FEA And Experimental Analysis of Energy Absorption Characteristic of The Circular Column with Honeycomb Structure

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***Abstract*—This Energy absorbing elements are very important in many crucial engineering fields, such as aircraft, spacecraft, vehicle and ship. This study investigates the crushing (Post buckling) response and energy absorption characteristics of the circular aluminium column with and without honeycomb structure to reduce injury to the passengers and damage to the vehicle. Post-buckling phenomenon has been performing advantages in many applications. Buckling has greater impact on the structures of automobiles. It is necessary to study the post buckling response of the metal structures. CAD model of the circular aluminium column is prepared using CATIA V5. FEA Analysis is carried out on the FEA model using Abaqus/Explicit®. Validation of post buckling results will be done using the experimental testing results obtained using UTM. The result & conclusion will be drawn after making the comparison between the experimental and analysis result.**

***Keywords*— Thin-walled circular aluminum column; Abaqus/Explicit®; Energy absorption; Nonlinear; CATIA V5.)**

I. INTRODUCTION

Energy absorbing elements are very important in many crucial engineering fields, such as aircraft, spacecraft, vehicle and ship. Many elements are designed to absorb the impact kinetic energy employing the cellular materials or thin-walled tubes. To avoid injuries or protect delicate structures, the thin-wall tubes are stacked laterally as an energy absorbing system on the highway, which may enhance the crashworthiness of the vehicle body structure during lateral impact [1].

Metal thin-walled tubes are expected to absorb the maximum amount of impact energy by controlling the collapse mode in a series of folding and hinging during the plastic deformation process. Many studies have investigated the effects of various geometry shapes such as circular [1,2,3,6], square [3,5], straight tubes and tapered or graded tubes [4] on the energy absorption capability. The ways to improve the energy absorption performance of metal thin-walled tubes by changing sectional shapes is mostly saturated because of limitations of mechanical processing shaping methods. Composite tubes formed by combining metal thin-walled tubes with other components have sprung up and exhibit many favorable characteristics [2].

Combination of thin-walled tube and lightweight foam is anticipated to enhance the energy absorption of the structure since both the tube and foam material have high energy absorption capacities [1].

Crashworthiness of foam-filled columns is the focus of research for the last two decades due to the development of metallic foam materials. Mirfendereski et al. considered the experimental and numerical analysis of the crashworthiness characteristics of foam-filled straight, double-tapered, triple-tapered and frusta geometries for static and dynamic impact loads. They found that the initial peak load was de-creased as the number of oblique sides increased. Ahmad and Thambiratnam determined that a foam-filled conical column absorbs significantly more energy and have a higher mean crush load than an empty one. Goel compared the energy absorption capability of empty and foam-filled columns with different cross-sections under impact loading and determined that foam-filled bi-tubular and tri-tubular structures absorb more energy than mono-tubular foam-filled columns. The axial crushing tests of empty and partially foam-filled thin-walled circular and square columns were performed by Altin et al. [4]. They determined that foam-filled square columns displayed the highest crash performance. The common main observation of these studies was that the energy absorption capacity can be increased by using metallic foams [4].

To improve the crashworthiness performance of foam-filled structures, the effects of cross-sectional geometry and foam densities have been widely investigated. Langseth and Hopperstad reported that increasing the wall thickness and foam density increased the SEA values of the columns under axial loading conditions. Hanssen et al. investigated the crushing behaviour of circular and square columns filled with aluminum foam under static and dynamic loads. They developed theoretical formulations to predict the average force, the maximum force, and the effective crushing distance. Sun et al. compared the energy absorption capacity of functionally graded foam-filled column structures and the uniform foam-filled column structures. They found that the crashworthiness performance of functionally graded foam-filled column is better than that of the uniform foam-filled column. They also found that the energy absorption capacity was dependent on the foam density. Santosa and Wierzbicki studied the effect of low-density filler material on the axial crushing resistance of square columns under quasi-static loading condition [4]. However, foam-filled single and double square tubes have a strong tendency to undergo tearing of the tube corners, which is inefficient and difficult to control [3].

