FORMULATION OF A NUMERICAL MODEL OF INSERTION AND RETENTION FORCES IN CANTILEVER HOOK SNAP-FITS JOINTS

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Thesis submitted in fulfillment of the requirements
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ABSTRAK

Kemajuan teknologi telah memberikan sumbangan yang signifikan kepada industri kejuruteraan dan automotif. Industri elektrik dan elektronik sering menggunakan aplikasi snap-fit seperti bezel pemegang pintu dan bekas kaca akrilik. Snap-fit adalah teknik penyambungan yang digunakan untuk menggabungkan dua atau lebih bahagian bersama-sama, sama ada plastik kepada plastik atau plastik kepada bahan lain. Biasanya, snap-fit dibentuk terus ke dalam bahagian kerana ia tidak memerlukan sumber tenaga luaran. Snap-fit boleh dipisahkan atau tidak bergantung kepada reka bentuk yang digunakan. Snap-fit mempunyai tiga jenis: julur, kilasan, dan annular, dan dalam kajian ini, fokus adalah kepada jenis snap-fit julur. Snap-fit julur banyak digunakan dalam industri kerana reka bentuknya yang mudah. Dalam kajian ini, parameter snap-fit dikaji berdasarkan daya sisipan dan pengekalan. Beberapa parameter mempengaruhi reka bentuk snap-fit seperti ketebalan rasuk (Tb), panjang rasuk (Lb), lebar rasuk (Wb), jejari tapak (Rb), sudut sisipan (α), dan sudut pengekalan (β). Dalam kajian ini, bahan ABS digunakan kerana ia adalah bahan termoplastik dengan kos pengeluaran rendah dan tahan terhadap bahan kimia, kekakuan, dan impak. Snap-fit juga disimulasikan menggunakan analisis tidak linear berasaskan permukaan sentuhan. Snap-fit julur direka bentuk menggunakan perisian Autodesk Inventor dan disimulasikan menggunakan perisian ANSYS untuk menghasilkan keputusan daya sisipan dan pengekalan. Kemudian, ia dicetak menggunakan pencetak 3D dan diuji menggunakan mesin UTM, dan keputusan simulasi dan eksperimen dibandingkan. Snap-fit diuji untuk menilai prestasi model berangka yang dicadangkan berdasarkan faktor reka bentuk, daya sisipan, dan pengekalan. Didapati bahawa peningkatan sudut sisipan dan pengekalan meningkatkan daya sisipan dan pengekalan snap-fit julur. Hasil menunjukkan bahawa snap-fit dari Model 10 mempunyai nilai daya sisipan terendah 3.3399N, manakala nilai daya pengekalan terendah adalah dari Model 2 dengan nilai 1.7219N. Dengan hasil yang diperoleh, dapat ditentukan reka bentuk mana yang kurang menyumbang kepada kecederaan semasa pemasangan dan penumpuan tekanan. Kesimpulannya, snap-fit banyak digunakan dalam kehidupan seharian, dan kajian ini boleh memberi impak kepada bidang pembuatan elektrik, automotif, dan lain-lain untuk penghasilan reka bentuk snap-fit yang lebih optimum, selamat, dan sesuai. Peratusan ralat kurang dari 10% menunjukkan bahawa kajian ini boleh digunakan dan dirujuk.

ABSTRACT

The advancement of technology has contributed significantly to the engineering and automotive industries. The electrical and electronic industries often utilize snap-fit applications such as door handle bezels and acrylic glass containers. Snap-fit is a joining technique used to combine two or more parts together, either plastic to plastic or plastic to other materials. Typically, snap-fit is directly formed into the part as it does not require external energy sources. Snap-fit can be separable or inseparable depending on the design usage. Snap-fit has three types: cantilever, torsion, and annular, and in this study, the focus is on the cantilever type of snap-fit. Cantilever snap-fit is widely used in industries due to its simple design. In this study, snap-fit parameters are examined in relation to insertion force and retention. Several parameters affecting the design of the snap-fit such as the thickness of beam (Tb), length of the beam (Lb), width of the beam (Wb), base radius (Rb), insertion angle (α) and retention angle (β). In this study, ABS material is used because ABS is a thermoplastic material with low production costs and resistance to chemicals, stiffness, and impact. Snap-fit is also simulated using nonlinear simulation based on contact surface analysis. Cantilever snap-fit is designed using Autodesk Inventor software and simulated using ANSYS software to generate insertion and retention force results. Subsequently, it is printed using a 3D printer and tested using a UTM machine, and simulation and experimental results are compared. Snap-fit is tested to evaluate the performance of proposed numerical models based on design factors, insertion force, and retention. It is found that increasing the insertion and retention angles increases the insertion and retention force of the cantilever snap-fit. The results show that the snap-fit from Model 10 has the lowest insertion force value of 3.3399N, while the lowest retention force value is from Model 2 with a value of 1.7219N. With the obtained results, it can be determined which designs contribute less to injury during assembly and pressure loading. In conclusion, snap-fit is widely used in daily life, and this study can have an impact on the electrical, automotive, and other manufacturing fields to produce more optimal, safe, and suitable snap-fit designs. The percentage of error less than 10% indicates that this study is applicable and referenceable.

