INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOLUME 22, ISSUE 3, 2025, 12573 - 12585
DOI: https://doi.org/10.15282/ijame.22.3.2025.3.0960

RESEARCH ARTICLE

Analyzing Insertion and Retention Forces in Cantilever Snap-Fits: A Combined Simulation and Experimental Approach

S.S. Abdul Manan, M.N. Osman Zahid*

Faculty of Manufacturing and Mechatronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pahang, Malaysia

ABSTRACT – Snap-fit joints offer a cost-effective and efficient alternative to traditional joining methods by eliminating the need for external fasteners and adhering to Design for Assembly guidelines. This study examines and optimizes cantilever snap-fits, a popular choice due to their simplicity. The study employs modeling and experimental testing to investigate how major design characteristics affect insertion and retention forces. Sixteen models were created in Autodesk Inventor, 3D printed with ABS material, then simulated using ANSYS. Experimental validation was performed utilising a Universal Testing Machine to quantify insertion and retention forces, and the results were compared to simulations to assess the accuracy of the Finite Element Model. The results show that Model 13 had the maximum force for simulation insertion at 34.346 N, while Model 10 had the lowest at 3.34 N. Model 5 had the largest retention force (39.458 N), while Model 2 had the lowest (1.722 N). Model 13 had the highest insertion force of 32.177 N, while Model 16 had the lowest at 3.234 N. Model 5 had the highest retention value (41.144 N), while Model 2 had the lowest (1.657 N). Model 16 was determined to be the best design, due to its consistently low insertion forces resulting from its longer beam length and higher insertion angle. The evaluation of percentage mistakes, particularly in Model 14 with retention and insertion error percentages of less than 1.2% and Model 15 with less than 2.4%, emphasizes the importance of experimental validation for accurate predictions. This study enhances the understanding of cantilever snap-fit mechanics, simplifying the development of optimized designs for numerous industrial applications by combining simulation and experimental analysis to achieve precise and reliable snap-fit performance.

ARTICLE HISTORY
Received : 04th Aug. 2024
Revised : 05th May 2025
Accepted : 27th May 2025
Published : 01st Sept. 2025

KEYWORDS
Snap-fits
Insertion forces
Retention forces
3D printing
Universal testing machine

1. INTRODUCTION

Snap-fits are a simple and cost-effective way to mechanically link parts, enabling repeated assembly and disassembly without damaging the component if the joint is properly engineered. Because of these advantages, snap-fits have essentially supplanted traditional connecting methods in plastic part assembly, therefore, Design for Assembly guidelines encourage their widespread use [1]. Snap-fits prevent engagement until the catch slips into an undercut in the mating component, resulting in an interlock. Until this interlock is reached, the assembly is incomplete and could come apart. Snap-fits can join many materials, such as metal and plastic, however, they are susceptible to fatigue-induced fractures, which is an important concern. Because of their transient nature, snap-fits are commonly utilised in consumer items and enclosures. The expression "snapping something open" likely means that there is a snap-fit mechanism [2].

Snap-fits can be categorized as either permanent [3] or non-permanent [4]. Permanent snap-fits cannot be taken apart, while non-permanent snap-fits can be put together and taken apart repeatedly. Since snap-fits enable quick disassembly for recycling, they are a sustainable method of assembly as the parts can be made from different materials [5]. Connecting techniques are very important in product design and engineering tasks, and they have a great impact on product efficacy and performance. The cantilever hook snap-fit design is especially appealing due to its ease and effectiveness in incorporating multiple parts in primarily one step, especially as companies strive for higher efficiency, lower costs, and better design. The snap-fit cantilever hooks' insertion and retention forces are among the most critical characteristics that influence the assembly's final performance. Engaging or disengaging the cantilever hooks during the assembly and disassembly processes requires energy, commonly referred to as insertion force or retention force. Optimal force levels must be maintained to achieve a secure snap fit while preserving the components' structural strength, regardless of the forces acting on them. Excessive force would risk breakage, and insufficient force would make the connection looser than needed, undermining the assembly's overall function.

Cantilever hook snap-fit behaviour has been modelled in the previous studies that developed analytical methods and equations designed for them [1] [6] [7]. Nonetheless, these models are inaccurate, as existing literature does not examine the nature of snap-fit deformation contact mechanics and the mechanics of snap-fit contact structure with sufficient detail. Various techniques have been proposed to model the behaviour of cantilever hook snap-fits, crucial elements in numerous contemporary products, and each has its benefits and detriments. Analytical models approximate calculations with equations based on theorems like beam theory. These models are accurate with the relationships they offer between design

***CORRESPONDING AUTHOR | M.N. Osman Zahid** | ✉ nafis@umpsa.edu.my

parameters and performance, and they provide results and insights remarkably quickly [6] [7]. However, accuracy suffers when complex geometry or nonlinear material behaviour is present due to over-reliance on assumptions. In contrast, numerical models employ numerical techniques to solve governing equations, which yield more complex scenarios while also accommodating nonlinear material properties. Finite Element Analysis (FEA) is one of the most powerful and flexible approaches available, which can accommodate a wide range of geometries, materials, and even complex loading conditions [8].

FEA is computationally expensive when compared to other options, however, the granular understanding of stress, strain, and deformation data it yields allows for in-depth analyses and optimization. The balance between precision, complexity, computational resources, and modelling purpose dictates the choice of modelling approach, which leads to many approaches being combined in a strategy for validating design or conducting thorough analysis [9]. To evaluate the reliability and precision of Finite Element Models in predicting snap-fit behavior, one must correlate the simulation outcomes with those of experiments. This research aims to simulate and test the behaviour of a cantilever snap-fit joint to evaluate its performance [10]. The overall goal is to verify whether the Finite Element Model accurately simulates real-world snap-fit behavior by performing validation through simulations and experiments, which includes measuring the insertion and retention forces as key performance metrics. The refinement of model predictions through experimental measurements helps strengthen the model, alongside adjustments proposed to the parameters and boundary conditions, or the material's properties, making the model more reliable for optimized simulations of snap-fit designs [11]. The issue of disparity between the model and the practical application of snap-fits is a severe concern, as it reduces the credibility and confidence in a design. This leads to erroneous design decisions, especially those based on simulations driven by Finite Element Analysis (FEA), which do not align with predictive behaviour simulations of snap-fits. [12]. For example, if the insertion force is underestimated, the snap-fit may require excessive effort to assemble, risking damage to parts or injury to users.

Conversely, if the retention force is overestimated, the snap-fit may disengage too easily, resulting in loose assemblies, product failure, or safety risks. Moreover, such discrepancies waste time and resources. Engineers can trust simulation results to finalize their design quickly, but then realize, when assembling a prototype or in production, that the product is not working as intended. This causes numerous design revisions, additional costs, and a longer time-to-market. It also limits the scalability and manufacturability of the product, particularly for high-volume production [13]. Consequently, it is important to comprehend and minimize these discrepancies, since numerical models of the simulation must be accurate, reliable, and represent reality as much as possible when, for instance, designing parts which are of critical importance to the 3D printing process and where the material characteristics and tolerances can change dramatically [14]. This work fills the gap in predicting the performance of 3D-printed snap-fits, as most earlier works use simple simulation models that do not consider actual material behavior, friction, and manufacturing variation. While analytical and numerical models are available, only a few have been experimentally verified for snap-fits of 3D printed systems, in particular with the material ABS. This work improves upon prior research by comparing Finite Element Analysis (FEA) results with experimental testing, using realistic design parameters and fabrication conditions [15]. The study offers more accurate insights into snap-fit performance, thereby helping to bridge the gap between simulation and real-world applications.

