

## Structural performance and failure analysis of bubbledeck concrete slabs in construction

Ali K. AL-Asadi

Civil Engineering Department, College of Engineering, University of Thi-Qar

### ABSTRACT

In this research paper, as the concrete material is eliminated from the locations situated around the middle of the cross-sections of bubbledecks (BDs), the BD type slabs are lighter than the traditional slabs. In the recent researches, the performance analysis (PA) is generally determined for the reinforced concrete (RC) structures with the moment-resisting frame (MRF) and dual systems. The dual system comprises mainly the MRF with shear wall of building under construction, as well as the flat slab having chiefly the BD system. In this paper, the evaluation of values of the performance and failure analysis of RC structures using BD system are submitted. We recorded a maximum load of 6.48, maximum stress of 75.00, maximum strain of 7.80, with minimum force of 0.83, while minimum slab length of 9.62 and lastly the maximum slab span of 27 for our bubbledeck concrete slab experiment in comparison with reinforced concrete slab to get the best results. The obtained results indicate that the lateral strengths of buildings increase by increasing the span length to story height ratio. Besides, the variations of the span length and the number of the story have more effects than the variation of the usage category buildings on the performance of structures. Furthermore, the span length has more effect than the number of stories in determining performance in an MRF. We observed that the bubbledeck concrete slabs are more lightweight and resistant in comparison with reinforced concrete.

**Keywords:** Bubbledeck; performance; nonlinear static analysis; failure analysis; seismic behavior; reinforced concrete; construction.

**Corresponding Author:** Dr. Ali K. AL-Asadi  
Civil Engineering Department,  
College of Engineering, University of Thi-Qar,  
Thi-Qar, Iraq  
Email: [alazhareco.2005@yahoo.com](mailto:alazhareco.2005@yahoo.com)

### 1. Introduction

Today, the usage of innovative structural systems has been augmented. As an example of these structures, Bubble Deck (BD) system can be noted. The behavior of this type of structural system is like the behavior of a lightweight two-way slab as mentioned in [1]. In the BDs, the recycled plastic made spheres are used to create the air voids and provide the strength through the arch action. The BD slabs have three-dimensional voids inside them with an arrangement in two horizontal directions that decrease the slabs' self-weights. The bubble diameter to the slab thickness ratio affects the BD slabs' behavior as mentioned in [2]. In the middle of spans where the Plastic balls are located, the design is controlled by flexural and direct shear stresses. While in the supports, the solid deck (without Plastic spherical hollow cores (PSHC)) is used and the design is controlled by the punching shear stress as mentioned in [3]. The shear reinforcements may be used to prevent the slab from shear failure (if required).

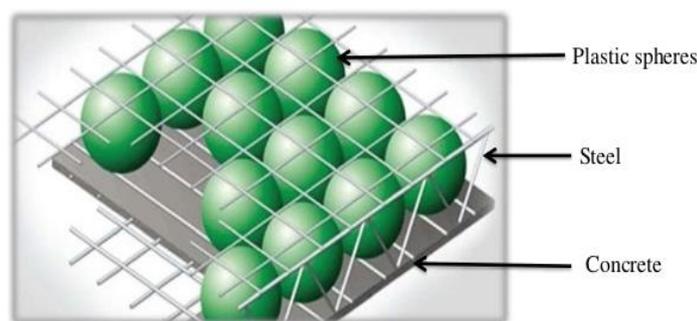


Figure 1. The composition of Bubbledeck (BD) concrete slabs [3]

The most important advantage of using BD concrete slabs for the reduction in the concrete and steel quantities required for the construction of the building as mentioned in [4]. This reduction affects both the slabs and the whole structure's weights, which reduces the earthquake forces and the cost of construction. Reduction in working time and costs, increase in the span lengths pointed out using bubbledeck system as mentioned in [5]. The experimental tests to find the shear strength of BD slabs. Their obtained results showed that for the studied BD slabs the ultimate shear force was around 97% of those of solid slabs with the same thicknesses. Since the inelastic analysis and design of structures is complex and time-consuming, most of the regulations with some conditions, replace the elastic analysis instead of inelastic analysis, and they use performance measures to determine the design resistance that it reduces the elastic force to design force as mentioned in [6]. The overstrength of the designed structures and also their ability to dissipate the energy imposed by an earthquake (ductility) are two important factors related to performance.

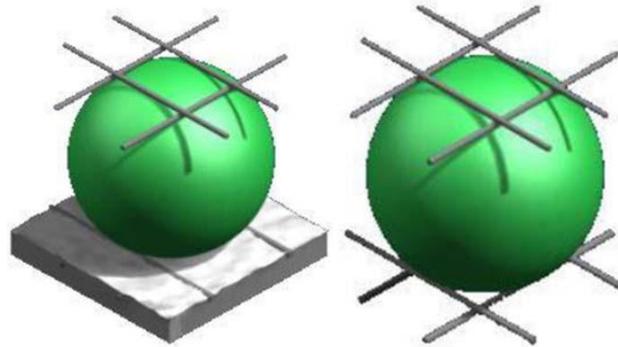


Figure 2. The simulated pre-cast bubble-deck in concrete slab on left-side while reinforced bubble-deck on the right-side [6]

Based on the performed bending tests, the BD slabs have greater ultimate flexural strengths compared to the values that theoretically are considered for solid slabs as mentioned in [7]. They also observed that the effective value of the shear strength of a BD slab was at least about 70% of the shear strength of a solid slab with the same thickness. The behavior of the BD slabs and recommended that the BD slabs be used in the lightweight bridge decks. An experimental program referring the concrete slabs with spherical voids for a full-scale test.

