Fracture and Vibration Analysis of Tessellation Domes

Aravind.M.K
PG Student, Structural Engineering
Department of Civil Engineering
Kumaraguru College of Technology
CBE, Tamilnadu, India.

Dr.P.Eswaramoorthi
Professor
Department of Civil Engineering
Kumaraguru College of Technology
CBE, Tamilnadu, India.

P.Nandhakumar
Assistant Professor
Department of Civil Engineering
Kumaraguru College of Technology
CBE, Tamilnadu, India.

Abstract - In this work the behavior of a tessellation dome was tested for Static analysis, Fracture analysis, and Vibration analysis. It was noted that the numerical and experimental results have large differences. Numerical static analysis were performed using STAAD Pro. Fracture analysis was performed using LISA and compared with experimental test and vibration analysis was performed using FFT Analyzer and energy accumulation was studied using accelerometer response. Possible causes for the differences involve the type of joint, the fixing of the elements in the joints, the profile adopted for the elements and boundary conditions for the numerical model.

***Keywords*—Dome; Static load; Fracture; Vibration; Response Spectrum; Time Waveform; Fast Fourier Transform; Accelerometer.**

I. INTRODUCTION AND SCOPE

A dome is a rounded vault made or curved segment or a shell or revolution known as arch rotated around its central vertical axis. The word 'dome' is come from the Greek and Latin word 'domus' which was used up through the renaissance to label a revered house due to the shape of its roof. Domes are stable during construction as each level is made a complete and self-supporting ring. Domes achieve their shape by extending each horizontal layer inward slightly farther than the previous one until they meet at the top. Domes are specially wanted to increase the aesthetic appearance and also to have large column free space. Special Domes are engineered to resist much loads with minimal self-weight. These domes are extremely strong offering the largest ratio of load carrying capacity in any known linear structures. Resilience of this dome in the face of disaster is a major advantage. Since this project majorly focuses on eco-friendly, aesthetically improved, effective and efficient structural design for future smart societies. Various materials such as steel tubes, timber, and bamboo are adopted. Based on the availability of material at the locality and need for the use, the structural profile could be changed with optimal material usage and secure structural design.

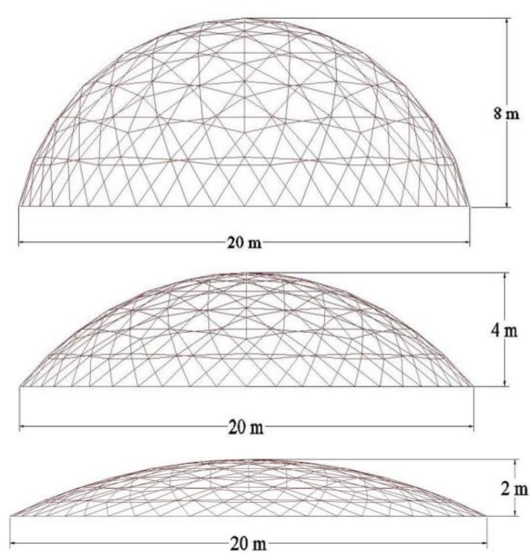
II. PROFILE OF THE DOME

Different profiles that have been considered for the analysis are, namely 20-08, 20-04, and 20-02. Where the 20m base is kept constant and central rise is varying as 8m, 4m, and 2m. The different joint connectors are disk, strip, clamp with ring.

Table I. Different Profiles and their Base to Rise ratio.

Profile type	20-08	20-04	20-02
Base to Rise ratio	2.5	5	10

Figures showing Different Profiles of Domes



III. STATIC ANALYSIS

A static analysis calculates the effects of *steady* loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. A static analysis can, however, include *steady* inertia loads (such as gravity and rotational velocity), and time-varying loads that can be approximated as static equivalent loads (such as the static equivalent wind and seismic loads commonly defined in many building codes).

A static analysis can be either linear or nonlinear. All types of nonlinearities are allowed- large deformations, plasticity, creep, stress stiffening, contact (gap) elements, hyperelastic elements, etc. This chapter focuses on linear static analyses, with brief references to nonlinearities.

Static analysis for 20m base dome was done using STAAD Pro, the steel tube section used for analysis are ST TUB38382.6, ST TUB35353.2, ST TUB32323.2 and optimal sections are assigned for test load of 2kN and following results were obtained as tabulated in table II.

Table II. Maximum Compression and Tension in struts of dome in different profiles.

