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Stability Analysis and Comparison of Conventional Concrete and Expanded Polystyrene Concrete Spherical Shells

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The authors declare that there is no conflict of interest.

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Abstract. The main purpose of this study is to investigate the buckling behavior of a light weight expanded polystyrene concrete (EPSC) spherical shell and compare it to an equivalent concrete shell. Such behavior of EPSC is not yet studied and the material has not been implemented in shell structures. The methods adopted are numerical linear buckling analysis (LBA), material non-linear analysis (MNA) and Geometric and material non-linear analysis with imperfection (GMNIA) for both concrete and EPSC spherical shells of the same geometric parameters in ABAQUS software. From the results of the study, the elastic and plastic buckling capacities of EPSC shell and the buckling resistance obtained from GMNIA method are smaller than that of equivalent concrete shell. The maximum displacements of the EPSC shell corresponding to the GMNIA method, with the application of first eigen and actual loads are greater than the concrete shell by small millimeters. Buckling capacities of EPSC shell obtained from the three methods exceed the actual external uniform pressure (self-weight of EPSC and actual snow load), and the displacement results are reasonable enough to ensure that EPSC spherical shells are stable and could be practically applicable.

Keywords: expanded polystyrene concrete, stability, buckling analysis, geometric imperfection

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Анализ устойчивости и сравнение сферических оболочек из обычного бетона и пенополистиролбетона

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Аннотация. Исследовано поведение сферической оболочки из легкого пенополистиролбетона (EPSC) при изгибе и проведено сравнение ее с аналогичной бетонной оболочкой. Такое поведение EPSC еще не изучено, и этот материал не применялся в конструкциях оболочек. В качестве методов были использованы численный анализ линейной потери устойчивости (LBA), нелинейный анализ материалов (MNA) и геометрический нелинейный анализ материалов с учетом дефектов (GMNIA) как для бетонных, так и для EPSC сферических оболочек с одинаковыми геометрическими параметрами в программном обеспечении ABAQUS. Согласно результатам исследования, упругие и пластические свойства оболочки EPSC на изгиб и сопротивление изгибу, полученные методом GMNIA, меньше, чем у аналогичной бетонной оболочки. Максимальные перемещения оболочки EPSC, соответствующие методу GMNIA, при приложении первых собственных и фактических нагрузок превышают размеры бетонной оболочки на несколько миллиметров. Способность оболочки EPSC к потере устойчивости, полученная с помощью трех методов, превышает фактическое внешнее равномерное давление (собственный вес EPSC и фактическая снеговая нагрузка), а результаты смещения являются достаточно обоснованными, чтобы гарантировать стабильность сферических оболочек EPSC и возможность их практического применения.

Ключевые слова: пенополистиролбетон, устойчивость, анализ потери устойчивости, геометрическое несовершенство

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1. Introduction

1.1. Buckling of spherical shells

Several research works have been conducted on the stability issues of spherical shells. The theory of shell buckling has originated from Euler's formula of critical load determination for a straight bar. Following this, a first theory of linear buckling of spherical shells was developed by Zoelly in 1915 where the elastic critical buckling load of complete spherical shells under external pressure was determined according to the formula [1]:

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$$P_z = \frac{2}{\sqrt{3\left(1-\upsilon^2\right)}} \cdot E \cdot \left(\frac{t}{R}\right)^2, \quad (1)$$

where t — thickness of the shell, R — radius of curvature of the shell, E — modulus of elasticity, υ — Poisson's ratio.

In most codes of design equation (1) is commonly taken as a reference load of buckling for elastic spheres. However, most experimental studies reveal that the actual buckling capacity is a fraction of the amount obtained from equation (1). External disturbances and imperfections whose magnitude can not be predicted at the design stage, are the main factors for the decreased capacity of the buckling load. The load carrying capacity of perfect shells is greater than shells that show deviations in material behavior, geometry and boundary conditions [2–6]. Numerical concepts for load carrying capability of shells with imperfection are based on perfect shell models and on the postcritical equilibrium paths which are estimated analytically. This idea was established first by Koiter [7]. The post buckling theory of Koiter describes the static non-linear load carrying behavior of a structure at the buckling initial stages. The post buckling analysis gives information about the post buckling path at the initial stage, the stability of the corresponding equilibrium state and the way geometric imperfections influence the load bearing behavior of a structure. Thus, in the computation of buckling capacity of a structure, it is necessary to apply reduction factors in consideration to the influence of imperfections and effects from plastic behavior of a material.

