splines and polylines as the simulation program required.

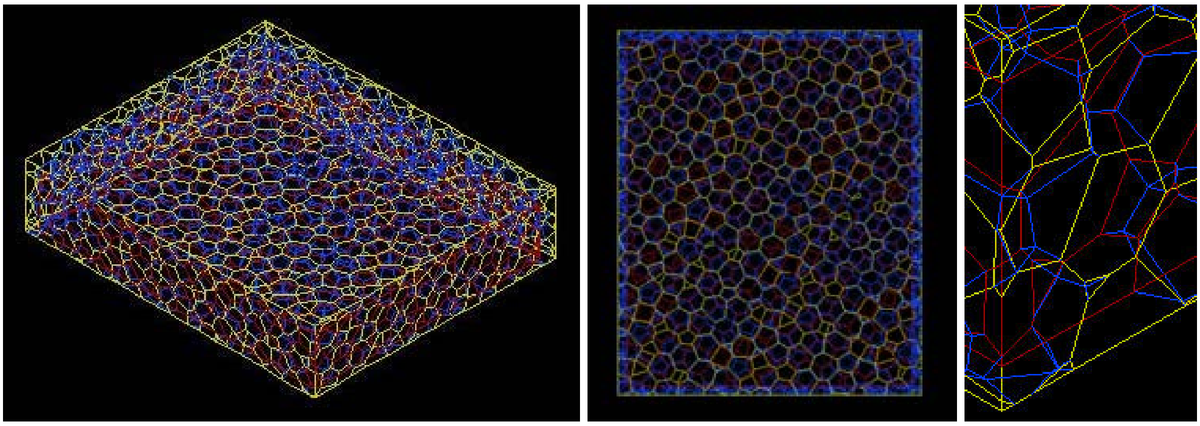


Figure 57: Load-bearing system model of base case foam model in AutoCad

The architectural dimensions of the base case foam model are 143.6 m x 123.6 m x 31m. The clear span of the base case structure is 140 m by 120 m. The distance between the axes which pass through from the middle of wall depth is assumed as the span of the structure.

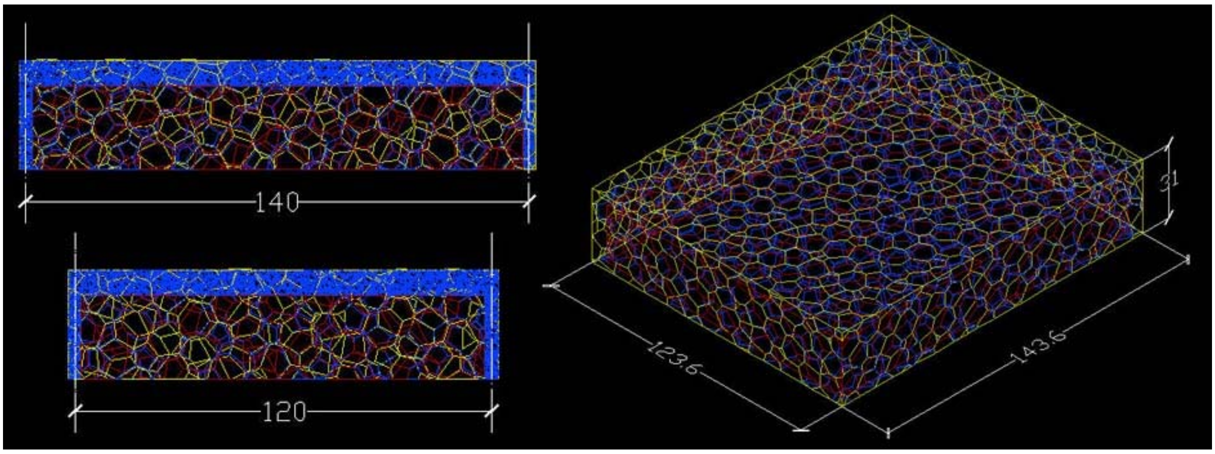


Figure 58: Dimensions of the load-bearing system model of base case foam model

3.3 Space Frame Structure

Firstly, the features of the Symbol Zone structure which is the physical example of space frame will be discussed and then the base case space frame model will be developed based on the Symbol Zone structure.

3.3.1 Overall structure

The space frame roof structure of the Symbol Zone of Expo'70 is 291.6 m long and 108 m wide. The structure has two equal spans in longitudinal direction which are a clear span of 108 m. The clear span across its width is 75.6 m. Thus, the largest clear span of the roof is 108 m x 75.6 m. The structure has cantilevers in both direction and both ends. The cantilevers of the longitudinal direction are 37.8 m and the cantilevers of the width are 16.2 m. The roof is supported on six columns at a height of 30 m.

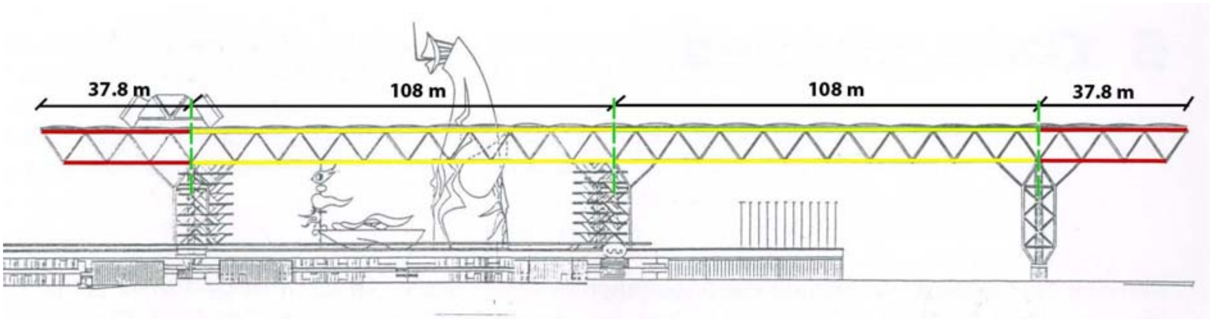


Figure 59: The clear spans in longitudinal direction

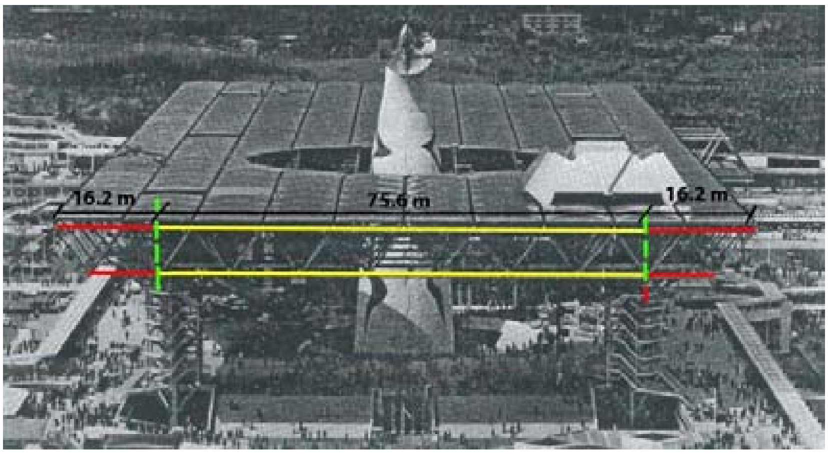


Figure 60: Clear spans across its width

The recursive unit of the space frame structure is half-octahedron. The basis of the half-octahedron is 10.8 m by 10.8 m and it's depth is 7.637 m. Repetition of these units forms the lattice structure of the roof. The lattice structure continues along the columns. Each column has a huge, circular hollow post with a diameter of 1.8 m in the center. The posts are surrounded by the lattice structure.

3.3.2 Developing the Base Case Space Frame Model

The largest span of the Symbol Zone is 108 m by 75.6 m. First of all, load-bearing system model is drawn based on the exact dimensions of the members and the largest span of the Symbol Zone structure. However, the cantilevers in both longitudinal and latitudinal directions are ignored.

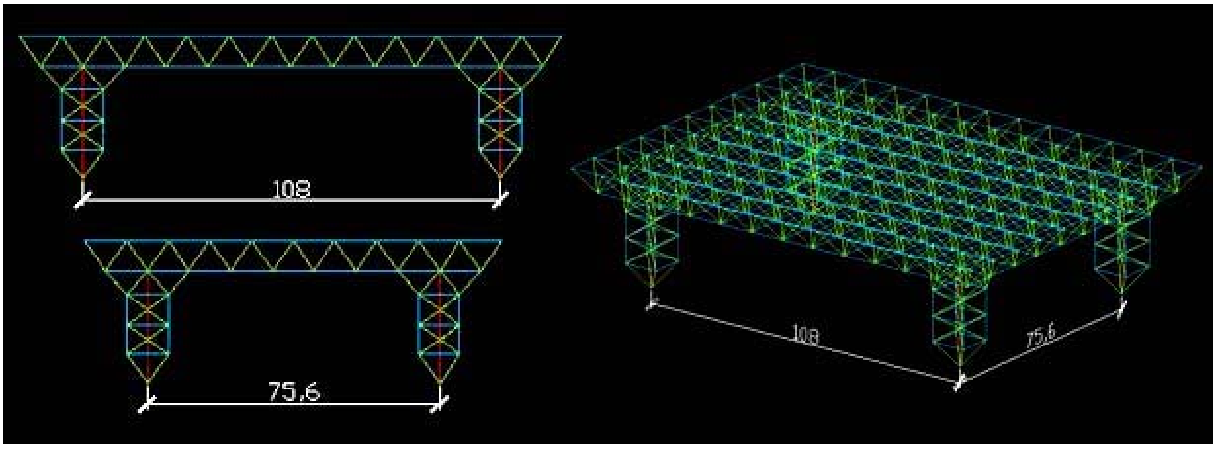


Figure 61: Load-bearing system model of the largest span of Expo'70 the Symbol Zone roof structure

In the second step, the system model is scaled in order to equalize the spans to 140 m by 120. But the structure achieved after scaling has a span of 140 m in longitudinal direction and 98 m in latitudinal direction because the span ratio of the Symbol Zone is different from the ratio of required spans. Therefore, in order to achieve a model with clear spans of 140 m by 120 m, one row of repeating unit of space frame is added to the structure along longitudinal direction and in this way the span in latitudinal direction is expanded from 98 m to 112 m.

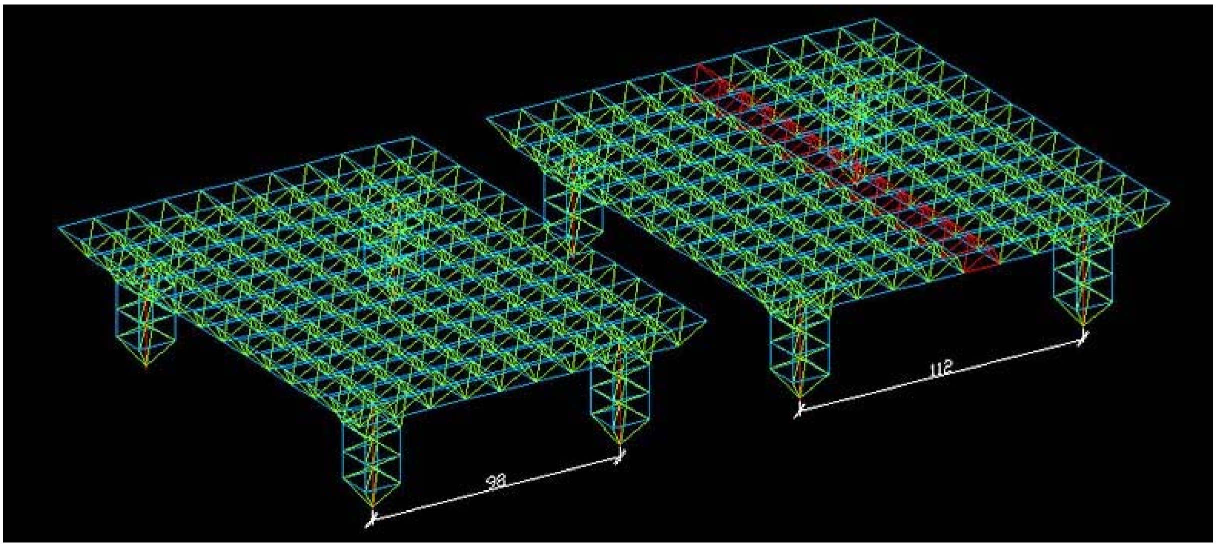


Figure 62: One row of half-octahedron space frame units are added in longitudinal direction

Finally, the system model which has a clear span of 140 m by 112 m is stretched in latitudinal direction and the span of 112 m is equalized to 120 m.

