Structural Behavior of BubbleDeck® Slabs And Their Application to Lightweight Bridge Decks

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1. Executive Summary

The BubbleDeck slab is a revolutionary biaxial concrete floor system developed in Europe. High-density polyethylene hollow spheres replace the ineffective concrete in the center of the slab, thus decreasing the dead weight and increasing the efficiency of the floor. These biaxial slabs have many advantages over a conventional solid concrete slab: lower total cost, reduced material use, enhanced structural efficiency, decreased construction time, and is a green technology.

Through tests, models and analysis from a variety of institutions, BubbleDeck® was proven to be superior to the traditional solid concrete slab. The reduced dead load makes the long-term response more economical for the building while offsetting the slightly increased deflection of the slab. However, the shear and punching shear resistance of the BubbleDeck floor is significantly less than a solid deck since resistance is directly related to the depth of concrete. Design reduction factors have been suggested to compensate for these differences in strength. This system is certified in the Netherlands, the United Kingdom, Denmark and Germany.

In this investigation, after verifying the validity of the prior research through a finite element analysis of an office floor in SAP2000, the BubbleDeck® slab was tested for a pedestrian bridge deck. Bridge design is dominated by the dead weight of the structure and by concentrated stresses from vehicular traffic. This new slab can solve both of these problems by reducing weight with the plastic spheres and by applying it to a pedestrian bridge to limit the high stresses. A set of bridge decks were modeled and analyzed in SAP2000 for this study.

2. Introduction

2.1. Concrete Floor Systems

Reinforced concrete slabs are components commonly used in floors, ceilings, garages, and outdoor wearing surfaces. There are several types of concrete floor systems in use today, and are shown in Figure 2-1:

- *Two-way flat plate (biaxial slab)-* There are no beams supporting the floor between the columns. Instead, the slab is heavily reinforced with steel in both directions and connected to the columns in order to transfer the loads.
- *Two-way flat slab with drop panels-* This system differs from the two-way flat plate system by the drop panel used to provide extra thickness around the columns. This strengthens the column to floor connection in consideration of punching shear.
- *One-way beam and slab-* This is the most typical floor system used in construction. The slab loads are transferred to the beams, which are then transferred to the columns.
- *One-way joist slab-* The joists act like small beams to support the slab. This floor system is economical since the formwork is readily available and less reinforcement is required.
- *One-way wide module joist slab-* This system is a variation on the one-way joist slab with wider spaces between the joists.
- *Two-way joist slab (waffle slab)-* This floor system is the stiffest and has the least deflection of those mentioned since the joists run in two directions (Concrete Reinforcing Steel Institute).

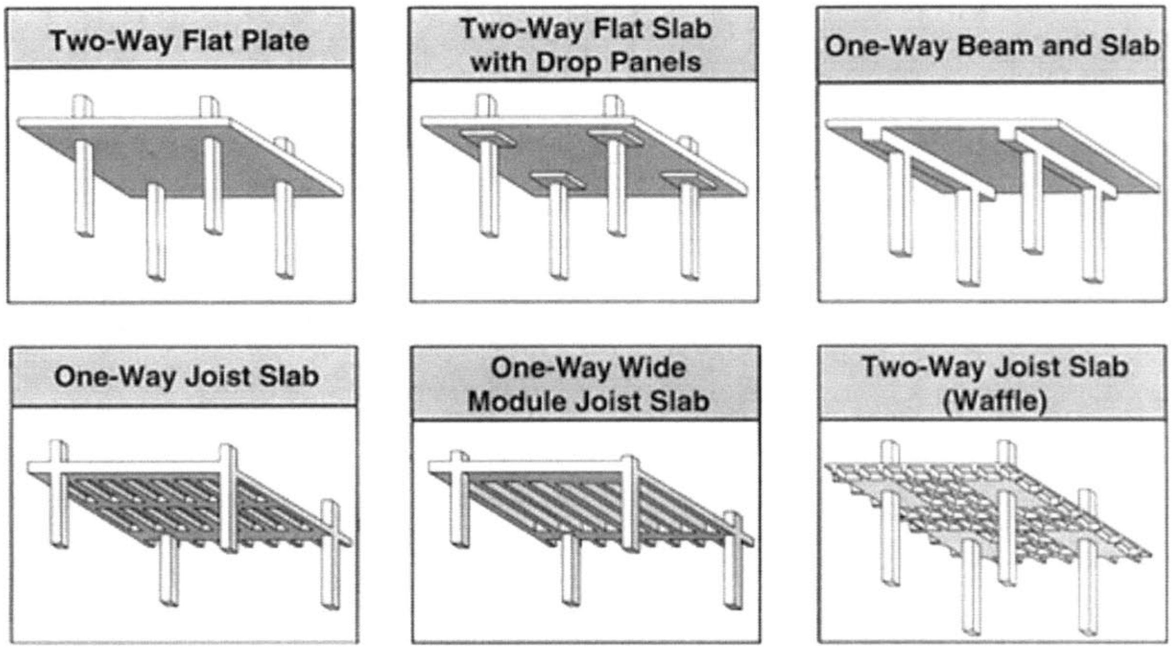

Figure 2-1: Types of Reinforced Concrete Floor Systems (Concrete Reinforcing Steel Institute)

Reinforced concrete has many advantages for floor systems- it provides resistance to high compressive stresses and to bending stresses; it is relatively cheap to produce and construct; and it can be molded into virtually any shape and size. Disadvantages include a high weight-to-strength ratio and difficulty in structural health monitoring (Reinforced Cement Concrete Design).

2.1.1. Hollow-Core Slabs

In the mid-20th Century, the voided or hollow core floor system was created to reduce the high weight-to-strength ratio of typical concrete systems. This concept removes and/or replaces concrete from the center of the slab, where it is less useful, with a lighter material in order to decrease the dead weight of the concrete floor. However, these hollow cavities significantly decrease the slabs resistance to shear and fire, thus reducing its structural integrity.

This floor system typically comes in the form of precast planks that run from 4 ft to 12 ft wide and consist of strips of hollow coring with pre-stressed steel strands in between. Figure 2-2 illustrates several types of hollow-core planks used in the industry. They are combined on site to form a one-way spanning slab and topped with a thin layer of surfacing (PCI).

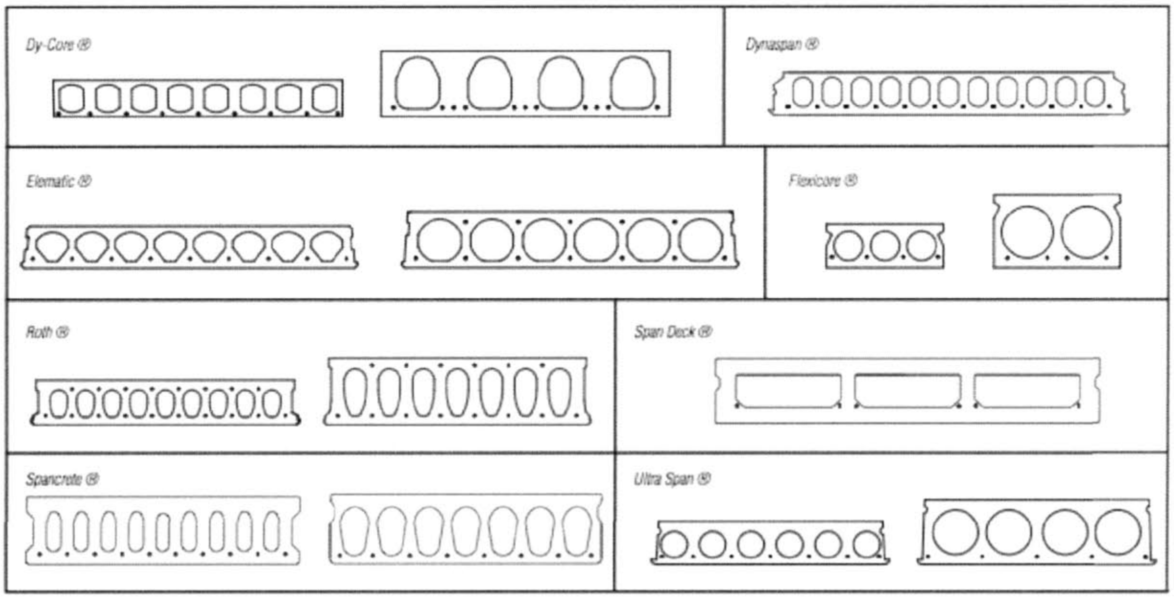

Figure 2-2: Types of Hollow-Core Planks (PCI)

2.2. Problem Statement

In the 1990's, Jørgen Breuning invented a way to link the air space and steel within a voided biaxial concrete slab. The BubbleDeck® technology uses spheres made of recycled industrial plastic to create air voids while providing strength through arch action. See Figure 2-3 for a section cut of a BubbleDeck. As a result, this allows the hollow slab to act as a normal monolithic two-way spanning concrete slab. These bubbles can decrease the dead weight up to 35% and can increase the capacity by almost 100% with the same thickness. As a result, BubbleDeck® slabs can be lighter, stronger, and thinner than regular reinforced concrete slabs (BubbleDeck®-UK).