A wide research on the buckling behavior of spherical shells became possible with the enhancement of computer technologies and finite element method. In numerical simulation, a method of construction for the relationship between the worst imperfection with its amplitude and the limit load are applied [8]. In this paper, a numerical simulation of the elastic, perfectly plastic and imperfect spherical shells of conventional concrete and EPSC are presented. The results are compared each other for investigating the possible application of EPSC in spherical domes.

1.2. Cement concrete

Cement concrete is one of the popular structural materials. Cement concrete is isotropic, homogeneous and elastic material of construction. The main ingredients of concrete are cement, sand, Coarse aggregate and water [9]. Concrete is strong in compression but weak in tension and in locations of a structure where there is tension, steel reinforcement is provided to give tensile strength to the structure. Strength of cement concrete increases with increasing hydration of cement. High strength concrete has a modulus of elasticity ranging from 14-41MPa [10] and generally a Poisson's ratio varying between 0.15 for high strength concrete and 0.22 for low strength [11; 12].

Concrete structural members have big cross-sections resulting from the high self-weight of the material. Coarse aggregate and sand are the main ingredients for the increased weight of concrete. Concrete's weight can be reduced by using lightweight aggregates such as cinders, pumice, shales, EPS… In this paper stability of a lightweight concrete, which is expanded polystyrene concrete (EPSC) is going to be investigated. It is produced by partially or totally replacing aggregates with expanded polystyrene (EPS) [13–16].

Expanded polystyrene concrete has a lesser density than conventional concrete with range of densities 800-200 kg/m^3. The density and compressive strength of EPSC decrease with increasing amount of EPS used in the concrete mix [17–20]. EPSC has been utilized in several applications like curtain walls, pavements and load bearing blocks [21]. However, its application, stability and strength capacity in shell structures has not yet studied. Therefore, this research will focus on:

- Studying the properties of EPSC to be used for the current study
- Analyzing the stability of conventional concrete and EPSC spherical shells considering elastic critical buckling, plastic buckling and buckling with geometric imperfection and material non-linearity. Moreover, the shells' displacements are also analyzed numerically in ABAQUS considering the same geometric data for both EPSC and concrete shells.

2. Methods

2.1. Experimental work

Figure 1. Testing for compressive strength
S o u r c e : photo by I.A. Sereke

In a 1:2:3 proportion by volume, 16.67 % of sand and 33.33 % of coarse aggregate were replaced by EPS to produce expanded polystyrene concrete. By using 0.6 water cement ratio, ingredients cement, sand, coarse aggregate water and EPS were thoroughly mixed. A flowing and homogeneous EPSC was then obtained and filled into three cubic molds of dimension 150 mm×150 mm×150 mm for testing at a laboratory. After demolding, curing and drying the specimens' compressive strength testing was followed as shown in Figure 1.

The mass, compressive strength and density were recorded as shown in Table 1.

Table 1

EPSC properties from experiment

Cubic EPSC No.	Measured mass, kg	Density, kg/m^3	Compressive force, kN	Compressive strength, MPa
1	7.15	2120	235	10.44
2	6.948	2058.66	207	9.2
3	6.898	2043.85	198	88

S o u r c e: made by I.A. Sereke

The computed average values of density and compressive strength are 2074.17 kg/m^3 and 9.48 MPa respectively.

The elastic modulus of EPSC is computed from the formula in equation (2), [22]: and obtained as 11.18GPa:

$$E_c = w_c^{1.5} \cdot 0.043\sqrt{f_c^{'}}, \tag{2}$$

where w_c — density ranging from 1440–22560 kg/m^3, E_c — modulus of elasticity in MPa, $f_c^{'}$ — compressive strength of a cylinder specimen in MPa.