Different types of energy absorber systems have been proposed and efforts need to be devoted to more thorough understanding of the crashing behaviour and energy absorption characteristics of different structures. Metal honeycombs have long been recognized as an excellent lightweight structural material due to their strength and energy absorption properties [7]. It is necessary to perform a comprehensive comparative analysis on the crashworthiness of empty and an aluminum honeycomb filled thin-walled tubes/columns and to present a set of well-accepted criteria to appropriately evaluate the energy absorption capacity of the structures.

In the present study, FEA and experimental analysis of post-buckling response and energy absorption of the circular aluminium columns with and without honeycomb structure is carried out using Abaqus/Explicit® code and this is a comparative analysis between circular aluminium columns with and without honeycomb structure. The load-displacement characteristics and energy absorption ability of these structures are investigated and generally compared.

II. LITERATURE REVIEW

A. Literature Survey

Zhifang Liu, et al [1] "Experimental and theoretical investigations on lateral crushing of aluminum foam-filled circular tubes"2017.

Mechanical response and energy absorption of aluminum foam-filled and empty circular tubes with different geometries were investigated experimentally and theoretically. All specimens including foam-filled circular and empty circular tubes were compressed laterally by two rigid plates. Effects of the geometrical characteristics of specimens and densities of aluminum foam on deformation and energy absorption of the foam-filled and empty circular tubes were considered. Experimental results show that the presence of aluminum foam filled in the circular tubes changes the deformation modes and increases the energy absorption of the foam-filled circular tubes. An analytical model for the plastic deformation of the foam-filled circular tubes under the lateral loading was proposed. The relations of lateral loading and energy absorption of the foam-filled circular tubes were obtained. Comparisons between the analytical predictions and the experimental results were performed and good agreement was achieved.

Fei Wu, et al [2] "Quasi-static axial crush response and energy absorption of layered composite structure formed from novel crochet-sintered mesh tube and thin walled tube"2018.

Their work investigates the quasi-static crush response and energy absorption of the layered composite circular tubes formed by matching thin-walled tubes with novel crochet-sintered mesh tubes (CSMTs). The matching effect existed between the CSMT and the thin-walled tube have been observed. The CSMTs are suitable for application as energy absorption components to improve the load-bearing capacity and energy absorption of thin-walled tubes. The load-carrying capacity, energy absorption, effective stroke ratio and crushing force efficiency of layered composite tubes all increases, compared to those of metal thin-walled tube. The increment scale of energy absorption can be reach 106%. The load-carrying capacity, energy absorption, crushing force efficiency and specific energy absorption of the three-layered structure are higher than those of the two-layered structures. The initial impact effect of the three-layered tubes is weaker than that of the two-layered tubes. These show that the former has better structure crashworthiness than the latter. The layered composite tubes show great potential for application as energy absorbers.

Zhibin Li, et al [3] "Comparative analysis of crashworthiness of empty and foam-filled thin walled tubes"2017.

Quasi-static axial compression tests were conducted on two types of empty aluminum alloy tubes (circular and square) and five types of aluminum ex-situ foam filled tube structures (foam-filled single circular and square tubes, foam-filled double circular and square tubes, and corner-foam-filled square tube). The load-deformation characteristics, deformation mode and energy absorption ability of these structures were investigated. Several parameters related to their crashworthiness were compared, including the specific energy absorption, the energy-absorbing effectiveness factor, etc. The influence of physical dimension on the crashworthiness of these structures was explored. Dimensions of the inner tube were found to have significant influence on the structural crashworthiness of foam-filled double tubes. The averaged crush force, specific energy absorption, energy absorption per stroke and energy-absorbing effectiveness factor of thin-walled circular structures are higher than those of thin-walled square structures, respectively. Foam-filled single and double circular tube structures are recommendedascrashworthystructuresduetotheirhighcrushforceefficiencyandenergy-absorbingefficiency.

M. Altin, et al [4] "Foam filling options for crashworthiness optimization of thin-walled multi-tubular circular columns"2018.

