International Journal of Engineering & Technology, 8 (1.7) (2019) 268-273

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



Buckling Analysis of Three Circular Tubes

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Abstract

Progressive collapse is a phenomenon in which a structure collapse continuously initiated by a local damage due to loss of one or a few load-carrying elements or disproportionately relative large region of it. Due to the fact that space truss structures are highly statically indeterminate structural system, where the failure of just only one critical member can result in the collapse of the entire structure, it is important to understand the buckling induced collapse mechanism before carrying out the design of the structure. This paper presents a study of three circular tubes as one the possible methods to improve the ductility and enhance the buckling capacity of steel tube truss members. This present study will involve numerical analysis using finite element software ABAQUS and results from the experiment data is compared. A full-scale assembly of a single truss steel member with application of three circular tubes is proposed and analyzed using finite element method for application in the critical members in the space truss system. In this paper improvement of local buckling resistance in the three circular tubes was stipulated which also highlights modelling techniques used for validation.

Keywords: *Steel connection; collapse analysis; shell; Riks method; buckling load.*

1. Introduction

Progressive collapse of space truss have received much attention in recent years due to its usage in public facilities such as swimming pool covers, shopping malls, stadium pavilions, sloped glazing, large-span warehouses, that their collapse-resisting capacities are directly related to public safety and social security. It is generally accepted that space truss structures are prevalent choice when designing a large span area without internal columns. A space truss consists of members joined together at the ends to form a stable three dimensional structures that can be built from the basic tetrahedral, formed by connecting six members with four joints. Whereas, a space frame refers to a spatial structure whose members are connected rigidly to each other so that they transfer moment and shear in addition to axial forces, contrariwise with space trusses that are pin-jointed and as a result, their members are in tension or compression and do not transfer moment or shear. Due to the fact that space truss structures is highly statically indeterminate structural system, where the failure of just only one member can result in the collapse of the entire structure, it is important to understand the buckling induced collapse mechanism before carrying out the design of the structure. Gerasimidis et al. [1] applied the column removal strategy of an exterior column which resulted in failure of two of its adjacent columns caused by the interaction of flexural-torsional buckling. In their progressive collapse analysis, even though prevalence of any sort of plasticization wasn't evident the load was found to drop at a lower load than the design load accompanied by the failure of another set of two adjacent columns which eventually caused the collapses of the entire structures. Therefore, this proves that the strength of the material is not regarded as a sole indicator of the buckling failures modes observed but may be due to strength of the material, but instead are characteristic of the component dimensions & modulus of elasticity. As a result, materials with a high strength are also susceptible to buckle simply as low strength ones. One method of increasing the ductility and capacity of tubular elements is filling them with another material such as steel foam [2]. Therefore, three layer circular tubes will be presented in this present study as one the possible method to improve the local buckling resistance of steel tube. This present study will involve numerical analysis using finite element software; ABAQUS. The analysis involved determination of the first buckling mode and critical forces for specimen 1 (inner tube only) and specimen 2 (duplicate the three circular tubes used in the experiment. The Finite Element models will be used to examine accurately overall buckling behavior of the three layer circular tubes. A full scale steel member with application of three layer circular tubes is proposed and analyses by using finite element method for application in the critical member in space truss structure. Analysis is conducted to enhanced structural response, and provides precise results and also provides a practical tool for the evaluation of buckling analysis for the member. In the chapter four, the small scale three layer circular tubes is extended to a full scale three layer circular tube for real member length for truss application.