1.1 Related Works

Snap-fit features are molded directly onto pieces, as opposed to screws and rivets, which are distinct fasteners. Assembly motions are frequently reduced as well, which is useful from an ergonomic aspect. Several problems were addressed in the study of snap-fits, including excessive use of force and stress concentration [16]. The use of excessive force can cause breaks on the snap-fits and contribute to injuries during assembly. This can happen to workers on assembly lines in manufacturing factories. By conducting this research, it can be determined which design of the snap-fits can lower the risk of injuries. This means that the force of insertion of the snap-fits must be low enough for the assembly to occur without causing finger injuries. Higher insertion and retention forces mean that the force exerted by the assembler will be high, potentially causing excessive force.

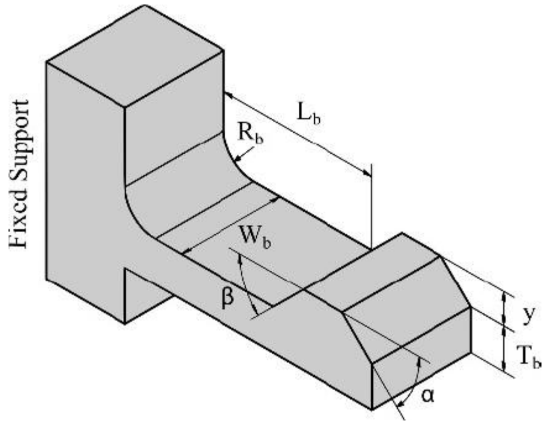


Figure 1. Parameters of cantilever snap-fits [17]

During insertion, two forces act on the tip of the snap-fit: the bending force (P) and the insertion force (Fi). The insertion force acts against the insertion direction, and its magnitude depends on the parameters of the snap-fits, specifically the insertion angle, length, width of the beam, and thickness of the beam. To disassemble a snap-fit feature, the retention force (Fr) must be exerted in the separation direction. Detachment or disengagement happens in a permanent assembly due to fracture, persistent deformation, or lack of engagement of two mating pieces. There are several parameters affecting the insertion and retention forces of snap-fits, which are the feature thickness (Tb), beam length (Lb), beam width (Wb), base radius (Rb), mounting (α), and dismounting angle (β) as shown in Figure 1. Table 1 shows the design considerations for cantilever snap-fits.

To determine the performance of snap-fits in complicated plastic parts, it is frequently essential to study the entire part, which can be an expensive and time-consuming process. Among the important design factors that can influence the problems mentioned previously are the thickness of the features, beam length, beam width, base radius, and mounting and dismounting angles. Small interferences between these factors will include the insertion and retention forces, which can influence joint quality. In this context, this exploration delves into a regression analysis to determine how one variable impacts another, focusing specifically on factors such as the thickness of the features, beam length, beam width, base radius, and mounting and dismounting angle. This method enables the identification of the most influential factors, providing a clear and comprehensive understanding of the insertion and retention forces acting on the snap-fit joint. Many earlier studies rely heavily on analytical models, which, while useful for initial design estimations, often oversimplify the behavior of snap-fits by assuming linear elasticity, ideal geometry, and neglecting friction and stress concentrations. Additionally, although finite element analysis (FEA) has been employed in some research, these models are often validated using injection-moulded components, not 3D-printed ones, which have different mechanical properties due to layer-based manufacturing. Very few studies have combined simulation with experimental validation for 3D-printed snap-fits, especially under realistic conditions. This gap limits the reliability of those models for additive manufacturing applications. This study addresses this shortfall by directly comparing FEA results with experimental data from abs snap-fits fabricated through 3d printing, providing a more accurate assessment of real-world performance.

In conclusion, the installation of cantilever hook snap-fits is a multidimensional process that demands careful consideration of design, materials and forces. The success of this joining mechanism relies on the collaboration between engineering expertise and cutting-edge technologies to ensure seamless, reliable, and efficient assembly, ultimately contributing to the overall functionality and longevity of the final product. Figure 2 shows the installation of the snap-fit during insertion. As can be observed, the hook deflected during insertion, and since the hook angle or the dismounting angle is 90°, this form of snap-fit is permanent [18].

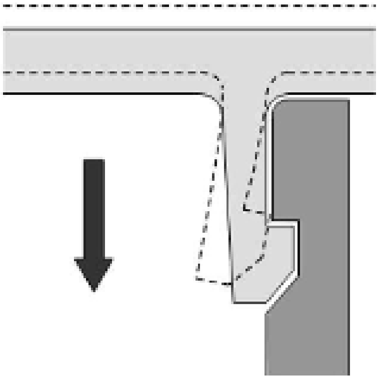


Figure 2. Direction of installation of snap-fit

The contact between the hook and the catch involves nonlinear behavior, friction and potentially large deformations, making it difficult to model accurately using simplified analytical approaches. Numerical methods like FEM can handle contact more realistically, they often require careful meshing, appropriate contact algorithms, and significant computational resources, especially for high-fidelity simulations. Furthermore, accurately predicting the long-term performance and failure of snap-fits remains an active area of research. Factors like creep, fatigue, and environmental degradation can significantly influence the lifespan of snap-fit assemblies. Modeling these long-term effects requires sophisticated material models, accelerated testing data and potentially coupled simulations considering multiple physics, posing significant challenges for researchers. The research articles provided illustrate the different approaches used to study and improve the performance of snap-fits. Ji, Lee et al. (2011) examined cantilever snap-fits for haptic devices, possibly addressing issues such as smooth engagement and disengagement, sound and vibration during actuation, and overall material feedback [19]. Otmani and Shin (2023) studied backside-supported snap-fits using large deformation analysis along with nonlinear material modeling techniques, capturing the behavior of this configuration under significant loading. Their findings emphasize the importance of verifying experimental procedures and results, particularly for large deformations and intricate geometrical structures [6]. In contrast, Wada (2020) seems to examine the mechanics of snap-fits more in-depth, potentially developing analytical models with some form of experimental verification for a range of snap-fit types [7]. It can be hypothesized that these works collectively demonstrate ongoing attempts to develop models that accurately predict snap-fit behavior for improved design reliability and efficiency.

That statement was more theoretical than anything. In practice, however, the most critical factor is determining the optimum beam thickness for cantilever hook snap-fits to maintain flexibility without compromising strength. According to Bonenberger (2017), the beam thickness (Tb) is normally the first parameter and constraint for the feature design [20]. Ideally, the beam should be thick enough to provide sufficient strength to secure the connection and resist breakage, yet thin enough to allow for the necessary deflection during engagement and disengagement. The beam length (Lb) in Figure 2 should be at least 5 times the beam thickness (Tb), but closer to 10 times the thickness is preferred. Beams can be longer than 10 times, but it will cause problems with warpage and filling [20]. Technically, the beam width (Wb) does not directly affect the maximum assembly strain; however, it does impact the forces during assembly and disassembly, as well as the retention strength. The optimum beam base radius (Rb) for cantilever hook snap-fits is crucial for reducing stress concentrations and enhancing the durability and performance of the snap-fit joint. A well-designed base radius ensures a smooth transition between the beam and the fixed part, distributing stresses more evenly and minimizing the risk of cracking or material fatigue. Each of the parameters is mostly dependent on each other as the design consideration can affect the functionality and strength of the parts. Table 1 shows the design considerations for cantilever snap-fits.

