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Nonlinear Analysis of a Critical Part Design

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Abstract

A nonlinear analysis is needed when the behaviour of a mechanical structure is not complying with Hooke's Law. Large deformation of the structure, changes in stiffness matrix, changes in boundary conditions caused by the loading and the stress-strain relationship of the material become nonlinear when the stress increases and passes the yield point. Once passed the yield point, the material is said to be nonlinear as it displays plastic or hyper-elastic behaviour. Therefore, the purpose of this project is to study and analyze problems of nonlinear behaviour. The conventional nonlinear analysis procedure is time consuming and complex as it uses an iteration method where the solution is lengthy and tedious. This study used CAD software which is SOLIDWORKS to design and perform nonlinear simulation. Additionally, displacement control analysis method and tangent modulus analysis method were carried out in this study. Galvanized steel is applied to the part design and plasticity von Mises material model is chosen to conduct the analysis. Nonlinear response curves of von Mises stress and displacement were generated from the analysis. Indeed, the parameters used in the nonlinear analysis influenced the result of von Mises stress and displacement. The results revealed that the nonlinear behaviour is initiated by the material nonlinear and geometric nonlinear.

Keywords: Non-linear Analysis, Von Mises Stress, plasticity.

1.1 INTRODUCTION

Nonlinearity can be categorized into three major types: geometric nonlinearity, material nonlinearity and boundary conditions nonlinearity. Nonlinear analysis approach derived from long back requires many incremental step solutions, thus making it a lengthy step by step procedure (1). Thus, it is time consuming to solve a complex problem. Based on research study, a new approach for material analysis is found where the tedious and lengthy step by step incremental procedure is eliminated (2). The new formulation uses stress and strain functions as the material input and eliminates the use of elastic moduli.

Critical parts or crack-like defects affect the stability of any structure and fracture mechanics is used to determine them. In addition, before the crack grows to failure, there is a value of stress that a part could withstand, and the exact amount is obtained through fracture mechanics analysis. Furthermore, the minimum load or critical size of the defects which will cause the analysed part to fail is determined by the amount of stress (3).

Nonlinear elastic-plastic analysis is one of the analyses used in fracture mechanics in an attempt to characterize a material. To determine the critical stress level for the critical part that must not fracture, stress analysis for the critical part is performed as usually done at all parts in a structure. Reducing failure in the critical part is the aim of the analysis so, focusing on the crack growth is an effective procedure in the study.

The nature of shape changes of structure or structure deformation due to external sources such as temperature and pressure happens in real life and when the deformation is large the structure is considered to have nonlinear behaviour. The stress strain curve of the material become nonlinear when the strains increase and passed the yield point (4). Once passed the elastic region or yield point, the material is said to be nonlinear as it displays plastic or hyper-elastic behaviour as shown in Figure 1.1. For example, the shape of a paper clip will not be as initial shape after some force is applied on it. This is because the force applied has reached the yield strength of the paper clip material.

As of now, the finite element method developed is for linear analysis where the displacement-based approach is only able to give solutions for the linear analysis case. Green- Lagrange strain approach is used for the current nonlinear analysis but not able to give an accurate solution to the nonlinear analysis behaviour in the range of material (2). In addition, the procedure to solve structural problems in nonlinear behaviour of material is lengthy and time consuming as it involves step by step incremental process (2).

1.2 RELATED WORKS

Finite Element Analysis is widely used in engineering such as in structural analysis. Eventually there are two categories of analysis in FEM which are linear and nonlinear analysis. However, the linear analysis assumption becomes invalid and the accuracy is lost when there is an existence of nonlinear behaviour in the analysis (5). There are three types of nonlinearities which are geometric nonlinearity, material nonlinearity and contact nonlinearity. Permanent deformations, major changes in geometry shape, local yielding, and cracks are examples of nonlinear behaviour. In addition, each of these nonlinear behaviour results in the changes of stiffness in any of nonlinear analyses (6).