Adhering to old customs of restoring or strengthening metal structures made of steel is generally to cut, replace and patched it with external metal plates so that the building functions as it is intended. Typically, these plates are bulky, heavy and the challenge is to match the corrosion resistance of the material and overcome fatigue problems. There seemed to be multiple issues related to steel and a need to look for practical alternatives is necessary. Reinforced Polymer (FRP) appears to have the tenacity to achieve excessive strength to weight ratios, and complies well to corrosion and environmental degradation. It is very flexible and can simply be formed into all types of shapes, and is easy to deal during construction. FRP has been extensively used in strengthening particularly concrete structures, and have been developed and distributed by many researchers. Tremblay et al. [3] discovered that the inter story acceleration of the self-

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centering energy dissipation (SCED) frame is much larger than the inter story acceleration of a buckling restrained braces (BRB) frame due to the large difference between the pre activation stiffness and the post activation stiffness of the SCED system, which increases the degree of damage of a non-structural component and precision equipment. Rubber exhibits incompressibility, when rubber is in compression, a large deformation will occur parallel and perpendicular to the force direction. A study done by Parke [4] on the behaviour of space trusses incorporating novel compression member known as soft member. This study considered ways of improving the load displacement response on square on square double layer space trusses. The result obtained from the compression test for the whole proposed soft member show that the novel soft member that has been constructed capable of exhibiting a steady load plateau followed by a reserve of strength before failure.

Experimental result done by Zhao et al. [5] inclusive with the numerical simulation have shown that the truss system with directly welded joints (specimen truss-WJ) adapted quickly following a loss of a member. Factors affecting the load distribution capacity also showed that the truss system mentioned has the ability to resist load through catenary action developed within the bottom chord members. Whereas truss with rigid joints (truss-RJ) failed due to progressive buckling and damaged three of its diagonal members severely. Wilson et al. [6] in their study revealed that longitudinal fillet weld in shear was considerably higher than the unit fatigue strength in tension of the plates connected. The values in the unit fatigue strength of the plugs in the unit fatigue strength of the plugs decrease with an increase in their diameter.

Taking into account fracture behavior and metal separation in steel is essential in collapse analysis studies. Besides experiments, finite element method is an important research method. Analysis of steel connections under compression is focused. An important problem of structural member under compression is buckling. Some will buckle under plastic state, some even under elastic state. Buckle may take place locally, as a whole, or both. There are two categories of finite element buckling or collapse analyses, one is eigenvalue analysis which includes further two, linear buckling analysis and nonlinear buckling analysis according to whether nonlinear factor is considered; the other is modified Riks method, whose solution is viewed as the discovery of a single equilibrium path in a space defined by the nodal variables and the loading parameter, and the existing load value may increase and then decrease when applying the method. Modified Riks method can give effective solution to high nonlinear buckling and collapse problem. Study have been done by Xie et al. [7] on dual tube self centering buckling restrained brace (SC-BRB) improved by adding rubber between the plates and tubes. To simulate the cycle characteristic of a BRB in an experiment, the combined hardening model, which includes kinematic and isotropic hardening, was utilized in ABAQUS. In the finite-element model of the self-centering system, the inner and outer tubes, end plates, and connection plates are discretized with the C3D8R element, and the pretension tendons are discretized with the truss element. The welding between the connection plates and inner and outer tubes is simulated via a tie constraint. The anchor connection between the pretension tendons and end plates is simulated via a coupled constraint. The coefficient of linear expansion is added to the material property of the BFRP. Another research done by Jamaluddin et al. [8] to represent numerical modelling elliptical concrete- filled steel tube columns and the finite element result show that refined technique of modelling the structure should be considered as the Finite element analysis under predicted the actual strength of concrete filled tube column and overestimate the strengths of the hollow column.

Table 1: Material properties of member types

Tension Material Behaviour	Member Type					
	T1		T2		T3	
Elastic Range	Young's Modulus (kN/mm^2)	Poisson's Ratio	Young's Modulus (kN/mm^2)	Poisson's Ratio	Young's Modulus (kN/mm^2)	Poisson's Ratio
	200.1	0.3	200.1	0.3	200.1	0.3
Density	7.85 e-5		7.85e-5		7.85e-5	

2. Preliminary study of a three circular tube using the finite element analysis method

2.1. Finite element modelling approach ABAQUS version 6.14

2.1.1. Formation of the numerical model

The model of a three layer circular tubes should reflect as accurately as possible the actual novel soft member conducted in the experiment. The welding between the connection plates and inner and outer tubes is simulated via a tie constraint. In this study, the radius per thickness is less than 10, the shell elements may give a more accurate or fair prediction of the buckling moment under global uniform bending for cylindrical tubes.