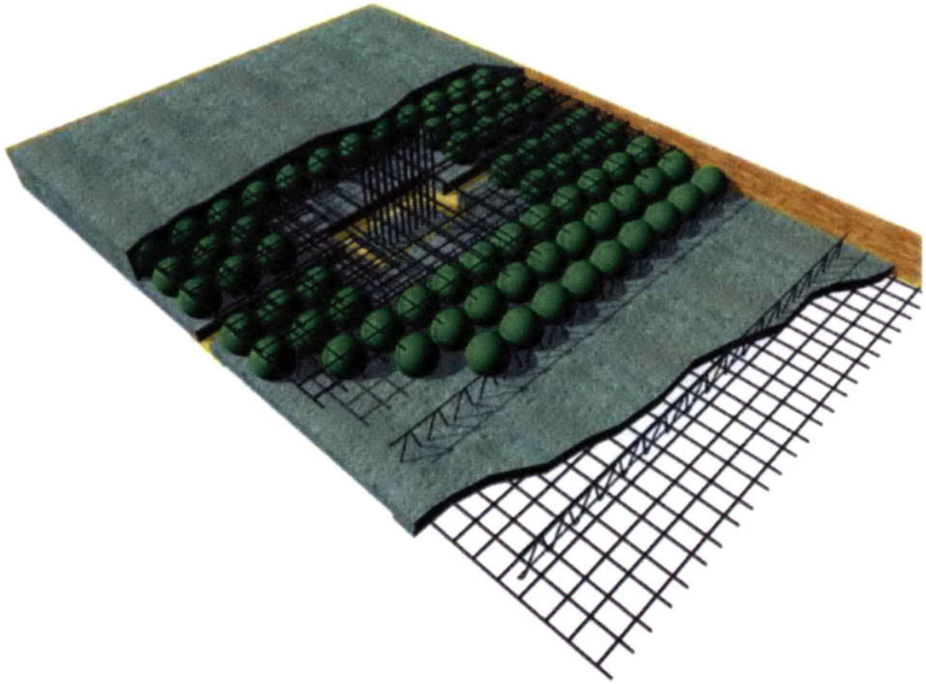

Figure 2-3: Cut-through Section of BubbleDeck® (BubbleDeck®-UK)

Currently, this innovative technology has only been applied to a few hundred residential, high-rise, and industrial floor slabs due to limited understanding. For this investigation, the structural behavior of BubbleDeck® under various conditions will be studied in order to gain an understanding on this new technique and to compare it to the current slab systems. This technology will then be applied to create lightweight bridge decks since a significant portion of the stress applied to a bridge comes from its own self-weight. By applying the knowledge gathered during the behavioral analysis, a modular deck component for pedestrian bridges that is notably lighter but comparable in strength to typical reinforced concrete sections will be designed.

3. BubbleDeck®

3.1. Materials

BubbleDeck is composed of three main materials- steel, plastic spheres and concrete, as see in Figure 3-1.

- *Steel*- The steel reinforcement is of Grade Fy60 strength or higher. The steel is fabricated in two forms- meshed layers for lateral support and diagonal girders for vertical support of the bubbles.
- *Plastic spheres*- The hollow spheres are made from recycled high-density polyethylene or HDPE.
- *Concrete*- The concrete is made of standard Portland cement with a maximum aggregate size of 3/4 in. No plasticizers are necessary for the concrete mixture. (BubbleDeck International)

Figure 3-1: Components of a BubbleDeck (Stubbs)

3.2. Schematic Design

BubbleDeck is intended to be a flat, two-way spanning slab supported directly by columns. The design of this system is generally regulated by the allowed maximum deflection during service loading. The dimensions are controlled by the span (L) to effective depth (d) ratio

(L/d) as stated by BS8110 or EC2. This criterion can be modified by applying a factor of 1.5 that takes into account the significantly decreased dead weight of the BubbleDeck slab as compared to a solid concrete slab. In addition, larger spans can be achieved with the use of post-tensioning as the L/d ratio can be increased up to 30%. (BubbleDeck®-UK)

$L/d \leq 30$ for simply supported, single spans

$L/d \leq 41$ for continuously supported, multiple spans

$L/d \leq 10.5$ for cantilevers

There are five standard thicknesses for BubbleDeck, which vary from 230 mm to 450 mm, and up to 510 mm and 600 mm for specific designs pending KOMO certification. The varieties of BubbleDeck can be found in Table 3-1.

Table 3-1: Versions of BubbleDeck® (The Biaxial Hollow deck- The way to new solutions)

Version	*Bubble Diameter (mm)*	*Minimum Slab Thickness (mm)*	*Minimum Center-to-Center Spacing (mm)*
BD230	180	230	200
BD280	225	280	250
BD340	270	340	300
BD390	315	390	350
BD450	360	450	400
BD510	405	510	450
BD600	450	600	500

3.3. Types of BubbleDeck

All of the BubbleDeck versions come in three forms- filigree elements, reinforcement modules, and finished planks. They are depicted in Figure 3-2. For all types of BubbleDeck, the maximum element size for transportation reasons is 3 m. Once the sections are connected on site however, there is no difference in the capacity.

3.3.1. Type A- Filigree Elements

BubbleDeck Type A is a combination of constructed and unconstructed elements. A 60 mm thick concrete layer that acts as both the formwork and part of the finished depth is precast and brought on site with the bubbles and steel reinforcement unattached. The bubbles are then supported by temporary stands on top of the precast layer and held in place by a honeycomb of interconnected steel mesh. Additional steel may be inserted according to the reinforcement requirements of the design. The full depth of the slab is reached by common concreting techniques and finished as necessary. This type of BubbleDeck is optimal for new construction projects where the designer can determine the bubble positions and steel mesh layout.

3.3.2. Type B- Reinforcement Modules

BubbleDeck Type B is a reinforcement module that consists of a pre-assembled sandwich of steel mesh and plastic bubbles, or "bubble lattice". These components are brought to the site, laid on traditional formwork, connected with any additional reinforcement, and then concreted in place by traditional methods. This category of BubbleDeck is optimal for construction areas with tight spaces since these modules can be stacked on top of one another for storage until needed.

3.3.3. Type C- Finished Planks

BubbleDeck Type C is a shop-fabricated module that includes the plastic spheres, reinforcement mesh and concrete in its finished form. The module is manufactured to the final depth in the form of a plank and is delivered on site. Unlike Type A and B, it is a one-way spanning design that requires the use of support beams or load bearing walls. This class of BubbleDeck is best for shorter spans and limited construction schedules (BubbleDeck®-UK).

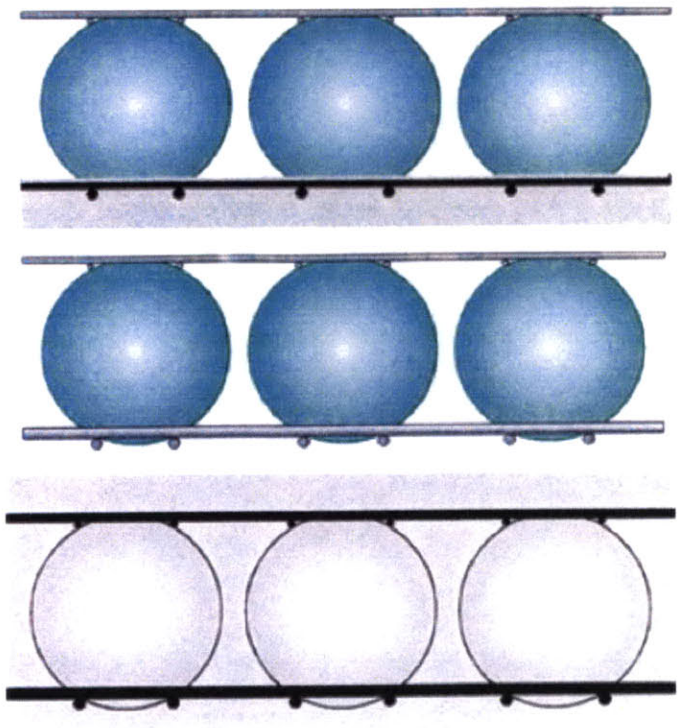

Figure 3-2: Three Types of BubbleDeck- Type A, B, & C (Björnson)

3.4. Advantages of BubbleDeck

3.4.1. Material and Weight Reduction

The dominant advantage of a BubbleDeck slab is that it uses 30-50% less concrete than normal solid slabs. The HDPE bubbles replace the non-effective concrete in the center of the section, thus reducing the dead load of the structure by removing unused, heavy material. Decreased concrete material and weight also leads to less structural steel since the need for reinforcement diminishes. The building foundations can be designed for smaller dead loads as well. Overall, due to the lighter floor slabs, the several downstream components can be engineered for lower loads and thus save additional material (Wrap).

3.4.2. Structural Properties

Due to the lower dead weight of the slab and its two-way spanning action, load-bearing walls become unnecessary. BubbleDeck is also designed as a flat slab, which eliminates the need for support beams and girder members. As a result, these features decrease some of the structural requirements for the columns and foundations.

Additionally, BubbleDeck slabs can be designed and analyzed as a standard concrete flat slab according to research performed on its strength and ductility, which will be discussed in depth later in the report. As summarized by Table 3-2, the dead load-to-carrying capacity of a solid slab is 3:1 while a BubbleDeck of the same thickness has a 1:1 dead load-to-carrying capacity ratio (Wrap).

Table 3-2: BubbleDeck vs. Solid Slab (adapted from BubbleDeck®-UK)

Relative % of solid slab	***Solid Slab***	***BubbleDeck® with same thickness***	***BubbleDeck® with same capacity***
Carrying Capacity	25	50	25
Dead Load	75	50	40
Dead Load to Carrying Capacity Ratio	3:1	1:1	1.5:1

3.4.3. Construction and Time Savings

On site construction time can be shortened since BubbleDeck slabs can be precast. Type A includes a 60 mm precast concrete plate as the base and formwork for the slab. This type of slab would eliminate the need for on site erection of formwork, thus significantly cutting down construction time. Similar to modern precast concrete flooring modules, BubbleDeck can be fully shop fabricated and transported on site for installation as well. Figure 3-3 is an example of how BubbleDeck® sections can be lifted into place at the construction site.