1.2.1 Nonlinear analysis

The difference between nonlinear analysis and linear analysis focuses on the changing of stiffness, K in the eq. (1.2.1). The stiffness K is constant in a linear analysis as there is no change in material behaviour. In a nonlinear analysis, the stiffness will increase with time, and the change in stiffness is due to material property. Furthermore, the difference is also due to the acting loads. The structure's or component's stiffness may vary depending on the total or individual applied load and load history (7). Moreover, when there are changes in the properties of material under process condition and the changes in stiffness occur, material nonlinearity is a concern in the study (6).

1.2.1.1 Geometric Nonlinearity

Nonlinear behaviour is defined as geometric nonlinearity when changes in stiffness are caused solely by changes in shape and if a structure has a substantially different geometric (6,8). In addition, this nonlinear behaviour is also related with structural elements problems that involve large displacement and twist with minor distortions such as beams (8).
Research papers by (9–11) studied on analysis of geometrically nonlinear bending of composites structures. The studies involved composite laminated shell panels with variable stiffness (9), composite beams of variable stiffness (10) , and composite stiffened panel (11). They stated that the von Kármán nonlinear strain-displacement relation is being used to evaluate deflections and stresses is the geometrical nonlinearity.

1.2.1.2 Material Nonlinearity

Material nonlinearity generally implies the behaviour of material. This means that the material's stress strain curve shows that the stress of a material has been beyond its yield point into the plastic region and this type of nonlinear behaviour also include materials such as rubber and most plastics even these materials never display nonlinear elasticity (12). The stress strain curve of the material is shown in Figure 1.1.
Nonlinear analysis involving material nonlinear is common because there is material defined to the structures or work piece in which every material has its own behaviour. Erkmen and Attard (2011) conducted a study on composite beams involving material nonlinear analysis (13). In the study, finite element formulations of displacement-based beam-column is used to account for the nonlinear material behaviour in the analysis. For modelling the behaviour of material of the beam components, rate-dependent plasticity with isotropic hardening or softening therefore elasto-plastic is employed in the study. A significant number of elastic-plastic large deformation investigations has been used to determine the strain hardening rate (14).

1.2.1.3 Boundary Conditions Nonlinearity

This type of nonlinear behaviour normally occurs when there is discontinuous support from the structural supports as it depends on direction and magnitude of the reaction (12). This is because when the load increases during deformation process, there is changes in boundary conditions and the stiffness also changing (6,8). Contact problems are an example of this where changes happened during the deformation at the contact zone between two objects, preventing the ingress of one object into the other. The boundary condition could be added or removed, and stress can be transferred between structural components due to changes in physical contacts.

Basically, there are different types of contact mechanics in FEA based on Pore et al. (2021) reviewing contact modelling in nonlinear FEA (5). The Hertz contact theory is a well-known formula for calculating maximal contact stress, contact area, and contact pressure. In addition, this theory assumes small deformation and the contact behaves elastically as the bodies under contact's material are homogenous. Besides, weld contact, stick contact, slip contact are the types of contact in the FEA modelling. Penalty method, Lagrange multiplier method, augmented Lagrangian and internal multi point constraints are methods that can be used in contact nonlinear analysis (15).

1.3 ANALYSIS FRAMEWORK

During this phase, the nonlinear analysis of the paper clips was conducted. Firstly, nonlinear study was selected from the study property manager options, Next, before starting the simulation and design analysis, the material model type was chosen and assigned. For this study, plasticity von Mises material model type was assigned to the model, displacement control analysis method and tangent modulus analysis method were conducted for the nonlinear simulation study. Then, displacement control simulation was conducted with displacement value of 30mm to get the amount of maximum force to be applied. Finally, that force was applied on the paper clip model and the von Mises result was obtained and graph was executed. The results of the three paper clips were then compared to justify the best design.

Besides, to stabilize the paper clip model, suitable restraints were required. The fixed geometry fixture was applied on the model at the part that should not move along when force was applied. The fixtures symbol which are the green colour simple arrows appeared on the selected part are shown in Figure 3.8. Then, from the external load menu, force was selected and applied to the selected face of the part model. The specified value of force was applied with direction normal to plane. The purple arrows in Figure 1 are the symbol for uniformly distributed force applied.