The deflections of BD slabs are about 6% greater than the deflections of the same size solid slabs, despite the fact that the stiffnesses are reduced due to the hollow parts' effect of these types of slabs. Based on their investigations, the shear strengths of BD slabs are about 60% of the shear strength of the solid slabs with the same thicknesses as mentioned in [8]. BD slabs and compared the design regulations, stiffness, deformation and shear strength of the BD slabs to those of solid decks carried out by numerical modeling or the experimental tests. In general, the BD slabs behave like the flat slabs. Consequently, the RC structures constructed with BD slabs allow a significant reduction in heights of stories and a great flexibility in architectural plan design, compared to the conventional moment-resisting frame (MRF) structures as mentioned in [9].

### 1.1. Problem statement

The main problem addressed in this paper is to conduct a theoretical study of the performance behavior and strength of simply-supported bubbledeck system and doubly reinforced concrete concrete slabs. The corresponding concrete slabs with hollow spheres are also studied for comparison, and are referred to as solid slabs. The theoretical problem is to develop rigorous nonlinear moment-curvature relations for these cross sections and then couple them with central finite-difference, finite integral and Newmark's solution scheme to predict the load-deflection relation of the concrete slab up to collapse. This theoretical data is then used to compare to the load-deflection curve obtained from the experimental results. Lastly, the theoretical prediction model is applied to full-scale slabs both with and without hollow spheres.

### 1.2. Aim of Study

The following are the given aim of study that contributed to the research:

- In this research, scale down model concrete slabs with cross-sectional dimensions of  $6 \times 6$  in., and a span of 36 in. to fill with the bubble-decks that are used. Ultimate strength of concrete used is 4,000 psi.
- The nominal yield stress of bubble-deck is 71,000 psi.
- The bubble-deck based concrete slabs consists of four rebar, and stirrups in the simulation on Matlab. Hollow spheres of bubbles have a diameter of 2.5 in.
- Generate an algorithm for nonlinear bubble-deck moment-curvature relationships.
- Predict theoretical load-deflection relationships by coupling a bubble-deck moment-curvature relationship with three numerical methods, namely, central finite-difference method, finite integral method and Newmark's method for failure analysis of bubble-deck concrete slabs.
- Predict both bubble-deck concrete moment-curvature and load-deflection curves for slabs with real-life span and with hollow spheres of three different diameters.
- Assess the effectiveness of bubble-deck concrete slabs with hollow spheres in comparison to solid slabs.

## 2. Background

The existing design codes of practices allow the flat slabs to be used in the low to moderate seismic risk zones as a lateral force-resisting structural member. The flat slabs are normally used together with the lateral force-resisting structural members like shear walls or MRF structures. The two 3-D RC framed structures designed according to ACI-318-14 and IS 2800-14 codes, employing linear response history analysis (LRHA) and also nonlinear response history analysis (NRHA) under an ensemble of 11 near-fault ground motions as mentioned in [10]. The obtained results reveal that the design spectrum of IS 2800-14 is incompatible with near-fault spectra and underestimates demands in the long periods range. They also found that the implementation of LRHA using RMF and deflection amplification factor leads to insufficient inter-story drift ratios as mentioned in [11]. It is observed that in the case of strong earthquakes, most of the structures have nonlinear behavior. Similar to the linear responses, the nonlinear responses are also controllable. In the other words, the length of the horizontal plateau of the base shear-displacement curve, when some methods are used is significantly increased. By applying some specific measures, taken in the design process of hinge composition, the horizontal plateau of the pushover curve, starting with the formation of the first plastic hinge and continuing up to the collapse mechanism, can be enhanced as mentioned in [12]. This means that some measures can be taken somehow that the initial plastic hinge remains safe during the formation of the next plastic hinge and is not crashed; this is the main philosophical point of the seismic design of the structures.

### 2.1. Bubbledeck Relation with Concrete Slab

A fundamental part of these procedures depends on the rapid and systematic calculations of shear and moment in concrete slab subjected to a series of concentrated loads. Essentially, the process is to compute shears from one end of the concrete slab to other by adding or subtracting the successive loads, then to compute the moments by adding or subtracting the successive shears, multiplied by the length of the concrete slab over which the shear acts. A definite sign convention is adopted in this system, in which moment will be considered as positive when it produces compression in the top fiber concrete slab as mentioned in [13]. When resultant force to the left of a section is upwards, shear will consider as positive. Loads will consider as positive when loads act upward. The procedure is simplified by omitting the length of the segment as a common factor so the multiplication of the shear by the distance between loads until the end of the computation.

### 2.2. Bubbledeck Structural System

The system developed by The BubbleDeck® Group uses similar precast planks for forms, but instead of polystyrene voids, it uses hollow recycled plastic balls to create the voids. These balls eliminate concrete in the slab that does not add any strength to the slab as described in [14]. A grid of steel is placed above and below these balls to reinforce the slab. Below is an illustration of the BubbleDeck® system.