2.1.2. Load and boundary condition

For the specimen 1 analysis the top support provides constraint in horizontal (x) and (Z) axis where Uz=0 and Ux=0, and free rotation about the three principal axes. Displacement boundary condition technique used for static general and linear buckling analysis applied at node 31 for Uy= -1 with amplitude increment 1mm every 5 second.

2.1.3. Material properties

Material nonlinear tension behaviour is incorporated so that plasticity effects are captured. The material properties assigned to each member type are displayed in Table 1 and shown in Figure 3.6. These values are taken from the material tensile test done by Yazmin et al. [8].

Table 2: Boundary condition for inner tube only

Node Number	Translation			Rotation		
	ux	uy	uz	θx	θy	θz
1	Restrained	Restrained	Restrained	Restrained	Restrained	Restrained
31	Restrained	Restrained	free	free	free	free

- The y-axis is the vertical axis.

- The z and x axes are in the horizontal plane.

2.1.4. Assembly

In the Assembly module, the parts of the model were combined together. Each part was set as independent. Independent in ABAQUS means all parts in the model must be meshed as a whole model together. For the complex model, each part of the model can be meshed by its own and it was set up as "dependent". In this analysis, the parts were set up as "independent".

2.1.5. Step

Step is method of analysis used to run the model. Several methods will be used to obtain accurate result. Static, general method is applied for the first method and continue with linear buckling analysis.

Table 3: Boundary condition for three layer circular tube

Node Set Number	Translation			Rotation		
	ux	uy	uz	**θx**	**θy**	θz
33	Restrained	Restrained	Restrained	Restrained	Restrained	Restrained
32	Restrained	Restrained	free	free	free	free

- The y-axis is the vertical axis.
- The z and x axes are in the horizontal plane.

2.1.6. Interaction

For this study, proper modelling of contact interaction between the inner core, middle tube and outer tube was studied to simulate the fillet weld connection. In this research, three types of interaction method have been introduced and the effectiveness of these interactions was studied. The first interaction by using surface to surface contact pairs are established between the inner core and middle tube and between the middle tube and the outer members as well. The normal behaviour of interaction was modelled using hard contact behaviour, allowing for separation of the interface in tension and no penetration in compression.

2.2. Nonlinear analysis

In order to trace the collapse behavior of the three circular tubes, a numerical post buckling analysis using Riks method is adopted which is capable of dealing with unstable, geometrically nonlinear collapse behavior of a structure. The Rikds Method needs to be considered due to the geometrically nonlinear static problems sometimes involve buckling or collapse behavior in the structure, where the load-displacement response shows negative stiffness and the structure must release strain energy to remain in equilibrium. Prior to submitting the buckling analysis job (Subspace solver was used-smaller run times when only a few modes are requested), the node coordinates for the different mode shapes must be written as output. This output will be consequently introduced as imperfections for the Riks analysis so as to achieve a smoother transition to the post buckling region and surpass the bifurcation problem.

3. Materials and Methodology

Comparison with inner tube compression result by Yazmin et al [8]. Based on the graph obtain from the nonlinear static and general analysis, the maximum displacement for inner tube is 25.00 mm with maximum load applied equal to 258.80 kN. For linear buckling analysis, Eigen value for this type of structure is 0.50163. In nonlinear buckling analysis, it can be observed that the specimen maximum displacement is 29.27 mm before it ruptured. However, in the experimental result, the maximum displacement of specimen 1 is 16mm which is 50% less than the nonlinear result. This is because, when the test conducted, it was forced to be stop and did not continue until it fails due to safety factor and to prevent machine from damaged. If the load applied on the specimen be able to continue, the displacement might be larger before it fails.
Based on Figure 2, it can be observed that the specimen could sustain vertical load of 513.887 kN displacement at 25 mm. Maximum load and displacement can be obtain due to convergence error.
Based on graph in Figure 3, 75.2% of the result obtains from the nonlinear buckling analysis is approximately matches with the experimental result compared with graph obtains from nonlinear static general analysis. Nonlinear buckling or Riks method use an arc length method to determine the response of the loaded structure and the nonlinear static and general analysis, the deflections are slightly small compared with nonlinear buckling as a result of resulting force effect is not included in the differential stiffness. From the result of nonlinear analysis of inner tube only and three layer circular tube, it can be observed that the three layer circular tube could sustain the highest maximum load which about 500 kN to 600 kN and the strength increase by 50% compared to inner tube which could resist load below than 300 kN.

