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RESEARCH ARTICLE

A parametric study of insertion and retention forces in cantilever hook

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ABSTRACT - Adhesive bonding, mechanical fastening, and snap-fit are all ways for attaching plastic components together. Snap-fit is employed to assemble plastic parts because it is an efficient, cost-effective, and fast joining technique. When it comes to snap-fits, you have two options: separable and inseparable. The term separable refers to the ability of the components to be dismantled successfully without breaking, whereas inseparable refers to the plastic parts being permanently attached. This investigation focuses on cantilever snap-fit since it is frequently used in the automotive, aerospace, and other sectors. Numerous aspects and parameters affect the functioning of snap-fits, notably on the forces of the insertion and retention. The parameters are the feature thickness (T_b), beam length (L_b), beam width (W_b), base radius (R_b), mounting (α) and dismounting angle (β). The forces required to attach and detach the snap-fits are thought to increase as the insertion and retention angles increase. The results can be seen that higher insertion and retention angle contributes to higher insertion and retention forces as portrayed from Set 7 with the value of 1.1052 N and -1.0214 N.

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1.0 INTRODUCTION

Adhesive bonding, mechanical fasteners, and snap-fit are just a few of the joining techniques that may be used to attach two or more pieces together. Each of these methods has unique applications, applicability ranges, and restrictions. According to Design for Assembly (DFA) [1], snap-fit fasteners can be used in place of traditional threaded ones when assembling plastic components since they can be fitted more quickly and with less force on the body [2]. Snap-fit is a rapid and inexpensive technology that is frequently used in manufacturing to attach flexible pieces together [3]. It is used in large variety of applications [4]. In everyday objects like remote control battery covers [5], pen caps, and door handle bezels, snap-fits are used. Furthermore, a snap-fit design can remove the need for an external source of energy which helps reduce the inventory of components. Snap-fit composes of one male and one female part and terms such as the insertion and retention forces and the locking ratio should be addressed. Several factors are essential for simulating the model for the forces since they have an impact on the outcomes. Snap-fit can break and induce fatigue failure if it is not designed properly [6]. Therefore, it is crucial to investigate how design elements affect the mating forces. The key to this research is determining the best design parameters for cantilever snap-fit using finite element analysis. The snap-fit design's dimensions significantly affect the accuracy and performance of mating as well as the likelihood that components will be able to withstand loads and stresses.

A mechanically connected form-fitting joint called a "snap-fit" is commonly moulded into a plastic part itself. The joint controls the relative part positioning, load transmission orientation and alignment, and degrees of freedom. The interplay of flexibility, frictional contacts, and the geometric structure of the snap-fit parts leads to mechanical asymmetry, which is a crucial characteristic of industrial snap-fits [7]. Snap-fit can be created with the objective of serving separate or complementary functions. When it is executed correctly, the parts may be joined and removed quickly and repeatedly without causing any damage to the assembly or the material. Snap-fit assemblies are the easiest to assemble and the most environmentally beneficial since they allow different parts to be recycled [8]. Snap-fit is a cantilever design with a hook attached to one end as in Figure 1. When the two pieces are put together, the hook's interference with another component generates a mating force that deflects and locks the two parts together [9]. There is no need to employ fasteners because the snap-fit design may perform the same job as a bolt and nut [10]. Cantilever, torsion, and annular snap-fit are a few of the several forms of snap-fit used in the market.

Cantilever snap-fits are the most common and notable sort of snap-fit [11]. The cantilever arm used in this connecting technique has a deflect hook at the end. They frequently come in useful shapes and can be made of materials other than plastics, such as metals [12] and fiber composites. From a more general standpoint of sustainability, snap fits simplicity of disassembly makes it easier to recycle parts [13] made of various materials, which promotes more environmentally responsible behaviour throughout the lifespan of both components and the final product. Cantilever constructions have existed for a very long time. They are well-known to design engineers due to their widespread application in bridges and architectural structures such as overhangs and balconies, not to mention their prevalence in single-wing aircraft design.