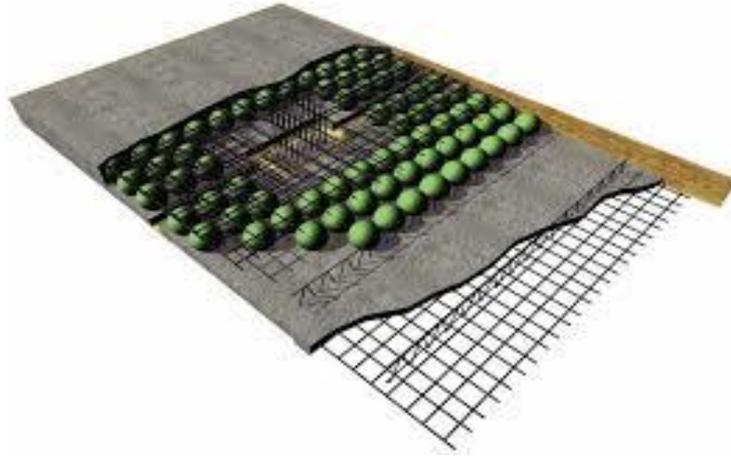


Figure 3. Structural design developed by the BubbleDeck® group

Along with structural advantages, the BubbleDeck system brings architectural advantages as well. The lightweight construction and biaxial behavior allow for long spans. The system can also be manufactured to fit to any shape. This could be especially important for this design because of the circular floor plan at each end of the Borgata. The bubbledeck system also brings many green design related aspects to the project as mentioned in [14]. The plastic balls are made from recycled material, and they can replace from 35-50% of the total concrete used in the slab. This is a substantial savings in raw material and great use of recycled material, which could help get LEED points for the project.

### 2.3. Architectural planning with bubbledeck

Building codes and the architectural floor plans with bubbledeck system will ultimately control where the shear walls may be located, and the ultimate and service loads will control their size. The floors plan for the buildings are constructed through the bubbledeck system as it sustains the performance for the long-term through the concrete slabs and solid concrete slabs and possible relocations for shear walls will be chosen. Once new and viable locations are found, a model will be created using bubbledeck systems as mentioned in [15]. With loads inputted into the model, the analysis will yield the force distribution in the building. From this analysis the shear walls can be sized and checked for adequate strength and serviceability requirements. Along with these requirements, a check on the overall torsion on the building will be calculated and deemed acceptable or not acceptable as mentioned in [16].

Once the investigation and redesign of the floor and lateral system is complete, a refinement in the column and foundation design may need to be done as mentioned in [17]. With a bubbledeck floor system, the ultimate loads on the columns should be greatly reduced. This reduction in load could yield significantly column sizes. With a new layout for the shear walls, torsion could be greatly reduced. With both reduced gravity loads and torsion, the foundation design may be able to be adjusted accordingly. An investigation will be carried to determine the effects on the foundation system.

## 3. Methodology

The bubbledeck concrete slab and reinforced concrete slabs for construction and their failure analysis were simulated using the Matlab R2018b. In order to ease the placement of the strengthening layer, the bubbledeck were manufactured upside down in Matlab environment. The conventional concrete was supplied by a local contractor. The upper surface of the bubbledeck concrete slab was prepared with a slight treatment consisting of wire-brushing and water-pressure cleaning. Though a more exhaustive surface treatment (e.g., sand blasting) is typically recommended, it has been preferred to keep a less demanding interface closer to real conditions of structures strengthened on the bottom side. An additional method for application of bottom strengthening is by bonding a prefabricated laminate with epoxy adhesive. Before pouring the strengthening material, the surface was washed again and kept moist. Fabrication and pouring of the strengthening material were carried out 15 months after manufacturing the reinforced concrete (RC).

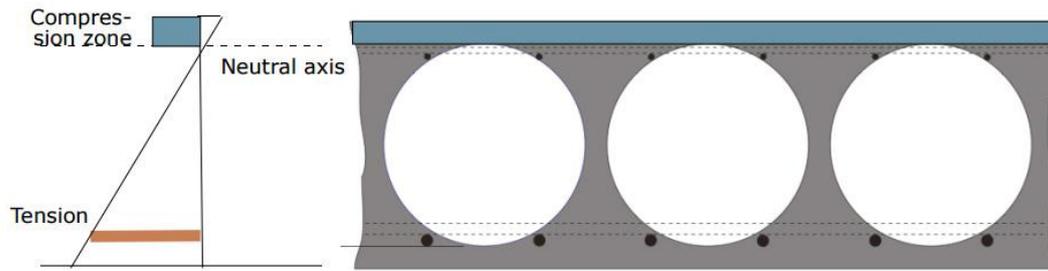


Figure 4. Stress distribution through bubbledeck under normal loading testing stage

The strengthening material consisted of a dry mortar premix of compact-reinforced concrete (CRC), which was mixed with water and fibers following the supplier's instructions. A 2% volumetric content of short steel fibers ( $l_f = 12.5$  mm,  $f_c = 0.3$  mm,  $f_c = 2950$  MPa) was used. The flow diameter in the slump flow test was larger than 550 mm, which allows classifying the mixture as self-compacting according to the bubble-deck concrete slab. The concrete slabs were tested 2 months after strengthening. The average cubic (150 mm) compressive strength of the strengthening material was 126.4 MPa and 135.4 MPa at 28 seconds on Matlab and testing age, respectively. Flexural-tensile tests were carried out on un-notched and notched prismatic ( $100 \times 100 \times 500$  mm dimension, with span length between supports of 420 mm in all cases) samples at the age of slab tests. Un-notched samples were tested in a 4-point bending scheme for BD slabs.

### 3.1. Failure analysis of the bubbledeck concrete slabs

The impact solicitation of the specimens can be understood from the measurements taken by the load cells and the accelerometer. Reactions measured at both supports are symmetrical in all tests, whereby the total reaction is represented. Both impact force and total reaction had a two-stage shape over time, first with a high-frequency peak followed by a second stage with a smaller frequency. The peak of the impact force was higher than that of the total reaction.

$$f_c = f_{c'} \left[ 2 \left( \frac{\epsilon_c}{\epsilon_o} \right) - \left( \frac{\epsilon_c}{\epsilon_o} \right)^2 \right]$$

$f_c$  = Computed bubble-deck concrete compression stress,

$f_{c'}$  = Specified bubble-deck concrete compression stress,

$\epsilon_c$  = Bubble-deck concrete slab strain,

$\epsilon_o$  = Bubble-deck concrete strain at maximum stress.