3.1. Design of a full length steel tube with and without three layer circular tube

3.1.1. Comparison for linear static and general analysis of full length steel member with and without three layer circular tubes

Based on the result obtain from static and general analysis of steel member without three layer circular tube as shown in Figure 4, the maximum load can be applied is 151 kN and the maximum displacement was 29mm. Whereas, steel member with three layer circular tubes could sustain maximum load of 384.409 kN and the maximum displacement was 27.6 mm. From the result of linear analysis of full length member without three layer circular tube and full length member steel with application of three layer circular tubes, it can be observed that the steel member with three layer circular tubes could sustain 60.8% more load compared with steel member only.

3.1.2. Result for nonlinear static and general analysis of full length steel member with three layer circular tubes

Based on the Figure 5 for nonlinear static and general analysis, it can be observed that the specimen could sustain load of 436.99 kN at displacement of 25 mm.

3.1.3. Result for linear buckling analysis of full length three layer circular tube and inner tube only

Eigenvalue obtain from linear analysis of full length three layer circular tubes is 0.16587 while for inner tube only 0.11495. Eigenvalue represent the buckling load factors; the higher the eigenvalue, the higher load can be applied before the member buckle. Therefore, member applied with three layer circular tube will be chosen for nonlinear analysis.

3.1.4. Comparison result for nonlinear buckling analysis of full length steel member with three layer circular tube

Based on graph in the Figure 8, the result of load and displacement obtains from the nonlinear buckling analysis is slightly different compared with nonlinear static and general analysis. Based on the Figure 5, it can be observed that the specimen maximum displacement is 27.826 mm and maximum load applied is 496.66kN which is 9.2% and 10.66% higher compared with nonlinear static and general analysis. This different percentage in the load displacement graph for nonlinear static general analysis due to the time step stop before the large converged increment occurred.

4. Conclusions

From this study, the results provide compelling evidence for long-term involvement with three layer circular tube and suggest that this approach appears to be effective to improve local buckling resistance of steel tube. Based on the nonlinear buckling analysis result for steel member with three layer circular tube and steel member without three layer circular tube, it can be concluded that, shell element are the most effective choice to study the deformation especially when thickness per length is small compared with beam element. To validate the numerical model using pre-existing models conducted by Yazmin et al. [8], a real connection need to be simulated in finite element software. Due to limitation of the software, tie connection is chosen as the best choice to represent the fillet weld. But, this connection does affect the buckling mode of the three layer circular tube. However, the results obtain from the nonlinear analysis of three layers circular tube can be accepted as it is 75.2% similar to the experiment data. For the application of three layer circular tube to full length steel member, the result obtain show that tube with three layer circular tube can sustain 60.8% more load compared with steel tube without three layer circular tube. Thus, application of 250 mm length three layer circular tube in the full length member helps to increase strength of the member. As a conclusion, the three layer circular tubes improve local buckling resistance of steel tube by using three layer circular tubes. Full length steel member also has been analyzed with and without three layer circular tube by using finite element method. As a result, the objectives of this study have been achieved. An improvement can be made in order to have better analysis for the application of this three layer circular in full scale space truss.