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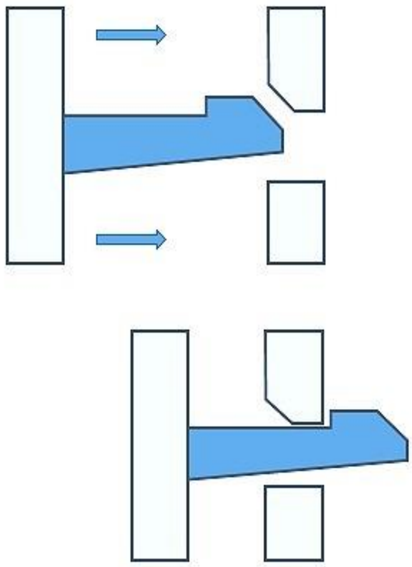

Figure 1. Cantilever snap-fit [14]

The aim of the study is to ensure the best cantilever snap-fit to be used with a minimal force during insertion and retention process with the help of the simulation. Most of the study done previously showed either one of the forces only and the insertion and retention forces are crucial to solve the problem statements and the research gap that can be seen is the meshing strategy and the simulation of the insertion and retention forces of cantilever snap-fit using ANSYS software using material polypropylene.

2.0 PARAMETRIC STUDY OF CANTILEVER SNAP-FIT

2.1 A Geometric Design of Snap-Fit

Numerous performance criteria must be considered while analysing the snap-fit mechanism's mating performance. These are the insertion force (F_i), retention force (F_r), and locking ratio (LR) [15]. The variables or parameters that are controlled are the insertion and retention angle, beam length, beam thickness, and base radius. The settings will affect the snap-mating fit's efficacy and load distribution. Insertion force (F_i), is a force that must be used during the snap-fit's insertion direction during the assembly of the protruding and undercut pieces. When conducting the cantilever snap-fit assembly process, the greatest forces necessary must be obtained [6]. Retention force (F_r), is the force needed to separate the snap-fit from the body cavity of the snap-fit. The locking ratio (LR), is the ratio of a snap-fit feature's maximum insertion force and maximum retention force [16]. It may be difficult to assess the effectiveness of a snap-fit using retention forces for a variety of reasons. Because of this, the locking ratio is a better metric for evaluating snap-fit performance.

$$LR = \frac{F_r}{F_i} \tag{1}$$

Table 1 displays the snap-geometric fit's layout. The connection between each parameter used to build the cantilever snap-fit is the geometric design [17]. Figure 2 shows the general design parameters of the cantilever hook snap-fit.

2.2 Design Consideration of Cantilever Hook

The design of the snap-fit has to consider some of the factors that include the utilized material's characteristics which is polypropylene (PP), the beam cross-sections and the beam tapering circumstances. For calculating the material's initial performance and figuring out how much strain is allowed in the design, it is essential to understand the properties of the material. Secant modulus, maximum allowable strain, and coefficient of friction are a few concepts to consider. Based on the study by Bonenberger [17], secant modulus, E_s , is calculated using the equation below:

$$E_s = \frac{\sigma_{design\ point}}{\varepsilon_{design\ point}} \tag{2}$$

According to the author, the secant modulus may be determined once the design point has been established. A material's ductility is indicated by a larger permissible strain, whereas brittleness is shown by a lower acceptable strain.

To create a design point, double an item's strength number by 10% to 25%. The secant modulus in MPa is also known as the strain-dependent modulus of elasticity. From 68 MPa to 170 MPa, the secant modulus is available.

The coefficient of friction is a crucial factor to consider when calculating the insertion and retention forces of a cantilever snap-fit. The lubricity of the material has a significant impact on the coefficient of friction. According to Bonenberger [17], lubricity is a material's capacity to support loads while moving relative to another object. The substance with high lubricity, therefore, has a lower coefficient of friction. The coefficient of friction for polypropylene, often known as PP, is between 0.25 and 0.30, according to a study.

Table 1. Geometric relationships of parameters

Variables	Description	Relationship
T_b	Thickness of a feature that extends from a wall	T_b = T_{wall}
	Thickness of a wall-protruding feature	T_b = 0.5 T_{wall}
L_b	Beam length	$5T_b$ < L_b< $10T_b$
W_b	Beam width	W_b < $0.5L_b$
R_b	Base radius	$R_b \leq 0.5L_b$
y	Height of the retention mechanism, for $L_b/T_b \cong 5$	y < L_b
	Height of the retention mechanism, for $L_b/T_b \cong 10$	y = L_b
α	Insertion angle	α = 25° ~ 30°
β	Retention angle, non-releasing joint (Permanent)	β ~ 80° - 90°
	Retention angle, releasing joint (No external, separation loads)	β ~ 35°
	Retention angle, releasing joint (Low external, separation loads)	β > 45°