### Solution Algorithm for Bubbledeck Concrete Slab Moment-Curvature Relation for Solid Cross Section

This algorithm detailed steps for generating failure analysis of bubbledeck moment-curvature relationships for the cross section. Algorithm steps are as follows:

1. Specify the dimension and bubbledeck properties of the solid reinforced cross section.
2. Assume a neutral axis depth and a value for stress and strain on concrete slab by the equation.
3. Divide the cross section in-to 2 number layers as predicted by the equation.
4. With strain and stress values from Step 3, compute stress  $f_c$ , values using Equation.
5. Specify all forces on bubble-deck slab to find out the failure stress diagram after step 4.
6. By using Equation find out the values for failure analysis.
7. Using equation, compute the value of each bubbledeck concrete slab in the simulation.
8. Using converged failure analysis of bubbledeck concrete slab for each load level, compute the corresponding curvature values.

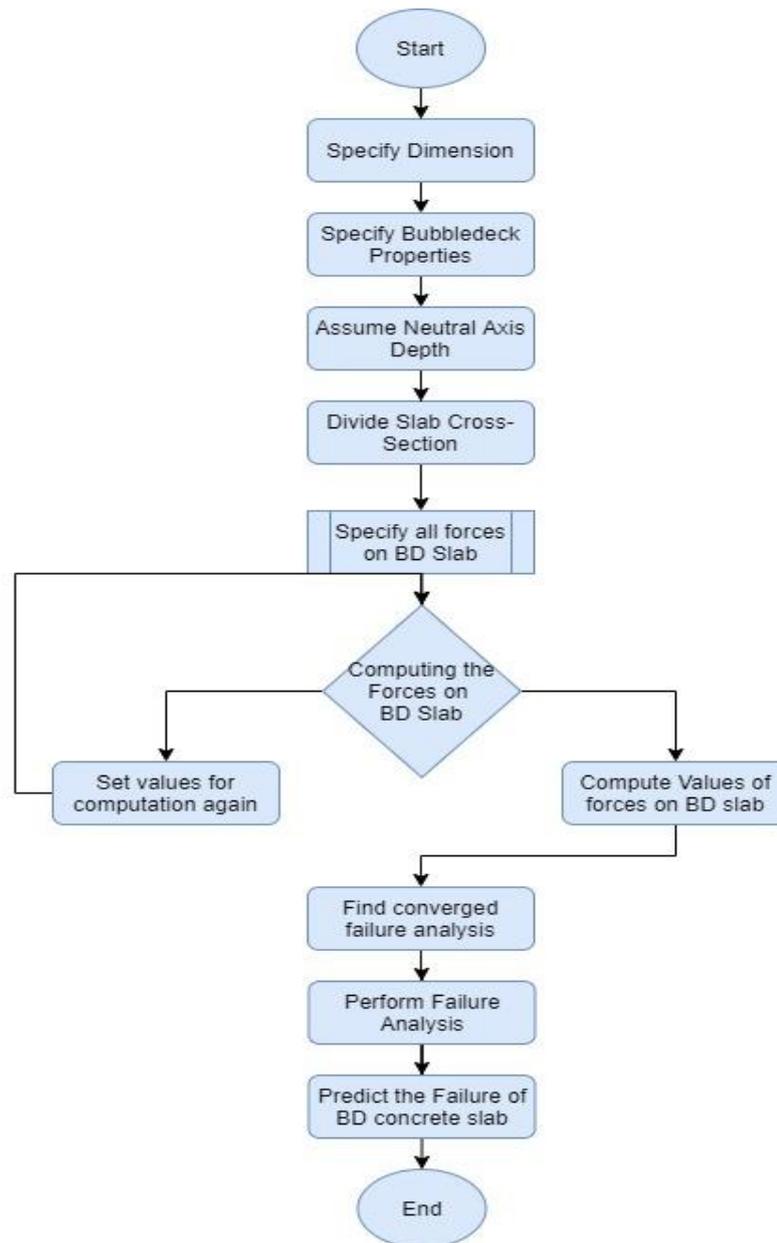


Figure 5. The methodological steps depicted by the diagram

Pictures of deformed shapes and failure patterns of slabs of all tested. The strength of BD slabs has been taken as the peak of the total reaction at both supports. It has to be noted that such a value differs from the maximum impact load due to the effect of inertia forces. The total reaction has to be used as a strength indicator rather than the impact load unless the effect of inertia forces is removed from the impact load, which in turn is equivalent to the total reaction. Total reaction-midspan deflection. The midspan deflection was calculated by double integration of the measured acceleration, in agreement with previous research. There is a shift of the origin of total reaction-deflection diagrams due to the fact that a deflection at the midspan already developed when the impact effect reached the supports.

### 3.2. Bubbledeck in mid-rise building structures

The pushover curves of the 4-story models are using the bubbledeck concrete slabs. As it can be seen from these figures, by increasing the value of the span length to story height ratio the strength of building is increased by 10%. Note that by introducing the bubbledeck slabs, the stronger columns and walls are made. Due to this reason the lateral strength and stiffness increase. The analysis of seismic parameters has been carried out for all of the 4-story models. Performance and failure of using bubbledeck structure slab in a 4-story building were calculated by idealizing pushover curves. The usage category application was imposed by applying different live loads, which leads to build dissimilar models with different specifications.