Acknowledgement

The Authors would like to thank Ministry of Higher Education Malaysia (MOE), and Universiti Teknologi Mara (UiTM) Shah Alam for providing financial support through Lestari Grant (File no: 600-IRMI/MyRA 5/3/LESTARI (0148/2016).

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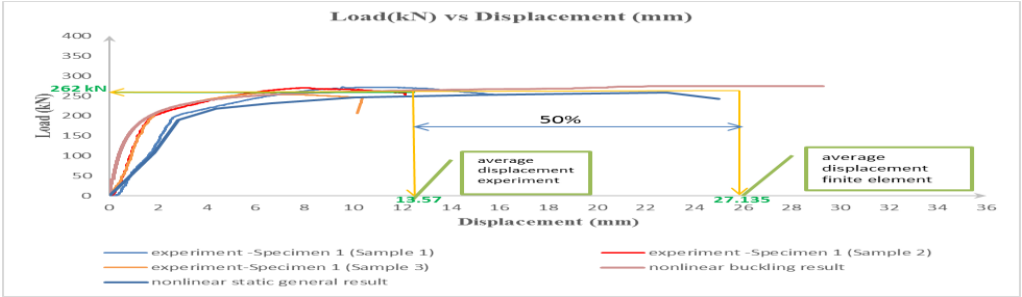


Fig. 1: Comparison with inner tube compression result by Yazmin et al. [8].

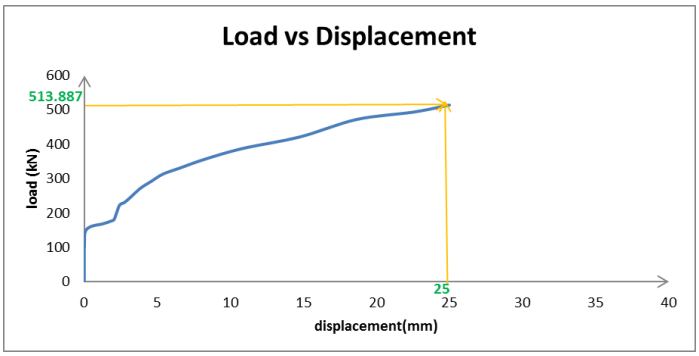


Fig. 2: Load vs Displacement for nonlinear static and general analysis of three layer circular tube.

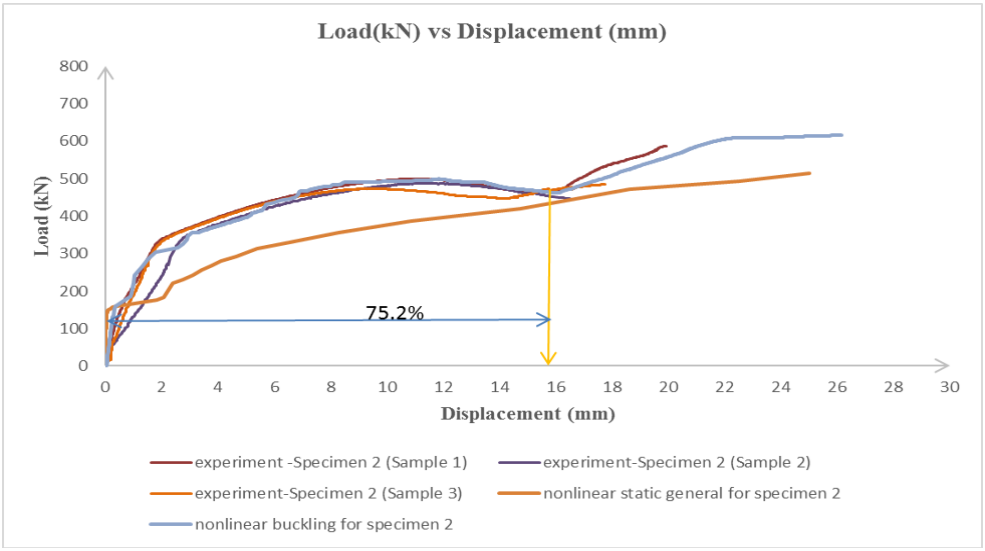


Fig. 3: Comparison of numerical result and experimental result of three layer circular tube.