*T_{wall} indicates the wall thickness

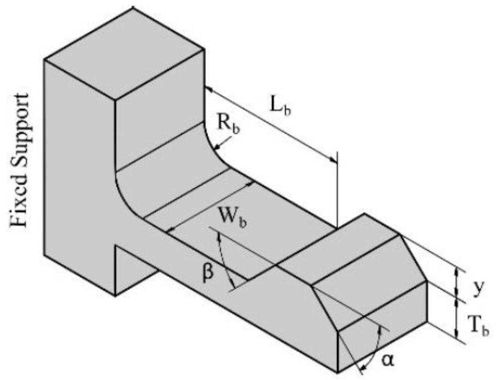

Figure 2. Design parameters of cantilever hook snap-fits [18]

2.3 Simulation of Snap-Fits

Before continuing with the finite element analysis, the displacement and the fixed boundary need to be set. The displacement boundary is set on the snap-fit meanwhile the fixed boundary is set on the small box in which the body deforms as shown in Figure 3. The meshing strategy for the cantilever hook snap-fit is by refining the surface of which the contacts between the male and female part connected.

During the simulation, after all the parameters were set, the software was able to generate information on the insertion and retention forces of the cantilever hook snap-fit. The simulation provides a better explanation of how the maximum forces can be generated as the snap is deformed under stress. Finite element analysis has been used widely to simulate the behaviours of the snap-fit in recent years and it has proved to be a great medium to understand the snap-fit performances [19]. Simulation is done to obtain calculations and precision in order to create a strong snap-fit. This can also reduce the amount of time to design and produce snap-fits [20].

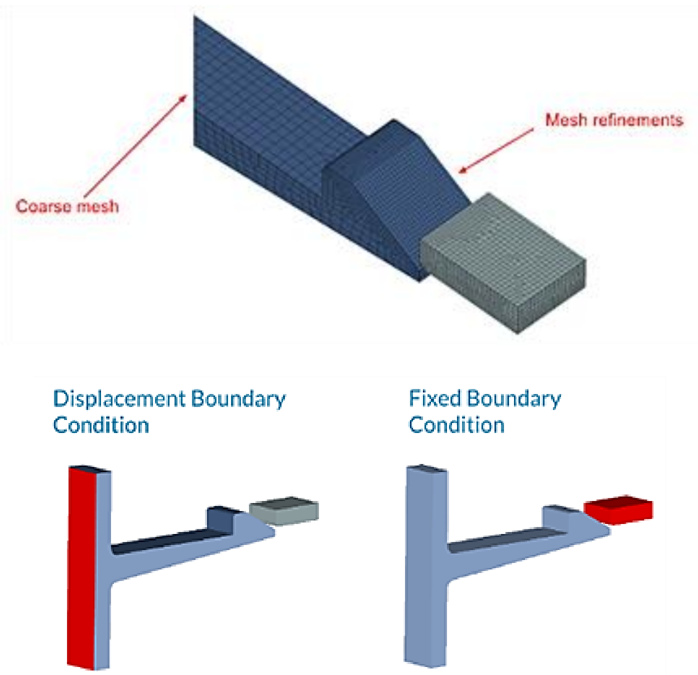

Figure 3. Conditions of snap-fit

3.0 METHODOLOGY

The flowchart of the research is shown in Figure 4. The process is divided into 3 phases. The flowchart shows the process from the construction of snap-fit models until the success of the evaluation of snap-fits. The model is built by adjusting the design parameters such as the insertion angle (α), the retention angle (β), the thickness of the wall (T_{wall}), the thickness of beam (T_b), the radius of base (R_b), length of the beam (L_b), the width of the beam (W_b). The model's simulation is dependent on the model's effective design applying the criteria from the literature study. If the snap-fit is fragmented or breaks in the middle of the simulation, it may signal that the model is failing. As a result, the model must be re-evaluated and re-modeled.