Time savings can also be achieved through the faster erection of walls, columns and MEPs due to the lack of support beams and load bearing walls for this innovative flat slab. Addition time may be saved from the quicker curing time since there is less concrete in the slab.

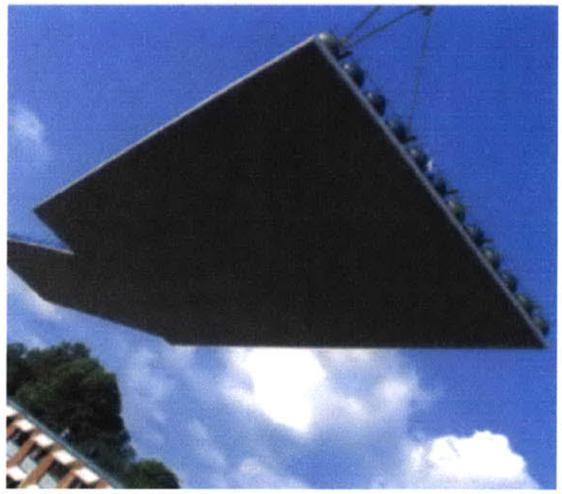

Figure 3-3: Lifting a Section of Type A BubbleDeck® (BubbleDeck®-UK)

3.4.4. Cost Savings

In relation to the savings in material and time, cost reductions are also typical with the BubbleDeck system. The decreased weight and materials mean lower transportation costs, and would by more economical to lift the components. With less on-site construction from the full and semi-precast modules, labor costs will decrease as well. In addition, money can be saved downstream in the design and construction of the building frame elements (columns and walls) for lower loads.

There is a slight rise in production costs for the BubbleDeck slab due to the manufacturing and assembly of the HDPE spheres. However, the other savings in material, time, transportation and labor will offset this manufacturing price increase (Stubbs).

3.4.5. Green Design

The number of owners, designers and engineers who desire green alternatives is growing exponentially. BubbleDeck is a fitting solution for lowering the embodied carbon in new buildings. According to the BubbleDeck® company, 1 kg of recycled plastic replaces 100 kg of concrete. By using less concrete, designers can save up to 40% on embodied carbon in the slab, resulting in significant savings downstream in the design of other structural members. Carbon emissions from transportation and equipment usage will also decrease with the use of fewer materials. Additionally, the HDPE bubbles can be salvaged and reused for other projects, or can be recycled.

Generally, for every 5,000 m^2 of BubbleDeck floor slab, the owner can save:

- 1,000 m^2 of on-site concrete
- 166 concrete truck trips
- 1,798 tonnes of foundation load, or 19 less piles
- 1,745 GJ of energy used in concrete production and transportation
- 278 tonnes of CO_2 emissions (BubbleDeck®-UK)

4. Structural Properties and Design

Research has been performed at several institutions in Denmark, Germany and the Netherlands on the mechanical and structural behavior of BubbleDeck. Studies include bending strength, deflection, shear strength, punching shear, fire resistance, and sound testing. This paper focuses on stiffness and shear resistance. Since all of the available research on BubbleDeck was performed in Europe, only European design codes and certifications will be mentioned in this section.

4.1. Technical Certifications

BubbleDeck® has been certified by several European authorities.

- *The Netherlands*- In 2001, BubbleDeck was incorporated into the Dutch standards NEN 6720 by the Civieltechnisch Centrum Uitvoering Research en Regelgeving (CUR) Committee 86.
  BubbleDeck also received the KOMO Certificate K22722/01 in 2002 from Kiwa N.V., an official European Organisation for Technical Approvals (EOTA) member.
- *United Kingdom*- The system was approved by the Concrete Research & Innovation Centre (CRIC) in 1997 for inclusion in the BS8110 as a normal biaxial, flat slab supported by columns.
- *Denmark*- In 1996, the Directorate of Building and Housing from the Municipality of Copenhagen stated that BubbleDeck could be designed according to the existing principles and standards.
- *Germany*- The Deutsches Institut fur Bautechnik acknowledged that the new system could be designed with the existing technical methods and codes, and was approved in the DIN 1045 (BubbleDeck Engineering Design & Properties Overview).

4.2. Bending Stiffness and Deflection

Only the top compressive portion, the "stress block", and the bottom reinforcement steel of a solid concrete slab contribute to its flexural stiffness in bending. A standard beam stress block is shown in Figure 4-1. BubbleDeck removes the ineffective concrete in the center of a flexural slab and replaces it with hollow HDPE spheres. The slab is designed in accordance with

EC2 and BS8110 so that the bubble zone is sandwiched between concrete layers of approximately the same stress block depth as in a solid slab. If the slab is highly stressed, the stress block may enter the bubble zone. However, tests have proven that anything up to a 20% encroachment has a trivial effect on the performance of the BubbleDeck.

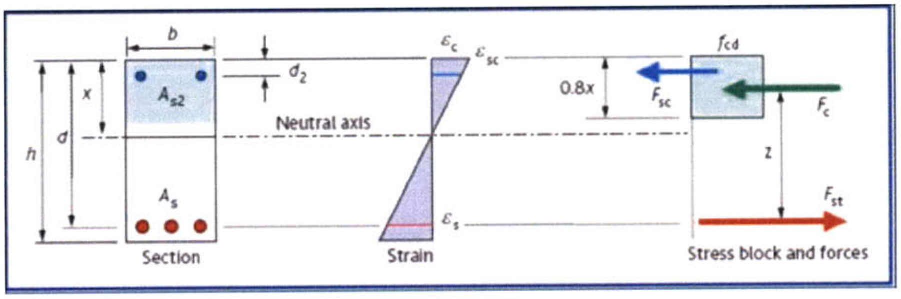

Figure 4-1: Standard Stress Block (Eurocode2)

It is also important to note that the voids in BubbleDeck are discrete volumes that contain HDPE spheres and are not prismatic like other hollow core slabs where the void runs the entire length of the floor. This 2D-array of bubbles does not weaken the strength or the stiffness of the slab but actually provides further support in an arch-like fashion (BubbleDeck® Slab Properties).

4.2.1. Approved Research

The Eindhoven University of Technology and the Technical University of Delft in the Netherlands have performed experiments on the bending stiffness of BubbleDeck slabs. They focused on the smallest and largest depths of the available slabs, 230 mm and 455 mm. The researchers found that the flexural behavior of BubbleDeck is the same as a solid flat concrete slab, practically and theoretically, and in short- and long-term situations.

The Technical University of Darmstadt in Germany also performed tests on the stiffness of a BubbleDeck slab. The results verified with the theoretical analysis and with the physical tests done in the Netherlands. For the same strength, BubbleDeck has 87% of the bending stiffness of a similar solid slab but only 66% of the concrete volume due to the HDPE bubbles. As a result, the typical deflection was marginally higher than that of a solid slab, as expected. However, the significantly lower dead weight compensated for the slightly reduced stiffness, and therefore gave BubbleDeck a higher carrying capacity. Table 4-1 summarizes the findings of their experiments (BubbleDeck Tests and Reports Summary).

Table 4-1: Stiffness Comparison (adapted from BubbleDeck Tests and Reports Summary)
***On the condition of the same amount of steel. The concrete itself has 220% greater effect.**

(in % of solid deck)	***Same Strength***	***Same Bending Stiffness***	***Same Concrete Volume***
Strength	100	105	150*
Bending Stiffness	87	100	300
Volume of Concrete	66	69	100

Analyses have also proven that deflections under service loads were a little higher than that of an equivalent solid slab. On the other hand, the reduced permanent load positively affects the long-term response in the serviceability limit state (SLS) design, which governs crack propagation. It has been concluded that adding a minimal amount of extra reinforcing steel would satisfy the criteria (BubbleDeck® Slab Properties).

4.3. Shear Strength

Shear strength of any concrete slab is chiefly dependent on the effective mass of concrete. Due to the inclusion of plastic bubbles, the shear resistance of a BubbleDeck slab is greatly reduced compared to a solid slab. From theoretical models, the shear strength of the voided slab was determined to be 60-80% of a solid slab with the same depth. Therefore, a reduction factor of 0.6 is to be applied to the shear capacity of all BubbleDeck slabs. Since shear is also a major concern for the design of solid slabs, several groups have performed tests on the shear capacity of BubbleDeck slabs in various situations (BubbleDeck® Slab Properties).

For all flat plate systems, the floor to column connection is a region of high shear. The design for this BubbleDeck section closely follows that of a typical flat slabs. The designer must first determine whether the applied shear is greater or less than the shear capacity of the BubbleDeck. If it is less, no further checks are needed; if it is greater, the designer shall omit the spheres surrounding the column and then check the shear in the newly solid section. If the shear resistance of the solid concrete portion is below the applied, shear reinforcement is then required (BubbleDeck® Design and Detailing Notes- guidance to engineers and detailers).

4.3.1. Approved Research

Professor Kleinmann at the Eindhoven University of Technology in the Netherlands, along with the A+U Research Institute, performed physical shear tests to compare a solid slab with two types of BubbleDeck with the same depth, 340 mm. The specimens contained either loose or secured steel reinforcement girders, and were loaded at two different locations. The ratios for distance of imposed force (a) to support to slab thickness (d), a/d, were 2.15 and 3. The researchers found that the shear capacity of a BubbleDeck as compared to a solid slab dropped off quickly with the loose girder configuration and as the distance of the load to the support increased. See Table 4-2 for the summarized results.