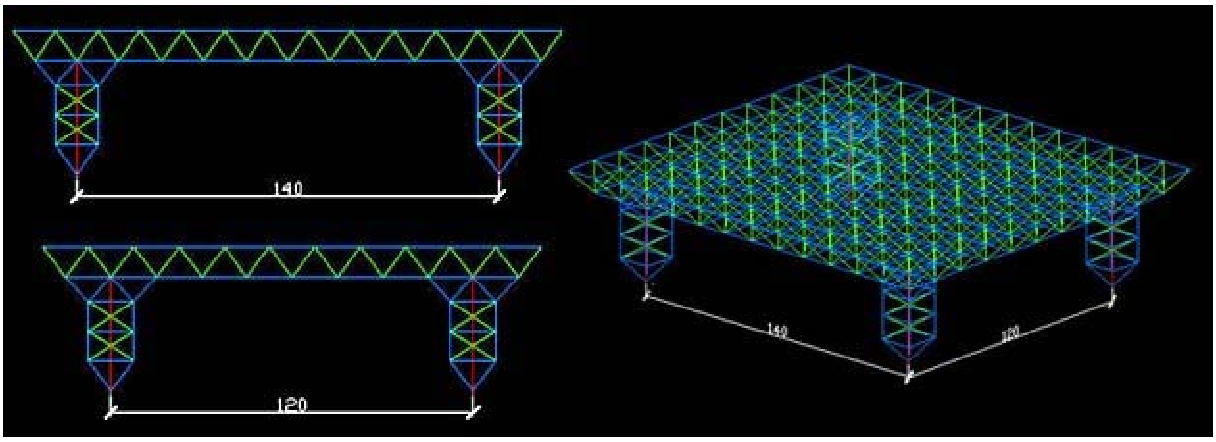


Figure 63: Load-bearing system model of the base case space frame model

During the stretching, the recursive unit of the space frame is deformed. The square basis of the half-octahedron becomes rectangular. Therefore, the lattice structure of the columns should be re-modeled based on the new dimensions of half-octahedron unit. The basis of the new half- octahedron is 14 m by 15 m and the depth is 9.9 m.

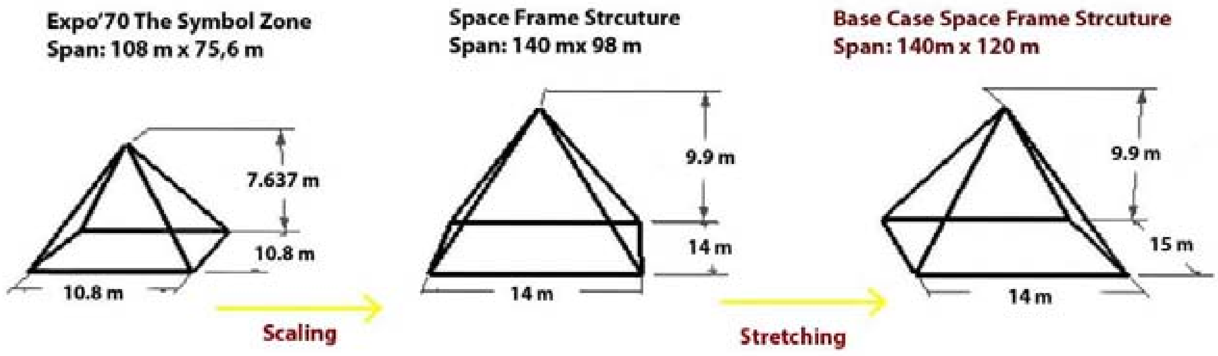


Figure 64: The steps of the development of the base case space frame model

Consequently, architectural dimensions of base case space frame model are 182 m x 165 m x 49 m. The clear span of the base case model is 140 m x 120 m.

4 Comparative Study

Parametric comparative efficiency analysis of foam structure will be made in this part based on the developed structural model cases which are the base case foam model (BCFM) and the base case space frame (BCSM) model. First of all, two large span building structures will be discussed: space frame vs. foam structure and the common, distinguishing and competitive features of the both structures will be exposed. Secondly, parameters of the comparative study will be explained. In the third part, structural behavior simulations and results of base case models will be demonstrated and finally results will be discussed.

4.1 Large Span Building Structures: Space Frame vs. Foam Structure

The space frame structure is the most convenient large span structure case for the comparative efficiency analysis of foam structure for several reasons. First of all, there are many types of large span building structures such as plate girders and truss systems. In fact, each structural type is efficient for a certain range. When the span of building is greater than 100 m, the space frame structure is considerably more efficient than other conventional large span building structures. Moreover, the comparative efficiency analysis of the foam structure will be done in this research with base case foam model with a span of 140 m x 120 m which is the largest span of the Water Cube. Hence, the space frame structure is a highly efficient and convenient structural type to compare. Secondly, the space frame and the foam structure are both light-weight structures. Thirdly, and most importantly, the space frame structure is a three-dimensional structure like the foam structure. Despite the fact that every structure is three dimensional in terms of length, depth and thickness, the action of structures under loads is either two-dimensional or three-dimensional. For instance, planer beams and trusses have a two-dimensional structural action and they only resist loads between their vertical supports. But a space frame and a foam structure have a three-dimensional action. When a load applied anywhere on the structure, the load is distributed whole structure and every member of the structure contribute to resistance. In spite of all the commons of space frame and the foam structure, they have some competitive features.

First of all, both structures are modular. Most common modules of space frame structure are tetrahedron, octahedron and half-octahedron. The module of a foam structure is a bubble cluster which is composed of eight polyhedral bubbles in the case of the Water Cube. But the appearance of a space frame structure is regular.

Figure 65: Regularity of space frame vs. randomness of foam structure

Despite its modular constitution, foam structure has random appearance. Even though, façades of the foam structure is still recursive of a group of polygons, the first perception about appearance is randomness.

Secondly, the most common and economical members of space frame structure are circular hollows and ball nodes. Members of foam structure in the case of the Water Cube are circular hollows and ball nodes. In this sense, the choice of the structural members of the Water Cube is highly economical. But there are thousands of beams and nodes in foam structure of the Water Cube which is quite higher than the number of nodes and beams of a space frame structure with the same span. This is considerably an uneconomical future of the foam structure comparison to the most economical space frame structure which consists of circular hollows and ball nodes.

Thirdly, foam structure provides a very large column-free span which is 140 m by 120 m in the Water Cube and a space frame as well. The space frame structure is supported by columns and the place of columns could be anywhere in the space frame structure. In this sense, the space frame allows many changes in the numbers and location of supports and in openings. The foam structure roof is supported by foam structure walls along four sides of the building. Actually, how many of there supporting walls are needed is a question mark. On the other hand, the supports of the space frame structure are considerably huge. These huge columns could cause problems in the use of space and façade in buildings. But the supports of foam structure are walls and façade at the same time and the depth of walls is quite small compared to the depth of the columns of the space frame structure. For instance, the depth of walls (supports) is 3.6 m in the Water Cube, but the depth of columns of Expo'70 the Symbol Zone space frame roof is 10.8 m.

Furthermore, the erection of a space frame is quite easy. All the prefabricated diagonals, chords and nodes of a space frame could be assembled together at near ground level and after the entire roof structure is completed, it could be jacked into its final position. On the other hand, the members of a foam structure are assembled at their final in the construction of the Water Cube.

Moreover, the most common examples of a space frame structure are the flat structures. As a matter of fact, complex geometries such as vaults, domes and hyperbolic paraboloids could be constructed with a space frame. The examples could be the Market hall, Eagle Center, Derby in UK and the Anoeta Stadium, San Sebastián in Spain. The first and only example of a macro-scale foam structure, the Water Cube, is a flat structure and it is unknown that if complex geometries could be constructed with a foam structure.

Finally, the space filling constitution of both structures provides space which could be used for different issues instead of structural issues. In other words, the space between chords and diagonals of a space frame of the space between beams of foam structure could be used for different functions. For instance, the space between the upper and lower layer of space frame roof structure of a food-processing factory in Nottingham in UK which is 3 m depth is used as refrigerated stores. Furthermore, the space between the outer and inner layers of the foam structure of the inner wall is proposed to use as a restaurant space in the Water cube.

Moreover, open structural constitution of a space frame and the foam structure is highly sufficient for a mechanical and electrical installation and it makes installation process easier.

Consequently, both the space frame and the foam structure are modular, lightweight and three-dimensional large span building structures. The space frame has been being used widely since the development of the first commercially available space frame structure which is called MERO in 1943 in Germany. Therefore, the space frame structure has been experienced, built and improved a lot. On the other hand, the foam structure is a new type a structure. The first and the only example of a foam structure is the Water Cube. Possibly, in the future, the foam structure will be improved and different buildings with different geometries will be built with it. Even though, there has been only one example of foam structure until now, and since it is a new type of building structure, in this research, the efficiency of a foam structure as a large span building structure will be tried to be explained by following a certain approach and comparing it with the most common conventional large span building structure, the space frame.

4.2 Parametric Comparative Efficiency Analysis

This research is based on the question of "how efficient foam structure is compared to conventional building structures." First of all, conventional large span building structures were explored and it was seen that the space frame is the most efficient structure for a span lager than 100 m. Furthermore, as you may recall from section 4.1., the space frame is lightweight and most importantly a three-dimensional structure, which means that it has three-dimensional structural behavior, like the foam structure. The other conventional large span building structures were eliminated because they have a two-dimensional structural behavior.

Secondly, efficiency is a term that has wide-spread use in many fields with many different evaluation criteria. For instance, efficiency from a structural point of view could be in for categories: material, assembly, cost or geometry efficiency. Therefore, the defining issues of efficiency were an important step of the work. In this way, the efficiency of BCFM and BCSM was decided to be analyzed and compared in terms of a structural displacement because displacement is an important subject of large span structures. The increase in the span causes an increase in the displacement. Therefore, displacement is always tried to be minimized in the structural design of large span buildings. One way of minimizing displacement is decreasing the dead load which is self-weight of the structure this means the dead load is critical for large span buildings. Therefore, the structural weight is a part of the analysis.

Parameters of the analysis are vertical and horizontal loads. Despite the fact that there are many vertical and horizontal load types, in this research wind load is chosen as a horizontal load and the snow load is chosen as a vertical load. On the other hand, the span is kept constant. The table below shows the parameters of the comparative efficiency analysis.

CASE	STRUCTURAL TYPE	SPAN (CONSTANT)	VERTICAL LOADS	HORIZONTAL LOADS	MAXIMUM DISPLACEMENT	STRUCTURAL	
						WEIGHT	DEPTH
ID1 ab	Foam Structure	140m x 120m	none	typical			
ID1 ac	Foam Structure	140m x 120m	none	extreme			
ID1 ba	Foam Structure	140m x 120m	typical	none			
ID1 ca	Foam Structure	140m x 120m	extreme	none			
ID2 ab	Space Frame	140m x 120m	none	typical			
ID2 ac	Space Frame	140m x 120m	none	extreme			
ID2 ba	Space Frame	140m x 120m	typical	none			
ID2 ca	Space Frame	140m x 120m	extreme	none			

Table 2: Parameters of the comparative efficiency analysis of the base case foam model

During the simulation process, the BCFM and the BCSM will be simulated under four different loading cases in the simulation program. Displacements and self-weights of the models will be calculated and deformation of the models will be illustrated by the program.

Another important issue of structural efficiency, which is directly affects architectural volume, is the depth of structure. As the span increases, the structural depth also increases, too. In large span buildings, even a little decrease in the depth of structure could save hundreds of m^3 of space in architectural volume which could be used for mechanical installations of buildings for instance. Therefore, depth of the BCFM and the BCSM will be compared and architectural volume of two models will be calculated.