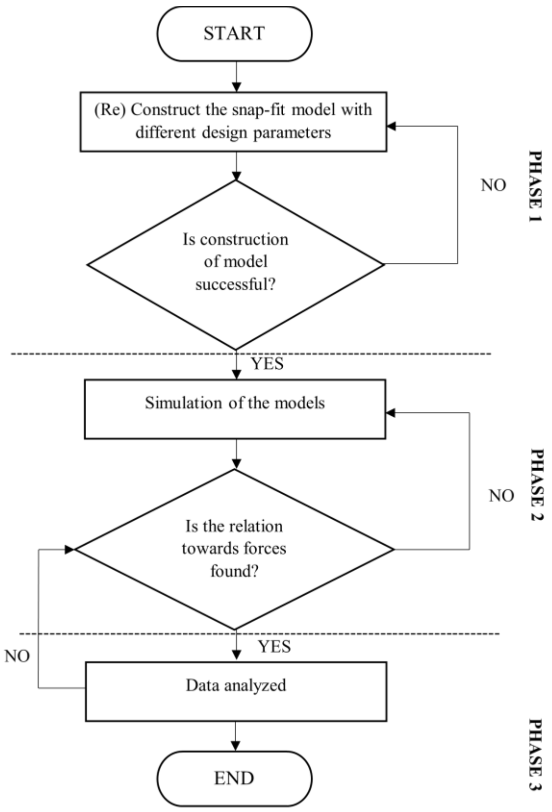

Figure 4. Flowchart of the research

3.1 Design of Cantilever Hook Snap-Fit

In this study, the design for the cantilever hook snap-fit is created using the computer-assisted design (CAD) software, Autodesk Inventor. Following the completion of the design, the finite element analysis program, ANSYS, is used to acquire the insertion and retention force results from the simulation. The design strategy is based on the criteria from the literature research. To test differences in the insertion and retention forces, the cantilever hook snap-fit design parameters must be manipulated. The equation for insertion force is shown below:

$$F_i = P \times \frac{\mu + \tan(\alpha)}{1 + \mu \tan(\alpha)} \tag{3}$$

In Eq. (3), μ denotes the coefficient of friction, and α denotes the insertion angle. Because the bending force P is initially unknown, the maximum deflection of the beam and the force of deflection may be determined using the cantilever hook snap-fit design parameters, as illustrated in Figures 5 and 6.

Shape of Design	Taper Direction	Maximum Deflection of the Beam	Force of Deflection
Rectangle	-	$Y_{MAX} = 0.67 * \frac{\mathcal{E} * l^2}{h}$	$P = \frac{b * h^2}{6} * \frac{E_s * \mathcal{E}}{l}$
	Thickness	$Y_{MAX} = 1.09 * \frac{\mathcal{E} * l^2}{h}$	
	Width	$Y_{MAX} = 1.64 * \frac{a + b}{2a + b} * \frac{\mathcal{E} * l^2}{h}$	
Ɛ = Permissible Strain		l = Length of Beam	h = Beam Thickness
E_s = Secant Modulus		a = Upper width	b = Bottom width

Figure 5. Maximum deflection of the beam and force of deflection in rectangle design

Shape of Design	Taper Direction	Maximum Deflection of the Beam	Force of Deflection
Trapezoid	-	$Y_{MAX} = \frac{a + b}{2a + b} * \frac{\mathcal{E} * l^2}{h}$	$P = \frac{h^2}{12} * \frac{a^2 + 4ab + b^2}{2a + b} * \frac{E_s * \mathcal{E}}{l}$
	Thickness	$Y_{MAX} = 0.86 * \frac{\mathcal{E} * l^2}{h}$	
	Width	$Y_{MAX} = 1.28 * \frac{a + b}{2a + b} * \frac{\mathcal{E} * l^2}{h}$	
Ɛ = Permissible Strain		l = Length of Beam	h = Beam Thickness
E_s = Secant Modulus		a = Upper width	b = Bottom width

Figure 6. Maximum deflection of the beam and force of deflection in trapezoidal design

The equation for retention force can be seen below:

$$F_r = P \times \frac{\mu + \tan(\beta)}{1 + \mu \tan(\beta)} \tag{4}$$

In Eq. (4), μ denotes the coefficient of friction and β denotes the retention angle. To allow disengagement, the retention angle is chosen to be smaller than the critical angle of friction. As a result, the equation for calculating the critical angle (β_{crit}) is as follows:

$$\beta_{crit} = \tan^{-1}\left(\frac{1}{\mu}\right) \tag{5}$$

3.2 Finite Element Analysis

Numerous engineering issues involving structural analysis and fluid flow are solved using the numerical analytical technique known as finite element analysis (FEA). It is used to simulate the consequences of forces that are applied to an object and applied to structures that have a complex design to get responses on the ordinary differential equation. FEA is also used to study the relationship between the form and functions of morphological structures. The model may be accurately predicted based on the current condition. This analysis can provide information on fatigue, the distribution of stress on beams, the existence of stress concentrations, material deformation, and other topics. It is therefore crucial to first understand the functionalities provided by FEA software. The snap-fit cantilever hook model was made using the Autodesk Inventor software. ANSYS software is used to do the simulation analysis of the snap-fits. Other software can be used to simulate the FEA such as DTS Simulia Abaqus, Altair Hyperworks and also Simscale.