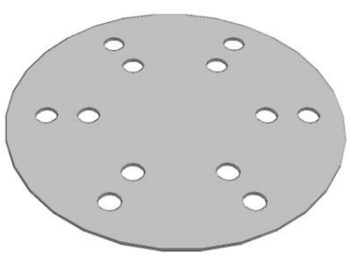
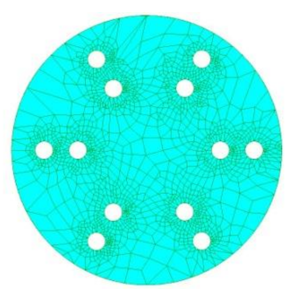
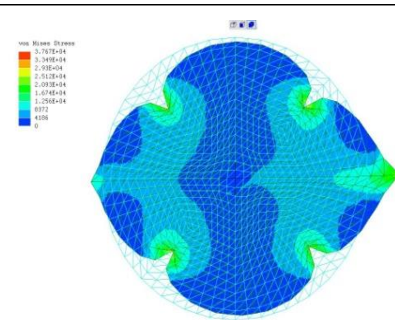
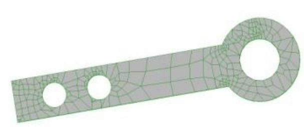
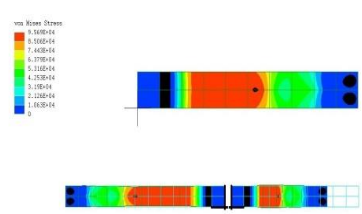
Profile type	**20-08**	**20-04**	**20-02**
Max compression (kN)	2.461	4.244	8.016
Max tension (kN)	1.116	2.041	4.053

By the analysis the percentage use of strength of strut was so less that the failure could happen only but failure of joints, thus the fracture analysis of different economical joints were studies.

IV. FRACTURE ANALYSIS

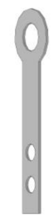
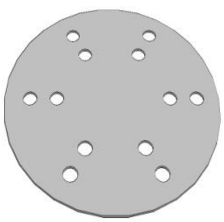
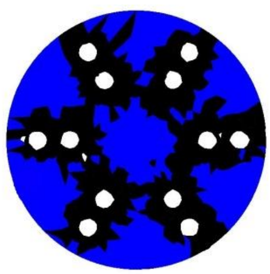
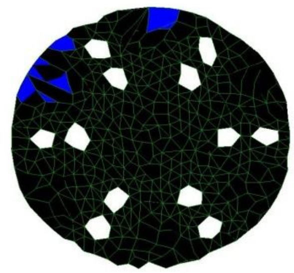
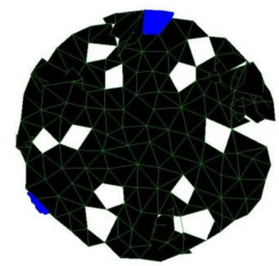
The types of joints connectors used for the analysis are disk, strip because they are economical and affordable. The efficiency of the plate is also calculated manually and stress is checked with finite element analysis. The following Table III shows the generated model, Finite Element Mesh model, and Spectrum of Stress Distribution of Disk and Plate used at joint of hexagonal arms of dome.

Table III. Model, Finite Element Mesh and Stress Distribution of connectors

	Generated Model	Finite Element Mesh	Spectrum of Stress Distribution
Disk for Hexagonal Joint			
Plate for Hexagonal Joint			

Fracture and failure of joint connectors

The maximum of 8kN Compression and 4kN tension load is applied for fracture analysis.

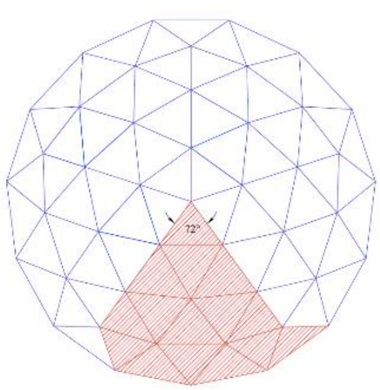
			
Model of a single arm	Fracture at load 2kN compression	Fracture at load 4kN compression	Fracture at load 8kN compression
			
Model	Fracture at load 1kN Tension and 2kN Compression	Fracture at load 2kN Tension and 4kN Compression	Fracture at load 4kN Tension and 8kN Compression

V. EXPERIMENTAL TESTING

A. Structure Construction

A down-scaled model of a dome is constructed with dimensions 1500 mm base dia and centre rise of 380 mm with overall scale of -13.33 and for 3V frequency. Steel tube of 19.05 mm x 19.05 mm cross section and thickness of 1mm is used. In total 120 struts with calculated strut lengths are assembled in order joined using circular disc drilled with a bolt hole of 5mm for a 4mm dia bolt.