There is an increasing trend in using aluminum foam-filled columns in crash management systems due to their light weight in automotive industry. The main goal of this study is to optimize the crashworthiness of aluminum foam-filled thin-walled multi-tubular circular columns under quasi-static loading. The existing studies in the literature considered only lateral foam filling (the foam lateral dimension is variable, and the foam height is equal to the column height). In the present study, we considered both lateral and axial foam filling and compared the performances of these two options. In optimization, the column thicknesses, taper angle, foam density, and foam height/diameter are considered as design variables. The quasi-static responses of the columns are determined through explicit dynamic Finite Element Analysis (FEA) using LS-DYNA software and validated with quasi-static tests conducted in our facilities. Response surface-based crashworthiness optimization of the columns for maximum Crush Force Efficiency (CFE)and maximum Specific Energy Absorption (SEA) is performed. It is found that lateral foam filling is superior to axial foam filling in terms of both CFE and SEA maximization. The maximum CFE obtained through lateral foam filling is 19% larger than the maximum CFE obtained through axial foam filling. Similarly, the maximum SEA obtained through lateral foam filling is 6% larger than the maximum SEA obtained through axial foam filling. For both CFE and SEA maximization, the columns should be tri-tubular type and have a large thickness and a taper angle. To attain the maximum CFE, foam should be designed with large density and medium foam diameter. However, foam plays an adverse role in maximization of SEA because of its weight. The increase in energy absorption obtained by using foam does not compensate the additional weight introduced by the foam.

Xuehui Yu, et al [5] "Crushing and energy absorption of density-graded foam-filled square columns: experimental and theoretical investigations"2018.

The static axial crushing and energy absorption of density-graded aluminum foam-filled square metal columns are experimentally and theoretically investigated. Typical deformation modes are observed in experiments, such as symmetric, asymmetric, extension and rupture modes. Theoretical analysis is carried out and the predictions are in good agreement with the experimental results. The effects of gradient pattern, density difference, average density of foam, and wall thickness on the crushing of foam-filled columns are discussed. It is shown that the density-graded aluminum foam-filled square metal column is a novel topological structure with higher energy absorption, higher load carrying capacity and much higher crushing force efficiency.

A. Praveen Kumar, et al [6] "Crush performance analysis of combined geometry tubes under axial compressive loading"2017.

Their research deals with crushing and energy absorption characteristics of combined geometry tubes composed of a cylindrical segment with end plain cap, Hemispherical cap and shallow spherical cap. The aluminium geometrical tubes were of three different thicknesses (1.65 mm. 2.05 mm 6 2.67 mm) and their large deformation was obtained by crushing between two flat plates under axial compressive loading. The performance of combined geometrical tubes was compared with non-capped tubes. It was found that maximum initial peak load can be controlled, and convenient crush protection systems can be obtained using combined geometrical tubes. furthermore. to gain more detailed insight into the crushing process, a three-dimensional non-linear finite element analysis was carried out using Abaqus/Explicit® code. The numerically predicted crushing force and fold formation were found to be in good agreement with the experimental results. The overall results revealed that combined geometry tubes can stabilize the deformation behaviour and thus the proposed method could be a good alternative as a controllable energy absorption element.

Tomasz Wierzbicki [7] "Crushing analysis of metal honeycombs"1983.

He showed a method for determining the crushing strength of hexagonal cell structures subjected to axial loading is given. The method is based on energy considerations in conjunction with a minimum principle in plasticity. The problem is shown to be equivalents to the analysis of a system of collapsing angle elements undergoing bending and extensional deformations. The theory is first developed for an arbitrary angle between panels and then is specified for the 120 ° angle, appropriate for the hexagonal cell structures. Simple formulas are derived relating the crushing force and the wavelength of the local folding wave to the wall thickness and diameter of the cell. The theoretical solution has been compared with experimental results published in the literature and an excellent correlation has been obtained for the wide range of geometrical parameters involved. This solution replaces the less accurate earlier analysis of the same problem due to McFarland. The purpose of this study was to provide a simple and rational means by which hexagonal cell structures can be designed for use as energy absorbers in impact or impulsive loading situations.

B. Closure of the Review

Literature review shows following research areas to be addressed for improving crashing behaviour and energy absorption characteristics.

• Square tubes have a strong tendency to undergo tearing of the tube corners, which is inefficient and difficult to control. Therefore, for practical purposes, the circular tubes are strongly recommended [3].