FEA can provide calculations such as the stress or von-Mises stress, the strain of the object and also the values of total deformation. Particularly in this study, it provides the values of maximum insertion and retention forces of the cantilever hook snap-fit. The three different nonlinearities of the FEA were the Material Nonlinearities, Geometrical Nonlinearities and Moving Contact.

With an Augmented Lagrange formulation, the snap-fits connections are classified as frictional with a 0.25 coefficient of friction. Normal Lagrange and the Pure Penalty technique are combined to create Augmented Lagrange. The best option is Augmented Lagrange since it allows for the least amount of penetration while yet managing to be reliable and have short run times. For bending-dominated situations, the stiffness factor that is specified for all snap-fits is 0.01. Meshing refinement has been done as it affects the convergence of the simulation. In this case, the surface used for meshing refinement would be the contact surface. The refinement value of the meshing would be 1 showing that the meshing is done with minimum refinement. The refinement of the meshing will affect the accuracy of the simulated model to its ideal form in which improves the forces results accuracy.

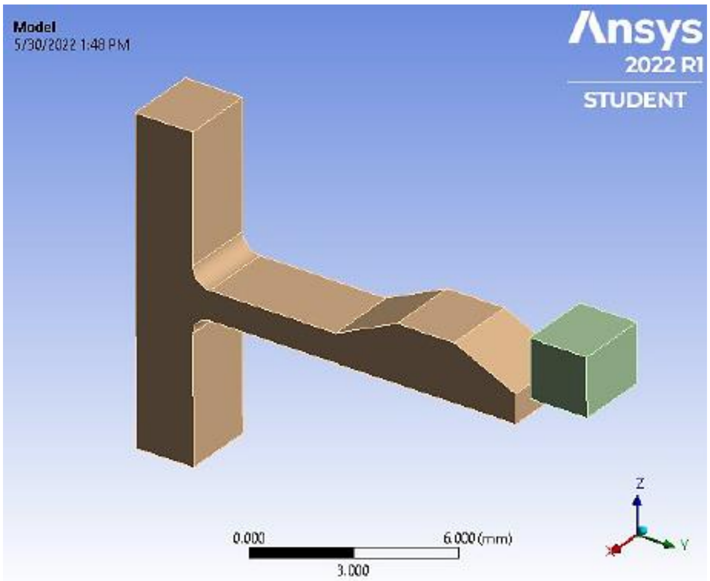

Figure 7. Snap-fit model in ANSYS

The results are obtained from the finite element analysis in ANSYS. Figure 7 shows the snap-fit model for Set 1 in ANSYS meanwhile Table 2 shows the parameters that are used in 8 sets of snap-fit models. The insertion angle (α), the retention angle (β), the thickness of the wall (T_{wall}), the thickness of the beam (T_b), the radius of base (R_b), length of the beam (L_b), the width of the beam (W_b) and maximum deflection of the beam (Y_{max}).

Several sets of design parameters are developed and shown in Table 2 in accordance to the design guidelines on parameters that are based on the literature study [add references]. The insertion and retention angle, wall and beam thickness, base radius, beam length, beam width, and the permissible deflection of the beam are the parameters that are used to construct snap-fit models. Three factors—insertion and retention angle, beam thickness, and beam length—have a significant impact on the insertion and retention forces. The first two categories of these eight design factors are low insertion and retention angle and high insertion and retention angle. Beam thickness and length are two additional factors that impact insertion and retention forces. After identifying all of the design requirements, the table may be sorted into eight categories. Other variables were constructed since they are highly dependent on the three aspects mentioned above.