During the simulation process, the BCFM did not full-fill the requirements of stability. The load-bearing system model of the BCFM was performed in the simulation program many times. Parameters of the load-bearing system model that could be changed in the simulation program are cross-sections of structural members, joint types and the parameters of structural material such as modulus of elasticity (E) and maximum allowable stresses (for tension, compression and shear). Many different cross-sections were tried and default steel material values in the program were changed but the stability wasn't achieved. It is known that the joints of foam structure all are rigid, therefore different joint types weren't tried. Some simulation results of the foam model with different cross-sections are given below.

	STRUCTURAL MEMBER	CROSS-SECTION				RELATIVE STRESS (sigma/fc)
		SIZE(m)				
		B	H	D	TICKNESS(m)	
1	Circular Hollow	-	-	0.508	0.016	7.483
	Rectangular Hollow	0.3	0.3	-	0.016	
2	Circular Hollow	-	-	0.508	0.016	6.360
	Rectangular Hollow	0.4	0.3	-	0.016	
3	Circular Hollow	-	-	0.508	0.016	5.267
	Rectangular Hollow	0.4	0.4	-	0.016	
4	Circular Hollow	-	-	0.8	0.016	2.147
	Rectangular Hollow	1	1	-	0.012	
5	Circular Hollow	-	-	0.8	0.02	1.530
	Rectangular Hollow	1	1	-	0.02	
6	Circular Hollow	-	-	1	0.02	1.483
	Rectangular Hollow	1	1	-	0.02	
7	Circular Hollow	-	-	1	0.02	1.317
	Rectangular Hollow	1.2	1.2	-	0.02	
8	Circular Hollow	-	-	1	0.02	1.248
	Rectangular Hollow	1.3	1.3	-	0.02	

Table 3: Simulation results of the BCFM with span of 140m x 120m under dead load case

The achieved lowest value of sigma/fc is 1.248. That means maximum allowable stresses in the BCFM are exceeded 1.248 times by maximum stresses occurred in the foam model. And this value was achieved with unrealistic cross-sections. Because, first of all, hollows with around 1 meter dimensions are too big to be beam members of the lightweight structure. For instance, a diameter of six column hollows of The Symbol Zone of Expo'70 is 1.8 m and this hollows transfer all the loads of roof structure to the ground. On the other hand, diameters of chords and diagonals of the Symbol Zone roof are 0.5 m and 0.35 m. Beams of foam structure are members like chords or diagonals of space frame. Secondly, based on some drawings of the Water Cube which are provided from Arup, the diameter of structural members should be round 0.5 m.

In conclusion, the strength of the BCFM could not be achieved. This could happen due to two reasons: First of all, the BCFM is not an optimized structure. It is assumed that all the beam members of the inner-structure have the same cross-section and frame members have the same as well. There are thousands of beam members in the BCFM. The members around the wall-roof connection are supposed to be the strongest elements which mean that they should have bigger or thicker cross-sections, because maximum stresses of the structure occur there. Actually, by assuming that all cross-sections are the same, at the same time it is assumed that all members are as strong as the members around wall-roof connection. So, these assumptions caused significant increase in self-weight of theBCFM. In fact, all members are neither the same nor as strong as the members around the corners. As a result, the BCFM definitely needs to be optimized. Furthermore, it is known that the optimization was an important step of structural design process of the Water Cube. A special program was developed by Arup for the optimization process of the Water Cube in order to minimize human errors.

Secondly, the reduction of bubble density might have caused this problem. As you may recall, during the modeling process of the base case foam structure, the bubble density was reduced roughly 35%. The results of the simulations show that the problem could not be only about optimization. If problem was optimization, the cross-sections of structural members should not be so big as to be unrealistic.

Therefore, the problem about providing the strength of the foam structure seems related with the bubble density of the structure. In order to clarify and examine the effect of bubble density reduction, the span of base case foam structure will be reduced 35% as well, and simulations will be repeated.

4.3 **Simulations of Structural Behavior**

In this section, the structural behavior of two model cases, base case foam model and base case space frame model will be simulated by using special structural engineering program. The scope of simulations and the path followed in analysis of results are explained below.

4.3.1 Context

Dead load is the self-weight of the structure. It is critical for large span building structures because maximum displacement always occurs in the middle of the span. There are two main factors which affect the displacement of the structure: the span and the dead load. The increase in the span and the dead load causes an increase in the displacement hence large span building structures should be light-weight. The dead load is related to size, material and cross-sections of structural members. Therefore, minimizing the dead load as much as possible is one of the important issues of designing large span building structures.

The first condition of stability and strength of structures is capability of carrying its self-weight. When stability and strength is provided under the dead load case, the structure is developed to resist other load cases such as earthquake loads, snow loads or occupancy loads. Therefore, in the structural simulation program, the BCSM and the BCFM will be performed under the dead load case in order to understand either they are stable or their deformation is in an allowable range.

Sofistik Build is the software used for the simulation of the structures. As complexity level of the program is not high, architects could easily handle it. The program has an AutoCad interface and this provides the users with an easy structural modeling process. The structure could be modeled in various drawing or modeling programs such as AutoCad, 3D Max or Rhino as long as the file could be saved ".dwg" or ".dxf" formats. ".dwg" and ".dxf "are the file formats used by the program AutoCad. And at the end of the modeling process, the file exported from AutoCad as Sofistik Build file which is basically a coordinate list of structural members. Another way of modeling the structure in Sofistik Build is entering the coordinates of each structural member manually. This is a long process and it is just convenient for simple structures.

4.3.2 Strategy

First of all, the span of BCFM and BCSM will be reduced 35% by using simple scaling tools of the modeling program. Then, the BCFM will be simulated under its dead load. If the stability and the strength of the BCFM are provided, the simulation analysis of the BCSM under the dead load case will be done. The important and sometimes long step of simulation process is finding the most convenient cross-sections of structural members, if the cross-sections are unknown. During the first simulation analysis, even though it is assumed that there are only two different cross-sections in the BCFM, one for inner structure, one for inner and outer frames, so much time was spent to find the most sufficient cross-sections of members.

Secondly, structural weight will be calculated. The volume of material used in the models is calculated automatically by BUILD; it is given in the result screen and BUILD has default property settings for different types of structural materials such as steel, concrete or timber. In simulations, either default settings could be used or properties of material are defined before simulations. In the simulations of this research, default material setting will be used for steel which is hot rolled steel.

Finally, the architectural volume of both models will be calculated. Structural depth will be significantly influential in this calculation. Furthermore, other load-bearing system members that are walls of the BCFM and columns of BCSM constitute architectural volume boundaries of the structures.

4.3.3 Base Case Foam Model Simulation Results

The clear span of the BCFM base case was 140 m by 120 m. But it is decided to be reduced 35% because of the reasons mentioned in section 4.3.1. Therefore the span of the BCFM was reduced simply by scaling it in to clear span of 91 m x 78 m.

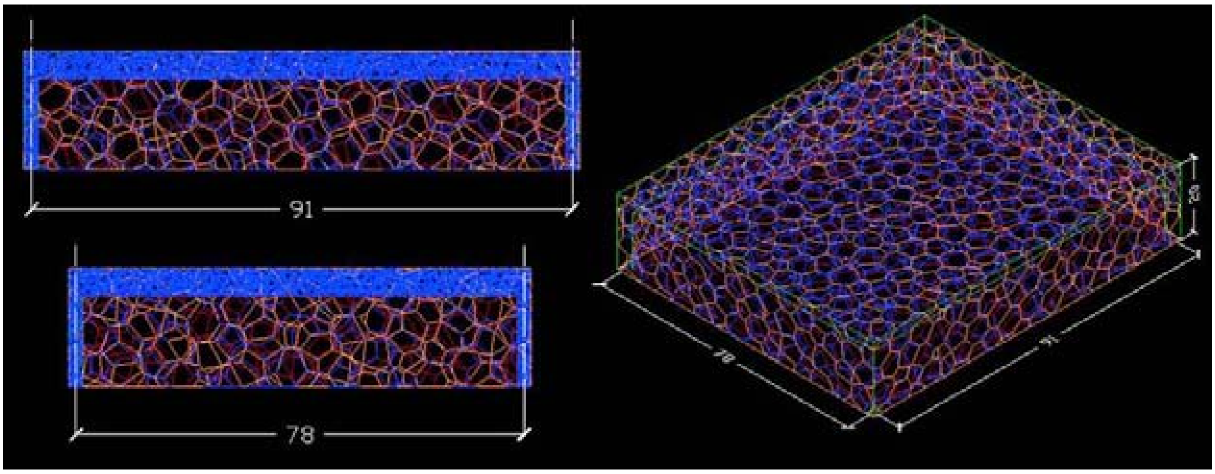


Figure 66: The load-bearing system model of the BCFM with a clear span of 91 m x 78 m

The load-bearing system model of the BCFM consists only of only polylines and each structural member is represented by a polyline. On the other hand, the BUILD file of the BCFM consists of a list of structural members and their coordinates. But the load-bearing system is illustrated based on coordinates and cross-sections of structural members by the animator of BUILD. Furthermore, results of simulations are shown on this model in Animator screen.

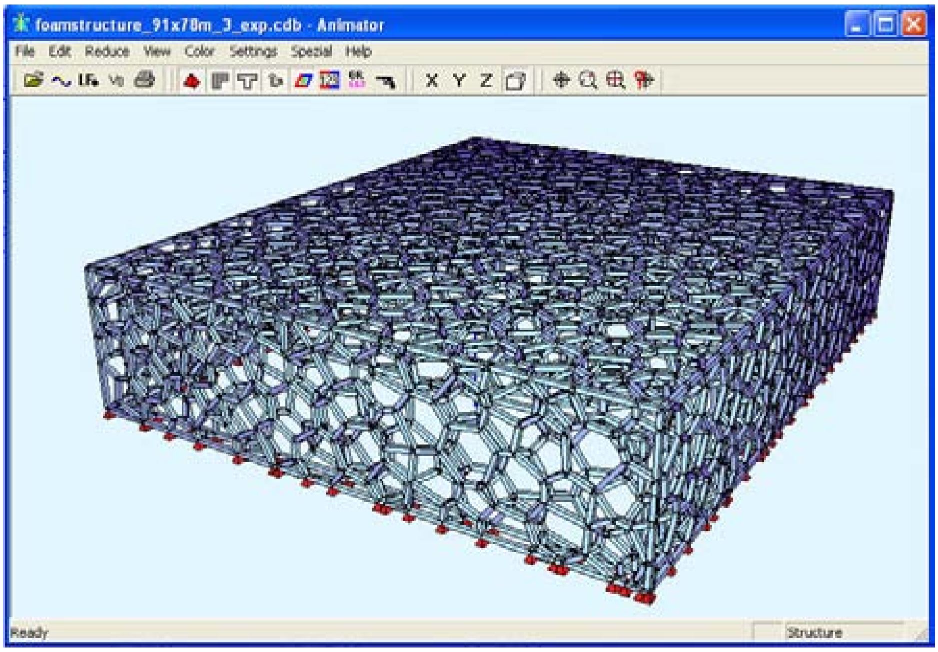


Figure 67: Illustration of the BCFM in BUILD Animator

First of all, the BCFM was simulated under the dead load case and the simulation turned out to be successful. Stability and strength of the BCFM was achieved. The most convenient cross-sections of members, which are close to the dimensions of the Water Cube structural members, were found after a few trials. This shows that the bubble density of the BCFM is in sufficient level. The results of simulations under the dead load case with different cross-sections of members are given below.