Table 4-2: Shear Capacity with Different Girder Types
(adapted from BubbleDeck Tests and Reports Summary)
***Corrected for test-elements with longer time for hardening**

(in % of solid deck)	***a/d =2.15***	***a/d= 3.0***
Solid Deck	100	100
BubbleDeck®, secured girders	91	78 (81)*
BubbleDeck®, loose girders	77	

The Technical University of Denmark and AEC Consulting Engineers Ltd, led by Professor M.P. Nielsen, tested both the shear strength and punching shear resistance. They used a slab depth of 188 mm, which is not a typical BubbleDeck thickness, and used an a/d ratio of 1.4. They found that shear strength was approximately 80% of a solid slab, and that punching shear was 90% of the same slab.

John Munk and Tomas Moerk from the Engineering School in Horsens, Denmark published the paper "Optimising of Concrete Constructions" on the shear resistance of BubbleDeck. They experimented on slabs that did not contain any girders, just the binding wire, with a thickness of 130 mm and an a/d ration of 2.3. The average shear strength was 76% of a solid slab (BubbleDeck Tests and Reports Summary).

4.4. Punching Shear

Punching shear, also known as hogging, is a phenomenon associated with failure from extreme, localized forces. This is a common concern for flat plate floor systems since there is a highly concentrated reaction from the column onto the slab, as demonstrated by Figure 4-2. The design of a BubbleDeck section for punching shear closely follows that of a typical flat slab.

The designer must first determine whether the applied shear is greater or less than the shear capacity of the BubbleDeck. If it is less, no further checks are needed; if it is greater, the designer shall omit the spheres surrounding the column and then check the shear in the newly solid section. If the shear resistance of the solid concrete portion is below the applied, shear reinforcement is then required. A modified column connection is illustrated in Figure 4-3. Other options to mitigate this problem are to widen the column, use drop panels or flared column heads, or increase the depth of the slab (BubbleDeck® Design and Detailing Notes- guidance to engineers and detailers).

Figure 4-2: Punching Shear Failure (Tassinari)

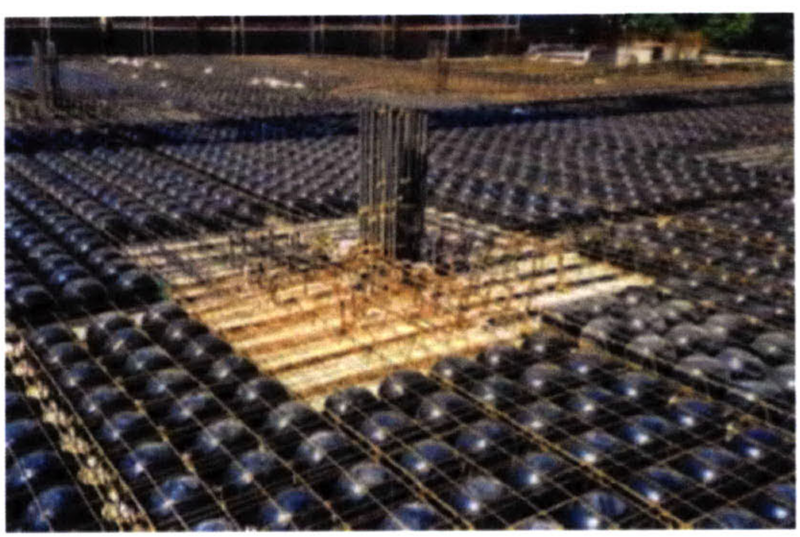

Figure 4-3: Floor to Column Connection Modification (BubbleDeck International)

4.4.1. Approved Research

Researchers conducted tests on the punching behavior of BubbleDeck and published their results in a paper called, "Darnstadt Concrete", in the journal *Concrete and Concrete Structures*. They experimented on slabs with depths of 230 mm and 450 mm. They found that the crack pattern was similar to that of a solid slab, and that local punching failure did not occur within the given load cases. The average experimental value of the shear capacity of this slab was about 80% of a solid slab. The test specimens actually performed better than the theoretical models, but still not as good as a solid concrete slab. See Figure 4-4 for the plotted results (BubbleDeck Tests and Reports Summary).

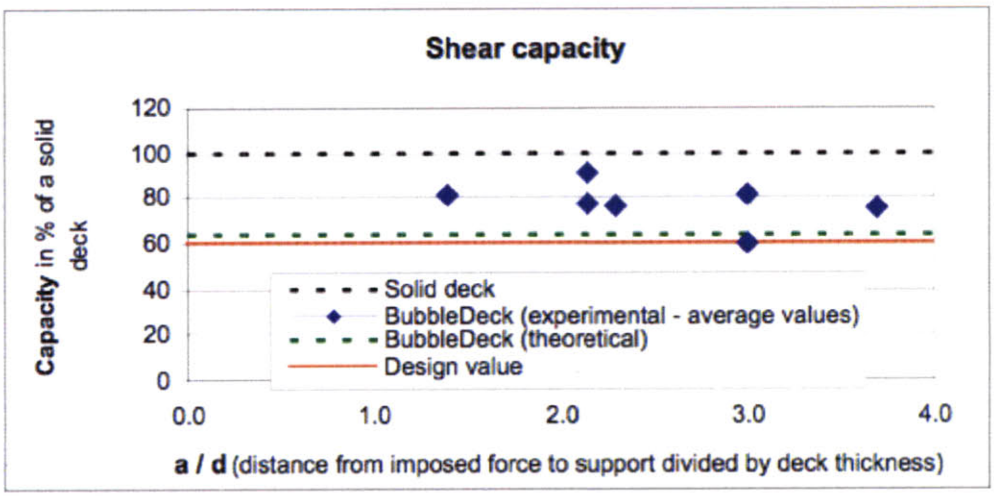

Figure 4-4: Experimental Shear Capacity (BubbleDeck Tests and Reports Summary)

Martina Schnellenbach-Held and Karsten Pfeffer from the Institute for Concrete Structures and Materials as the Darnstadt University of Technology conducted another large study on the punching behavior of BubbleDeck. Two different depths, 240 mm and 450 mm, were used to model the shallowest and deepest variety of the slabs. The slab was made of standard B25 and B35 concrete with a maximum aggregate size of 16 mm, and attached to a short column in order to simulate the response. The slabs were radially supported at eight points and were monitored by strain gauges, deflection gauges, and extensometers. Figures 4-5 and 4-6 illustrate the test set-ups.

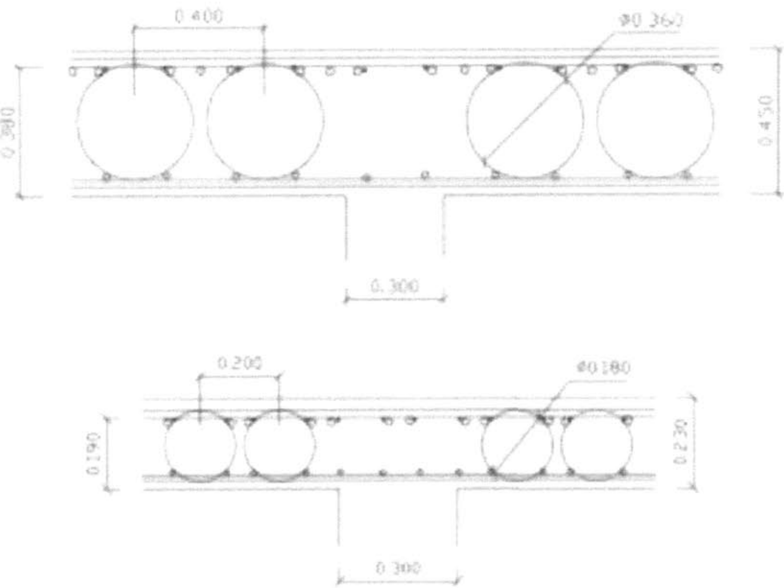

Figure 4-5: Cross-Section of BubbleDeck Test Slabs (Pfeffer)

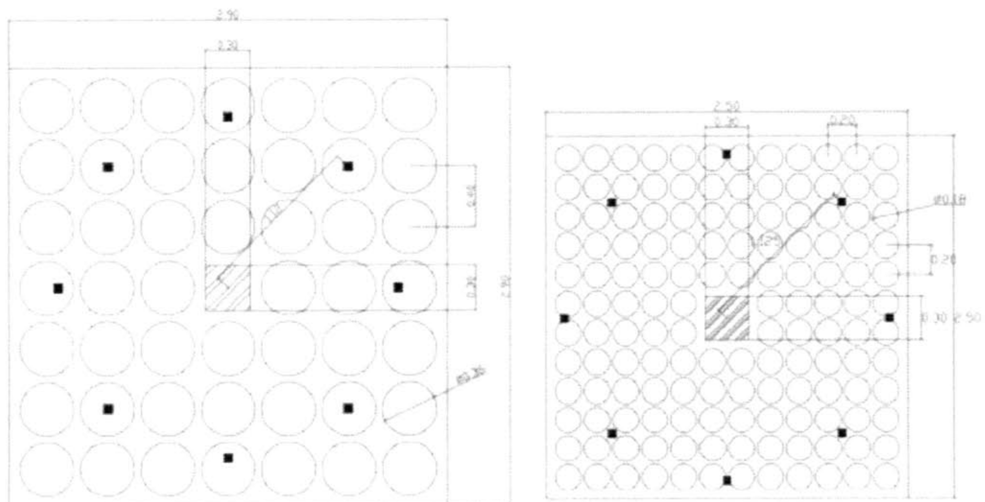

Figure 4-6: Test Set Up (Pfeffer)

The tests proved that although the HDPE spheres did not influence the crack pattern along the slab, the resistance to punching shear was less than a solid slab. When sawn open, the cross section showed that the crack angle varied from 30° to 40°. See Figure 4-7 for the approximate crack patterns found in the test subjects.