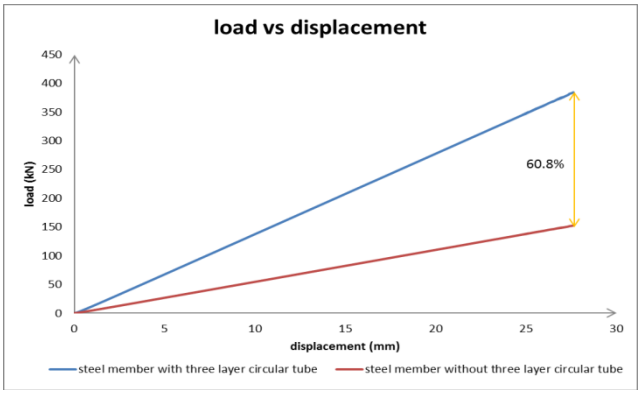


Fig. 4: Nonlinear static and general analysis of full length steel member with three layer circular tubes.

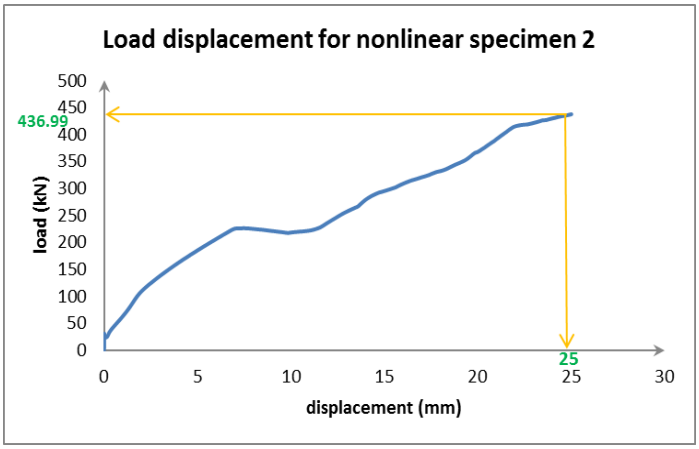


Fig. 5: Nonlinear static and general analysis of full length steel member with three layer circular tubes.

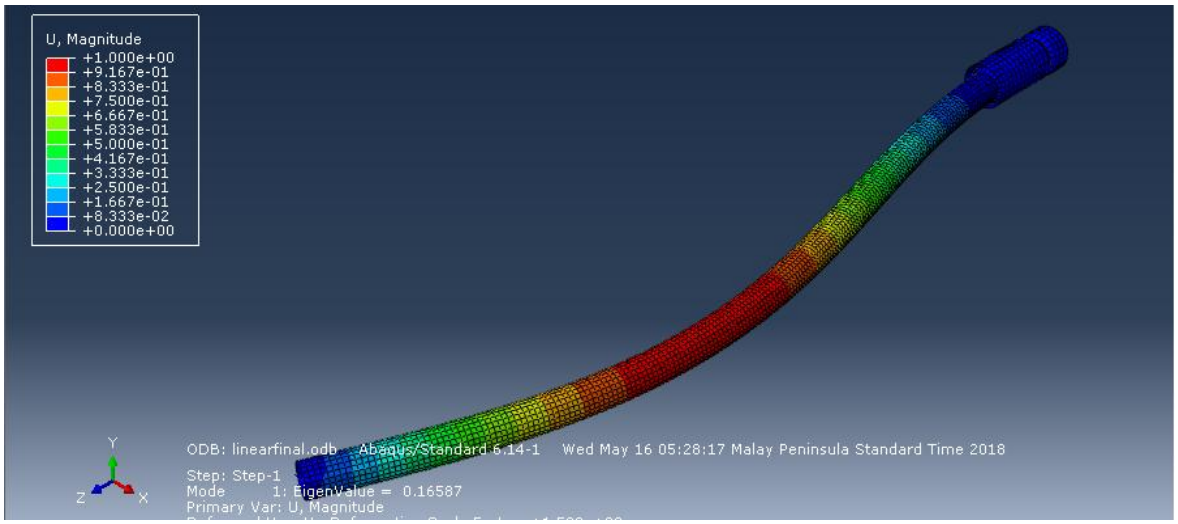


Fig. 6: Buckling analysis of full length three layer circular tube.