Table 1. Geometric relationship for deflection mechanism dimensioning [20]

Variable	Description	Relationship
Tb	Thickness for feature extending from a wall	Tb = Tw
	Thickness for feature protruding from a wall	Tb = 0.5Tw
Lb	Beam length	5Tb < Lb < 10Tb
Wb	Beam width	Wb < 0.5Lb
Rb	Base radius	Rb ≤ 0.5 Tb
y	Retention mechanism height, for Lb/Tb ≅ 5	y < Tb
	Retention mechanism height, for Lb/Tb ≅ 10	y = Tb
α	Mounting angle	α = 25°~30°
β	Dismounting angle, non-releasing joint	β > 80°
	Dismounting angle, releasing joint	β = f (retention)

2. METHODS AND MATERIALS

The methodology, as shown in Figure 3, employs the Finite Element Method (FEM) Analysis to meticulously model the insertion and retention forces that arise during the mating process of snap-fits, using ABS as the simulated material. Initially, a series of simulations are conducted, varying key design parameters to generate predictive insertion and retention force curves based on a detailed CAD model. These simulations are crucial for understanding how changes in design parameters, such as dimensions, material properties, and geometric features, affect the forces experienced during the assembly and disassembly of snap-fit joints. The experimental phase involves constructing a dedicated test fixture that replicates the conditions under which snap-fits are typically used. This fixture integrates components including the snap-fits themselves, a controlled sliding mechanism to simulate insertion and disengagement, precision load cells for force measurement, and other instrumentation to capture relevant data. The experimental testing is conducted using a Universal Testing Machine (UTM). The compression test function within the Instron Universal software is utilized to measure and record the insertion and retention forces of the snap-fits. Through these experiments, researchers can validate the accuracy of the simulated force predictions and gain insights into how different variables interact in real-world scenarios.

In snap-fit design, a constant parameter is a feature or characteristic that remains unchanged throughout the design process. It is a factor that designers intentionally maintain to achieve specific outcomes or ensure certain functionalities in the snap-fit assembly. The constant parameter is a parameter that is not manipulated and remains the same for the whole experiment. One common constant parameter in snap-fit design is the material properties of the components involved. Other constant parameters may include geometric features such as the dimensions and shape of the snap-fit elements, especially those related to the cantilever hooks or undercuts that facilitate the engagement and disengagement of the components. Consistency in these dimensions helps ensure reliable and repeatable performance across multiple units of a product. In this research, the constant parameters are as shown in Table 2.

Several design parameters are varied and evaluated across 16 models, as indicated in Table 1. Each model features distinct sets of design configurations. The specific parameters are detailed in Table 3. The beam lengths and angles used in the snap-fit models were determined with reference to the overall dimensions and functional constraints of a standard electrical outlet cover. While the foundational parameters from Bonenberger (2017) and Amaya (2019) guided the general design approach, particularly regarding stress distribution and retention force, the exact values for beam geometry were adapted to suit the physical size, wall thickness, and required flexibility of the outlet cover assembly. The chosen beam lengths provide adequate deflection within the available space, ensuring proper engagement and disengagement during installation, while minimizing the risk of material failure. Similarly, the insertion and retention angles were selected to offer a secure fit under typical assembly forces, without compromising user ergonomics or manufacturability. These values were further validated through modelling and design iteration to ensure reliable performance under expected loading conditions.

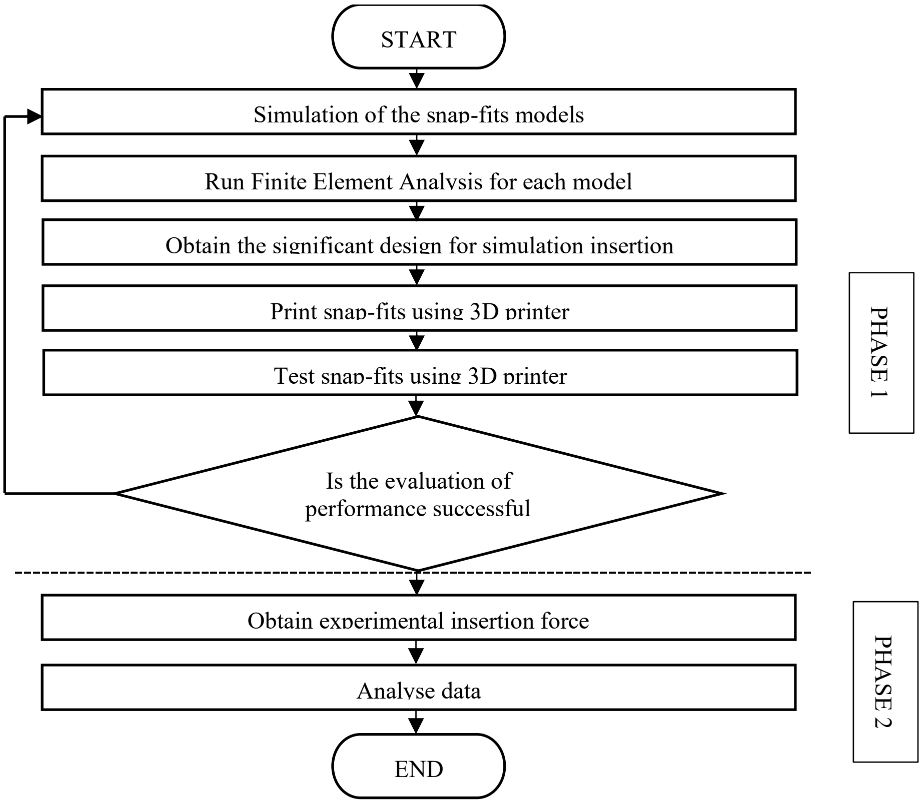


Figure 3. Flowchart of the research

Table 2. Constant parameters for snap-fits

Width of the beam, W_b	7 mm
Thickness of the wall, T_w	6 mm
Radius of the base, R_b	2 mm

Snap-fits can also be made using metamaterials, which means that snap-fits can be created using multiple materials simultaneously. This can be designed to achieve multistability, allowing each stable state to be maintained without continuous energy input [21]. However, there is also a downside to using metamaterials: producing metamaterials with precise and intricate structures required for snap-fit joints can be challenging. Achieving consistent properties, intricate geometries, and suitable surface finishes in metamaterials adds complexity to the manufacturing process. The material used in this research is Acrylonitrile Butadiene Styrene (ABS), a thermoplastic polymer commonly used for injection molding and 3D printing [22]. ABS polymers consist of three monomer units, which are acrylonitrile, butadiene and styrene [23]. ABS was selected due to its moderate Young's Modulus of 2174 MPa, which provides sufficient stiffness for structural integrity while still allowing flexibility for deflection. Its density of 1050 kg/m^3 makes it lightweight, which is beneficial for portable or enclosed components like socket covers. The tensile strength of 29.6 MPa and bending strength of 72.8 MPa indicate good resistance to mechanical loading and deformation, while the Charpy impact strength of 12.6 kJ/m^2 reflects the material's ability to absorb energy during sudden impacts. These properties collectively contribute to the durability, performance, and reliability of ABS in functional snap-fit designs.