• It is suggested to further study on the design optimization of the tube filling structures for more efficient and reliable energy absorbing components [3].

• Significant energy gets absorbed by plastic deformation during the progressive fold formation process during axial loading as compared to lateral loading.

C. Problem Statement

To investigate the crushing response and energy absorption characteristics of the circular aluminium column with and without honeycomb structure to reduce injury to the passengers and damage to the vehicle.

D. Objectives

1. A non-linear finite element analysis of aluminium Specimen (With and Without Honeycomb)
2. Experimental study of aluminium specimen (With and Without Honeycomb) by using UTM
3. Find buckling loads Vs displacement plots.
4. Find energy absorption Vs deformation plots.
5. To validate the FEA and Experimental results.

E. Methodology

- CAD model generation (CATIA-V5)
- Finite Element Analysis (ABAQUS/Explicit®)
- Manufacturing Stage
- Fabrication of Assembly
- Compression Testing (UTM)

Using the knowledge from literature review, we know how the 3D CAD model is to be prepared. The conditions required for applying various constraints will be decided based on literature review.

- 3D CAD Model Generation
  - Getting input data on dimensions aluminium column
  - Creating 3D model in CATIA-V5
- Determination of boundary conditions
  - Determination of different loads and boundary condition acting on the component by studying various ref papers, and different resources available
- Testing and Analysis
  - Using the best suitable material for the application referring different literatures
  - Meshing the CAD model and applying the boundary conditions
  - Solve for the solution of meshed model using ABAQUS/Explicit®
- Fabrication, Experimental validation and Result
  - Fabrication of specimens
  - Suitable experimentation (UTM)
  - Validation of result by comparing with software results

III. DESIGN

A. CAD

Computer-aided design (CAD) is the use of computer systems (or workstations) to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations. The term CADD (for Computer Aided Design and Drafting) is also used.

Its use in designing electronic systems is known as electronic design automation (EDA). In mechanical design it is known as mechanical design automation (MDA) or computer-aided drafting (CAD), which includes the process of creating a technical drawing with the use of computer software.

CAD software for mechanical design uses either vector-based graphics to depict the objects of traditional drafting or may also produce raster graphics showing the overall appearance of designed objects. However, it involves more than just shapes. As in the manual drafting of technical and engineering drawings, the output of CAD must convey information, such as materials, processes, dimensions, and tolerances, according to application-specific conventions.

CAD may be used to design curves and figures in two-dimensional (2D) space; or curves, surfaces, and solids in three-dimensional (3D) space.

B. CAD Moldel Dimensions

The dimensions for the parts were suitably taken (Ø100 x 450 x 2 Thickness) mm [3] which were later used in modelling. The extruded profiles were created on the top plan. The CAD model is created in the CATIA software. The accuracy of any simulation depends on how accurately the modelling work has been carried out. The Modelling is done by CATIA modelling software using the following drawing.