BASE CASE FOAM MODEL						
		CROSS-SECTION				
		SIZE(m)				
	STRUCTURAL MEMBER	B	H	D	TICKNESS(m)	RELATIVE STRESS (sigma/fc)
	circular hollow	-	-	0.508	0.016	1.902
1	rectangular hollow	0.5	0.3	-	0.016	
	circular hollow	-	-	0.508	0.016	1.045
2	rectangular hollow	0.6	0.6	-	0.02	
	circular hollow	-	-	0.508	0.02	1.051
3	rectangular hollow	0.6	0.6	-	0.02	
	circular hollow	-	-	0.6	0.016	0.975
4	rectangular hollow	0.6	0.6	-	0.016	

Table 4: Simulation results of BCFM with span of 91m x 78m under dead load case

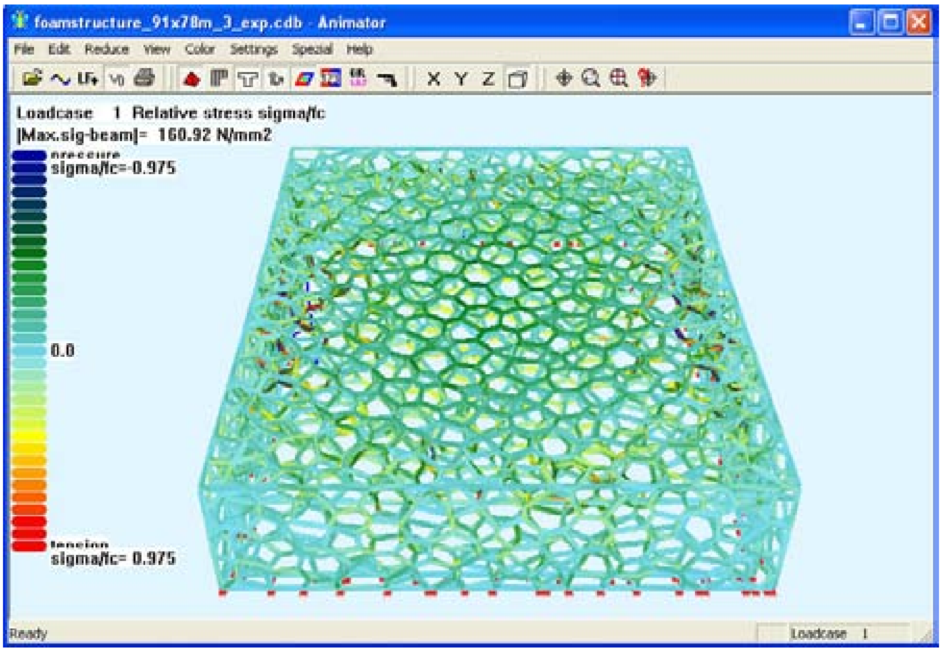


Figure 68: Illustrated simulation result of the BCFM under dead load case

According to the result of simulation, high stresses occurred in the middle of the span. The maximum stress is occurred in members around the edges where the roof and walls meet. Therefore, these parts need to be strengthened which is an issue of optimization process.

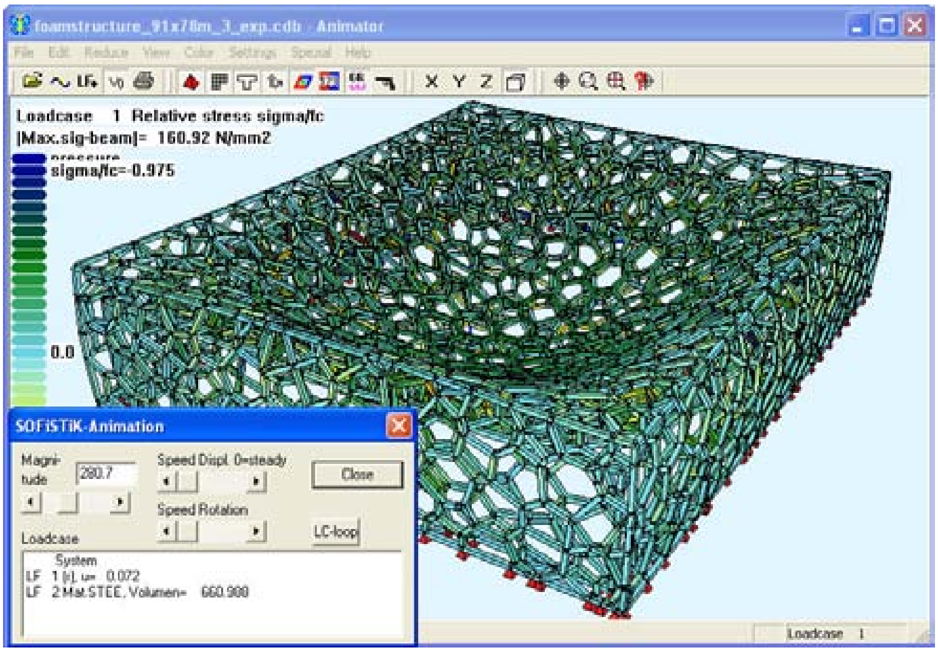


Figure 69: Exaggerated view of deformation of the BCFM under dead load case and simulation results

In the table below, all simulation results and the other structural information of the BCFM are given.

BASE CASE FOAM MODEL					
STRUCTURAL INFORMATION			SIMULATION RESULTS		
ARCHITECTURAL DIMENSIONS	CLEAR SPAN	STRUCTURAL DEPTH of ROOF	RELATIVE STRESS	MAX. DISPLACEMENT	STRUCTURAL WEIGHT
~ 93.5 m x 80,5 m x 20 m	91 m x 78 m	4.68 m	0.975	0.072 m	5189 tons

Table 5: Structural information and simulation results of the base case foam model

<u>Calculation of structural weight:</u>

Structural material is hot rolled steel and the density of material is 78.5 kN/m^3. The total volume of the material used in the BCFM based on the calculations in the program is 660.988 m^3.

Structural Weight = Material Density x Total Volume of Material

= 78.5 kN/m^3 x 660.988 m^3

= 51887.558 kN (1 kN = 0.1 ton)

= 5188.7558 ton ≈ **5189 tons**

4.3.4 Base Case Space Frame Model Simulation Results

First of all, a clear span of base case space frame model was scaled from 140 m by 120 m into 91 m by 78 m, in this way the span was equalized to the clear span of the base case foam model.

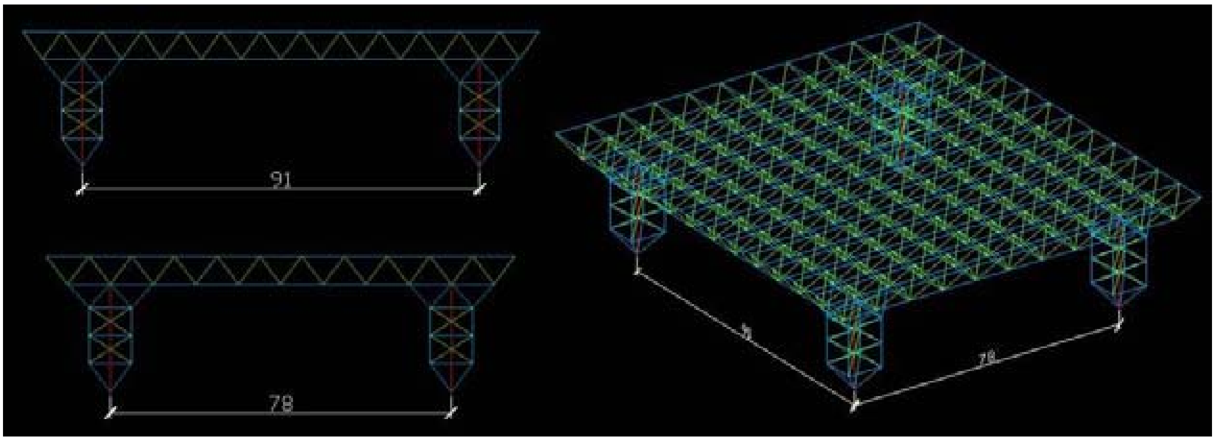


Figure 70: The load-bearing system model of the BCSM with a clear span of 91 m x 78

Diameters of each chord, diagonal and column members of Expo'70 the Symbol Zone are the same but chords and diagonals vary in thickness. This means the Symbol Zone structure is optimized like the Water Cube structure. But its optimization process mustn't be complicated as much as the Water Cube structure and it doesn't require high computer power.

In the Symbol Zone structure, the diameter of diagonals is 350 mm, the diameter of chords is 500 mm and the diameter of posts is 1.8 m. The thickness of chords and diagonals vary from 7.9 mm to 30 mm. Therefore, an optimum thickness was used for chords and diagonals in the simulation of the BCSM. The thickness of tubular posts is unknown therefore it was assumed 40 mm.

But before the simulations, all diameters of members should be scaled with the scaling factor of the BCSM as well. Therefore, firstly, the scaling factor was calculated and then diameters of all members were scaled.

While developing the BCSM, the longitudinal span of the Symbol Zone was not modified. It was just scaled firstly from 108 m in to 140 m then from 140 m in to 91 m. That means in short, the span was scaled from 108 m in to 91 m. And the scaling factor is ~84.26.

In the table below, the original dimensions of cross-sections of the Symbol Zone structure and cross-section dimensions of BCSM are given.

STRUCTURE	CLEAR SPAN	LOAD-BEARING SYSTEM MEMBER	CROSS SECTION	
			DIAMETER (mm)	THICKNESS (mm)
the Symbol Zone	108 m x 75.6 m	chord	500	7.9 - 30
		diagonal	350	7.9 - 30
		post	18000	40
base case space frame model	91 m x 78 m	chord	~420	~6.7 - 25.3
		diagonal	~295	~6.7 - 25.3
		post	~15200	~34

Table 6: Cross-sections of members of Expo'70 the Symbol Zone and the BCSM

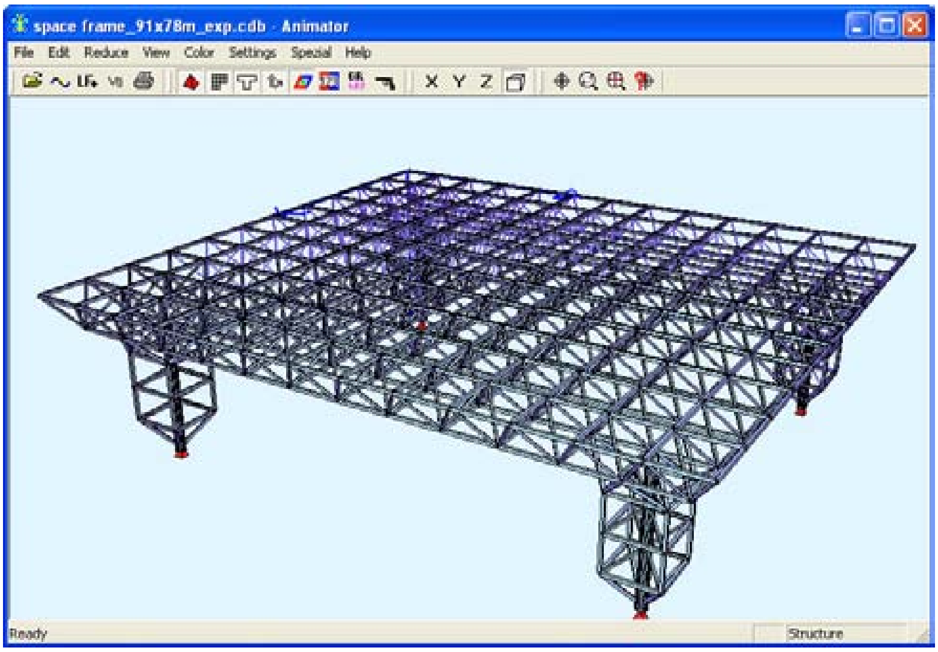


Figure 71: Illustration of the BCSM in BUILD Animator

The result of the simulation is given in Table 5. The structural performance of the BCSM is quite good. The desired relative stress achieved with three of the thinnest cross-sections. That means maximum stresses occurred in the model could be borne by even the members with small cross-sections. This could happen because of the reason that the BCSM was scaled from a larger span in to a smaller span and in this way the density of structural units was increased and this caused higher structural performance.

BASE CASE SPACE FRAME MODEL					
STRUCTURAL MEMBER	CROSS-SECTION SIZE(m) B	H	D	THICKNESS(m)	RELATIVE STRESS (sigma/fc)
chord	-	-	0.420	0.01	0.615
diagonal	-	-	0.295	0.01	
column	-	-	1.520	0.034	

Table 7: Simulation result of the BCSM with span of 91m x 78m under dead load case

According to the result of simulation under the dead load case, the maximum stress occurred in the BCSM is 101.54 kN/mm^2. Higher stresses occur in the middle of the longer span and in the members around column-roof connection.