Table 2. Parameters of 8 sets of snap-fits models

Set	α (°)	β (°)	T_{wall} (mm)	T_b (mm)	R_b (mm)	L_b (mm)	W_b (mm)	Y_{max} (mm)
1	25	25	2	1 (0.5 T_{wall})	0.6 (R_b/T_b= 0.6)	5 (5 T_b)	2.5 (0.5 L_b)	1.34
2						10 (10 T_b)	5	5.36
3				1.2 (0.6 T_{wall})	0.72	6 (5 T_b)	3	1.61
4						12 (10 T_b)	6	6.43
5	35	35		1	0.6	5	2.5	1.34
6						10	5	5.36
7				1.2	0.72	6	3	1.61
8						12	6	6.43

4.0 RESULTS AND DISCUSSION

The highest insertion and retention forces may be shown in ANSYS analysis graphs, and as shown in Figure 8, the maximum insertion and retention forces for set 1 are 0.60634 N and -0.57 N respectively, meanwhile Figure 10 shows the maximum insertion and retention forces for set 7 are 1.1052 N and -1.0214 N respectively. Table 3 displays the findings for the additional sets. For set 1, it has lower angle for insertion and retention angle and normal thickness with normal length which contributes to the lower insertion and retention forces. But in this research, the lowest insertion and retention forces is portrayed by Set 2 as seen in Table 3. The higher insertion and retention angle for the snap-fit can generate higher insertion and retention forces as portrayed by Set 7 in Figure 9.

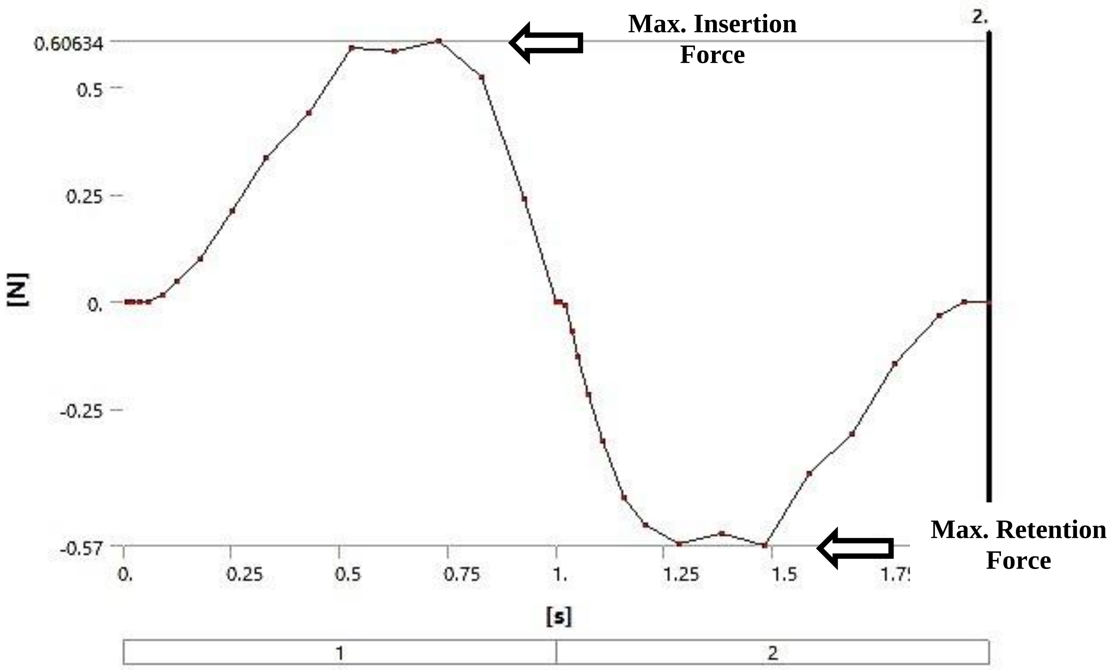

Figure 8. Maximum insertion and retention force for Set 1

Figure 9 shows the snap-fit position for set 1 as it is in contact with target (small box) with stress value on the snap-fit body. The stress value of Set 1 can be seen in the stress legend with the maximum value of 39.147 MPa. The lower insertion and retention forces should contribute to the lower value of stress for the cantilever hook snap-fit.