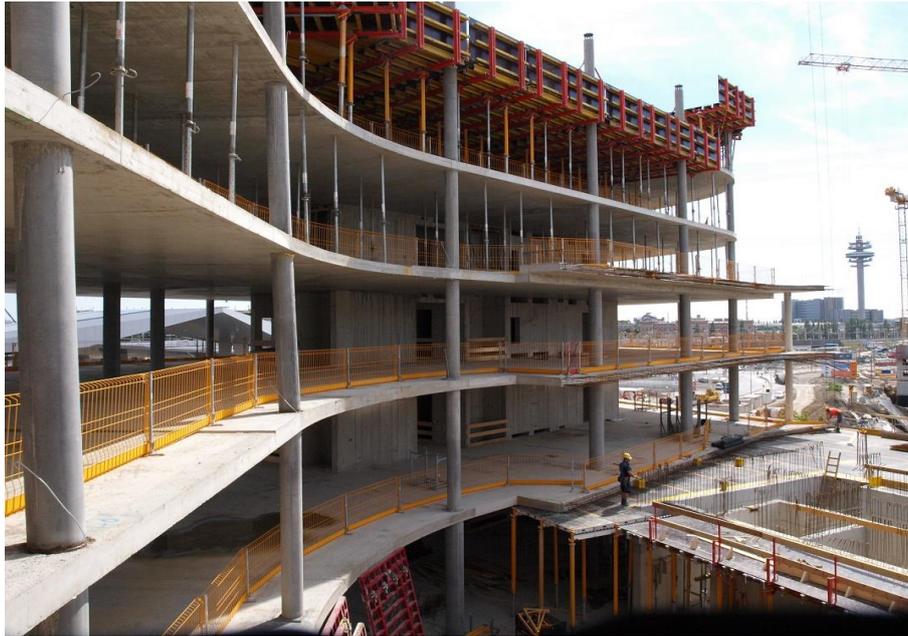


Figure 6. Bubbledeck slab structure in a low-rise building structures (4-story structures) [18]

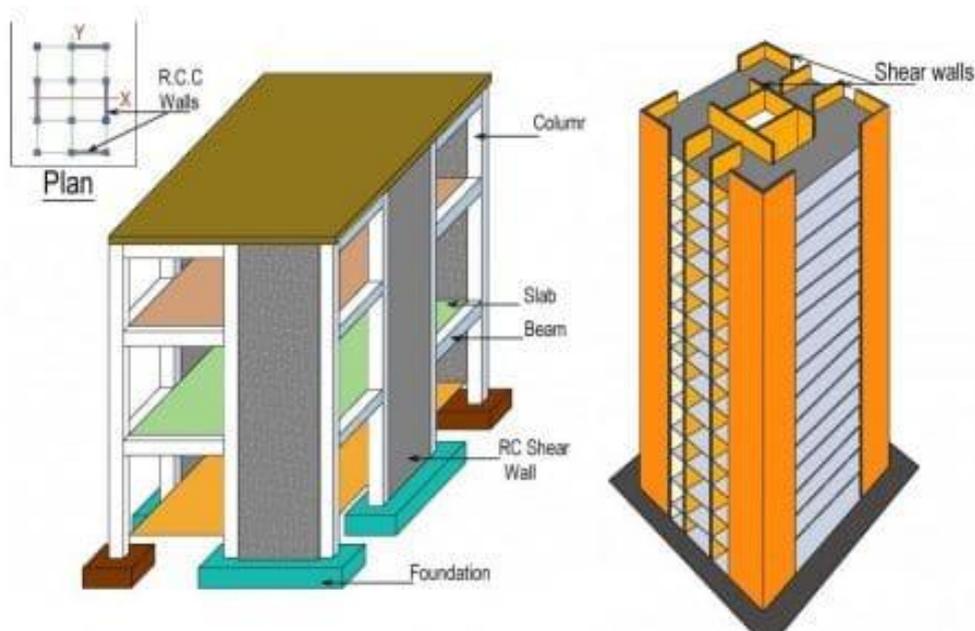


Figure 7. Bubbledeck slab structure in a mid-rise building structures [19]

By introducing the bubbledeck concrete slabs in the design process, stronger columns and walls are made. Due to this reason, the lateral strength and stiffness are increased. The performance of using bubbledeck in a mid-rise building offers Design Freedom, longer spans between columns, Environmentally Green and Sustainable and Reduced Dead Weight. The seismic parameters were analyzed for all the 8-story models, then the performance and failure analysis were computed by the idealization of the pushover curves.

#### 4. Results

A definite sign convention is adopted in this system, in which moment will be considered as positive when it produces compression in the top BD slab. When resultant force to the left of a section is upwards, shear will consider as positive. Loads will consider as positive when loads act upward. The procedure is simplified by omitting the length of the segment as a common factor so the multiplication of the shear by the distance between loads until the end of the computation. Then the moment will be computed as a numerical quantity, multiply all by a common factor, which is the factor for the loads multiplied by the distance between loads.

Table 1. The parameters are set upon which BD slabs are collapse

Slab Type	Slab No.	Load	Stress	Strain	Force	Slab Length	Span (ft.)
<b>Reinforced</b>	1	3.00	40.00	2.35	1.28	17.08	15
	2	4.52	51.20	5.25	0.86	9.76	21
	3	6.74	77.00	10.8	0.62	7.13	27
<b>BD Concrete Slab</b>	1	2.88	38.98	1.92	1.50	20.3	15
	2	4.44	50.00	4.14	1.08	12.1	21
	3	6.48	75.00	7.80	0.83	9.62	27