Since this dome is radially symmetrical for 72°, dome is constructed as 5 sections and assembled to a single structure. $1/5^{th}$ of a dome looks like as shown in figure below.



There are 120 struts and are classified according to its length and their count is given below in Table IV.

Table IV. Number of struts in each length.

S. No	Length	Total numbers
1	210 mm	10
2	230 mm	10
3	240 mm	10
4	250 mm	10
5	260 mm	40
6	270 mm	25
7	300 mm	5
8	310 mm	10
Total	31050 mm	120 no’s

The struts are arranged accordingly and a layout as shown is created to get assembled into a $1/5^{th}$ panel of dome as shown in figure II.

The struts are joined using 100mm circular disk of thickness 1mm and have been drilled a bolt hole of 5mm that carry 4mm bolt.

Steel struts are joined according to the formulated disk that are classified according to the angles similarity. Classification of joint disks are given in Table V.

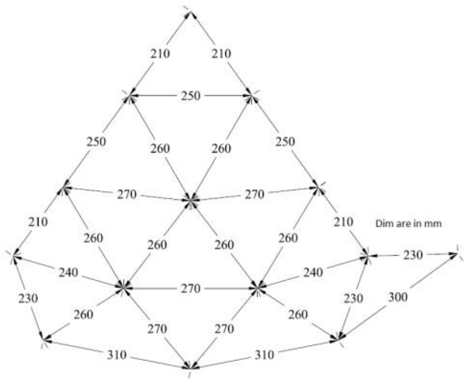


Figure II. 1/5th panel struts length and layout.

Table V. Joints Classification.

Name	Angle	No's
Joint A	72°; 72°; 72°; 72°; 72°.	1
Joint B	61°; 64°; 64°; 61°; 53°; 53°.	5
Joint C-01	60°; 60°; 60°; 60°; 60°; 60°.	5
Joint C-02	57°; 56°; 59°; 63°; 59°; 56°.	5
Joint D-01	70°; 67°; 81°; 67°; 70°.	5
Joint D-02	49°; 63°; 59°; 60°; 72°; 55°.	5
Joint D-03	59°; 63°; 49°; 55°; 72°; 60°.	5
Joint E-01	56°; 58°; 49°.	5
Joint E-02	49°; 58°; 56°.	5
Joint E-03	53°; 60°; 53°.	5

After assembling the struts according to the layout and fixing with the joint in adopted angles the completed structure looked like this as shown in figure IV.

Figure IV. Completed structure of Tessellation dome.

B. Joints Tensile Test

Tensile testing, is also known as tension testing, is a fundamental materials science test in which a sample is subjected to a controlled tension until failure. Circular plate is been subjected to tensile test in UTM- Universal Testing Machine. Test setup is shown in Figure III.

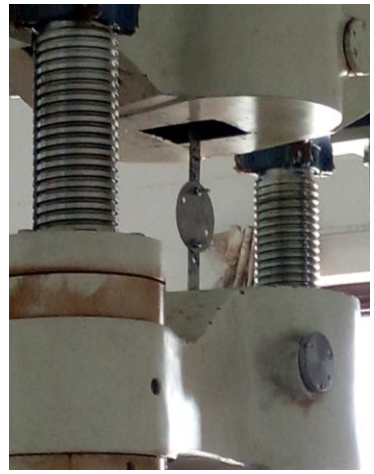


Figure III. Test Setup of Tensile test on joint.

Finding a method of clamping the discs that would accurately represent the conditions to which the joint experiences in situ was problematic.

A geodesic tensegrity network of the dome is three dimensional, whereas the Tension could only emulate one dimensional loading. Several clamping methods were considered for the disc that would preserve the uniaxial tension case.

It was decided to opt for a simple test rig using thumbscrews to attach the joint to predrilled (2.5mm thick) steel bars considerably stiffer than the test joint, as shown in Figure V.

Figure V. Test rig attached to the joint.

Three different size bolts as shown in Figure VI were adopted for testing i.e. 3mm, 6mm, 8mm. and test results were noted as shown in Table VI.