To begin 3D printing the snap-fit model, open Ultimaker Cura and import the .stl file. Adjust the model's scale, if necessary, then click "Prepare" to slice the model. Select ABS as the printing material and ensure the settings match ABS requirements, including a nozzle size of 0.4 mm, bed temperature, and printing temperature. Set the infill pattern to concentric and infill density to 100% for maximum strength, which helps prevent the snap-fit from breaking. Once sliced, send the file to the Ultimaker S5 printer. On the printer, choose the file, confirm ABS as the material, and load the filament if it's not already loaded. The printer will automatically calibrate the nozzle offset and begin printing. During printing, the display will show the remaining time. After printing is complete, the model can be safely removed from the print bed. The flow process can be seen in Figure 4. Any change in the 3D printing process can significantly affect the quality and performance of the snap-fit model. For example, adjusting the scale may impact fit accuracy, while incorrect print settings, such as temperature, infill density, or material choice, can lead to weak or deformed parts. Using a different infill pattern or reducing density can make the snap-fit more prone to breaking. Even small changes, such as nozzle size or slicing settings, can significantly impact surface finish and dimensional precision. To ensure a reliable snap-fit function, it is essential to maintain consistent and optimized printing parameters throughout the process.

Table 3. Manipulated parameters in snap-fits

α	β	T_b	L_b	Model
25°	35°	0.5 T_w (0.5 × 6 mm) = 3 mm	5 T_b (5 × 3 mm) = 15 mm	1
			10 T_b (10 × 3 mm) = 30 mm	2
		0.6 T_w (0.6 × 6 mm) = 3.6 mm	18 mm	3
			36 mm	4
	45°	3.0 mm	15 mm	5
			30 mm	6
		3.6 mm	18 mm	7
			36 mm	8
30°	35°	3.0 mm	15 mm	9
			30 mm	10
		3.6 mm	18 mm	11
			36 mm	12
	45°	3.0 mm	15 mm	13
			30 mm	14
		3.6 mm	18 mm	15
			36 mm	16

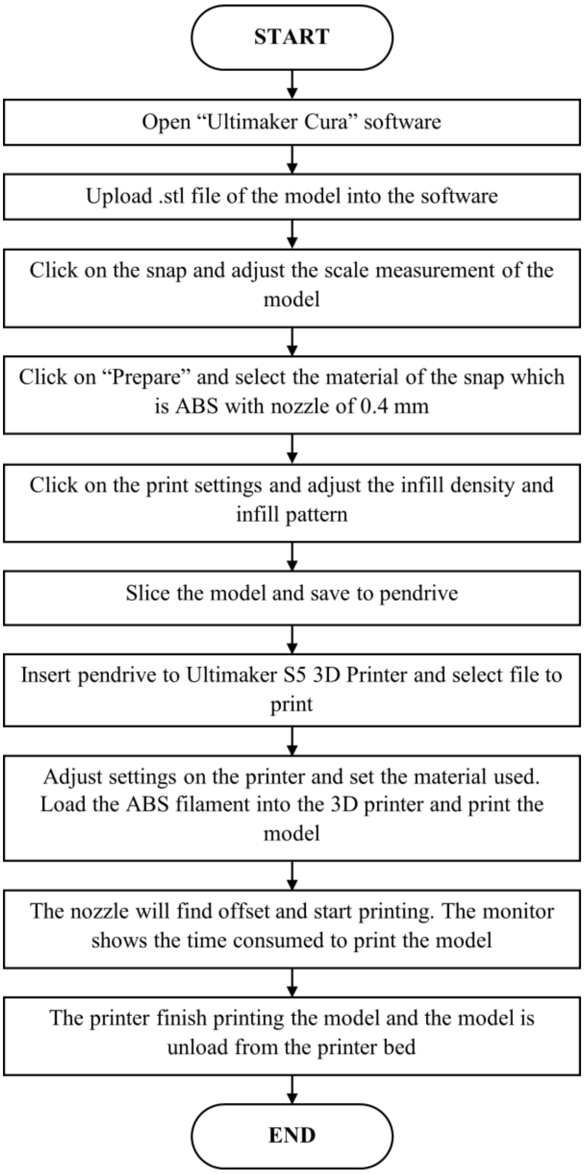


Figure 4. 3D printing process

To perform the simulation in ANSYS Workbench, the Static Structural module is selected, and ABS is assigned as the material. The 3D model, created in Inventor and saved as a .stp file, is imported into the Geometry section. In ANSYS Mechanical, contact surfaces are manually defined, where the snap-fit is assigned as the "Contact" and the female part as the "Target," with a friction coefficient of 0.4 to simulate realistic ABS surface interaction. A friction coefficient of 0.4 was used, which is a typical value for dry ABS-to-ABS contact in plastic assemblies. This coefficient directly influences the predicted insertion and retention forces in the FEA model, as it affects the resistance at the interface during sliding. While surface finish, print orientation, and real-world wear can cause slight variation in friction, using 0.4 provides a reasonable approximation that balances realism and computational stability. Including accurate material and friction parameters ensures the simulation closely reflects physical behavior, improving confidence in the results when comparing them with experimental data. The formulation is set to Augmented Lagrange for better contact convergence. For meshing, tetrahedral elements are used due to their ability to conform to complex geometries. Quadratic elements are applied to the snap-fit part to ensure higher accuracy in stress and deformation analysis, while linear elements are used for the female part. The default mesh sizing is used under the “Sizing” function. In the Analysis Settings, the number of steps and substeps is defined, and nonlinear controls are activated with “Force Convergence” turned on. Boundary conditions are then applied, a fixed support is assigned to the female part, and a tabular displacement is applied to the snap-fit along the X-axis, while the Y and Z directions are held constant. In the Solution section, Total Deformation and Reaction Force are selected to compute insertion and retention forces. The simulation is then run, and once it is completed successfully, the results are extracted and analyzed.

During the simulation, the results for total deformation and force reaction are generated. Thus, the insertion force of the snap can be obtained from the value of the force reaction [24]. In the simulation, several assumptions were made to simplify and focus the analysis on the insertion and retention performance of the snap-fits. The material behavior of ABS was assumed to be linearly elastic, based on standard mechanical properties from datasheets, meaning that plastic deformation and time-dependent effects, such as creep, were not considered. This assumption is suitable for capturing initial deformation behavior but may not fully represent real-world conditions under repeated loading. For the boundary conditions, the base of the snap-fit model was fixed to simulate attachment to a rigid socket cover, preventing translation and rotation. The mating component (representing the part being inserted) was assigned a prescribed displacement in the insertion direction, allowing the software to calculate resulting forces. A friction coefficient of 0.4 was applied to the contact surfaces to represent dry ABS-to-ABS interaction. These simplifications help streamline the analysis but also introduce limitations. For example, the model does not account for manufacturing imperfections, variation in surface roughness, or nonlinear behaviour during large deformations. Future work could include more advanced material models and real-contact simulations for greater accuracy.