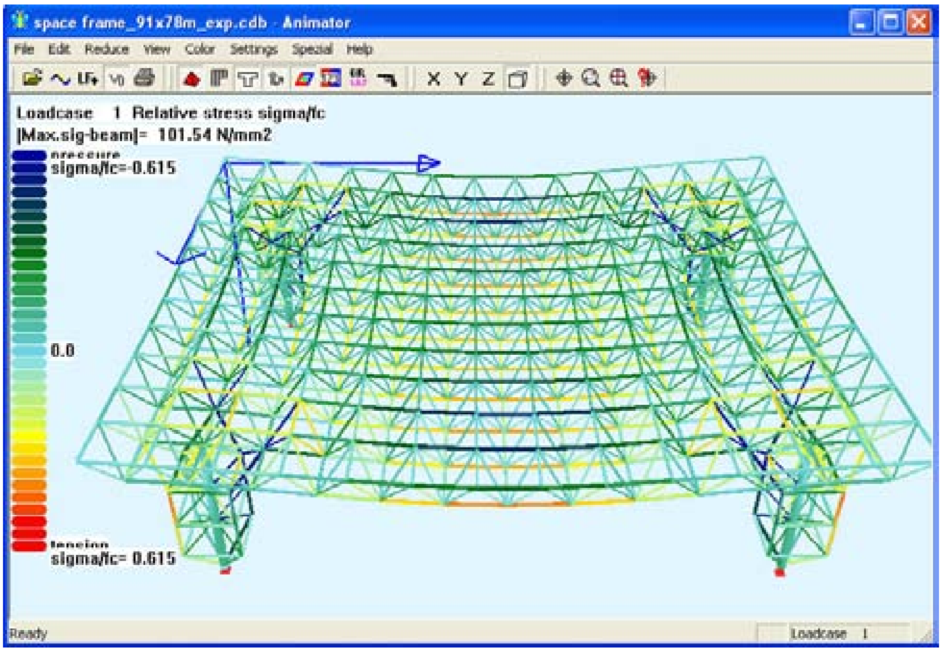


Figure 72: Illustrated simulation result of the BCSM under dead load case

In the table below, structural information and all simulation results of the BCSM are given.

BASE CASE SPACE FRAME MODEL					
STRUCTURAL INFORMATION			SIMULATION RESULTS		
ARCHITECTURAL DIMENSIONS	CLEAR SPAN	STRUCTURAL DEPTH of ROOF	RELATIVE STRESS	MAX. DISPLACEMENT	STRUCTURAL WEIGHT
~ 107 m x 118 m x 31 m	91 m x 78 m	6.43 m	0.615	0.085 m	1200 tons

Table 8: Structural information and simulation results of the BCSM

In the calculation of structural weight of the BCSM, the same calculation process with the BCFM was followed. The structural material is BUILD program default steel type which is hot rolled steel.

Calculation of structural weight:

Density of hot rolled steel is 78.5 kN/m^3. The total volume of material used in the BCSM based on the calculations in the program is 152.818 m^3.

$$\text{Structural Weight} = \text{Material Density x Total Volume of Material}$$
$$= 78.5\ \text{kN/m}^3 \times 152.818\ \text{m}^3$$
$$= 11996.213\ \text{kN} \quad (1\ \text{kN} = 0.1\ \text{ton})$$
$$= 1199.6213\ \text{ton} \approx \mathbf{1200\ tons}$$

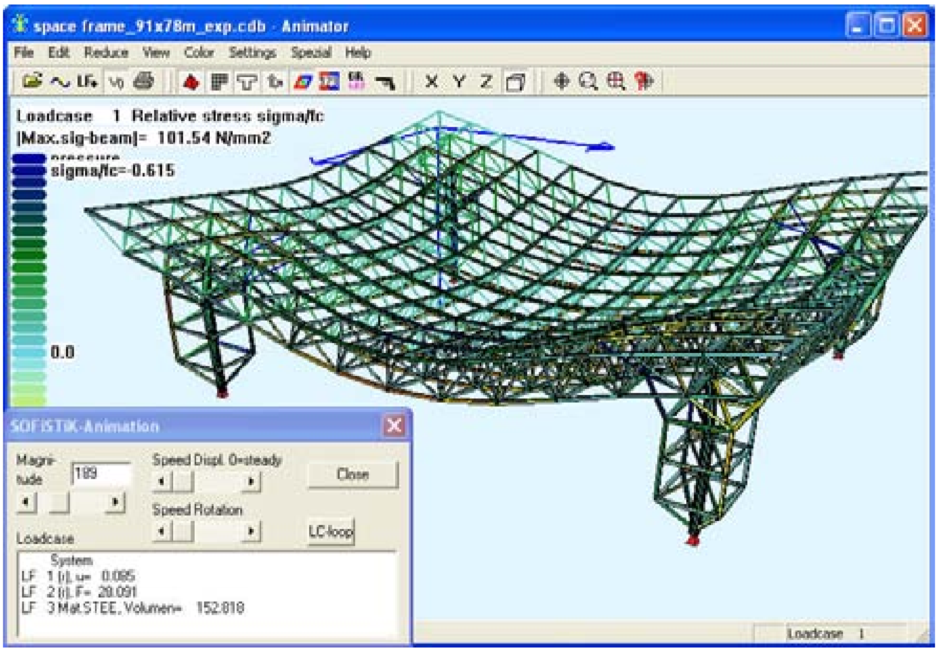


Figure 73: Exaggerated view of deformation of the BCFM under dead load case and simulation results

4.4 Discussion

Simulation results sets a base case foam model as an inefficient structure in terms of structural performance and weight while at the beginning, it was expected to develop a BCFM, at least, with average efficiency. At this point, a discussion of some modeling issues about BCFM and the base case space frame model may help us better understanding of the results.

Concerning the stability and the strength of BCFM, it was needed to reduce the clear span of structure by 35%. After reduction, stability and strength was provided by cross-sections which are quite big relative to cross-sections of the Water Cube members. As a result, BCFM has a quite high weight. Even though, BCFM is much smaller than the Water Cube, their structural weights are 5189 and 6500 tons respectively.

Regarding the modeling process of the BCFM, two major problems are encountered. The first is related to the modeling scale. At the beginning, the same modeling process with the Water Cube was followed but it required a higher computer processor and ram for simulations. Therefore, the bubble density of BCFM is reduced leading to a larger mean bubble sizes. As expected, a completely different façade from the Water Cube was obtained. Moreover, after slicing, small bubble parts were observed in the façade. Probably, these parts do not have any structural function in the load-bearing system and they are just increasing the dead load of the BCFM. The second problem was structural optimization. There are thousands of beam members in BCFM and just hundreds of them are subject to high structural stress. In order to reduce relative stress of these members, cross-sections of all members were increased with the assumption that all members have the same cross-section. As a result, structural weight significantly increased.

Finally, BCFM revealed not as efficient as it was expected in terms of structural performance. The model definitely needs to be optimized structurally and geometrically. Therefore, further simulations are not conducted under different load cases, since the comparative analysis with BCSM will not give realistic results about the efficiency of BCFM in terms of displacement and structural weight. However, as the stability and the strength of BCFM were provided during the analysis, it is worth roughly comparing the simulation results of BCFM and BCSM.

BASE CASE	STRUCTURAL TYPE	STRUCTURAL INFORMATION			SIMULATION RESULTS		
		ARCHITECTURAL DIMENSIONS(m)	CLEAR SPAN(m)	STRUC.DEPTH of ROOF(m)	RELATIVE STRESS	MAX. DISPLACEMENT(m)	STRUC. MASS(t)
BCFM	Foam Structure	~ 93.5 x 80,5 x 20	91 x 78	4.68	0.975	0.072	5189
BCSM	Space Frame	~ 107 x 118 x 31	91 x 78	6.43	0.615	0.085	1200

Table 9: Comparison of results of the BCFM and the BCSM simulations

First of all, the clear spans of both base case models are equal. The design of the large span building structures; the depth of the structure is highly important because the structural depth increases in accordance with the increase of the span length. For space frame structures, the depth of structure changes roughly between a span lenght/15 and a span length/ 30. According to this formula, the depth of space frame structure with 91 m x 78 m could be between 3 m and 6 m and as it can be seen in table above, the depth of both base case models are more or less in this range. But the depth of BCFM is quite less when compared to the depth of BCSM. There is almost 2 m difference between the depths of two base case models. This could save hundreds of m^3 space in the architectural volume of the building.

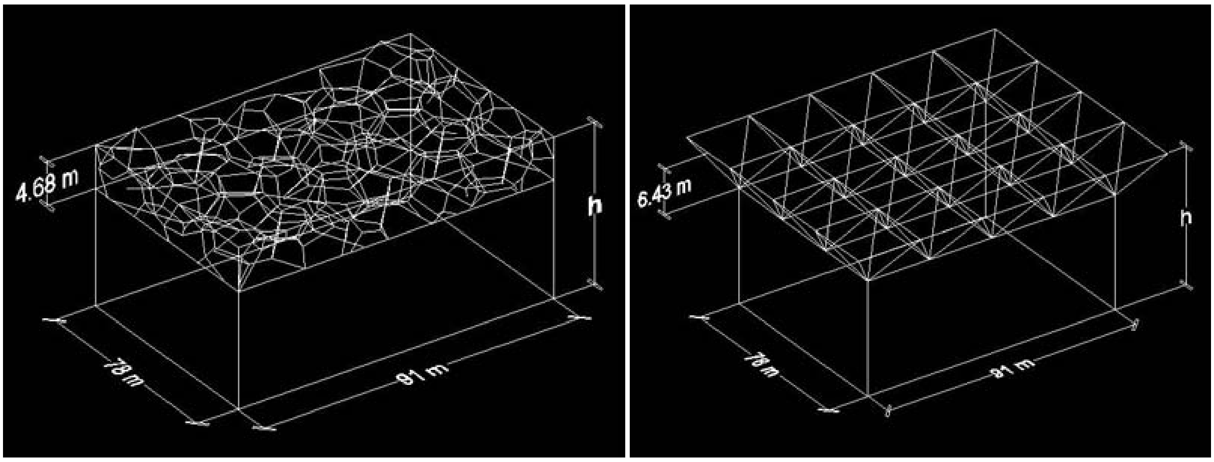


Figure 74: Illustration of the foam structure and space frame simple models in structural depth comparison

If the floor area of both models is 91m x 78m and heights of both models are equal, the saving in architectural volume (A.V) is 12421.5 m^3 is:

$A.V._{(foam\ model)} = 91 \times 78 \times (h - 4.68)$
$= 7098\ (h - 4.68)$

$A.V._{(space\ frame)} = 91 \times 78 \times (h - 6.43)$
$= 7098\ (h - 6.43)$

$A.V._{(differance)} = A.V._{(foam\ model)} - A.V._{(space\ frame)}$
$= 7098 \times [(h - 4.68) - (h - 6.43)]$
$= \mathbf{12421.5\ m^3}$

Secondly, the maximum displacement of BCFM is 0.072 m while the one of BCSM is 0.085 m. There are two major factors, which increase the displacement: The span and the structural weight. Spans of the two structures are the same, and the structural weight of BCFM is quite high. In spite of its high structural weight, maximum displacement of BCFM is less than the displacement of BCSM.

In conclusion, cross-sections of BCFM's members are quite big and the relative stress of the structure is still around 1. Moreover, the structural weight is unrealistically high. Despite all these facts, as a result of our comparison, it can be said that the BCFM is more efficient than BCSM in terms of structural depth and the maximum displacement.

5 Conclusions and Prospects

In this study, efficiency analysis of foam structure was projected with a parametric comparative study of foam structure and space frame based on structural models which were developed based on the real projects the Water Cube and the Symbol Zone of the Expo'70. These models are the base case foam model (BCFM) and the base case space frame model (BCSM). Structural behavior of BCFM and BCSM were simulated. Analysis of both model cases and their structural behavior simulations demonstrated significant facts.

First of all, BCFM is more efficient than BCSM in terms of structural depth which is an important issue from architectural point of view because the structural depth of large span structures is significantly high and therefore it is always tried to be minimized. Decrease in structural depth causes increase in architectural volume which could be used for mechanical installations or other functions of the large span building. The fact that the structural depth of BCFM is less than the one of BCSM makes foam structure a preferable structure for large spans.