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LIST OF SYMBOLS

T_b	Thickness of Beam
L_b	Length of Beam
W_b	Width of Beam
R_b	Radius of Base
T_{wall}	Thickness of Wall
α	Mounting/Insertion Angle
β	Dismounting/Retention Angle
F_i	Insertion Force
F_r	Retention Force
LR	Locking Ratio
μ	Coefficient of Friction

LIST OF ABBREVIATIONS

3D	3-Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CAD	Computer Aided Design
DFA	Design for Assembly
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FEM	Finite Element Method
PC	Polycarbonate
PP	Polypropylene
PLA	Polylactic Acid
STL	Stereolithography
UTM	Universal Testing Machine

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Many technologies have been developed, innovated and improved in the modern era, particularly in the fields of technology and engineering. As a result, to grow and develop the country, continual study must be conducted to demonstrate progress accomplished throughout the process. As modern technology has advanced, numerous intricate designs have been created. For the complex design, several structures are manufactured independently and must be assembled to form a product.

There are numerous joining techniques that can be used to integrate or join the parts together, such as adhesive bonding, mechanical fasteners, and snap-fit with each of these joining methods has its functions, suitability, capabilities and limitations. Snap-fit is the easiest, fastest and most cost-effective joint method to assemble two or more parts. Additionally, the use of snap-fit eliminates the need for external energy sources, and it also reduces the inventory of components. When properly designed, elements with snap-fit can be joined and disjointed repeatedly without any negative impact on the attachment.

Snap-fit connections were invented primarily to provide an efficient, cost-effective, and easy-to-assemble method for joining components together, particularly in the manufacturing of products made from materials like plastics.

The motivations behind the invention of snap-fit connections are multifaceted such as the assembly efficiency, in which snap-fit eliminate the need for additional fasteners (such as screws, bolts, or adhesives) in assembling components. This simplifies the assembly process, reduces production time, and streamlines manufacturing operations. Then, the cost reduction that can significantly reduce manufacturing costs by eliminating the need for separate fasteners and reducing part count. Simplifying the assembly process often translates into lower labour costs and material savings. Then, the design flexibility of the snap-fits that offer designers more freedom in creating complex shapes and designs for components. They allow for innovative and sleek product designs, enabling engineers to integrate functional features and aesthetics into the design of products.

The ease of the disassembly also contributes to the invention of snap-fit as it provides a secure connection, and they can also facilitate easy disassembly and repair of products when needed. This can be advantageous for maintenance or recycling purposes. Snap-fit can contribute to weight reduction in products by eliminating heavier fasteners. This is particularly important in industries where lightweight materials are essential for achieving specific performance criteria. Using snap-fit simplifies the overall design of products by reducing the number of separate parts and assembly steps, which can improve reliability and reduce the chances of assembly errors. Overall, the invention of snap-fit connections was driven by the desire to enhance manufacturing efficiency, reduce costs, improve design flexibility, and simplify the assembly process for various products across industries such as consumer electronics, automotive, medical devices, and more (Ji et al., 2011). The versatility and ease of use associated with snap-fit connections have made them a popular choice for joining components in many applications.

The cantilever design is used in most engineering material applications with snap-fits. It is not uncommon for a designer to go through numerous iterations while developing a cantilever snap, adjusting length, thickness, and deflection specifications, to build a snap-fit with a lower allowable strain for a given material. Although snap-fit has been around for a long time, their use in automotive engineering has recently increased for a variety of reasons (*BASF Snap-Fit Design Manual,* 2007). Increased emphasis on Design for Assembly (DFA) favours snap-fit because they can be assembled in less time and with less ergonomic strain than other fasteners (Dolah et al., 2007). Snap-fit enable users to swiftly disassemble pieces made of different materials, which aids in the recycling process (Ruan, 2005). Finally, advances in polymer technology and composite materials have enabled snap-fit to be used in heavier applications requiring higher retention forces. Air filter housings, throttle bodies, temperature and pressure sensors, electrical connectors, and engine intake manifolds are some examples of snap-fit utilized in automobile engineering (*BASF Snap-Fit Design Manual*, 2007). In this research, this snap-fit can be utilized in electrical industry such as for the usage for wall socket cover. This is to improve the safety for children especially when nearby wall socket or electrical plugs. The extensive explanation on this wall socket cover can be seen in Chapter 2.6. Wall socket covers are typically made from a durable and fire-resistant thermoplastic material such as polycarbonate (PC) or acrylonitrile butadiene styrene (ABS). These materials are chosen for their ability to withstand high temperatures, resist impact, and provide electrical insulation. Additionally, they are often chosen for their ease of moulding into intricate shapes and their affordability.