In the experimental stages, the Universal Testing Machine (UTM) is used to test the mechanical properties (tension, compression, etc.) of a given test specimen by exerting tensile, compressive or transverse stresses. The snap-fits are loaded on both grips of the UTM as in Figure 5. The experimental testing in this research involves both compression and tension tests [25]. The compression test is used to measure the insertion force, while the tension test determines the retention force. These results are then compared with the simulation data obtained from ANSYS. During testing, the snap-fit specimens are securely clamped between the grips of the Universal Testing Machine (UTM), and the tests are carried out using Instron Universal software. The Instron Universal Testing Machine (UTM) Model 3369 used in this study has a load capacity of 50 kN and supports a maximum test speed of 500 mm/min, with a minimum speed of 0.005 mm/min, allowing for precise control during testing. It can apply up to 25 kN of force at full speed and operate at 250 kN maximum speed under full load. The machine features a return speed of 500 mm/min, a total crosshead travel of 1122 mm, and a vertical test space of 1193 mm, providing ample room for a variety of test setups. With a column spacing of 420 mm, and overall dimensions of 1582 mm in height, 756 mm in width, and 707 mm in depth, it offers a stable testing platform. The UTM weighs 141 kg with a typical load cell and requires a maximum power input of 700 VA, making it suitable for high-precision mechanical testing such as the tension and compression of snap-fit samples. Before proceeding with the experimental test, the machine is calibrated to 0 z-position, indicating the machine is in the initial state. Each snap-fits were tested three times to obtain the average value.

Figure 5. Snap-fit loads on UTM

The equation (1) below is for insertion force, while equation (2) is used to determine retention force. The terms "μ" denote the coefficient of friction. "α" is the insertion angle, and "β" represents the retention angle, respectively [27]. The maximum deflection of the beam and the force of deflection may be determined using the design parameters of the cantilever hook snap-fit.

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

$$F_i = P \times \frac{\mu + \tan(\beta)}{1 + \mu \tan(\beta)} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1 Simulation Results

The snap-fit model is designed using Autodesk Inventor. Designing a cantilever hook snap-fit using Autodesk Inventor yields a detailed and precise 3D model that encapsulates the key features and functionalities of the snap-fit assembly. Autodesk Inventor's comprehensive set of tools enables users to simulate assemblies, apply materials, and refine designs with precision. The software allows for meticulous control over dimensions, tolerances, and geometric features, ensuring that the cantilever hook snap-fit meets specific requirements. The documentation and annotation features facilitate clear communication of design details. Figure 6 shows an example of a snap-fit model design. Sixteen models are created according to the design guidelines in Table 1. After designing, all 16 models are simulated in ANSYS software.

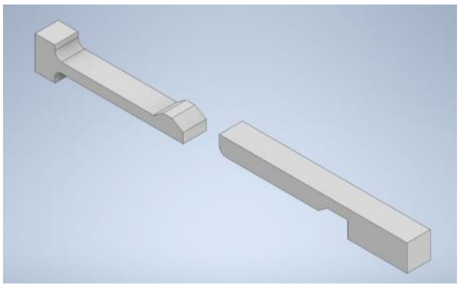
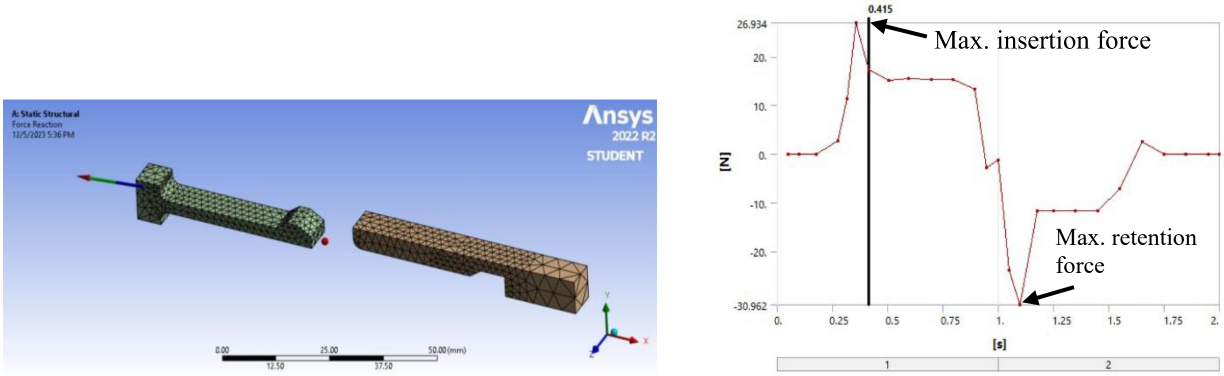


Figure 6. Snap-fit design in Autodesk Inventor



(a) Force reaction of the cantilever hook snap-fit model

(b) Illustration of the maximum point of insertion and retention force

Figure 7. Force reaction for the snap-fit model in ANSYS

Simulating cantilever hook snap-fit joints using ANSYS provides valuable insights into the mechanical behaviour and performance of the designed assembly. The simulation results offer a comprehensive understanding of how the snap-fit components interact under different loading conditions, aiding in the refinement and optimization of the design. Figure 7(a) shows the force reaction of the cantilever hook snap-fit model, and the graph in Figure 7(b) illustrates the maximum point of insertion and retention force.

The histogram in Figure 8 visualizes the distribution of insertion and retention forces for 16 models. The odd-numbered models (1, 3, 5, 7, 9, 11, 13, 15) exhibit higher insertion and retention forces compared to the even-numbered models (2, 4, 6, 8, 10, 12, 14, 16), which show lower forces. Among the odd-numbered models, it is generally observed that these models exhibit higher forces compared to the even-numbered ones. Notably, Model 5 stands out with a significant difference between its insertion force of 26.90 N and its retention force of 39.46 N, suggesting that this model is highly secure once assembled, requiring substantial force to disassemble. For odd-numbered models, retention forces are generally higher than insertion forces, indicating greater effort needed for disassembly. On the other hand, even-numbered models typically show lower forces, with insertion forces often surpassing retention forces. Model 16 is particularly noteworthy in this category. It demonstrates a lower retention force of 1.97 N compared to an insertion force of 3.36 N, which indicates that disassembly is easier after assembly. This trait makes Model 16 ideal for systems that undergo repetitive assembly and disassembly cycles. The findings also imply that the beam length for each model plays an important role in determining these forces. Variability in beam length directly influences both the insertion and retention forces, illustrating its significance regarding the design and performance of these models. The higher retention forces associated with odd-numbered models imply that they are designed to resist disassembly, while lower forces in even-numbered models make them more suited for removable fittings. Verification of simulated results against experimental data is crucial to validate these assumptions, thereby ensuring that applicable, further refinements and optimizations in snap-fit joint configurations can be achieved.