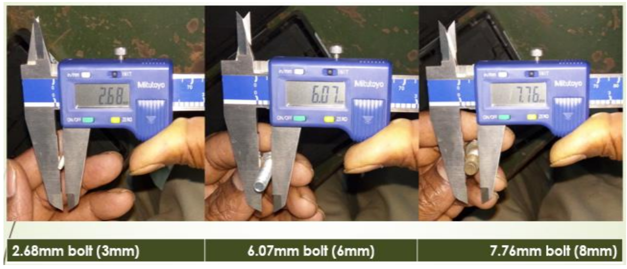


Figure VI. Dimension check for the bolts used.

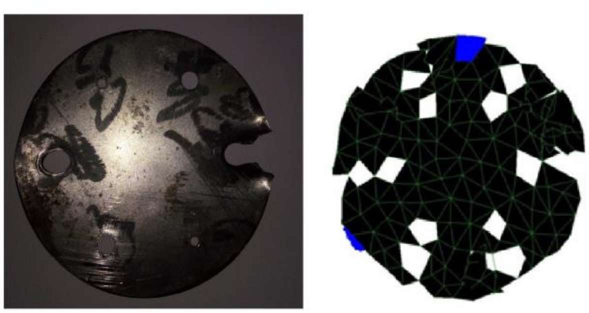
Ultimate breaking load of the specimen is observed and scaled model is adopted for the load very much less compared with peak load. So 4mm bolt is used in 6mm hole with washer to provide ductile joints

Test number	Failed specimen	Type of failure	Peak load
Test 1	Bolt	Shear failure	1.70 kN
Test 2	Plate	Tear failure	7.00 kN
Test 3	plate	Tear failure	6.20 kN

C. Comparison of Analytical and Experimental Specimen after failure.

The plate shows good resistance to axial compression and observed that the fatigue life of the plate reduces significantly in presence of cracks and bending loads along with axial tension in connecting members.

Of particular interest was that the pentagonal joints in each case failed at a lower force than the hexagonal equivalents. This is counter intuitive as that for a common load, the pentagonal bolt array will have a greater equivalent area to resist loading, so failure would be expected to occur hexagonal disc first.



Analytical and Experimental Specimen comparison is not satisfactory, this is because of nodes generated manually and deviations and slip in joints of the plate and bolt, is observed experimentally. Since the plate failed only after peak load of 7kN which is far for the scaled model, the plate of 1mm thickness and bolt of 4mm is adopted.

VI. VIBRATION ANALYSIS

Vibration is a mechanical phenomenon whereby oscillations occur about an equilibrium point. Vibration testing is accomplished by introducing a forcing function into a structure, usually with some type of shaker. VA can use the units of Displacement, Velocity and Acceleration displayed as a Time Waveform (TWF), but most commonly the spectrum is used, derived from a Fast Fourier Transform of the TWF. The vibration spectrum provides important frequency information that can pinpoint the faulty component.

Vibrational motion could be understood in terms of conservation of energy.

The test involved the use of FFT (Fast Fourier Transform) Analyzer and accelerometer device that is capable of recording triaxial variations and standard mean. The experimental test setup is shown in Figure VII to Figure X.