Secondly, geometrical and structural optimizations are vitally important structural design processes for BCFM. During the development process of BCFM, it has seen that rotation axes and angles and position of slicing planes are critically important, because slight changes in each of them could change the appearance of foam model and cause to left structurally unnecessary, quite small recursive units after slicing. Geometrical optimization process provides efficient composition of the recursive units without any unnecessary small unit remnants to foam model. Furthermore, structural behavior simulations of BCFM showed that structural performance of BCFM could be increased by optimizing it structurally. The foam model consists of thousands of beam members and structural weight of the foam model could be significantly reduced by structural optimization. BCFM is a model simply composed of thousands of recursive bubble units which definitely needs to be optimized structurally and geometrically.

Finally, for further researches, the answer of the question that what kind of shapes could be built with foam structure is still unknown. The both BCFM and BCSM developed in this study are flat structures. There are many example of space frame structure with different shapes such as vaults, domes and hyperbolic paraboloids. Constructability of curved shapes with foam structure could be examined in further researches.

Moreover, even thought foam structure basically is just a three-dimensional structure composed of recursive bubble units, the geometrical design concerns such as rotation axes, slicing plane positions, density of recursive units of the structure is critically important for foam structure. Therefore, the importance and relationship between geometrical design concerns of the foam structure could be demonstrated in a research which could be a geometrical design guideline for it.

Bibliography

AISC. *Steel Construction Manual.* USA:AISC. ISBN 156424055X

Architecture Australia (2006). “Engineering The Water Cube.” *Architecture Australia July/August 2006.*

Arup Consulting Engineers, Designers, Planners and Project Managers *www.arup.com*

A+U (2005). “Future Structures&Materials: PTW Architects+CSCEC+Design+ARUP National Swimming Center.” *Architecture and Urbanism 01/2005*

Bradshaw, R. (2002). “Special Strcutures:Past, Present, and Future.” *Journal of Structural Engineering 128:6/2002.*

Chilton, J. (2000). *Space Grid Structures.* Oxford, UK: Architectural Press. ISBN 0 7506 3275 5

Detail (1970). “Bauten der Weltausstellung in Osaka.” *Detail 5/1970, 1019-1024.*

Eggen, A. P., Sandaker, B.,N. (1995). *Steel, Structure and Architecture.* Whitney Library of Design/New York: USA: Watson-Guptil Publications. ISBN 0-8230-5020-3

El-Sheikh, A. (1996). *Engineering Structures* 22/2000,1070-1085.

El-Sheikh, A. (2) (1996). “Development of a New Space Truss System.” *Journal of Constructional Steel Research 37:3/1996,* 205-227.

“Future Structures & Materials PTW Architects+ CSCEC +Design +ARUP National Swimming Center.” *Architecture and Urbanism* 1/2005,124-129.

Fu, X., Gu, L., Yang, X., Yu, W. (2005). (Only Abstract) “Structural Design Optimization of National Swimming Center Watercube.” *Jianzhu Jiegou Xuebao (Journal of Building Structure)* 26/2005, 13-19+26.

Gibson, L. J., Ashby, M. F. (1997). *Cellular Solids: Structure and Properties.* Cambridge, UK: Cambridge University Press. ISBN 0 521 49560 1

Hensel, M., Menges, A., Weinstock, M. (2006). “Self-Organisation and Materail Constructions.” *Techniques and Technologies in Morphogenetic Design (Weinstock, M.).* London,UK: John Wiley&Sons Ltd. 34-41. ISBN 13-9780470015292

Hoke, JR. (2000). *Architectural Graphical Standards.* New York,USA:John Wiley&Sons,Inc. ISBN 0-471-34816-3

Kose, K. (1995).: “3D NMR Imagining of Foam Structures.” *Journal of Magnetic Resonance* Series A118/1995, 195-201.

Kraynık, A., Reinelt, D. (1996).: “Linear Elastic Behavior of Dry Soap Foams.” *Journal of Colloid and Interface Science* 181/1996, 511-520.

Schulitz, H., Sobek, W., Habermann, K. *Steel Construction Manual.* Munich:Germany: Institute für Internationale Architektur-Dokumentation GmbH. ISBN 3-7643-6181-6

Structural Engineer(1) (2004). “Beijing’s Water Cube of Breathtaking Bubbles.” *The Structural Engineer 82:11/2004, 14-16.*

Structural Engineer(2) (2004). “Beijing Water Cube-The IT Challenge.” *The Structural Engineer 82:13/2004, 23-26.*

Structural Engineer (2006). “Analysing Beijing’s Water Cube.” *The Structural Engineer 83:3/2006, 26.*

Weaire, D., Hutzler, S. (1999). *The Physics of Foams.* New York, USA:Oxford Universty Press. ISBN 0-19-850551-5

William, T. (1887). “On the Division of Space with Minimum Partitional Area.” *The London, Edinburgh and Dublin Philosophical Magazine* 24/1887, 503-518.

Williams, R. E. (1968). “Space Filling Polyhedron: It’s Relation to Aggregates of Soap Bubbles, Plant Cells, and Metal Crystallites.” *Science 161:3838/1968, 276-277.*

Yu, W., Zhao, Y., Gu, L., Fu X., Dong, S. (2005). (Only Abstract) “Optimization od Geometric Constitution of New Polyhedron Spatial Frames.” *Jianzhu Jiegou Xuebao (Journal of Building Structure)* 26:6/2005, 7-12.

Yu, W., Wang W., Gu L., Zhao, Y., Fu, X., Dong, S. (2005). (Only Abstract) “Study on Basic Cells of New Polyhedron Spatial Frames.” *Jianzhu Jiegou Xuebao (Journal of Building Structure)* 26:6/2005, 1-6.

Zhao, Y., Wang, W., Xing, L., Fu, X., Gu, L., Dong, S. (2005). (Only Abstract) ”Experimental Study on Reinforcing Moment Connections for Square Steel Tubes in National Swimming Center.” *Jianzhu Jiegou Xuebao (Journal of Building Structure)* 26:6/2005, 45-53+63.

Arup Web (2007). http://www.arup.com/eastasia/project.cfm?pageid=1250. Last visited in June 2007.

Steel Pillow (2007). http://www.steelpillow.com/polyhedra/wp/wp.htm. Last visited in June 2007.

Structurae (2007). http://en.structurae.de/structures/data/photos.cfm?ID=s0015480. Last visited in June 2007.

Chris Bosse (2007). http://www.chrisbosse.de/. Last visit in June 2007

Architen (2007). http://www.architen.com/. Last visit in May 2007.

Appendix

Simulation results of each base cases in Table 3, in chapter 4;section 4.3, are given below. First of all, quarter of the BCFM was simulated under dead load case in order to examine it's stability and strenght. Simulation of the entire model gives more or less same results with simulation of quarter of the structure for three-dimensional strcutures i.e. foam strcuture, space frame.

Case 1:

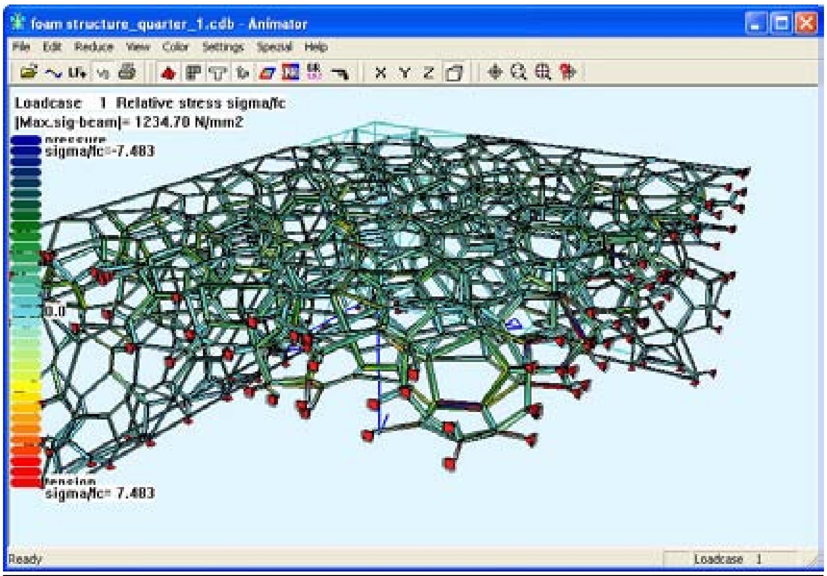


Figure A- 1.1: Relative stress of BCFM is very high.