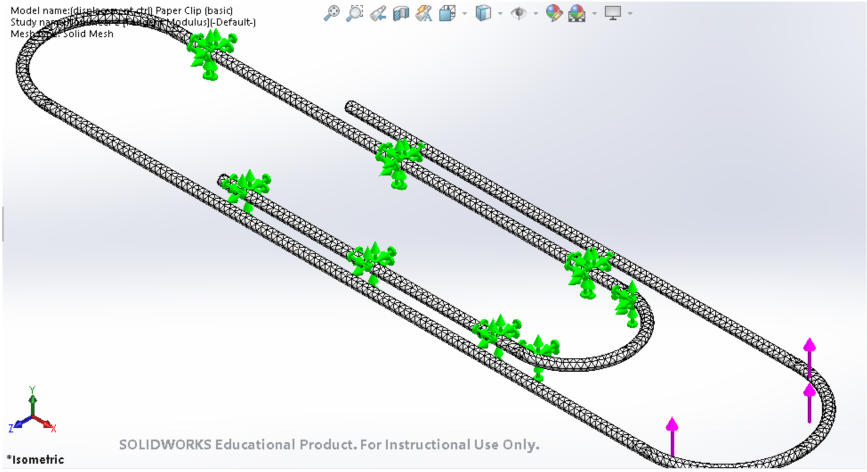

Figure 1 Fixtures and forces applied.

1.3.1 Displacement Control

In nonlinear analysis, the displacement control approach could handle post buckling behaviour. Besides, at each solution step in displacement control methods, all loads change correspondingly as this method computes a multiplier for all loads (16). Therefore, this analysis method was used to find the load factor for the paper clip. A reference point was created on the face of the paper clip at the area of force applied. Figure 2 shows the reference point on the paper clip model.

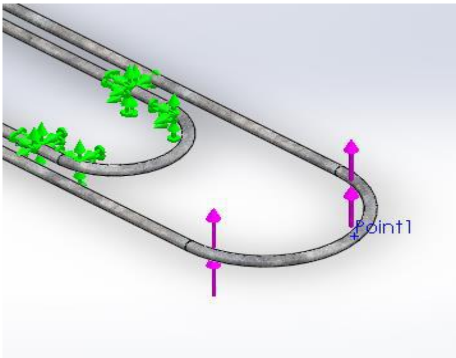

Figure 2 Reference Point

1.3.2 Tangent Modulus

Plasticity von Mises material model type is used for nonlinear analysis in this study. One of the parameters required for this type of material model is tangent modulus. The tangent modulus property was employed to determine the plasticity in the von Mises stress criterion and approximate the slope of the post-yield stress-strain curve. Furthermore, this parameter together with the elastic modulus and yield strength result in a bilinear material model (17). The value of tangent modulus was determined from the 10% of elastic modulus of the material as shown in Table 1.

Table 1: Elastic Modulus and Tangent Modulus of the Material

Elastic Modulus	**Tangent Modulus**
200000 N/mm^2	20000 N/mm^2

1.4 RESULT AND DISCUSSION

1.4.1 Displacement Control Analysis Method

The displacement control analysis result performed on the paper clip model is shown in Figure 3. From the figure, it can be seen that the surface of the paper clip model is coloured with different colours. The colour represents the displacement value occurring ranging from minimum to maximum. Clearly, the dark blue is at the whole area where it is defined as fixed geometry which means that part is not moving and furthest from the load thus it has the minimum displacement. The minimum displacement obtained is 1.00e-30mm which is very small. It is evident that the fixed part is not moving.
Furthermore, the maximum displacement occurred at the area where the load is applied, and the area can be observed at the red colour part. The maximum displacement for the paper clip model is 30.37mm. The value indicates that the part undergoes maximum displacement as the load is applied directly on top of it. The displacement results obtained are within the 1 second ending solution time with 23 plot steps. The displacement result obtained of 30.37mm is approximately close to the controlled displacement of 30mm. The results obtained show that 1N force caused the paper clip model to have a displacement of 30.37mm.