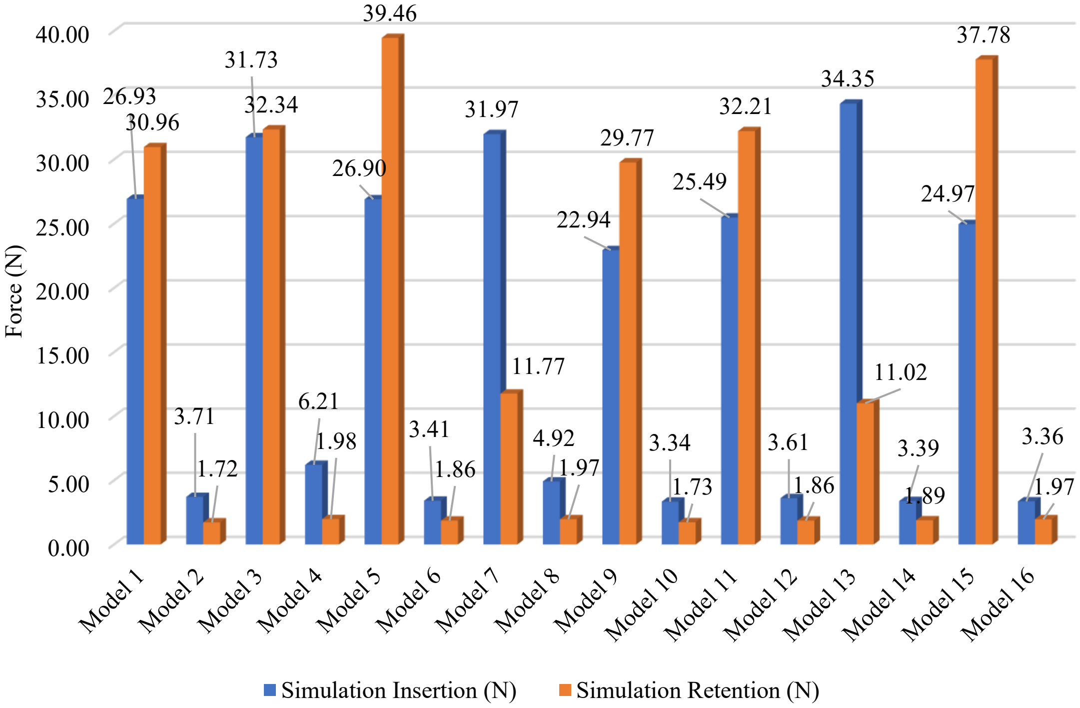


Figure 8. Simulation results of 16 models of snap-fits from ANSYS showing the trends for insertion and retention forces

3.2 Experimental Result

In the experiment, the snap-fits are printed using a 3D printing machine with the infill pattern concentric and a density of 100% to prevent the snap-fits from breaking. Then, the compression test is done using UTM for all 16 models. The experiment is done three times for each model, and the average value for insertion force is taken. The values of average force generated are obtained after the test is done three times for each model. Figure 9 illustrates the trends from experimental analysis.

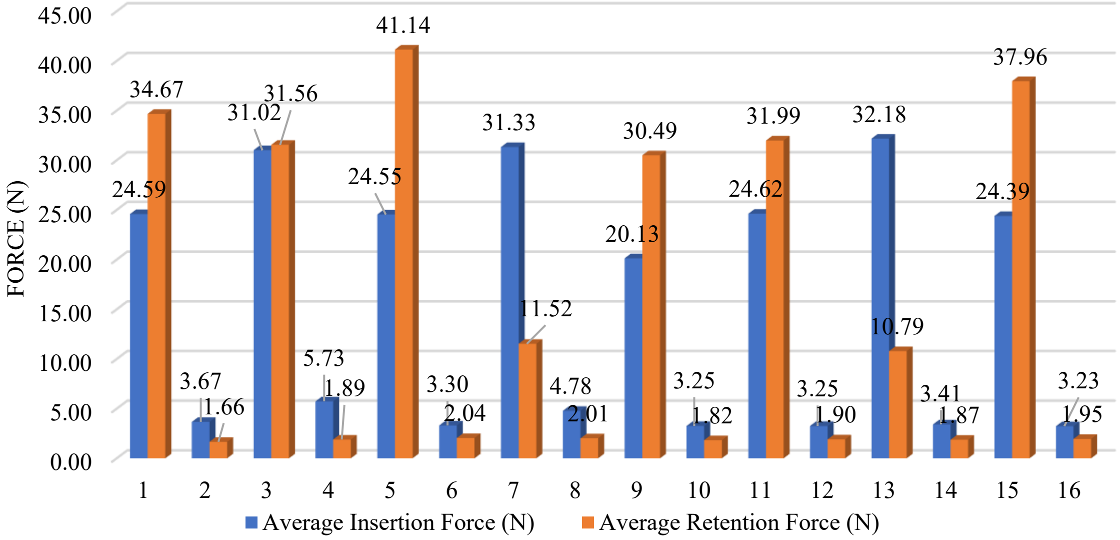


Figure 9. Experimental results of 16 snap-fits models by using UTM showing the trends for insertion and retention forces

The odd-numbered models (1, 3, 5, 7, 9, 11, 13, 15) exhibit higher insertion and retention forces compared to the even-numbered models (2, 4, 6, 8, 10, 12, 14, 16), which show lower forces. Also, odd-numbered models tend to have retention forces greater than insertion forces, while even-numbered models' fields have greater insertion forces than retention forces. These trends are comparable to the results we achieved in the simulation. Model 13 has the highest insertion force of 32.18 N while Model 16 possesses the lowest insertion force at 3.23 N. Holding of forces, Model 5 has the highest value of 41.14 N and Model 2 shows the lowest value of 1.66 N. This data indicates a distinct boundary on force requirements relative to the model order and most likely corresponds to a change in structure, like beam length or design specifications. The odd-numbered models having higher forces indicate that such models are likely to be more robust or tightly fitted, because greater effort is needed to both insert and retain these models. Such a feature may be useful in situations where secure fitting is vital.

3.3 Comparative Analysis

The information provided in Figures 8 and 9 displays a comprehensive evaluation of the retention and insertion forces for 16 models, accompanied by both simulation and experimental data. In model 1, a large difference was noted in simulated results as opposed to actual results. Simulated values for retention and insertion forces were 26.93 N and 30.96 N, respectively, while experimental values were 24.59 N and 34.67 N. This indicates that the experimental retention force is much higher than the simulated value, which indicates a tighter assembly in real-world conditions. Model 5 also stands out with a large difference in retention forces. The required retention forces in the simulation were 26.90 N for insertion and 39.46 N for retention. In the experiment, the insertion force is similar at 24.55 N, but retention is much greater at 41.14 N. These values further bolster the fact that the retention forces in real-world conditions are higher. From both datasets, model 13 can be noted for having the highest insertion force. Simulated inclusion and retention forces are noted as 32.21 N while retention is 34.35 N and, in the experiments, 32.18 N and 31.99 N are both noted. The retention force in the experiment is slightly lower than the simulated value, which indicates that the datasets are closely aligned for the model.

In contrast, the forces are lowest overall in Model 16. The simulated-inserting and retention forces are 3.36 N and 1.9652N, respectively, while their experimental values are 3.23 N and 1.49 N, and this tight agreement corroborates that the model herein shows a good gap-bridging between simulation and actual performance. These results reveal marked differences between simulation and experimental data for the retention force of some models, stressing the importance of considering both types of values in a design framework. These discrepancies between the medium and simulation retention forces, and the (especially in the odd-numbered models) simulation forces calculated by each of the two methods, can have several explanations. First, simulations typically assume that materials behave perfectly, but in real-world 3D prints, slight flaws can happen because of layer adhesion, how prints are oriented or how accurately the dimensions are maintained. Additionally, friction and contact behavior in the simulation may not accurately match real-life behavior, especially if the surfaces differ in roughness or if wear occurs. Changes in geometry due to printer calibration, warping or shrinkage may affect the fit of snap-fits. Reducing these discrepancies means making the printer precise, using the same print settings all the time, adjusting FEA mesh definition and comparing results from several sample tests.