In order to further understand the structural mechanics of the BubbleDeck, the researchers generated a 3D nonlinear finite element model of the slab with *DIANA*. The FEM analysis conformed to the results of the physical investigations and verified the punching shear behavior of BubbleDeck. They suggest reducing the allowable shear area if any bubbles intersect the control perimeter so that those spheres will not play a role in the punching shear resistance (Pfeffer).

These findings correspond with other studies in that they recommend mitigating the punching shear response by excluding HDPE spheres from the shear perimeter. Other groups advise the removal of bubbles in the vicinity of the column zone rather than minimizing the impact area.

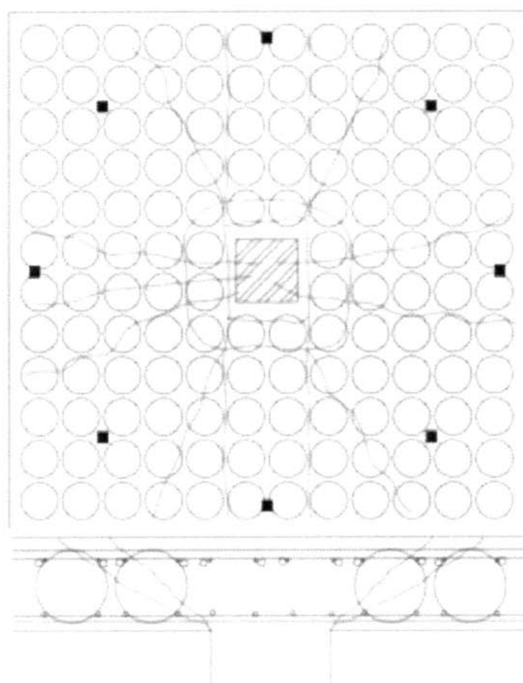

Figure 4-7: Crack Patterns (Pfeffer)

5. Further Analysis and Application in Bridge Decks

5.1. Test Office Slabs

5.1.1. Office Slab Models

In order to fully understand the previous research conducted on BubbleDeck, further analysis was performed to compare the response of this new type of floor with a typical flat, solid concrete slab. A 3D solid slab and a BubbleDeck slab were constructed in SAP2000 with all the same dimensions and as two-way spanning floor systems, shown in Figure 5-1. The units change from metric to English since these models are for an American building. The biaxial slabs were modeled after a standard office floor with each bay measuring 40 ft x 40 ft wide and 17.75 inches thick, the deepest certified BubbleDeck. There are nine bays in the full model, with three bays per side and a total of 120 ft a side. Each office slab finite element model has approximately 8,100 elements. A 3D rendering of the office slab with the column supports is displayed in Figure 5-2. The solid slab was generated as a thick shell of pure concrete while the BubbleDeck slab was designated as a layered shell. For simplicity in the full BubbleDeck model, a rectangular layer of HDPE was sandwiched in between two thin layers of standard concrete on top and bottom only. See Figure 5-3 for the simplified BubbleDeck layers as used in the analysis. Both models were subjected to a 100-psf live load in addition to their own self-weight for the static and dynamic design.

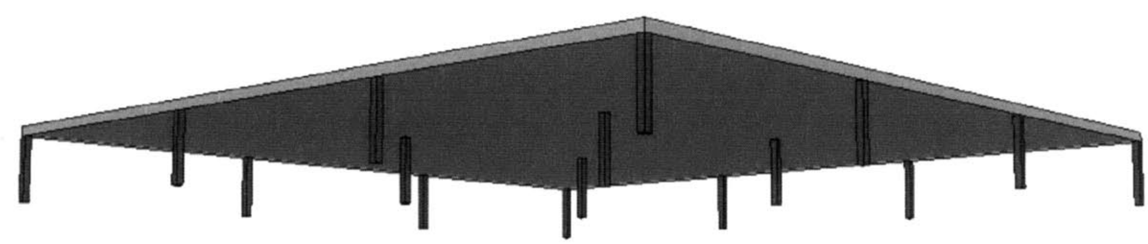

Figure 5-1: 3D Rending of the Office Slab

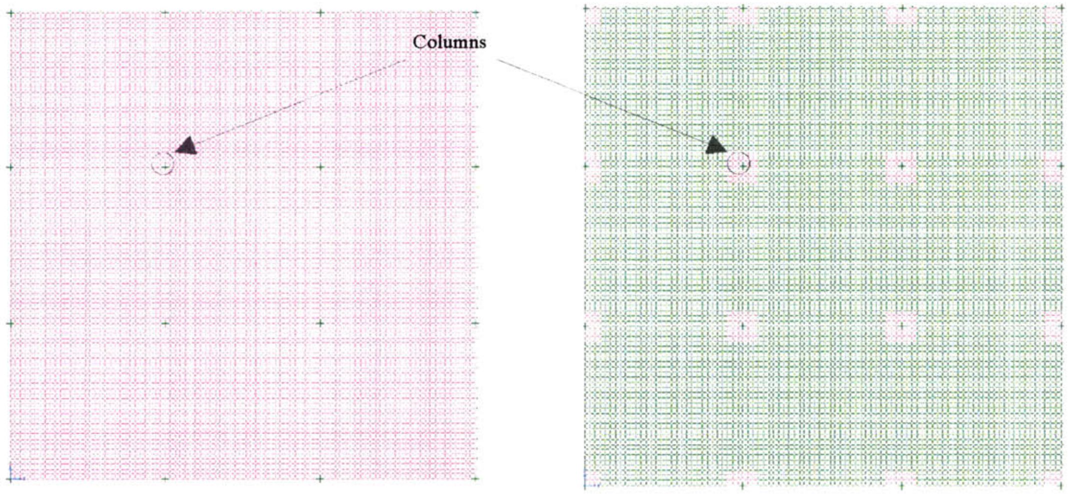

Figure 5-2: Office Slab Finite Element Model of Solid Slab (left), BubbleDeck (right)

A single module for the BubbleDeck slab measured 15.25 in per side, and consists of one standard 360 mm or 14.17 in HDPE sphere surrounded by concrete on all sides. The material properties used are typical for standard concrete and HDPE in the United States. See Figure 5-4 for the single module in SAP2000, Table 5-1 for module dimensions, and Table 5-2 for the properties used in the models. Each bay contains 31 such modules, and is corner-supported by columns that are represented in SAP2000 by pin supports restrained in translation. In consideration of punching shear, all bubbles within a three-module radius of the support were removed and replaced with solid concrete.

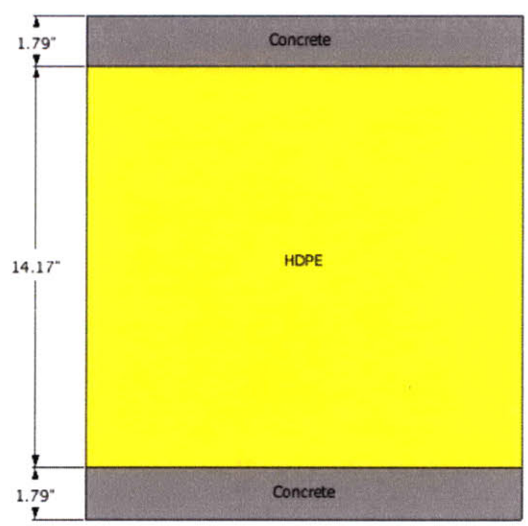

Figure 5-3: Simplified BubbleDeck Shell Layers

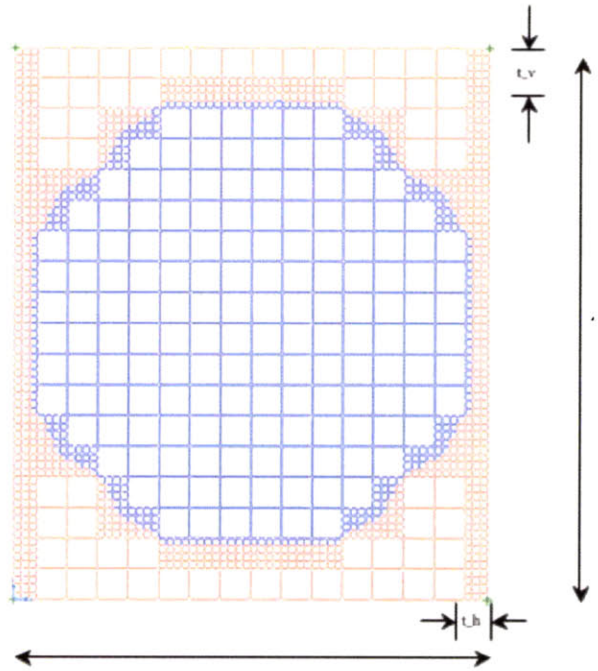

Figure 5-4: Finite Element of a Single Module in Cross-Section

Table 5-1: 360 mm Module Dimensions

Single Module	
Bubble Diameter (d)	360 mm
	14.17 in
Thickness (t)	17.75 in
Width (w)	15.25 in
Vertical Concrete Thickness (t_v)	1.79 in
Horizontal Concrete Thickness (t_h)	0.50 in

Table 5-2: Material Properties

Material	*Compressive Strength (psi)*	*Young's Modulus (ksi)*	*Poisson's Ratio*	*Thermal Expansion (/°F)*	*Density (pcf)*
Concrete	4000	3600	0.30	5.5E-6	150.0
HDPE	2900	120	0.42	2.0E-5	60.6

5.1.2. Analysis Results

5.1.2.1. Static Response

The solid slab and BubbleDeck SAP2000 models were analyzed for both static and dynamic response under dead (DL) and live load (LL). A factored load of 1.2DL + 1.6LL was applied to the two schemes in the load and resistance factor design (LRFD). The results of these finite element analyses correspond to the results from the official research on bending stiffness and deflection that was conducted in Europe. Table 5-3 summarizes the static response results from the test office slabs.