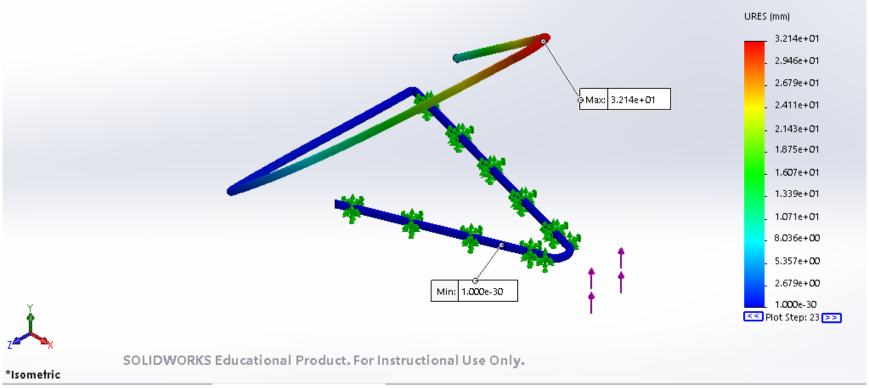

Figure 3: Displacement Result by Displacement Control Method

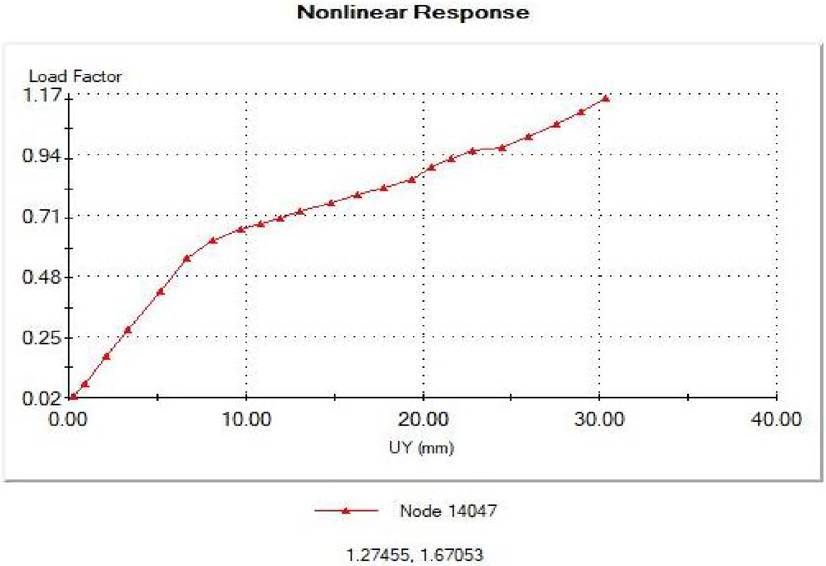

Figure 4: The result of the nonlinear response.

Table 2 shows all the results acquired from the displacement control analysis for the three designs of paper clip. The analyses of the three designs have the same input value which are 1 N of force and 30 mm of controlled displacement as well as projected in the Y direction. Besides, all the results are obtained at the maximum node by using probe results and graphs of results are also generated for each design. As the analysis was performed with different designs of the paper clip model, it can be seen that the design has significant influence on the load factor and displacement. The analysis conducted on Design 1 gave the result of 0.57 N load factor with 29.68 mm of displacement. The displacement that Design 1 acquired is the smallest among the three designs. Furthermore, Design 3 has the smallest load factor with 0.17 N and displacement of 30.07 mm. To compare with Design 1, Design 3 is only able to hold a smaller load than Design 1 but still resulting in large displacement. This can be explained that Design 1 is better than Design 2 in terms of holding load. As for Design 2, it has the biggest load factor and largest displacement than the other two designs with 1.16 N and 30.37 mm respectively. This is thought to be due to the surface area where the load is applied on is small. The results obtained agreed that the design of part model influences the load factor and displacement.

Table 2 Load Factor Obtained from Displacement Control Method

Design	Load Factor	Displacement (mm)
Design 1	0.57	29.68
Design 2	1.16	30.37
Design 3	0.17	30.07

1.4.2 Von Mises Stress result

The chart in the figure also shows a few different colours which represent the value of von Mises stress created on the model. The part with dark blue colour displays minimum von Mises. This is because that part is defined as fixed geometry and there is no load applied. There is a label that shows the minimum von Mises stress value which is 2.628×10−14 N/m^2. The part where the maximum von Mises stress is created is displayed with red colour. This design of paper clip has a maximum von Mises value of 5.213×108 N/m^2 at the inner part of the paper clip's edge as can be seen in the figure with the maximum label. This is because the edge is more prone to break first than the other parts due to deformation.