The cylinder compressive strength is computed from equation (3) [23].

Cylinder strength = 0.8×cube strength. (3)

In the stability analysis, a cylinder strength of conventional concrete C20, unit weight of concrete 24 kN/m^3, Poisson's ratio 0.2 and corresponding modulus of elasticity 22.61 GPa are adopted. Similarly, for EPSC, a unit weight of 20.74 kN/m^3 a cylinder strength of 7.58 MPa, modulus of elasticity 11.18 GPa and a Poisson's ratio of 0.22 are used.

2.2. Numerical methods of analysis

Application of finite element method with advanced computer programs accelerated research works, that shells of different material, geometry, loading or support condition were able to be analyzed with high accuracy and reliability. In this study linear buckling analysis (LBA), material non-linear analysis (MNA) and geometric and material non-linear analysis with imperfection (GMNIA) are applied for both concrete and EPSC spherical shells. For analysis and comparison, a spherical shell with radius of curvature 35 m, half central angle 55°, base radius 28.67 m, thickness 0.15 m and rise of 14.92 m is considered as shown in Figure 2. The buckling pressures are compared to the external pressures coming from the respective self-weights and assumed snow load of 1.5 kN/m^2.

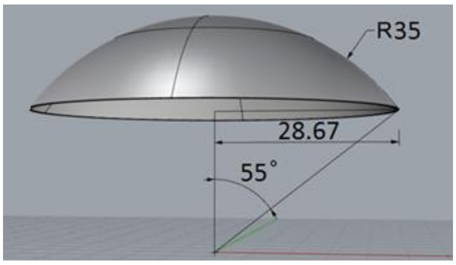

Figure 2. Shell geometric details
S o u r c e: made by Sereke I.A.

2.2.1. Linear buckling analysis

Elastic critical buckling load PR_{cr} of a shell is determined with eigenvalue linear buckling analysis where, the shell is considered as elastic without imperfection [24–26]. This kind of analysis is necessary for arbitrarily loaded spherical shells, and the critical buckling load obtained is going to be applied for further analysis in the estimation of ultimate buckling load. LBA is based on the bending theory of elastic thin-walled shells considering linear material characteristics and small deflections. At the value of the elastic critical pressure which is the lowest eigen value, elastic linear stability analysis gets reduced and the shell ceases to be stable.

2.2.2. Material non-linear analysis

The plastic resistance PR_{pl} of a shell is determined by using material non-linear analysis (MNA). It is based on the bending theory of perfect shell structures; assumption of small deflections and a nonlinear elastic-plastic material law is adopted. MNA is used to make an estimation of the plastic resistance while checking the plastic limit state (LS1), cyclic plasticity (LS2) and the ultimate limit state of buckling (LS3) [24–27]. The plastic resistance in conjunction with the elastic critical resistance is used to determine the relative slenderness of an entire spherical shell.

2.2.3. Geometric and material non-linear analysis with imperfection

A numerical analysis that considers geometric and material nonlinearity with imperfections (GMNIA) is the one that currently gives the most accurate result of the buckling capacity of a structure. It is based on the non-linear elastic-plastic material characteristics and theory of large deflections. Geometric imperfections are considered in determining a structure's elastic plastic design capacity [24–27]. The shape deviations from the ideal geometry may be caused due to shortage of sphericity happening during casting. Imperfections that correspond to the first two buckling modes of an analyzed system may also be considered. Similarly, the material homogeneity is influenced by creep, cracking and plasticity of the materials. [28]. For this study the first eigen buckling form of the analyzed shell with a randomly selected imperfection amplitude of 0.1 is considered in the GMNIA method of analysis.