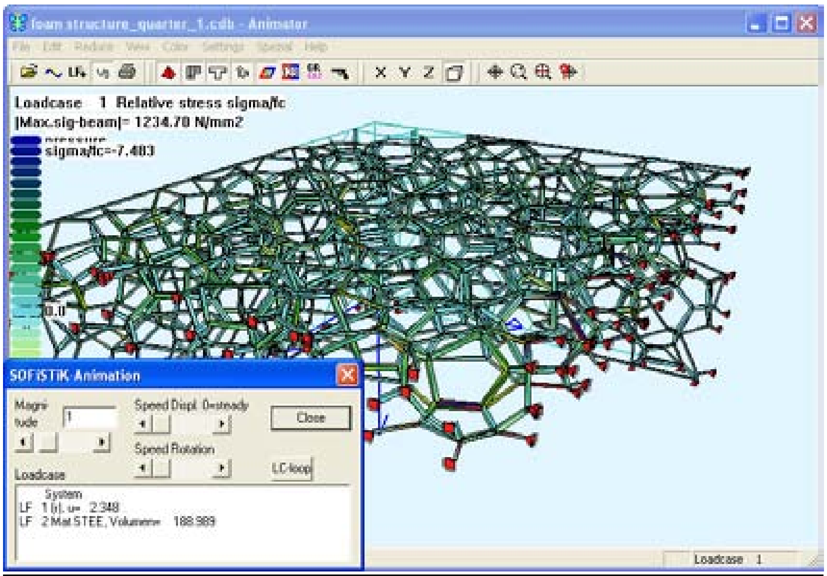


Figure A- 1.2: Max. Displacement 2.348 m

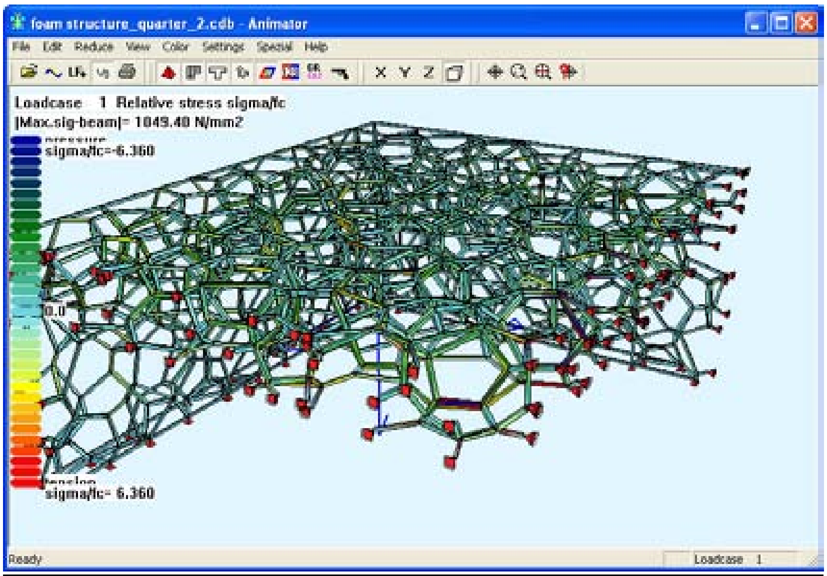


Figure A- 2.1: Relative stress was decreased but it is still high

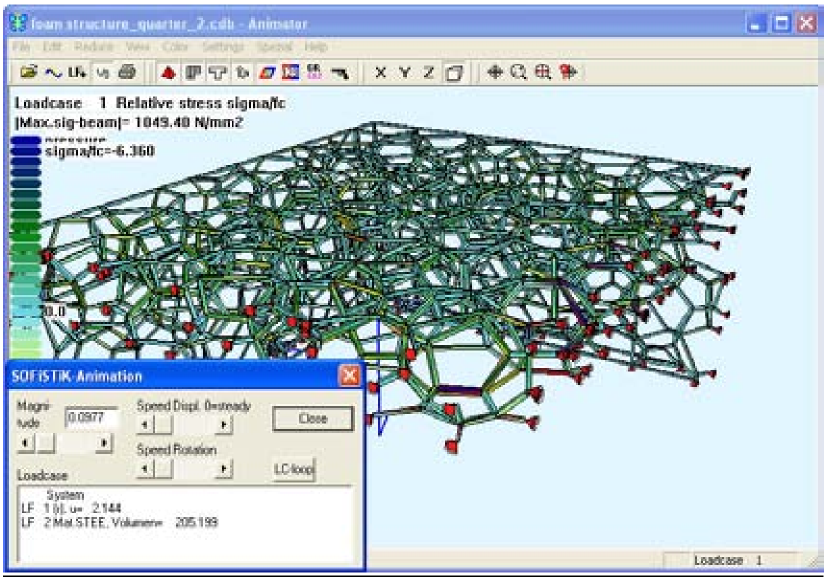


Figure A- 2.2: Max. displacement is 2.144 m, it is also decreasing

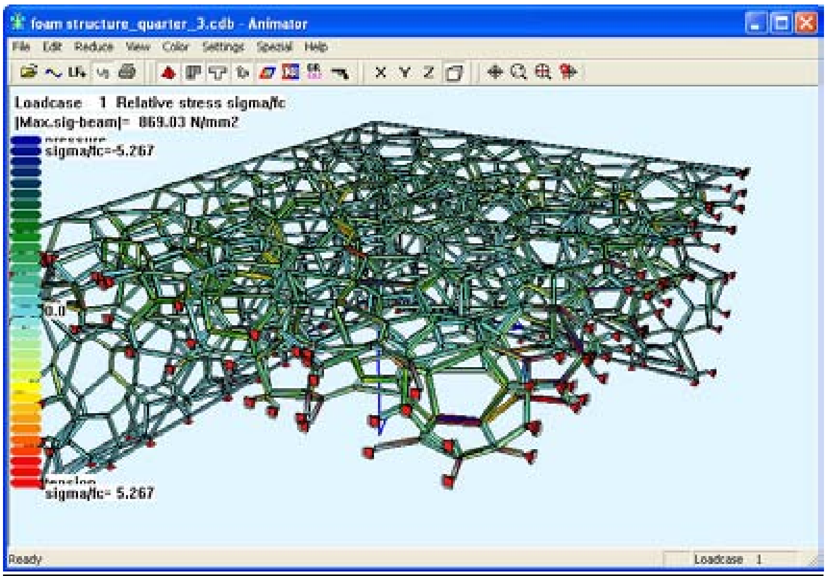


Figure A- 3.1: Relative stress is still greater than 1

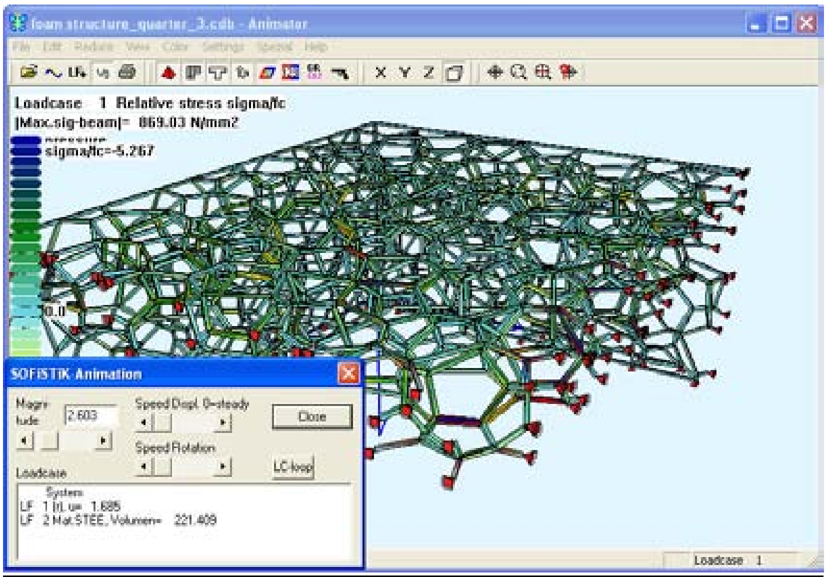


Figure A- 3.2: Max. displacement was decreased to 1.685 m

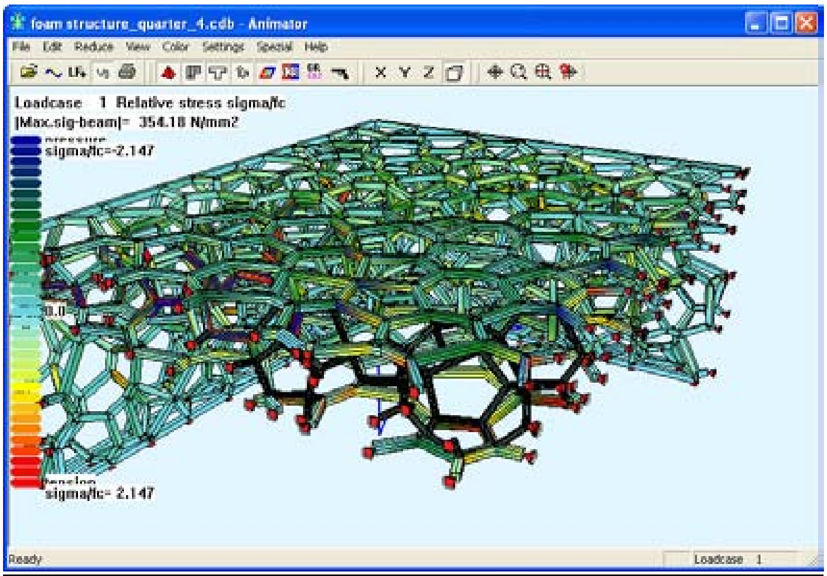


Figure A- 4.1: Cross-sections are enlarging while relative stress is decreasing

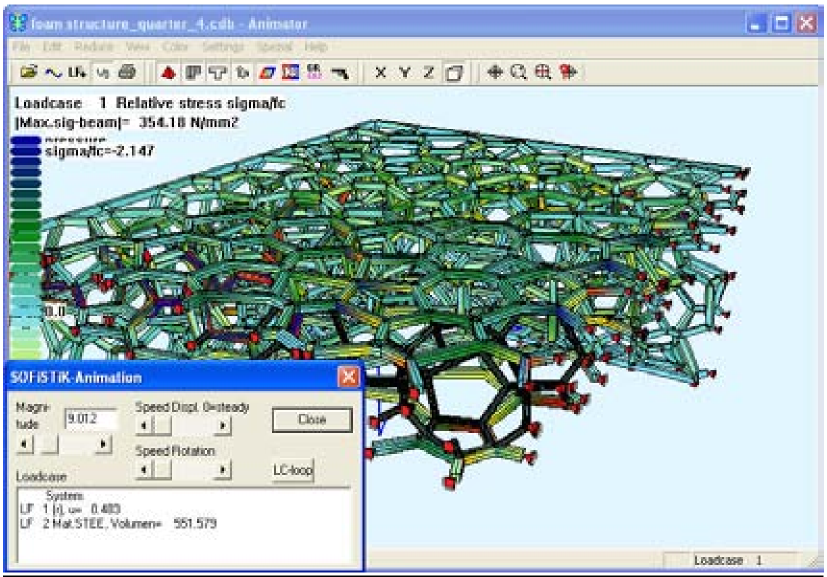


Figure A- 4.2: Max. displacement was reduced to 0.483 m by big cross-sections

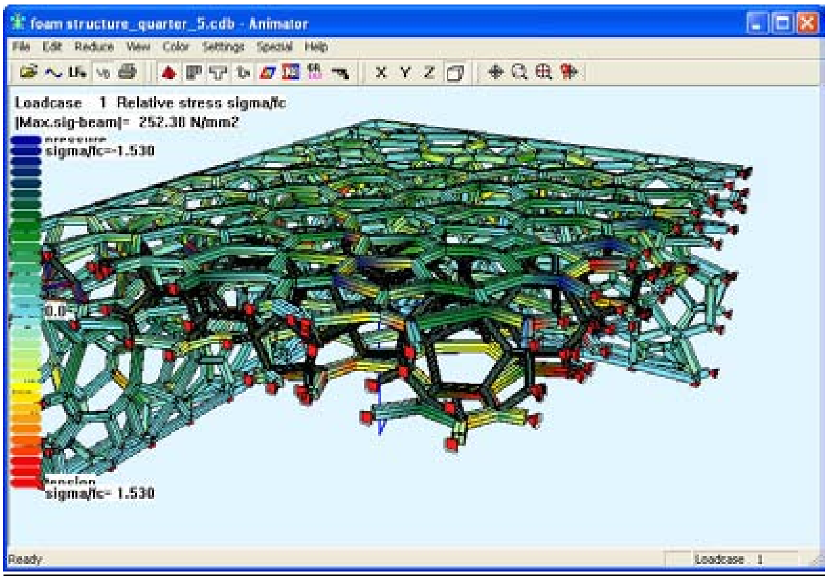


Figure A- 5.1: Max. stresses occurred in structure are decreasing

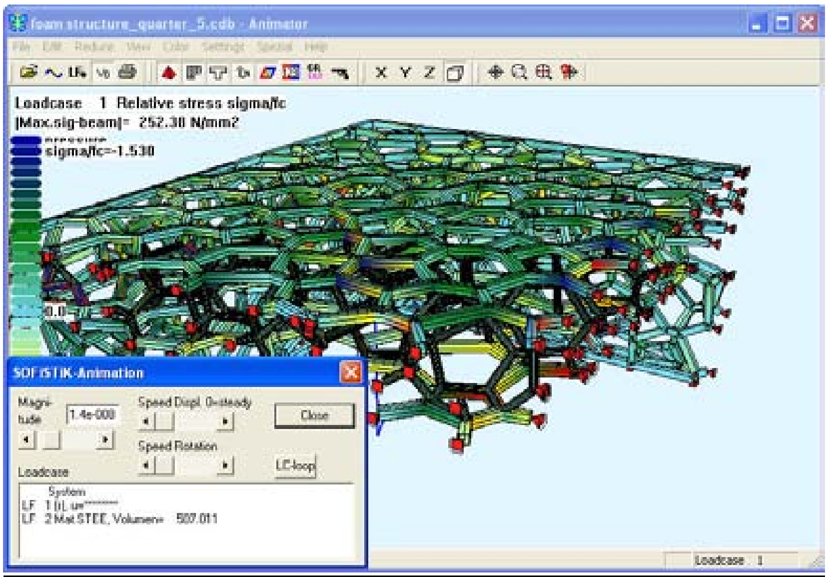


Figure A- 5.2: Displacement is very small

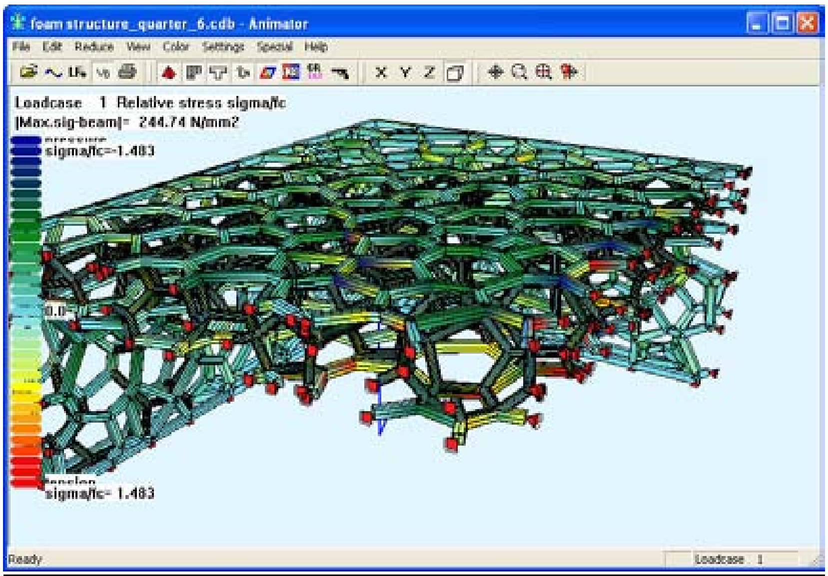


Figure A- 6.1: Relative stress is decreasing slowly

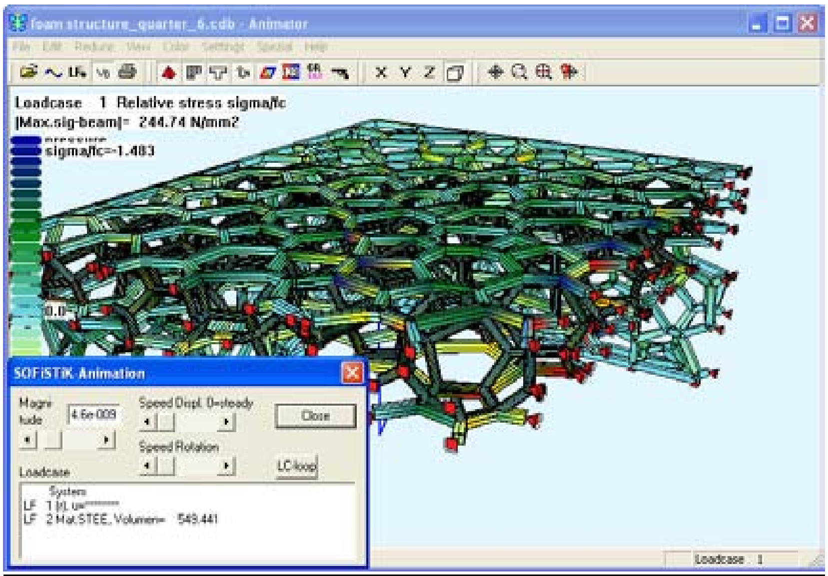


Figure A- 6.2: Displacement is very small because structural members are quite big