Table 5-3: Office Slab Maximum Static Response Comparison

STATIC RESPONSE- OFFICE SLAB									
	M11	***M22***	***M12***	***V13***	***V23***	***S11Top***	***S22Top***	***S12Top***	***U3***
	(lb-in/in)	*(lb-in/in)*	*(lb-in/in)*	*(lb/in)*	*(lb/in)*	*(lb/in^2)*	*(lb/in^2)*	*(lb/in^2)*	*(in)*
Solid Slab	-203850	-203879	-37446	-12327	-12321	3882	3883	713	-0.746
BubbleDeck	-134554	-134567	22365	7479	7479	2562	2563	508	-0.821
% Difference	-34%	-34%	-40%	-39%	-39%	-34%	-34%	-29%	10%

The SAP2000 results show that the maximum moments, shear forces and in-plane stresses in the BubbleDeck floor are 30-40% less than that of the solid concrete slab under the same conditions. This is a consequence of the decreased dead load from the HDPE spheres in place of concrete. Additionally, this load reduction for the permanent condition lowers the overall stress and is therefore beneficial for the long-term response of the floor system. Figures 5-5 and 5-6 show the stress distributions along the XX and XY axes. However, the deflection of the BubbleDeck is approximately 10% higher than that of the solid slab due to the reduced stiffness from the bubbles. This was the expected result, and researchers have suggested applying a 0.9 reduction factor to the ultimate bending capacity in order to compensate for this. Figure 5-7 shows the maximum 3D slab deflections from the FEM analysis.

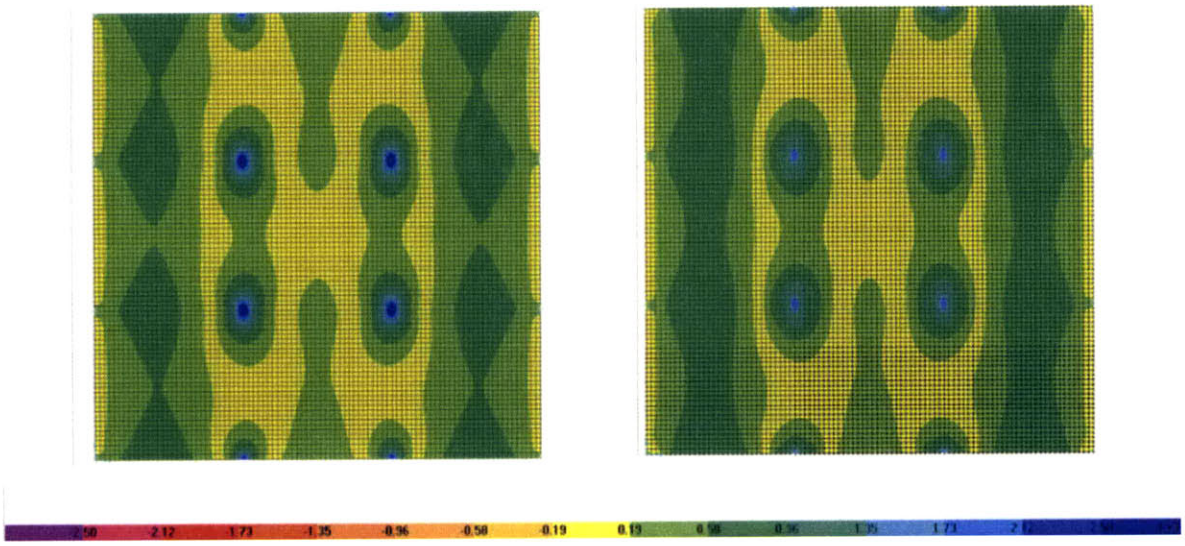

Figure 5-5: Solid (left) vs. BubbleDeck (right)- XX axis from -2.5 to 2.5 psi

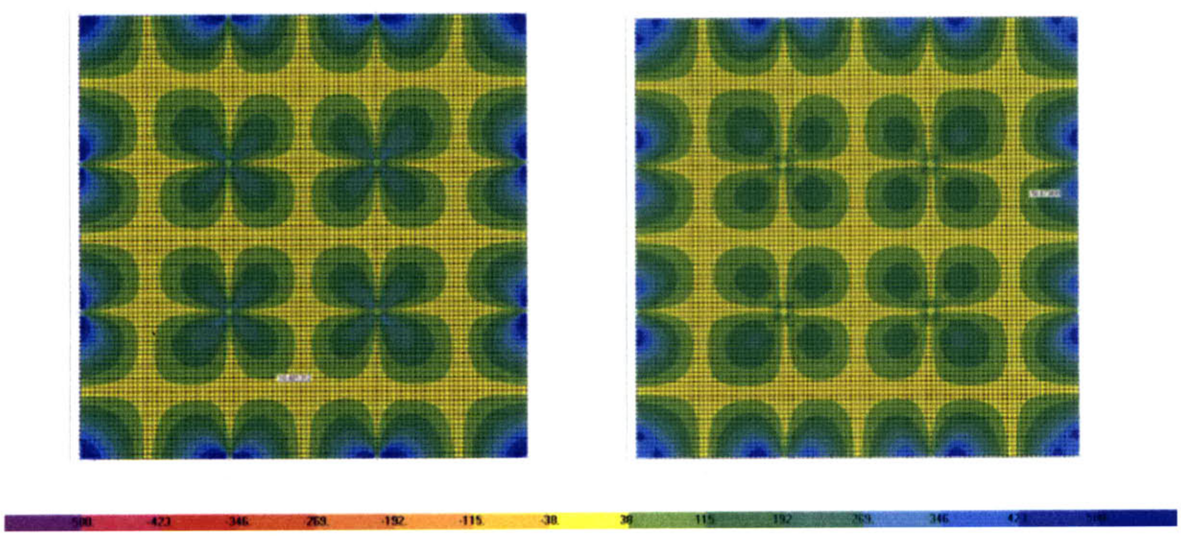

Figure 5-6: Solid (left) vs. BubbleDeck (right)- XY axis from -500 to 500 psi

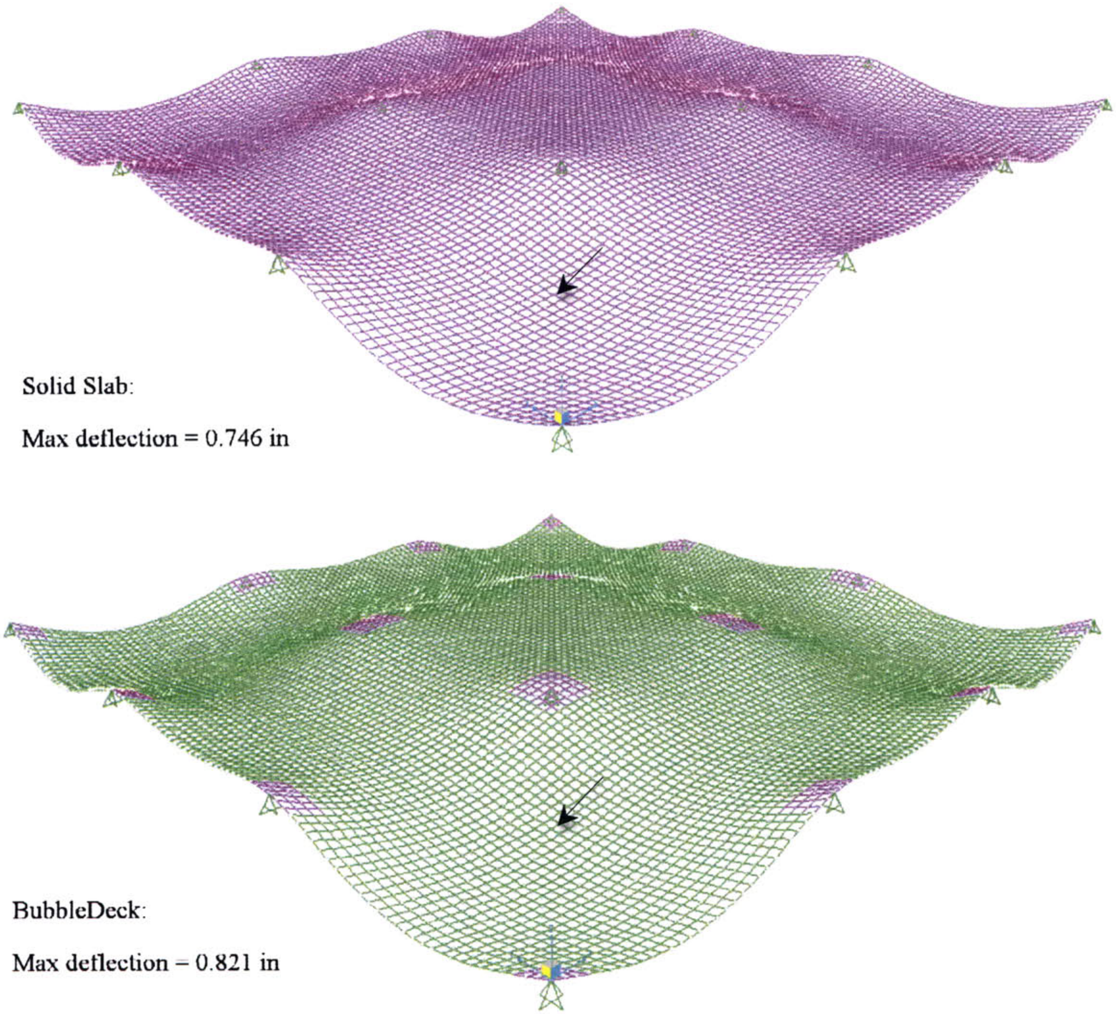

Figure 5-7: Office Slab Deflections Magnified by 100

5.1.2.2. Dynamic Response

The dynamic reactions of the BubbleDeck slab were nearly identical to the solid slab in this analysis. The modal periods differed by only thousandths of a second, and both were well above the resonant frequency of human walking at 2 Hz. There is no need to modify the structure or mitigate the design for dynamic instability. Table 5-4 lists the modal responses of the two floor systems.