3. Results and Discussion

3.1. Results of LBA analysis

The elastic critical buckling loads for concrete and EPSC corresponding to the first Eigen mode are 469.83 kN/m^2 and 244.19 kN/m^2 respectively. Computation of linear buckling analysis is performed considering the elastic modulus and Poisson's ratio of the respective materials. Accordingly, the critical resistance of EPSC is 1.92 times lower than that of concrete. Since the obtained elastic critical buckling resistances is greater than summation of EPSC shell's self-weight (3.05 kN/m^2) and assumed snow load of (1.5 kN/m^2), the shell will continue elastically stabile.

3.2. MNA results

The plastic buckling resistance of concrete and EPSC spherical shells is computed from material nonlinear analysis (MNA). In this analysis yield strength of the respective materials is introduced while neglecting strain amplification. The plastic load capacity of concrete and EPSC from the numerical analysis are obtained as 171.43 kN/m^2 and 64.97 kN/m^2 respectively. similarly, the corresponding maximum plastic displacements are 0.062 m for concrete and 0.045 m for EPSC as shown in Figures 3 and 4. EPSC's plastic load capacity is 2.63 times smaller than that of concrete. Nevertheless, the plastic load resistance is greater than the external uniform load, indicating that the load capacity of the EPSC shell will not get exhausted.

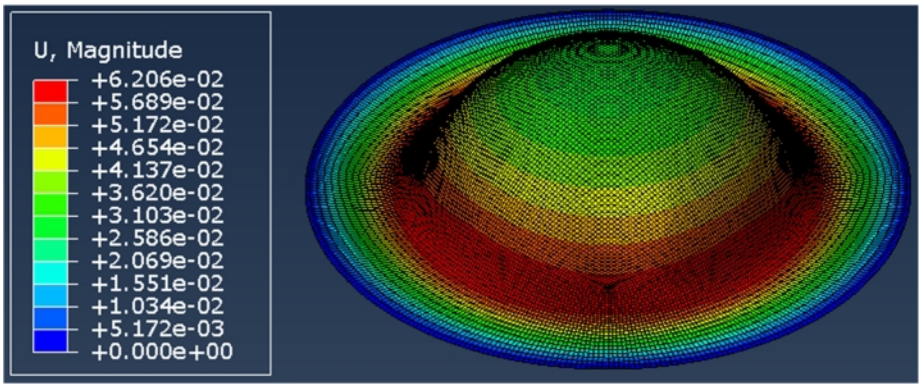

Figure 3. Maximum plastic deformation of concrete shell from MNA method
S o u r c e: made by I.A. Sereke

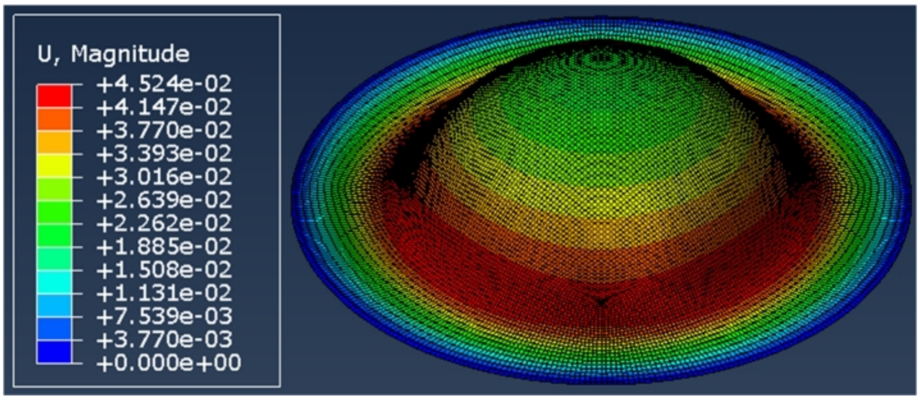

Figure 4. Maximum plastic deformation of EPSC shell from MNA method
S o u r c e: made by I.A. Sereke