To see if measurements or results are correct, you must check the percentage of error by comparing them with standard or expected outcomes. It shows the difference between a measured value and the true or accepted value. Performance of experiments is evaluated more easily with percentage error, helping scientists to see the risks and reliable results involved in their data, experiments and model predictions. Being able to identify percentage errors matters a lot in making decisions, especially about risks, predictions and adjustments made with measured or calculated information. The figure below (Figure 10) displays the percentage of errors. Model 14 gave the correct answer to insertion force with the least error, and Model 15 achieved the accuracy for retention force. For data to be correct and highly detailed, the error percentage should be as close to zero as it can be. The difference between the two retention forces gives helpful information, especially when the results are far apart. Such larger errors can arise when 3D-printed parts have geometric imperfections, printing orientation affects the materials, and the simulation makes simple assumptions about behavior and contact. Small differences in how assembly force or measurements are applied or taken during experiments can change the results. One way to achieve more accurate findings in the future is to adjust the mesh used in FEA, refine contact modeling, work on material characterization, standardize how models are printed and tested, and include multiple samples per study to prevent large swings in the results. Although what defines an error in one field may be different, it is very important to reduce errors and aim for accuracy in all experiments and simulations. This ensures that simulated results align closely with the real-world behavior of the snap-fit joints. Validating simulation results against experimental data and conducting rigorous testing can help determine the acceptable level of error for a particular application or industry. The acceptable margin of error depends on the experiment, but it should ideally be 10% or lower, as a lower percentage error indicates more accurate results.

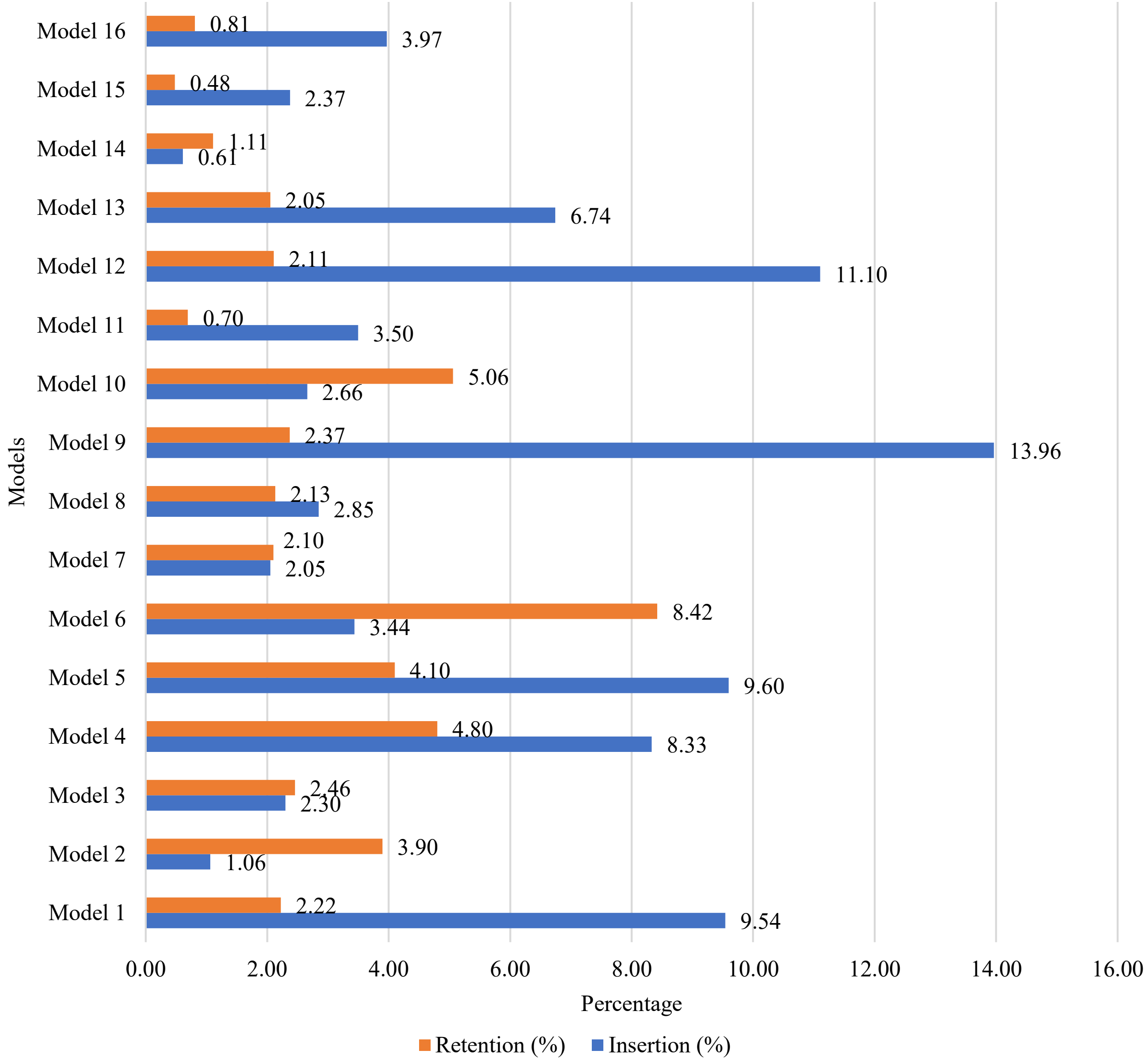


Figure 10. Percentage of errors between the simulation and experiment insertion and retention forces results for all 16 models of snap-fits

4. CONCLUSIONS

A study was done to test how cantilever hook snap-fits work through both simulation and experiments involving 16 different models that changed in length and angle. The simulations were done in ANSYS using ABS material, 0.4 friction coefficient and tetrahedral meshing, and then their models were printed using an Ultimaker S5 before testing on the Instron 3369 machine. By doing insertion and retention force comparisons in simulations and experiments, each model's performance could be reliably reviewed and used to help with practical design decisions. Comparing the insertion and retention forces from simulation and experiments for all models helps understand if the findings are accurate and consistent. Most odd-numbered models produced higher forces than the even-numbered models, but some models had clear differences. Models 1 and 5 showed significant discrepancies between simulated and experimental results, with Model 1 reporting 26.93 N vs 24.59 N (insertion) and 30.96 N vs 34.67 N (retention), and Model 5 showing 26.90 N vs 24.55 N (insertion) and 39.46 N vs 41.14 N (retention), indicating tighter real-world assemblies. In contrast, Model 13 (34.35 N vs 32.18 N insertion; 11.02 N vs 10.80 N retention) and Model 16 (3.36 N vs 3.23 N insertion; 1.07 N vs 1.95 N retention) demonstrated strong agreement between simulation and experiment, highlighting their reliability and consistency.