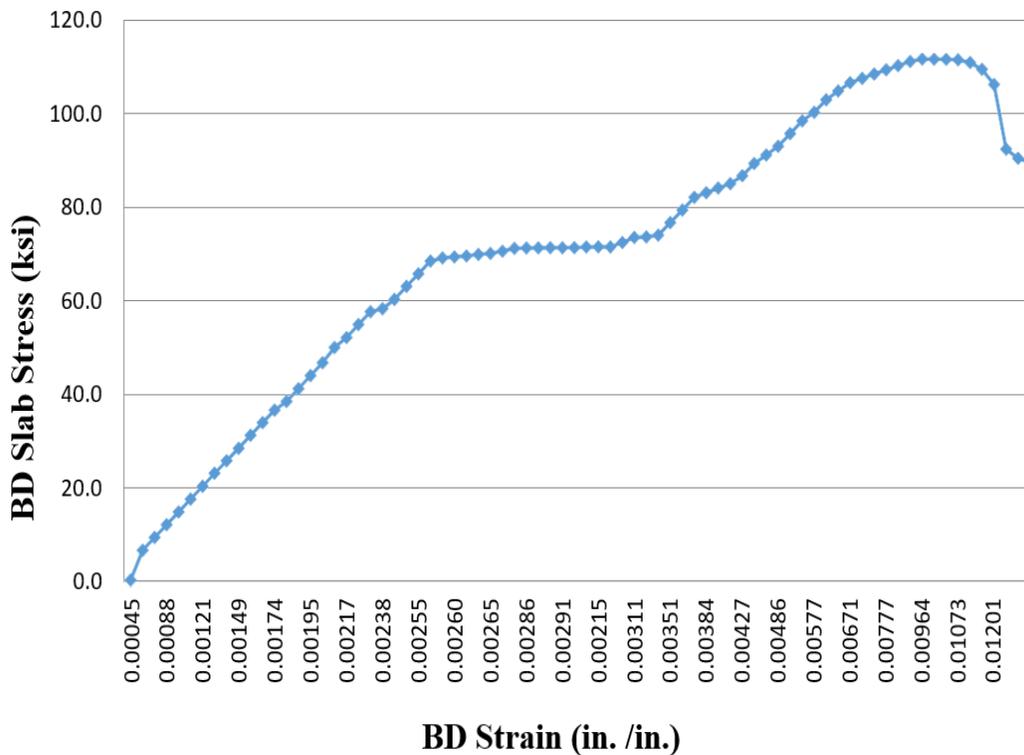


Figure 8. The relationship of stress-strain for bubbledeck concrete slabs

Table 2. The maximum cracking and collapse load provided for the different BD slabs

Number of BD Filled Slabs	Cracking load (kip)	Collapse load (kip)
Slab 1	1.55	5.90
Slab 2	1.45	5.45
Slab 3	1.50	5.85
Slab 4	1.45	5.50

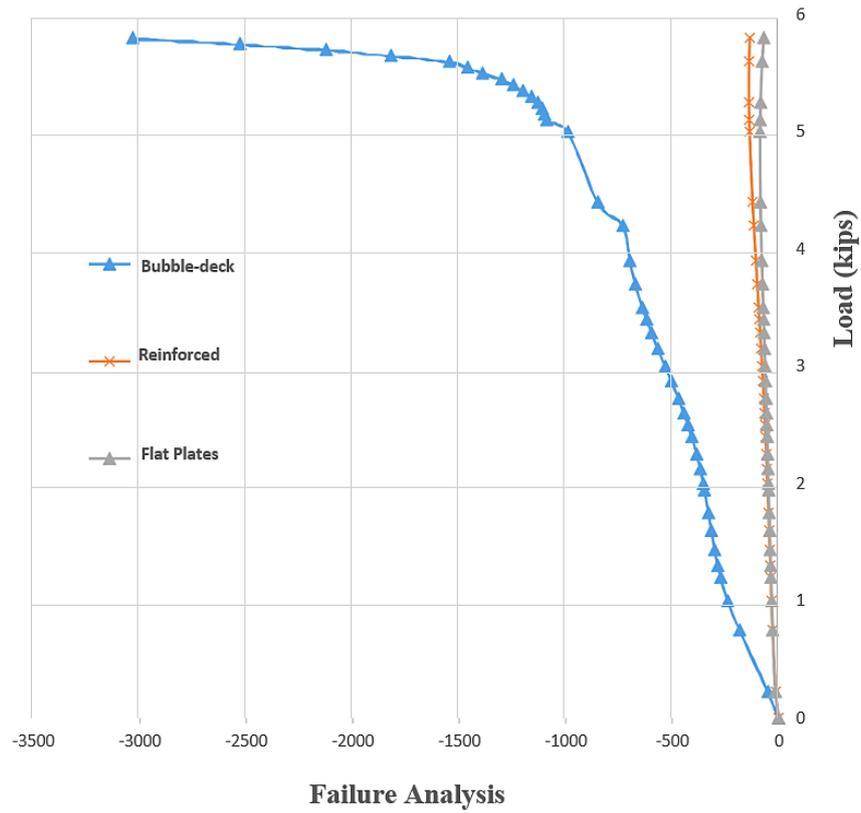


Figure 9. Failure analysis of all three types of slabs in terms of load where bubbledeck has the highest potential to bear the load