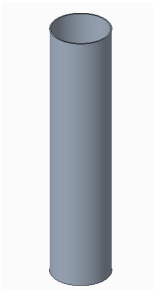


Fig.1 Model of Circular Column without Honeycomb Structure

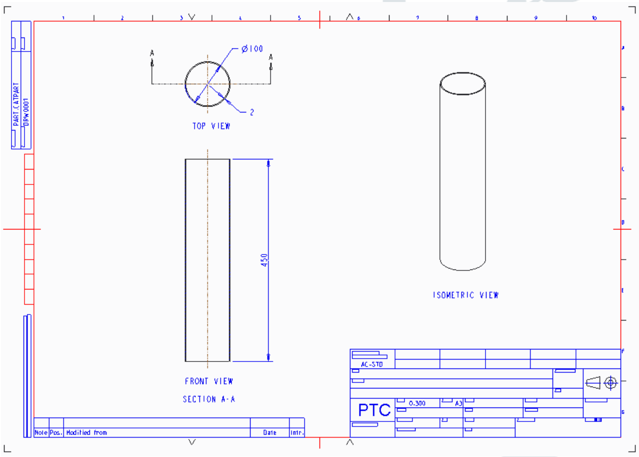


Fig.2 Drawing of Circular Column without Honeycomb Structure

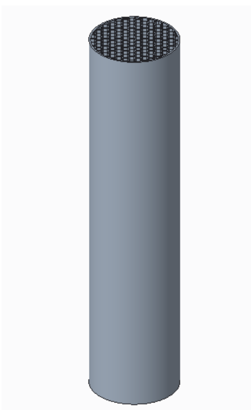


Fig.3 Model of Circular Column with Honeycomb Structure

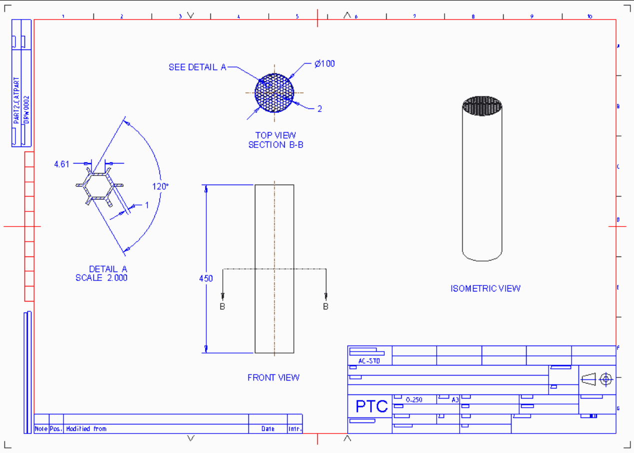


Fig.4 Drawing of Circular Column with Honeycomb Structure

IV. Analysis

The finite element method (FEM), is a numerical method for solving problems of engineering and mathematical physics. Typical problem areas of interest include structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential. The analytical solution of these problems generally requires the solution to boundary value problems for partial differential equations. The finite element method formulation of the problem results in a system of algebraic equations. The method yields approximate values of the unknowns at discrete number of points over the domain. [1] To solve the problem, it subdivides a large problem into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function.

Studying or analyzing a phenomenon with FEM is often referred to as finite element analysis (FEA).

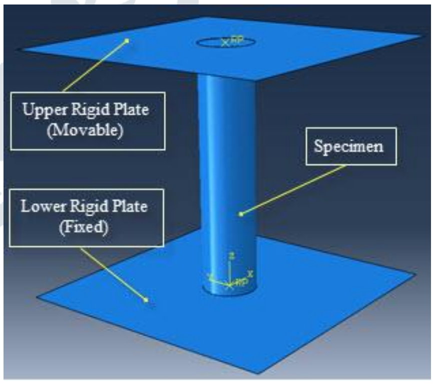


Fig.5 FEA Model Simulated Using Fixed and Moving Plate

A. Pre-Processing

a. Meshing

ABAQUS/Explicit® meshing is a general-purpose, intelligent, automated high-performance product. It produces the most appropriate mesh for accurate, efficient Multiphysics solutions. A mesh well suited for a specific analysis can be generated with a single mouse click for all parts in a model. Full controls over the options used to generate the mesh are available for the expert user who wants to fine-tune it. The power of parallel processing is automatically used to reduce the time you must wait for mesh generation.

Creating the most appropriate mesh is the foundation of engineering simulations. ABAQUS/Explicit® meshing is aware of the type of solutions that will be used in the project and has the appropriate criteria to create the best suited mesh. Meshing is automatically integrated with each solver within the ABAQUS/Explicit® environment. For a quick analysis or for the new and infrequent user, a usable mesh can be created with one click of the mouse. Meshing chooses the most appropriate options based on the analysis type and the geometry of the model. Especially convenient is the ability of meshing to automatically take advantage of the available cores in the computer to use parallel processing and thus significantly reduce the time to create a mesh. Parallel meshing is available without any additional cost or license requirements.