Therefore, lower insertion forces are preferred to reduce skin deformation during assembly. Based on this, Model 16 is considered the most optimal design, as it has the lowest forces and still meets application requirements for a wall socket cover. Its longer beam length (36 mm) contributes to flexibility, and the higher insertion angle improves grip strength. Snap-fits should be set up so the retention force is stronger than the insertion force, which guarantees their secure attachment during assembly. Its strong performance in both testing and simulation was due to its low insertion force of 3.36 N (in simulation) and 3.23 N (experiment), characteristics linked to its longer beam and higher angle at which the hook was inserted. A total of 16 snap-fit models were studied in detail to analyze the impact of parameters such as beam length and angle on how easily snap-fit parts can be fitted and kept in place. Earlier models were mostly designed from measurements or long production runs with injection molding tools. Combining FEA and physical testing made the assessment of snap-fit performance better, and Models 14 and 15 were recognised for their high accuracy in insertion and retention forces. The research results recommend that simulation results be checked against experiments and that more work be done on inseparable models for better design in factories. What this study finds is significant for building plastic enclosures and components that use cantilever snap-fits in industrial projects. Model 16 offers high retention strength while needing low insertion force, which allows manufacturers to improve how fast and reliably jigs can be assembled. This improves ergonomics, minimizes injuries and helps keep the product usable. Because of this, you can use the tool to speed up and reduce costs in the optimization of your design before prototyping it.

ACKNOWLEDGEMENTS

We acknowledge with gratitude Universiti Malaysia Pahang for providing financial support under UMP-IIUM-UiTM Sustainable Research Collaboration (RDU200749) and the Faculty of Manufacturing and Mechatronic Engineering Technology, Universiti Malaysia Pahang, which realizes this research project.

CONFLICT OF INTEREST

The authors declare no conflicts of interest

AUTHORS CONTRIBUTION

M.N. Osman Zahid (Conceptualization; Formal analysis; Visualisation; Writing – review & editing; Supervision)

S.S. Abdul Manan (Methodology; Data curation; Writing - original draft; Resources)

REFERENCES

[1] L. P. Rusli, A. F. Luscher, and C. M. Sommerich, “Force and tactile feedback in preloaded cantilever snap-fits under manual assembly,” *International Journal of Industrial Ergonomics*, vol. 40, no. 6, p. 618, 2010.

[2] A. Demirer Kahraman and F. Kahraman, “Mechanical fastening methods of polymer-based composites”, *International Journal of Advanced Natural Sciences and Engineering Researches*, vol. 7, no. 10, pp. 234–239, 2024.

[3] A. G. He, H. Li, and K. Jin, “Shape memory polymer actuated hollow snap-fit design analysis,” *Materials & Design* (1980-2015), vol. 47, p. 539, 2013.

[4] A. Klahn, D. Singer, and M. Meboldt, “Design guidelines for additive manufactured snap-fit joints,” *Procedia CIRP*, vol. 50, p. 264, 2016.

[5] T. Jeandin and C. Mascle, “A new model to select fasteners in design for disassembly,” *Procedia CIRP*, vol. 40, p. 425, 2016.

[6] S. Otmani and D.-K. Shin, “Large deformation analysis of a backside-supported snap-fit with nonlinear behavior,” *Heliyon*, vol. 9, no. 9, p. e19388, 2023.

[7] K. Yoshida and H. Wada, “Mechanics of a snap fit,” *Physical Review Letters*, vol. 125, no. 19, p. 194301, 2020.

[8] K. Jorabchi and K. Suresh, “Nonlinear algebraic reduction for snap-fit simulation,” *Journal of Mechanical Design*, vol. 131, no. 6, p. 061004, 2009.

[9] J. Krzywański, M. Sosnowski, K. Grabowska, A. Żyłka, L. Lasek, and A. Kijo–Kleczkowska, “Advanced computational methods for modeling, prediction and optimization—A review,” *Materials*, vol. 17, no. 14, p. 3521, 2024.

[10] X. L. Guo and B. H. Sun, “Assembly and disassembly mechanics of a cylindrical snap fit,” p. 2022010076, 2022.

[11] J. J. Singh, J. S. Mehta, R. Kumar, and G. Sapra, “FEA simulations of lower limb prosthetics,” in *IOP Conference Series Materials Science and Engineering*, IOP Publishing, p. 12030, 2022.

[12] F. Erdemir and M. Özkan, “Application of Taguchi method for optimization of design parameters in enhancement the robust of ‘C’ type snap-fits,” *Journal of Polytechnic*, vol. 25, no. 3, p. 1385, 2022.

[13] A. R. Moghrabi, S. A. Bhat, P. Szczuko, R. A. AlKhaled, and M. A. Dar, “Digital transformation and its influence on sustainable manufacturing and business practices,” *Sustainability*, vol. 15, no. 4, p. 3010, 2023.

[14] L. Zhou, J. Miller, J. Vezza, M. Mayster, M. Raffay, Q. Justice, et al., “Additive manufacturing: A comprehensive review,” *Sensors*, vol. 24, no. 9, p. 2668, 2024.

[15] R. T. Mushtaq, A. Iqbal, Y. Wang, M. Rehman, and M. I. Petra, “Investigation and optimization of effects of 3D printer process parameters on performance parameters,” *Materials*, vol. 16, no. 9, p. 3392, 2023.

[16] H. Salmanzadeh and M. Rasouli, “The influence of effective factors on mechanical stress on fingertips during snap-fit assembly,” *Iranian Rehabilitation Journal*, vol. 13, no. 3, p. 39, 2015.

[17] J. L. Amaya, E. A. Ramírez, G. F. Maldonado, and J. Hurel, “Detailed design process and assembly considerations for snap-fit joints using additive manufacturing,” *Procedia CIRP*, vol. 84, p. 680, 2019.

[18] S. S. Suzamri and M. N. O. Zahid, “Insertion force in snap-fits assembly based on different design parameters: A simulation study,” in *Lecture Notes in Mechanical Engineering*, p. 991, 2021.

[19] Ji, K.-M. Lee, and S. Zhang, “Cantilever snap-fit performance analysis for haptic evaluation,” *Journal of Mechanical Design*, vol. 133, no. 12, p. 121004, 2011.

[20] P. R. Bonenberger, The First Snap-Fit Handbook. Carl Hanser Verlag GmbH & Co. KG. 2017. (Original work published 2005)

[21] R. Xu, Y. He, X. Li, M. Lu, and Y. Chen, “Snap-fit mechanical metamaterials,” *Applied Materials Today*, vol. 30, p. 101714, 2022.

[22] A. Arivazhagan and S. H. Masood, “Dynamic mechanical properties of ABS material processed by fused deposition modelling,” *International Journal of Engineering Research and Applications*, vol. 2, no. 3, p. 2009, 2012.

[23] S. Vishwakarma, P. Pandey, and N. Gupta, “Characterization of ABS Material: A review,” *Quest Journals Journal of Research in Mechanical Engineering*, vol. 3, p. 2321–8185. 2017.

[24] S. S. A. Manan, L. P. Chien, and M. Zahid, “A simulation of insertion and retention forces in cantilever hook snap-fit joint,” *IET Conference Proceedings*, vol. 2022, no. 22, p. 57, 2023.

[25] M. E. Chenthil, S. S. Praneeth, D. S. Anand, and M. Srikanth, “Universal Testing Machine,” *International Journal of Innovative Research in Technology*, vol. 9, no. 1, p. 1572-1575, 2022.

[26] S. S. A. Manan and M. N. O. Zahid, “Experimental analysis on retention forces of cantilever hook snap-fits,” in *Lecture Notes in Networks and Systems*, pp. 361-375, 2024.

[27] S. S. A. Manan and M. Nafis, “A parametric study of insertion and retention forces in cantilever hook,” *Journal of Mechanical Engineering and Sciences*, vol. 17, no. 1, pp. 9360-9369, 2023.