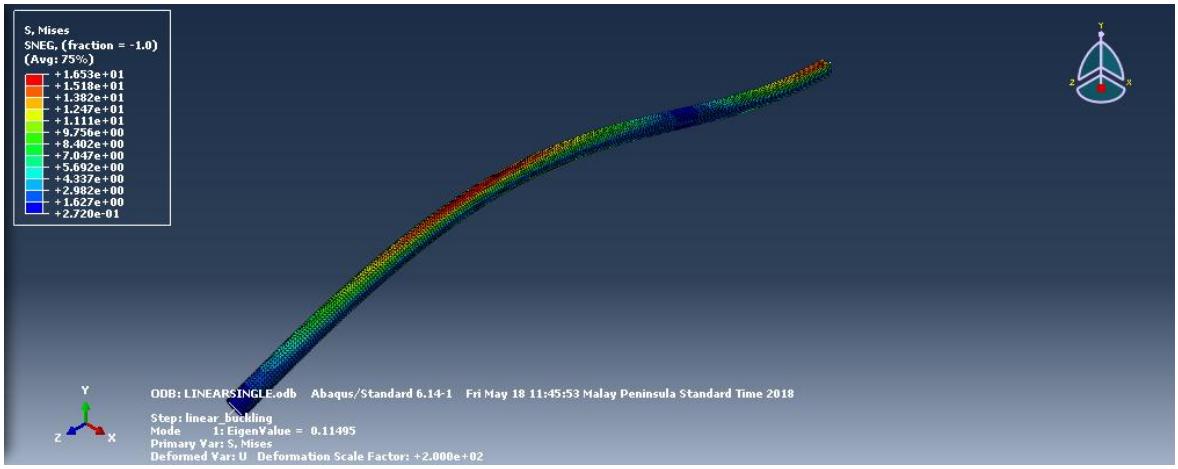


Fig. 7: Buckling analysis of inner tube 2m.

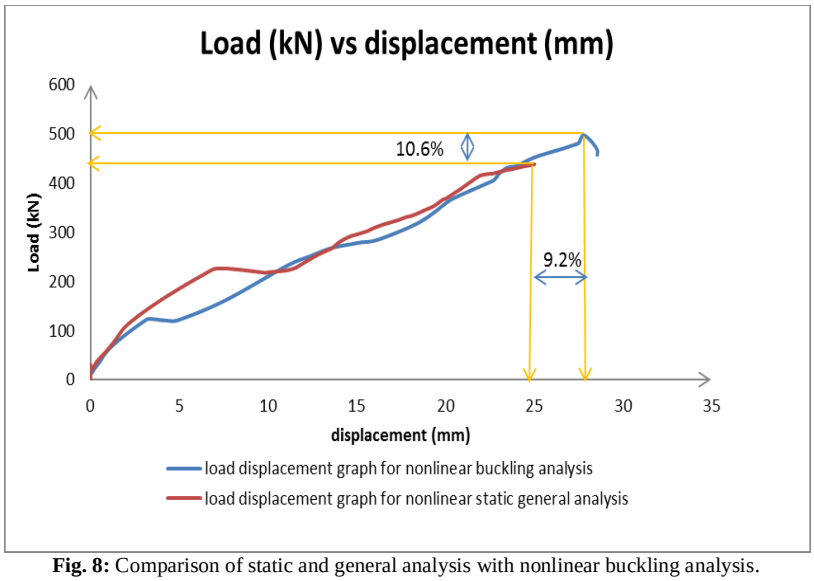


Fig. 8: Comparison of static and general analysis with nonlinear buckling analysis.