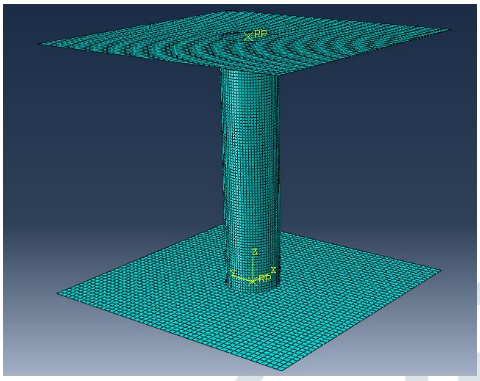
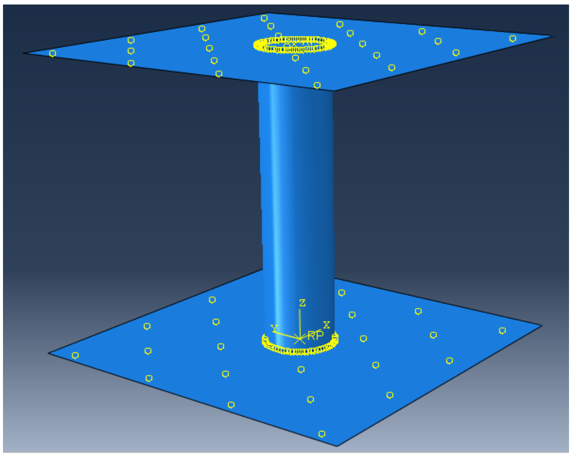


Fig.6 Meshing of Model

b. Loading and Boundary condition

A boundary condition for the model is the setting of a known value for a displacement or an associated load. For a node you can set either the load or the displacement but not both.

The main types of loading available in FEA include force, pressure and temperature. These can be applied to points, surfaces, edges, nodes and elements or remotely offset from a feature. The way that the model is constrained can significantly affect the results and requires special consideration. Over or under constrained models can give stress that is so inaccurate that it is worthless to the engineer. In an ideal world we could have massive assemblies of components all connected to each other with contact elements, but this is beyond the budget and resource of most people. We can however, use the computing hardware we have available to its full potential and this means understanding how to apply realistic boundary conditions.



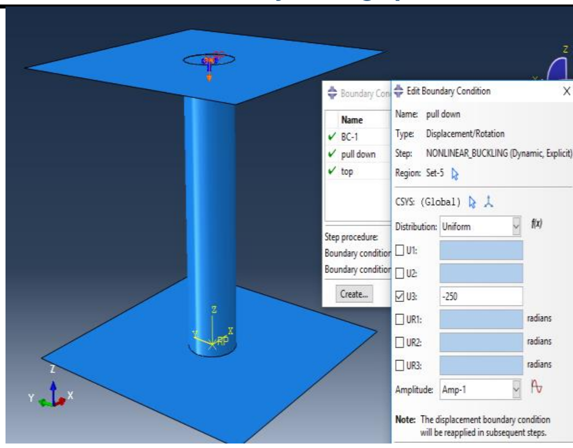


Fig.7 Boundary Condition

c. Material Assignment

Engineering data helps to define the material properties in the ABAQUS/Explicit®. Once we input the properties, it can be assigned to each of the part. The material used in this study is Aluminium Alloy AA6063-T6 [3]. The mechanical properties for this alloy is as follows;

Sr. No.	Material	Density (ρ) (g/cm^3)	Young's Modulus (E) (GPa)	Poisson's Ratio (υ)	Tensile Strength (σ_t) (MPa)
1	Aluminum Alloy (AA6063-T6)	2.69	68.3	0.3	145-186

Table.1 Material Properties

B. Post-Processing

1. Total Deformation

The total deformation & directional deformation are general terms in finite element methods irrespective of software being used. Directional deformation can be put as the displacement of the system in an axis or user defined direction.

Total deformation is the vector sum all directional displacements of the systems.

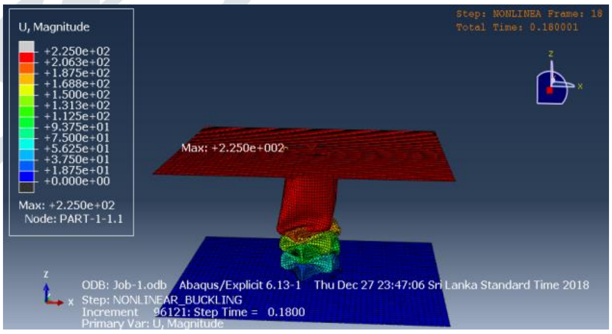


Fig.8 Total Deformation of Model

2. Equivalent Stress

Equivalent stress σe is related to the principal stresses by the equation:

$$\sigma_e=\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2}$$

Equivalent stress (also called *Von Mises Stress*) is often used in design work because it allows any arbitrary three-dimensional stress state to be represented as a single positive stress value. Equivalent stress is part of the maximum equivalent stress failure theory used to predict yielding in a ductile material.