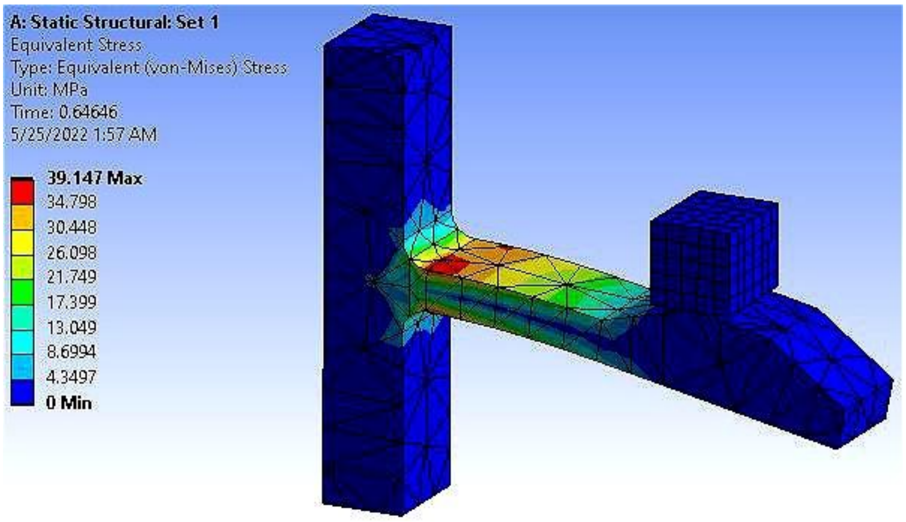

Figure 9. Stress distribution of snap-fit for Set 1

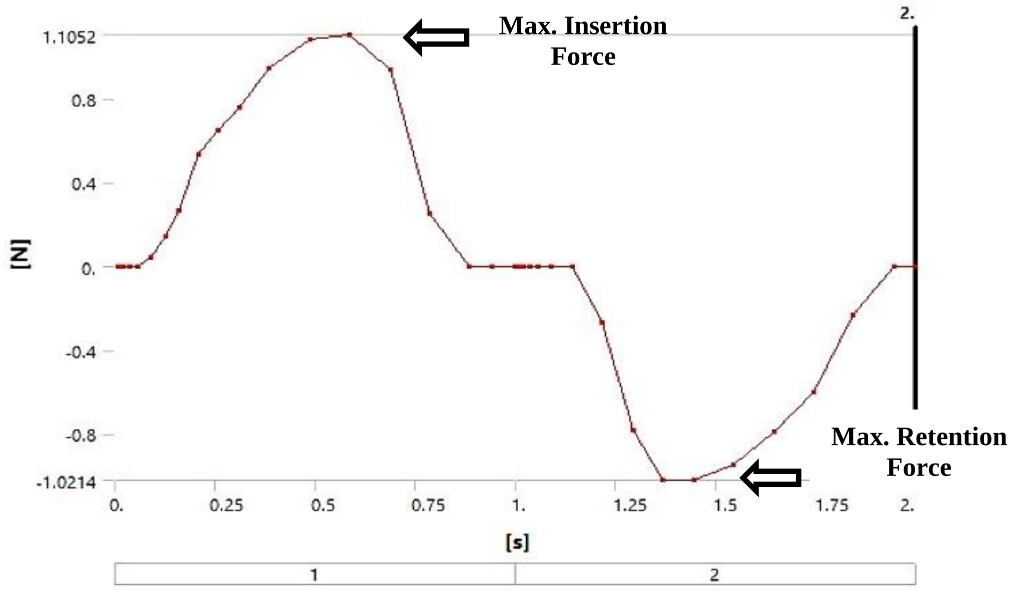

Figure 10. Maximum insertion and retention force for Set 7

Figure 11 shows the snap-fit position for set 7 as it is in contact with target (small box) with stress value on the snap-fit body. The higher value of insertion and retention angle for snap-fit contributes to the higher stress value as in Figure 10 which shows the maximum value of stress for Set 7 is 41.128 MPa. In terms of insertion and retention angles, sets 1 and 5, 2 and 6, 3 and 7, and 4 and 8 may be contrasted. When inserting and retaining a cantilever snap-fit mechanism, a larger insertion and retention angle required more forces. Sets 1 and 2 may be compared to Sets 3 and 4, respectively, while Sets 5 and 6 can be compared to Sets 7 and 8, respectively. The force of insertion and retention of the cantilever hook snap-fit is improved by having a thicker beam, as may be inferred.

The beam lengths of sets 1 and 2, 3 and 4, 5 and 6, and 7 and 8 may be compared. Because of this, a cantilever snap-fit mechanism with a greater beam length required less pressure for insertion and retention. When designing a snap-fit mechanism that requires a low insertion force for quick assembly, it is preferable to employ design features such as a lower insertion angle, a thinner cantilever beam, and a longer cantilever beam length. On the other hand, creating a snap-fit mechanism with a tighter grip needed a higher retention force. The optimal design characteristics include a larger retention angle, a thicker cantilever beam, and a shorter cantilever beam length.