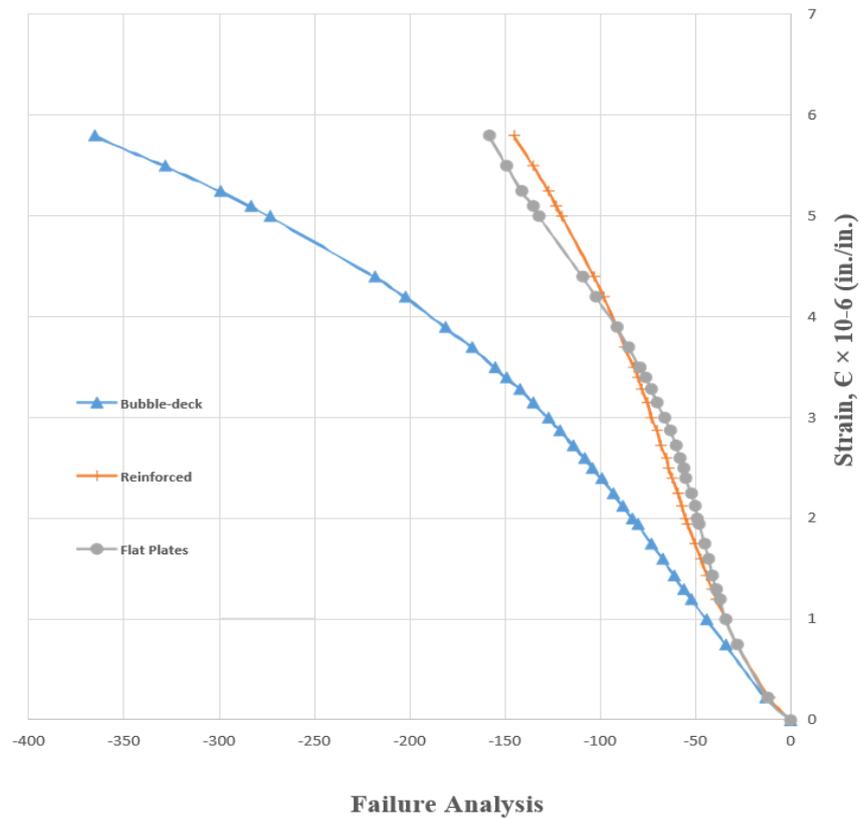


Figure 10. Failure analysis of all three types of slabs in terms of strain where bubbledeck has the highest potential to bear the strain

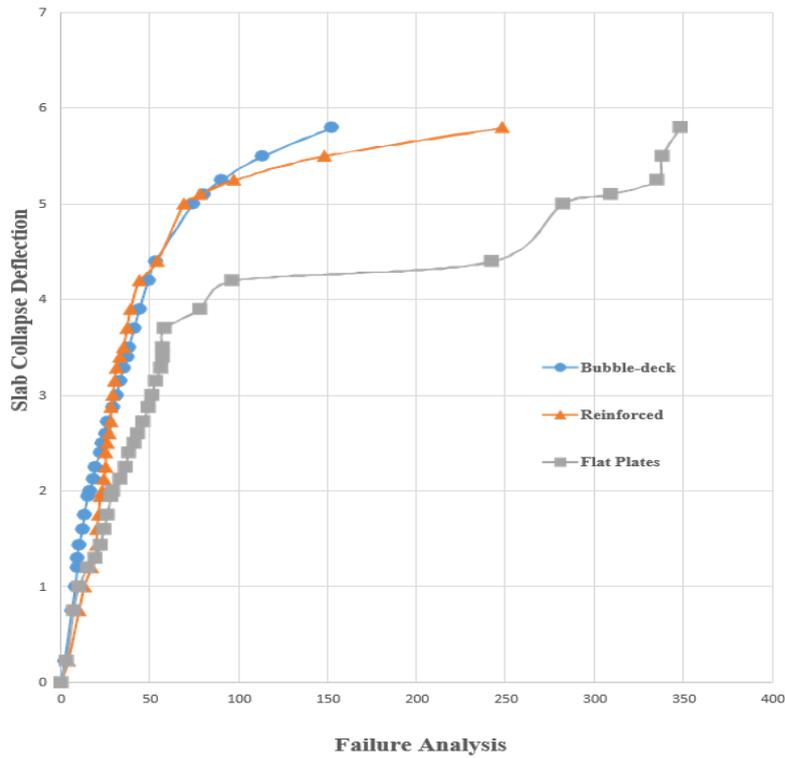


Figure 11. Failure analysis of all three types of slabs in terms of slab collapse deflection where bubbledeck has the lowest risk of collapsing

Experimental results for sample slabs in simulation environment are presented. Load is applied at specific incremental rate and respective strain values are measured. After collecting values till breaking point, graph for stress-strain relation is generated. We show the graphical representation of stress-strain relation for bubbledeck and two more types of slabs. For testing concrete slabs, two-point load system which is shown in our work, is used. For setting up the loading system, concrete slabs are first placed on simply supported ends in the simulation environment. To transfer the point load into two-point load system, BD slabs and two more types of slabs are used for comparison.

**5. Discussion**

The discussion section provides us with the insight of comparison for this work as BD finite integral procedure involves replacing the continuous differential concrete slabs which must be satisfied everywhere by a series of simultaneous construction of buildings, represent the differential of building strength at a series of discrete points. All but the highest differential coefficients in these equations are eliminated by replacing them by linear combinations of the highest differential coefficients and of the constants of integration for reinforced concrete and bubble-deck concrete, these combinations being determined by the method of finite integrals. The resulting simultaneous construction of buildings may be combined with the boundary conditions using bubble-deck material slabs and solved for the highest differential coefficients. The discrete values of the dependent variables are then calculated by back-substitution into the finite integral expressions for construction using the bubbledeck concrete slabs.

Table 3. Comparison of different slabs with their evaluated performance in terms of accuracy

MATERIAL	70%	80%	90%	100%
<b>BD Concrete Slabs</b>	67.86	76.63	88.06	98.39
<b>Flat Plate Slabs</b>	65.50	75.27	85.01	93.28
<b>Reinforced Concrete Slabs</b>	66.92	74.92	85.61	93.89

Table 4. Evaluation of different comparison parameters between reinforced concrete slabs and bubble concrete slabs

Comparison Parameters	Reinforced Concrete Slabs	BD Concrete Slabs
Weight (lbs.)	112	100
Experimental collapse load index	51.78	55.00
Experimental cracking load index	12.70	14.00
Ultimate moments (kip-in.)	66.00	64.30
Ultimate curvature (rad. /in.)	0.00337	0.003157
Elastic stiffness, k for theoretical load deflection curve	83.89	59.17
Elastic stiffness, k for practical load-deflection curve	32.69	27.83

A time gap of 2–3 ms was observed between the beginning of the simulation on Matlab and the activation of the support reactions due to the time required for the wave propagation from the midspan to the supports in Matlab. Then the moment will be computed as a numerical quantity, multiply all by a common factor, which is the factor for the loads multiplied by the distance between loads.