3.3. GMNIA results

The geometric and material nonlinear analysis was started by imposing a first buckling form of imperfection of the analyzed shell and scaling it to a randomly selected amplitude of 0.1. The ultimate level of the buckling capacity is considered as the load value at which a complete plasticization is occurring. This value of buckling resistance is obtained as 27.38 kN/m^2 for concrete and 10.87 kN/m^2 for EPSC with EPSC's buckling resistance 2.5 times smaller than concrete's resistance. Nevertheless, it is greater than the actual external pressure. In addition, the corresponding maximum displacements for concrete and EPSC are computed as 2.27 m and 2.29 m for both concrete and EPSC shells respectively as shown in Figures 5 and 6. These displacements are very high however, they are computed when the shells are loaded to the first Eigenvalue pressures 469.83 kN/m^2 and 244.19 kN/m^2. These displacement values will significantly get reduced when the shells are loaded with their respective actual external pressures, resulting to 5.1 mm and 8.9 mm for concrete and EPSC shells respectively as depicted from Figures 7 and 8.

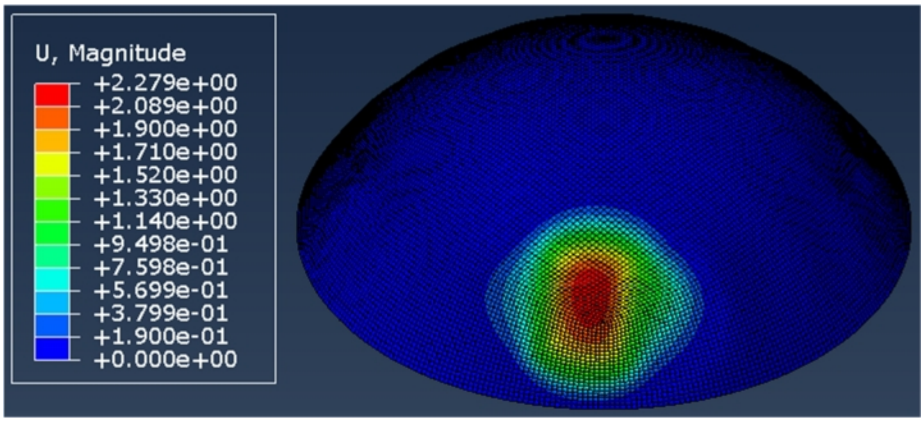

Figure 5. Maximum displacement of concrete shell from GMNIA method
S o u r c e: made by I.A. Sereke

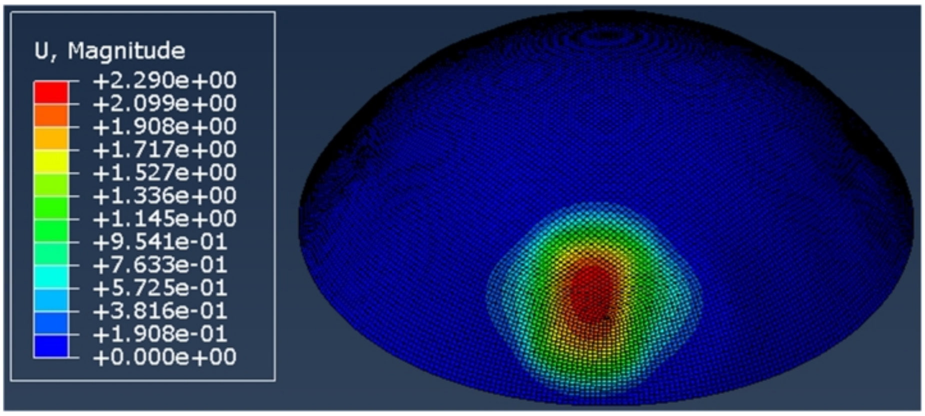

Figure 6. Maximum displacement of EPSC shell from GMNIA method
S o u r c e: made by I.A. Sereke