Table 5-4: Office Slab Modal Response Comparison

MODAL RESPONSE- OFFICE SLAB				
Mode	***Solid Slab***		***BubbleDeck***	
	Frequency (Hz)	*Period (s)*	*Frequency (Hz)*	*Period (s)*
1	4.234	0.236	4.226	0.237
2	4.482	0.223	4.522	0.221
3	4.482	0.223	4.522	0.221
4	4.558	0.219	4.524	0.220
5	4.575	0.219	4.679	0.214
6	5.192	0.193	5.322	0.188
7	5.192	0.193	5.322	0.188
8	5.641	0.177	5.692	0.176
9	6.298	0.159	6.640	0.151
10	8.282	0.121	8.224	0.122
11	8.404	0.119	8.397	0.119
12	8.404	0.119	8.397	0.119

5.2. Application to Pedestrian Bridge Decks

Since the results from the test case BubbleDeck slab corresponded with the prior research, this concept could now be tested for a lightweight pedestrian bridge deck. A pedestrian bridge was chosen over a vehicular bridge since the shear capacity of a BubbleDeck slab is significantly less than a solid slab. Due to the type of loading that bridge decks experience, high shear resistance is a major design requirement and the current design of BubbleDeck cannot economically accommodate this need.

Punching shear is another significant concern for a bridge deck filled with HDPE bubbles. In the case for floor slabs, if the shear forces are too large near a column, spheres may be left out and that area filled with solid concrete. This is not possible since the high loads are constantly varying in time and position, and the shear resistance must be great enough to support this movement. The wheels of a vehicle are point loads that travel along the deck at varying speeds and locations instead of being stationary, distributed loads as in a building. Therefore, the current structural design of a BubbleDeck slab is most likely inadequate for vehicular bridges.

However, this new floor system may be applicable for pedestrian bridges due to the lower live loads and minimized shear forces.

5.2.1. Bridge Deck Models

The theoretical pedestrian bridge is 16 ft wide and 200 ft long, and is broken down into 12.5 bays of 16 ft each. No girders will be used to support this deck slab since it will be simply supported by columns at the corners of each bay. This creates a biaxial plate section similar to the office slabs. Figure 5-8 is a simple rendering of a typical portion of the pedestrian bridge. As with the test office floors, a solid slab and a BubbleDeck model were created in SAP2000 with a depth of 9.25 in as 3D shells. The same material and layer properties were used in this study for consistency. The smallest bubble size of 180 mm was chosen for this analysis, and the dimensions of a single module can be found in Table 5-5.

Figure 5-8: 3D Rendering of the Pedestrian Bridge

Table 5-5: 180 mm Module Dimensions

Single Module	
Bubble Diameter (d)	180 mm
	7.09 in
Thickness (t)	9.25 in
Width (w)	7.75 in
Vertical Concrete Thickness (t_v)	1.08 in
Horizontal Concrete Thickness (t_h)	0.54 in

The SAP2000 models consist of three typical bays along the bridge, totaling 48 ft long. 3 in of solid concrete fringe the non-continuous edges of the deck while 6 in of concrete separate each bay. These finite element models have approximately 7,500 elements each. See Figure 5-9 for diagrams of the SAP2000 bridge deck models. The decks were both loaded with a full pedestrian live load of 100-psf, and then analyzed for static and dynamic responses.

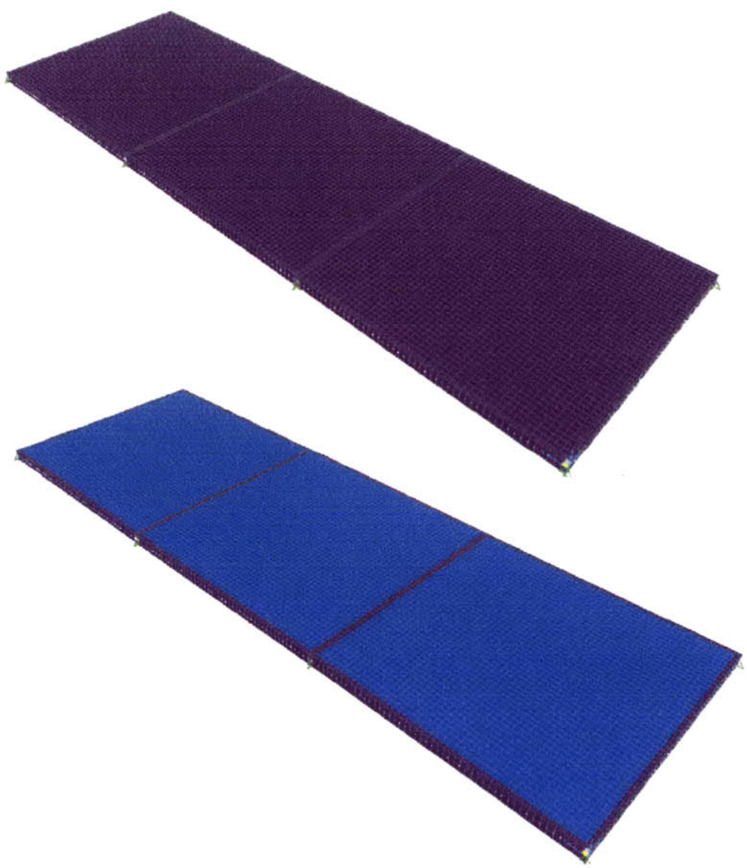

Figure 5-9: Bridge Deck Finite Element Model of Solid Slab (top), BubbleDeck (bottom)

5.2.2. Analysis Results

5.2.2.1. Static Response

The maximum internal stresses and forces in the BubbleDeck model exceeded those of the solid slab. The maximum moment and internal stress of the BubbleDeck was 64% higher than the solid deck while the maximum shear was approximately the same in both models. The bridge deflection was also 68% greater in the BubbleDeck than in the solid slab. These results show a significant difference in the behavior of the voided slab due to the continuity of the deck. Unlike the office floor slab, the bridge deck is continuous on two sides at most, rather than on all four. This may account for the decreased performance of the BubbleDeck slab as a bridge deck. Table 5-6 summarizes the SAP2000 results Figure 5-10 shows the maximum deflections, and Figures 5-11 to 5-13 show the maximum stress distribution in each deck.

Table 5-6: Bridge Deck Maximum Static Response Comparison

STATIC RESPONSE- BRIDGE DECK									
	M11	***M22***	***M12***	***V13***	***V23***	***S11Top***	***S22Top***	***S12Top***	***U3***
	(lb-in/in)	*(lb-in/in)*	*(lb-in/in)*	*(lb/in)*	*(lb/in)*	*(lb/in^2)*	*(lb/in^2)*	*(lb/in^2)*	*(in)*
Solid Slab	5232	-27789	4666	-10602	10606	-367	1949	-327	-0.125
BubbleDeck	8594	-32324	5432	-10640	10666	-603	2267	-381	-0.210
% Difference	64%	16%	16%	0%	1%	64%	16%	16%	68%