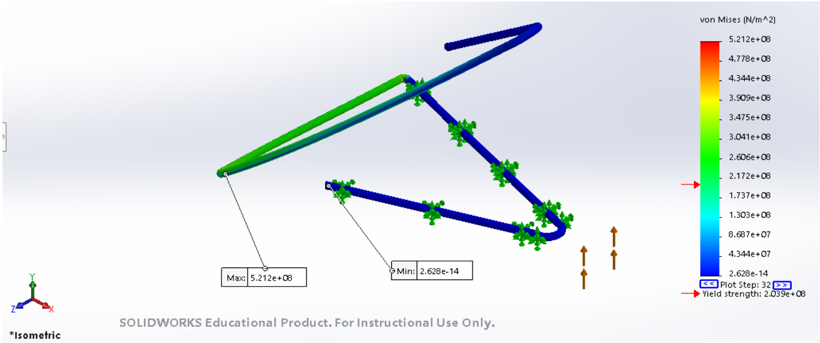

Figure 5: Von Mises Stress Result

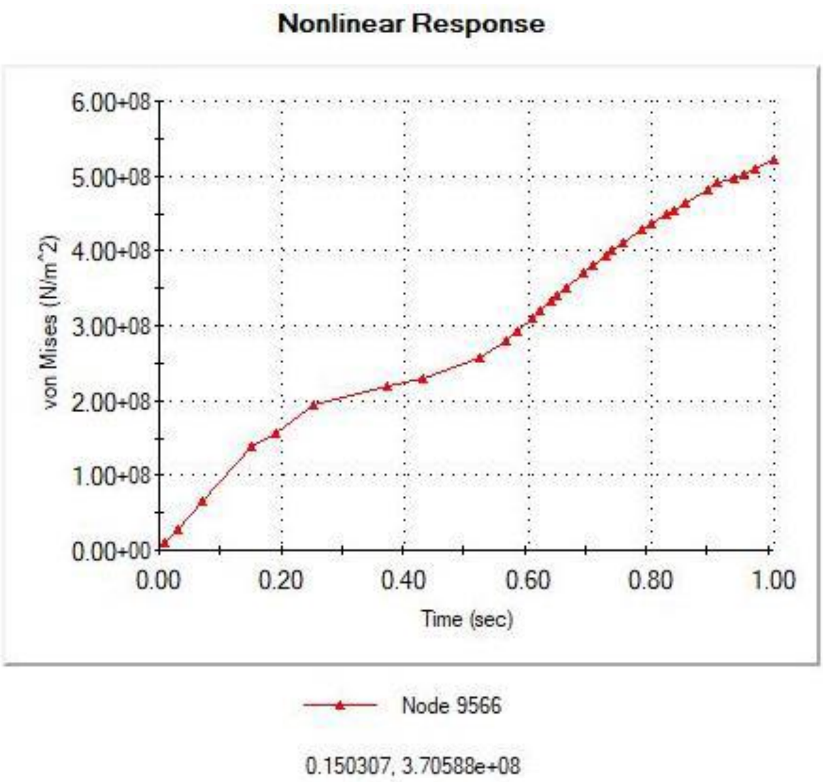

Figure 6: Nonlinear Response Curve of von Mises (N/m^2) vs Time (sec)

1.4 CONCLUSION

The results of nonlinear analysis studies show that several parameters such as design of paper clip, load applied, and material defined for the paper clip had the greatest influence on the von Mises stress and displacement as well as the nonlinear behaviour. Furthermore, from the results obtained, it can be concluded that the nonlinear behaviour is initiated by the material nonlinear and geometric nonlinear.
The nonlinear analysis was found to be an affective technique to improve the reliability of a design and consequently reduced the risk of failure. With the completion of this study, it is deemed that the research objectives stated in the introduction have been met.

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