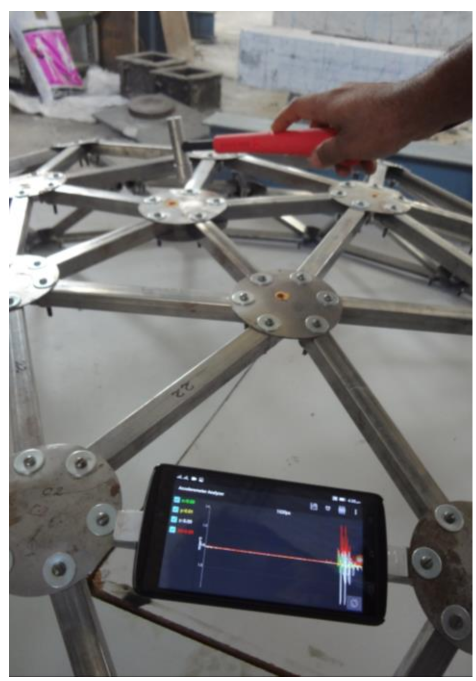


Figure VII. Test setup for Vibration Analysis

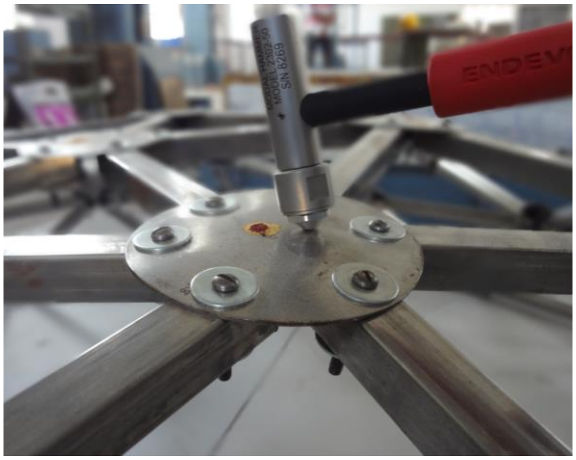


Figure VIII. Inducing vibration with Impulse Hammer

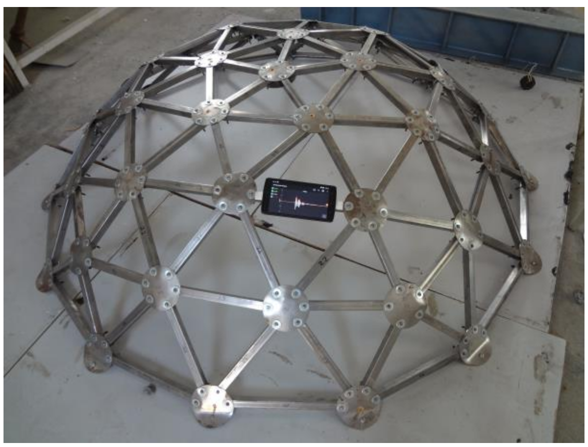


Figure IX. Accelerometer in horizontal strut.

Figure X. Accelerometer in vertical strut.

This force is applied 4 times at the same point in order to evaluate the average behavior. This procedure is repeated 4 times with the application of impulsive forces at the points. From these signals, a normalized signal is obtained as a function of excitation force.

The purpose of this operation is to locate regions of concentration of energy that are related to system resonance frequencies. Through a scan of the signals measured at joints it is possible to identify dynamic behaviors which are not identified in the computational results.

Through the analysis of the curves it is possible to identify energy concentration regions associated with the natural frequencies of the system. The goal was to identify energy concentration regions using vibration signals at the joints.

The curves generated from the signals during vibrational excitation is plotted for the two critical joints and are shown in the figure XI.

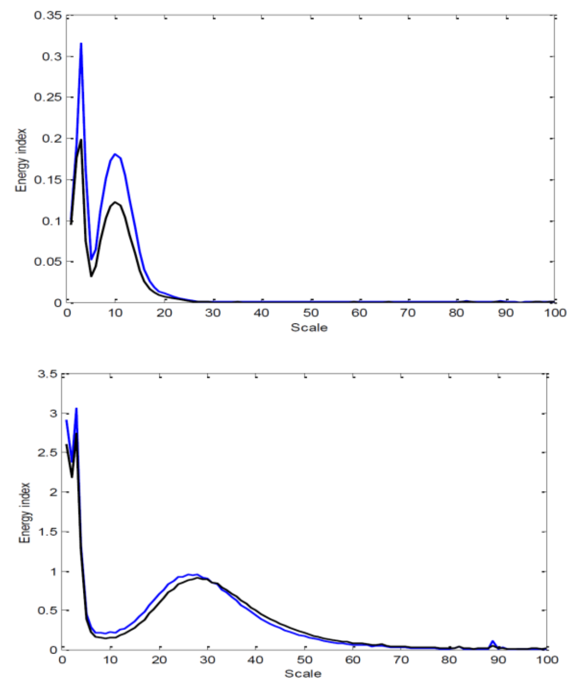


Figure XI. Lines of curves from generated signal during vibration.

It is evident from the figures that there are large differences in signal behavior in the joints. These energy concentration regions are related to different resonance frequencies of the system.

VII. CONCLUSION

- Over all observation of the results shows that the B/R ratio of 5, has the effective and economical dome design and affordable with steel struts.
- Aerodynamically dome with high B/R ratio has less effect to wind and vortex effect is much reduced.
- Failure of the dome is only by fracture at joints, thus suitable design of joint connectors, increase the effectiveness of dome.
- Plate show less fracture compared with disk but bolt failure is high with low load, when six plates get combined at single bolt, so disk joint connector is preferable and economical.
- Dynamic tests using force impulsive was performed.
- Several factors may have influenced this difference in numeric and experimental values of the natural frequencies.
- These factors may be related to the way of fixing elements (circular piece and screws that may have gaps); the type of element used that for fixing it was necessary to decrease the contact area; the properties of the material, the boundary conditions used in the numerical model (the elements of the ends are fixed on a circular structure that was not considered in the numerical model).

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