Figure 5-10: Maximum Bridge Deck Deflection Magnified by 100

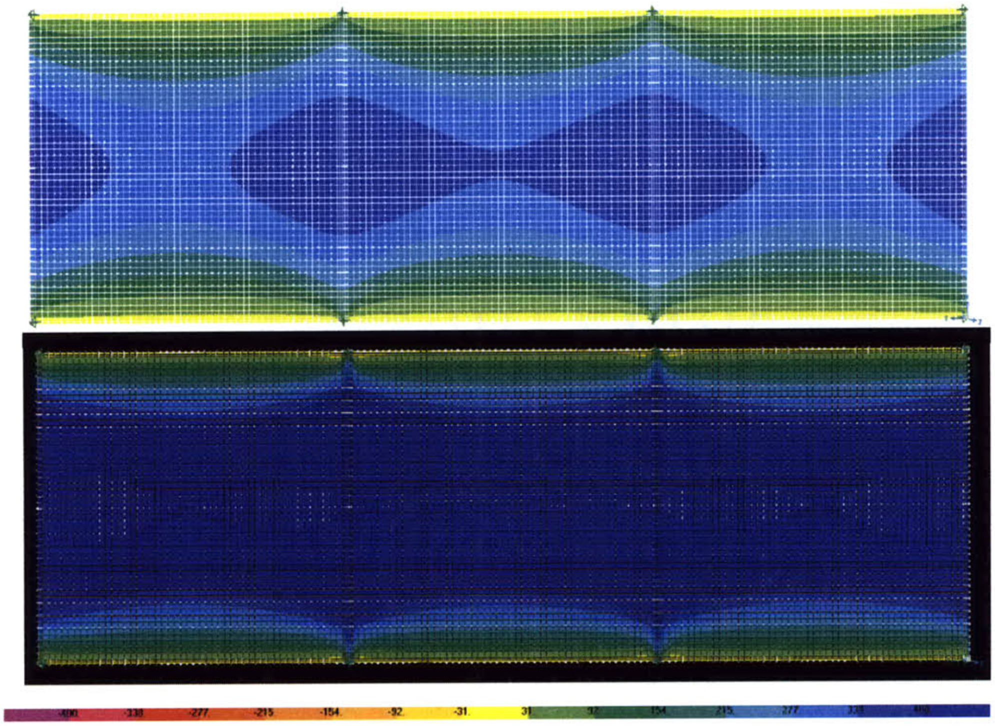

Figure 5-11: Solid (top) vs. BubbleDeck (bottom)- XX axis from -400 to 400 psi

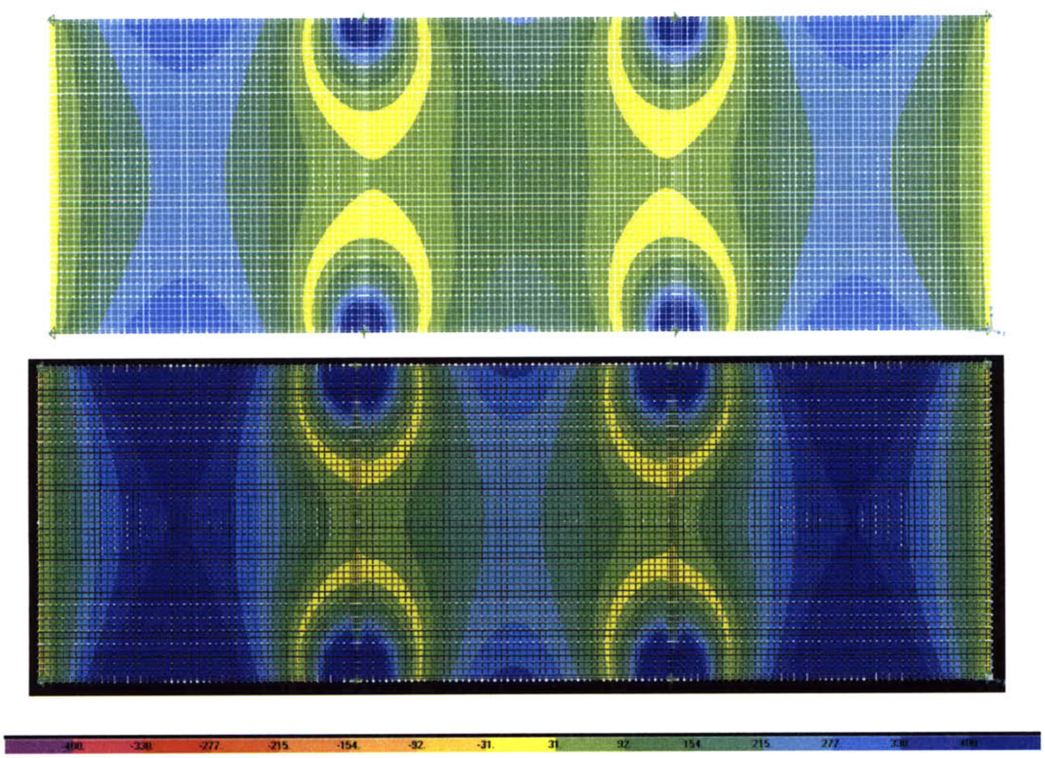

Figure 5-12: Solid (top) vs. BubbleDeck (bottom)- YY axis from -400 to 400 psi

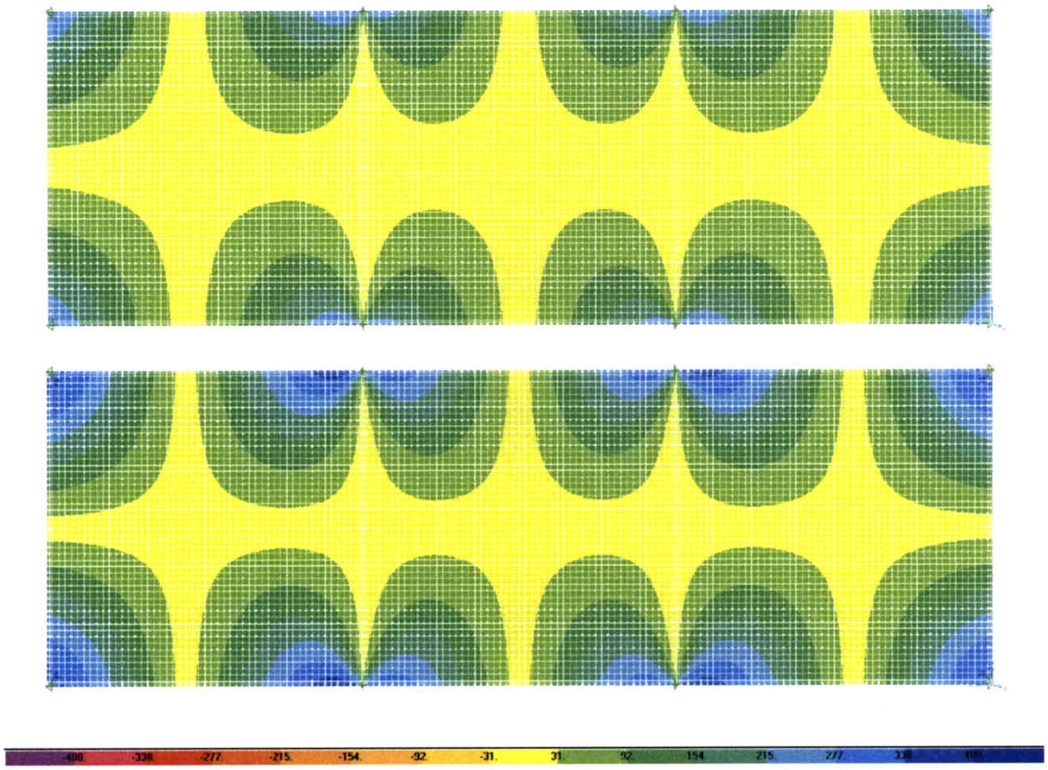

Figure 5-13: Solid (top) vs. BubbleDeck (bottom)- XY axis from -400 to 400 psi

5.2.2.2. Dynamic Response

Once again, the difference between the modal periods of the two deck types was only thousandths of a second. The modal frequencies of both decks are considerably higher than that of a pedestrian walking at 2 Hz, and therefore would not excite a resonant response. Table 5-7 summarizes the dynamic responses from each bridge model.

Table 5-7: Bridge Deck Modal Response Comparison

MODAL RESPONSE- BRIDGE DECK				
	Solid Slab		*BubbleDeck*	
Mode	*Frequency (Hz)*	*Period (s)*	*Frequency (Hz)*	*Period (s)*
1	11.940	0.084	12.378	0.081
2	12.300	0.081	12.785	0.078
3	13.939	0.071	14.356	0.070
4	24.201	0.041	24.549	0.041
5	25.590	0.039	25.998	0.038
6	25.963	0.039	26.268	0.038
7	26.211	0.038	26.601	0.038
8	30.057	0.033	31.135	0.032
9	33.051	0.030	32.748	0.031
10	41.775	0.024	41.371	0.024
11	56.595	0.018	56.371	0.018
12	57.714	0.017	58.101	0.017

5.3. Discussion of Results

The office slab test set confirmed the results of prior research, proving that the BubbleDeck slab performed better than a traditional solid concrete, biaxial slab. The maximum stresses and internal forces in the voided deck were up to 40% less than the solid one due to the decreased dead weight from the use of HDPE spheres in place of concrete. The deflection of the BubbleDeck slab was marginally higher by 10% since the stiffness decreased from the presence of the bubbles but this did not overshadow the reduced overall stress in the slab. These results demonstrate that this type of biaxial deck will give better long-term results and a more durable floor slab under a dominant gravity, uniform load.

However, the bridge deck test set did not function as well as the office slab set. The models were created with the same general parameters but had smaller dimensions and a different layout. The BubbleDeck response was higher than that of the solid slab by over 60% in all categories. Factors that could play into this diminished performance are the continuity of the deck and the dimensions of the system. For the bridge deck, there was just a single row of bays instead of a grid of bays. This changed the continuity of the edges from four to two, thus allowing the deck to act as a one-way slab rather than a biaxial slab. Since this was a pedestrian bridge, the general dimensions of each bay were smaller and the bubble size was the smallest available in order to create a slim, lightweight design. These reduced proportions could have influenced the reduced performance of the BubbleDeck slab in relation to the solid slab.

The dynamic responses were nearly equivalent for each pair of tests. The modal frequencies varied by one thousands of a second between the solid slab and the BubbleDeck slab in both the office slab and the bridge deck models. None of the slabs were in danger of resonance from human walking.

6. Conclusion

This investigation has proven that the BubbleDeck® technology is more efficient than a traditional biaxial concrete slab in an office floor system. The finite element models of the office slabs created for this study in SAP2000 verify the prior analysis and experiments. However, the performance of the voided slab is not as successful in a pedestrian bridge deck. The non-continuous, simply supported bay layout of this test bridge was not optimal for this system since it generated a one-way slab response rather than a biaxial one. This does not discount the use of BubbleDeck in a bridge deck, but requires further studies on a variety of bridge layouts to fully determine the feasibility of this slab in a bridge.

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