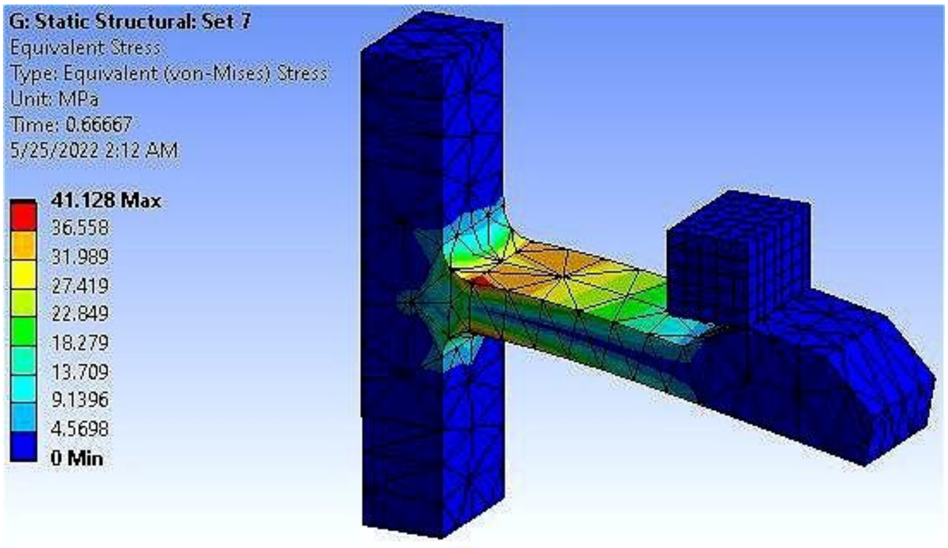

Figure 11. Stress distribution of snap-fit for Set 7

Table 3. Sets of snap-fits and the maximum insertion and retention forces

Set	α, β	T_b	L_b	F_i (N)	F_r (N)
1	Lower angle	Normal thickness	Normal length	0.60634	- 0.57
2			Longer length	0.27162	- 0.25645
3		High thickness	Normal length	0.86051	- 0.79725
4			Longer length	0.34719	- 0.33672
5	Higher angle	Normal thickness	Normal length	0.80827	- 0.75063
6			Longer length	0.30456	- 0.28944
7		High thickness	Normal length	1.1052	- 1.0214
8			Longer length	0.40273	- 0.38837

Snap-fit is one of the easiest ways to connect two parts together, and in this study, it is emphasized on cantilever hook snap-fits joints. There are several factors that are taken into considerations which are the thickness of the beam (T_b), beam length (L_b), beam width (W_b), base radius (R_b), insertion (α) and retention angle (β). The differences in the parameters contributes to the force of the insertion and the retention of the cantilever hook snap-fit. Thus, there are several results that can be obtained with various parameters. In this research, it is stated in the results that Set 7 has the highest value of insertion and retention forces as it has the higher angle with higher thickness and normal length. With the results, it can be seen that the higher thickness of the beam, the higher forces for the snap fit meanwhile as for the length, the longer the beam, the lower forces that are needed to insert and detach the snap-fit.

5.0 CONCLUSIONS

This paper reports the simulation results for cantilever hook snap-fits in terms of evaluating its performance on insertion and retention forces. The results are obtained for the 8 sets of models that are simulated and it can be concluded that higher insertion and retention angle required a higher force during insertion and retention of the cantilever snap-fit mechanism. The results are summarized below:

1) Set 7 has the maximum force of insertion and retention which are 1.1052 N and -1.0214 N, respectively, due to the high angle of insertion and retention.
2) The higher thickness of the cantilever beam increases the forces needed to insert and retract the cantilever snap-fit as shown in set 3 and set 7. Lastly, beam length that is longer in a cantilever snap-fit mechanism required a lower force during insertion and retention of cantilever snap fit which has been shown by set 8 if compared to set 7.
3) It can be seen the lowest insertion and retention forces required is from set 2 and the highest force needed is from set 7.

For future research, it is advisable to conduct experimental analysis using the same material for insertion and retention forces of cantilever hook snap-fit.

6.0 ACKNOWLEDGMENTS

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