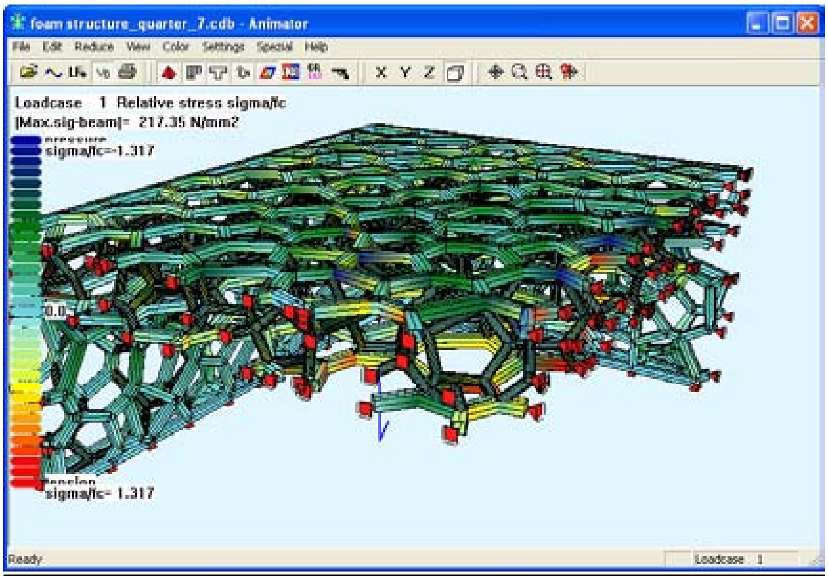


Figure A- 7.1: Relative stress is around 1

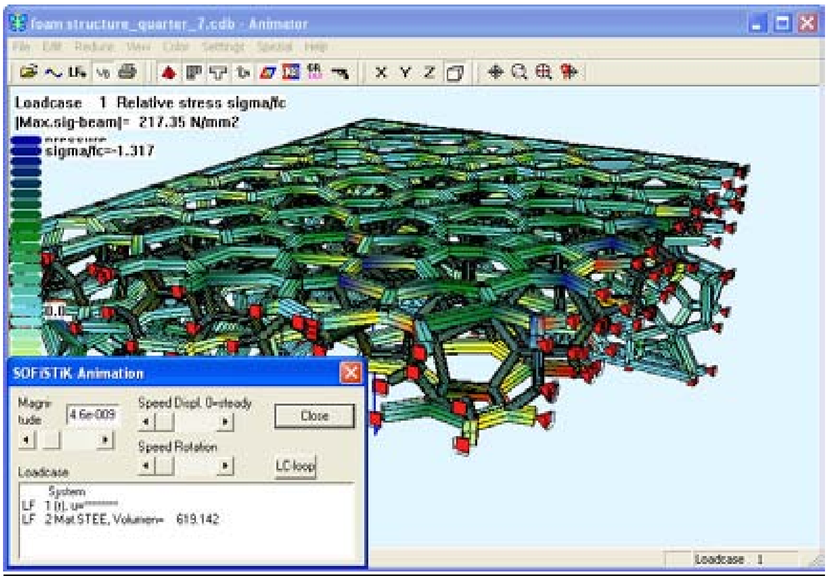


Figure A- 7.2: Displacement is too small because structural members are quite strenght

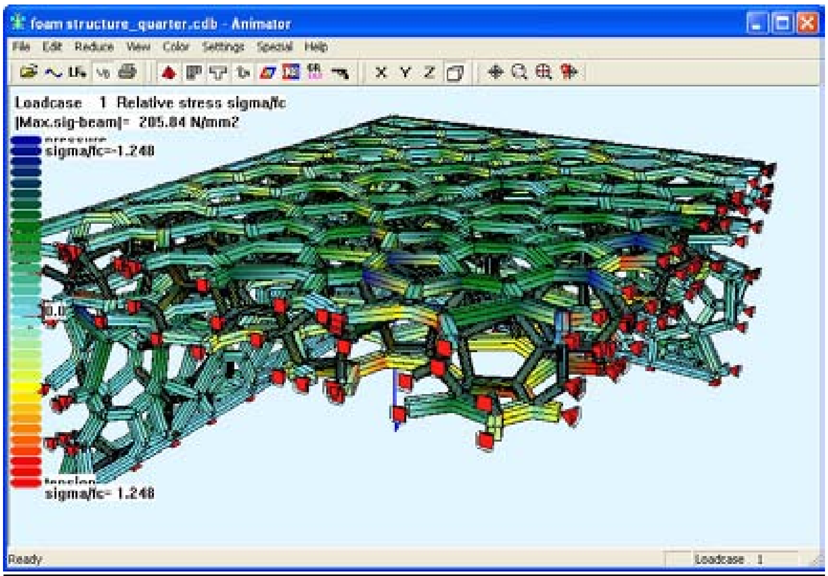


Figure A- 8.1: The lowest relative stress achieved during simulation anlyses.

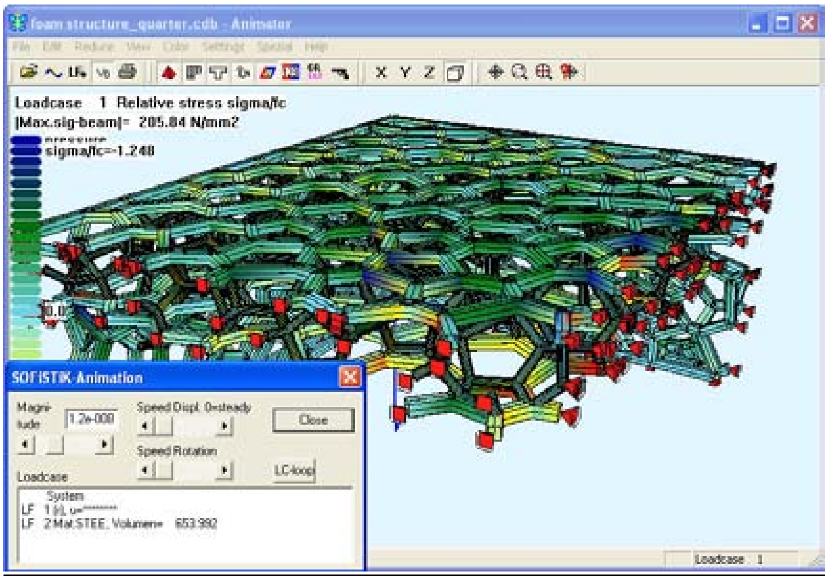


Figure A- 8.2: Displacement is unknown, max. stresses of BCFM are increasing related with increasing dead load.

Simulation of base case foam model with span 140 m by 120 m were done under dead load case. But this simulations weren’t used in comparison. Cross-sections of members used in simulation are given below.

SPACE FRAME BASE CASE with span of 140 m x120 m					
STRUCTURAL MEMBER	CROSS-SECTION SIZE(m) B	H	D	THICKNESS(m)	RELATIVE STRESS (sigma/fc)
chord			0.500	0.03	0.925
diagonal			0.350	0.03	
column			1.8	0.05	

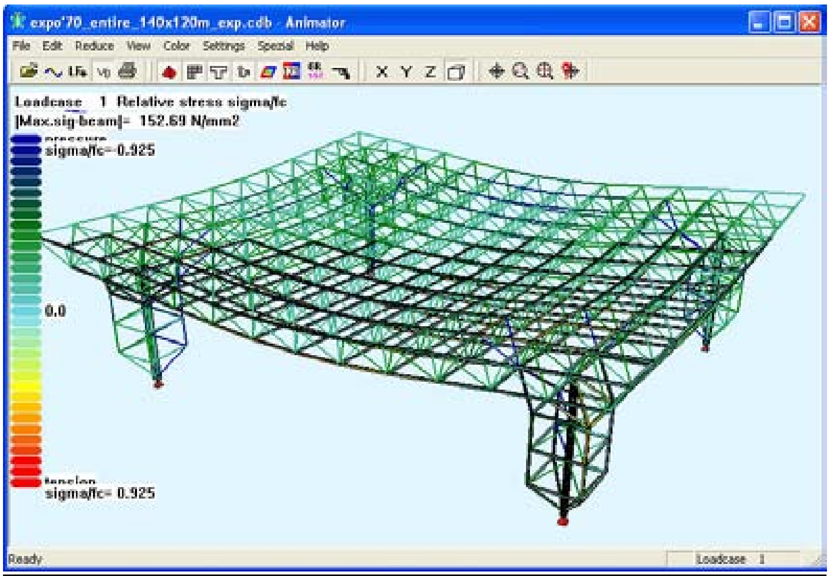


Figure B-1: Relative stress of base case space frame model is less than 1. Stability and strength of structure was provided under dead load case.

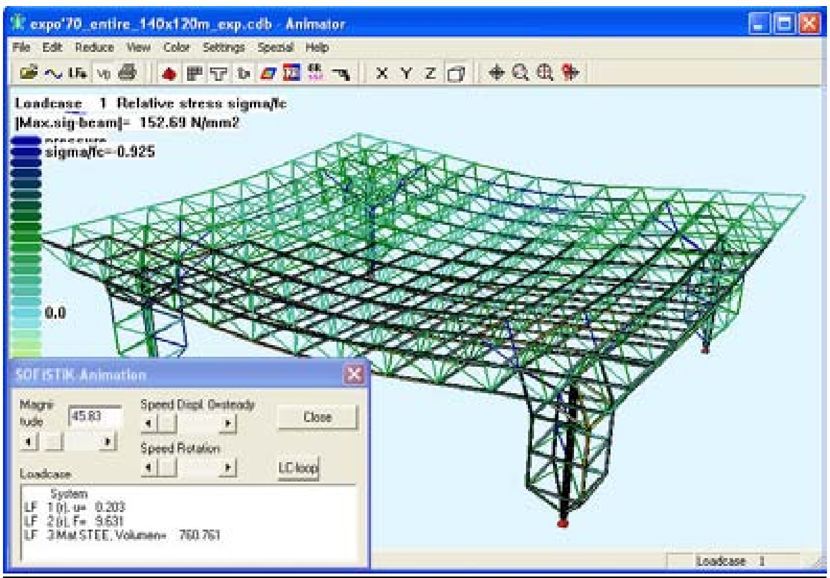


Figure B-2: Displacement of BCSM around 20 cm