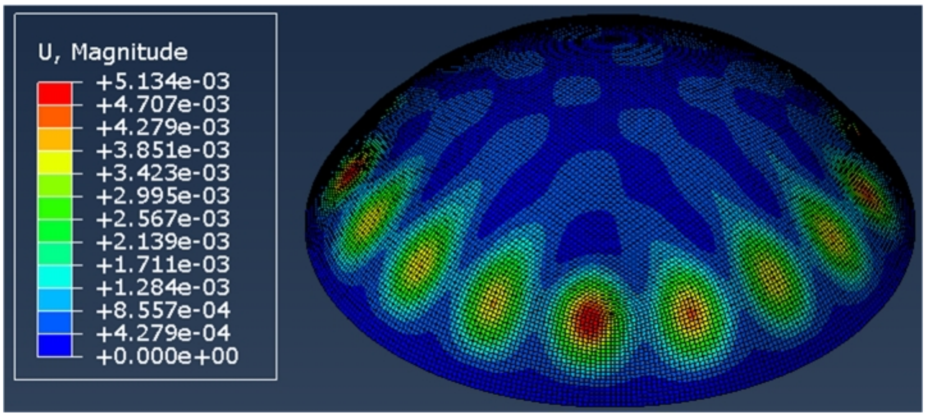

Figure 7. Displacement of concrete shell under the actual load
S o u r c e: made by I.A. Sereke

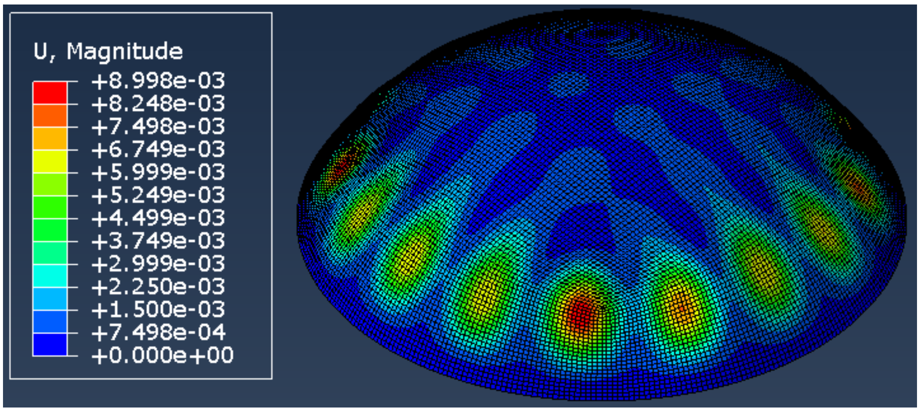

Figure 8. Displacement of EPSC shell under the actual load
S o u r c e: made by I.A. Sereke

4. Conclusion

From this conducted investigation the following statements could be concluded:

1. Since both geometric imperfection and material non-linearity are considered in GMNIA method of analysis, accurate buckling capacity of the shells correspond to this method of analysis.

2. The difference in the obtained buckling capacities of the three methods arose from a snap-through buckling that controls the case of spherical shells buckling. A progressive change of geometry resulted from the snap through analysis derives an imperfection reduction factor which is accounted in the GMNIA method only to have more accurate result.

3. The GMNIA results may vary depending on the considered types of imperfections and corresponding amplitudes.

4. The buckling resistance of EPSC dome obtained from GMNIA method (10.87 kN/m^2) exceeds the external pressure (4.55 kN/m^2) by 2.38 times, showing to the stability and practicality of EPSC in the real-world construction of spherical shell roofs.

5. The maximum displacement of EPSC shell from the GMNIA method is found to be 1.42 times greater than that of concrete when both shells are loaded to their respective first eigen loads and 1.74 times greater when the shells are loaded to their actual external pressures. Moreover, under the actual load, a displacement of 8.9 mm in a span of 57.34 m EPSC shell is negligible, which reveals EPSC spherical shell is a stiff shell.

6. The linear buckling capacity of EPSC shell is 53.67 times greater than the external pressure acting on the shell, which indicates the continuity of the shell to be elastic and stable.

7. Similarly, the plastic buckling capacity of EPSC shell, which is 14.28 times greater than the external pressure, this confirms that there will not be plastic flow mechanism in the EPSC spherical shell.

8. Finally, it is recommended to conduct large-scale experiment on EPSC shells by considering different proportions of EPS to best optimize concrete in the construction of spherical domes.

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