## 6. Conclusion

To conclude the paper, the study of the structural behaviour of bubbledeck panels and slabs under impact loading is relevant in design for building constructions and against accidental actions. This paper proposes a combined theoretical and simulation approach to predict localized performance of bubbledeck panels under different slabs types. We recorded a maximum load of 6.48, maximum stress of 75.00, maximum strain of 7.80, with minimum force of 0.83, while minimum slab length of 9.62 and lastly the maximum slab span of 27 for our bubbledeck concrete slab experiment in comparison with reinforced concrete slab to get the best results. In this approach, the dynamic punching shear capacity is obtained in terms of the slab rotation around the impact region by means of the buildings. The rotation is obtained from the global response analysis using different models with shell elements. The purely theoretical approach of predicting performance and failure using solid elements provided similar results although this analysis was highly demanding computationally and required significant work beforehand to validate the models used.

## References

- [1] J. Shen; X. Gao; B. Li; K. Du; R. Jin; W. Chen; Y. Xu. Damage evolution of rc beams under simultaneous reinforcement corrosion and sustained load. *Materials*. 12, 627,2019.
- [2] T.S. Ng; R.M. Yau; T.N. Lam; V.S. Cheng. Design and commission a zero-carbon building for hot and humid climate. *Int. J. Low-Carbon Technol.* 11, 222–23, 2016.
- [3] Available Online: <https://www.slideshare.net/ashlinvilon/bubble-deck-slab-system-86632426>
- [4] M. Gruszczyński. The use of thin cement-polymer layers to repair and strengthening concrete floors. *Mater. Bud.* 9, 30–33, 2018.
- [5] M. Sánchez; P. Faria; L. Ferrara; E. Horszczaruk; H. M. Jonkers; n,A. Kwiecie; J. Mosa; A. Peled; A. S. Pereira; D. Snoeck; et al. External treatments for the preventive repair of existing constructions: A review. *Constr. Build. Mater.* 193, 435–452,2018.
- [6] C. Czaderski; U. Meier. Ebr strengthening technique for concrete, long-term behaviour and historical survey. *Polymers*. 10, 77,2018.

- 
- [7] S. Soares; J. Sena-Cruz; J .R. Cruz; P. Fernandes. Influence of surface preparation method on the bond behavior of externally bonded cfrp reinforcements in concrete. *Materials*, 12, 414,2019.
- [8] K. R. Harishma; K. N. Reshmi. ‘A study on bubble deck slab’, *International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)* Vol. II, Special Issue X, March 2015.
- [9] K. Subramanian. and P. Bhuvaneshwari. “Finite Element Analysis of Voided Slab with High Density Polypropylene Void Formers”, *International Journal of ChemTech Research* Vol.8, No.2, pp 746-753,2018.
- [10] C. Sergiu Calin. G. Mugurel; C. Dascălu, Asăvoaie. “Computational simulation for concrete slab with spherical gaps”, *Proceedings of The 8-th International Symposium, Concepts in Civil Engineering*, Ed. Societății Academice "Matei-Teiu Botez", pp. 154-161,2010.
- [11] A. Churakov., “Biaxial Hollow Slab with Innovative Types of Voids,” *Construction of Unique Building and structure*, Vol. 6(21),pp. 70-88,2014.
- [12] A. Ibrahim, K. N. Ali; and W.D. Salman. "Flexural Capacities of Reinforced Concrete Two-way Bubble Deck Slabs of Plastic Spherical Voids," *Diyala Journal of Engineering Sciences*, Vol. 06, June, pp. 9-20,2013.
- [13] S. Calin, R. Gintu, and G. Dascalu. “Summary of Tests and Studies done on the Bubble Deck System,” *The Buletinul Institutului Politehnic din Ia i, LV*,2018.
- [14] P.P. Teja, and V. P. Kumar. “Structural Behavior of Bubble Deck Slab,” *JISBN: IEEE*, Vol. 81, ISBN: 978-81-909042-2-3, March, 2012, pp. 383- 388,2012.
- [15] S. Anusha, C.H. Mounika, and Purnachandra. “Study on Fire Resistance of Bubble Deck Slab,” *JISBN: IEEE*, Vol. 81, ISBN: 978- 81-909042-2-3, 2010.
- [16] K. Pfeffer; M. Schnellenbach, "Punching behavior of biaxial hollow slabs," *Cement & Concrete Composites*, Vol. 24, Issue 6, December, 2011, pp. 551-556,2011.
- [17] K. Krzywi ński; L. Sadowski. The effect of texturing of the surface of concrete substrate on the pull-off strength of epoxy resin coating. *Coatings*, 9, 143,2019.
- [18] Taipei City Government. Table of the Service Life and Annual Depreciation Rates of Building Improvements in Taipei City for the Purpose of Land Price Survey. Available online: <http://www.land.gov.taipei/ct.asp?xItem=12519&CtNode=56902&mp=111001> (accessed on 19 June 2020).
- [19] S.W. Tang, S.W.; Y. Yao. Andrade, C.; Li, Z. Recent durability studies on concrete structure. *Cem. Concr. Res.* 2015, 78, 143–154, 2015.