The Von Mises or equivalent strain εe is computed as:

$$\varepsilon_e=\frac{1}{1+\nu'}\left(\frac{1}{2}\left[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2\right]\right)^{\frac{1}{2}}$$

Where:

ν' = Effective Poisson's ratio

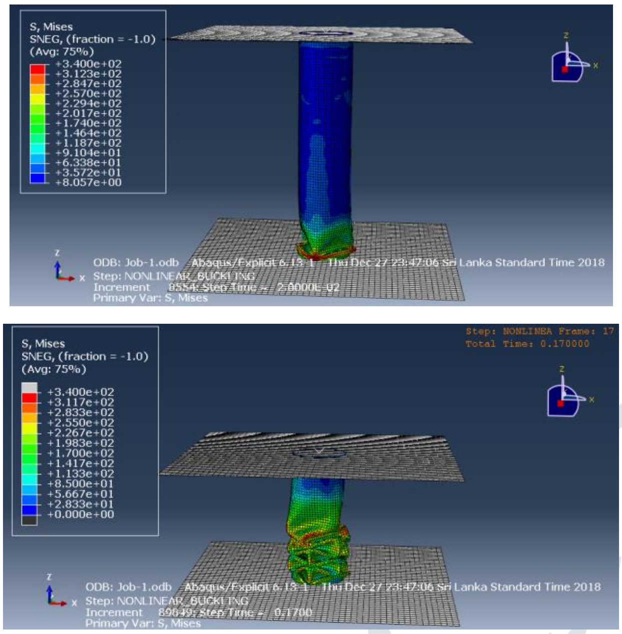


Fig.9 Equivalent stress on Model

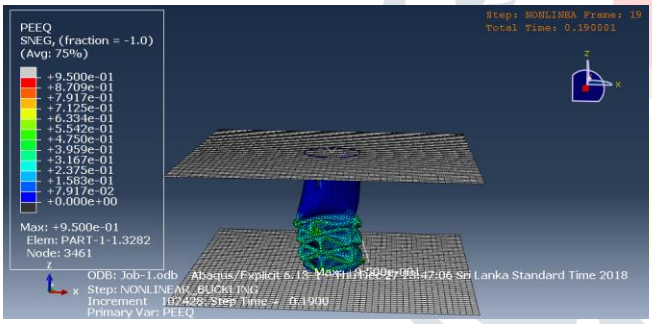


Fig.10 Plastic strain 95 %

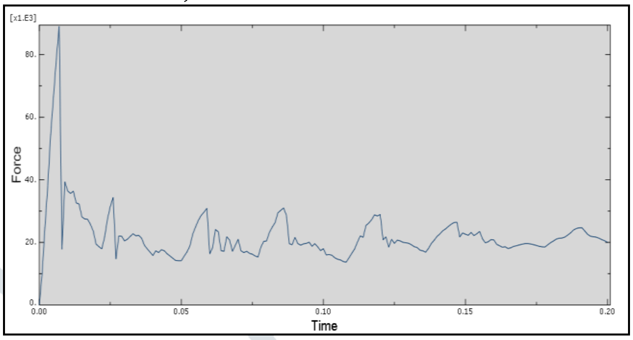
3. *Results and Discussion*

a. *Results for Circular Aluminium Column:*

Results obtained from the non-linear analysis of circular aluminium columns are as follows;

- The Reaction Force = 85 KN.
- The maximum Stress = 340 MPa.
- Plastic Strain = 95%
- Total Deformation = 250mm

The graph is plotted against Reaction Force Vs Time which is as follows;



b. *Results for Circular Aluminium Columns with Honeycomb:*

Analysis for circular aluminium column with honeycomb structure is under process.

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