Before comes up with mass production, it is crucial to create a prototype and assess the tactile experience of the product during assembly and disassembly before settling on its form and materials. Traditionally, crafting accurate prototypes necessitated costly moulds, yet advancements in additive manufacturing have enabled efficient and economical prototyping in recent times (Taguchi et al., 2023).

Figure 1.1 shows the basic cantilever hook nomenclature that consists of parameters used in designing a snap-fit model. The parameters that are measured in this research are the thickness of the features (Tb), beam length (Lb), beam width (Wb), base radius (Rb), mounting (α) and dismounting angle (β). In this study, the prime important factors observed are the insertion and the retention forces of the cantilever hook snap-fit joint.

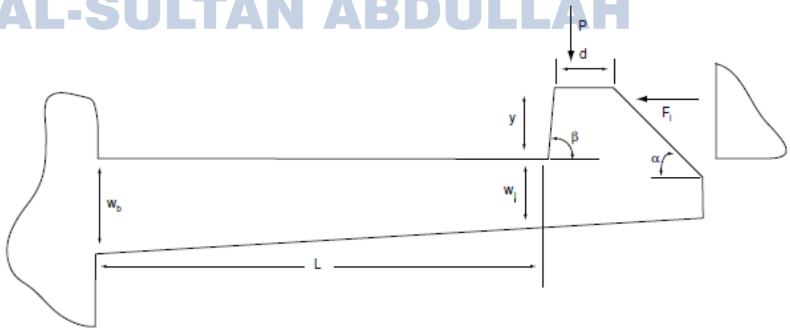


Figure 1.1 Basic cantilever hook nomenclature
Source: (Suri, 2002)

Song (2020) made a study on snap-fit but in special-shaped as in Figure 1.2 based on the technology of finite element, and the material used in the study is polycarbonate

(PC)/ Acrylonitrile Butadiene Styrene (ABS). The study shows the mechanical performance of the special-shaped snap-fits and suggesting some selections on the main parameters. It also discussed on the reliability of finite element analysis (FEA) on the test results. Special-shaped snap-fit is used as the common plastic snap-fit such as cantilever, torsion, and annular might have been unable to fulfil the demand on the shell design requirements of electronics communication products. The simulation of FEA is done using ANSYS Workbench software and it is stated that through FEA, the optimization of the product structure can be achieved to a certain extent such as the mechanical properties, fillet radius and better product can be produced by properly changing the design parameters.

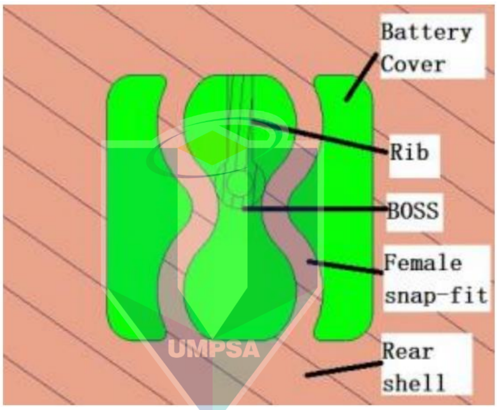


Figure 1.2 Sectional view of special-shaped snap-fit structure
Source: (Song, 2020)

Every design surely has weaknesses that need to be addressed, and so does in this study. The cantilever snap-fit design has weaknesses such as the base radius angle as shown in figure 1.3. Figure 1.3 showing a sharp corner can generate stress beyond the material's strength. The insertion of the radius of the angle between the snap-fits wall and its beam can reduce the stress concentration and prevent the snap-fits from break. Figure 1.3 shows the design of the snap-fit that can lead to high-stress generation and the design to reduce the stress of the snap-fit. The good design suggests 0.5 times of the thickness minimum for the radius between the beam and the wall where it is attached.

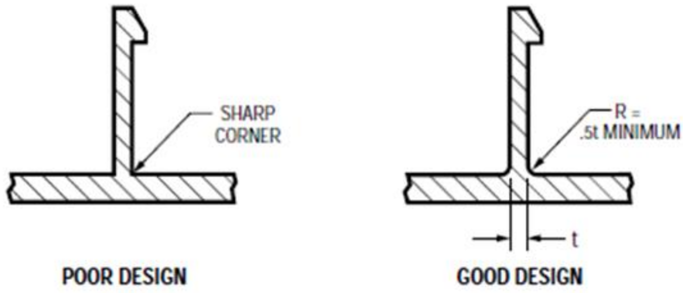


Figure 1.3 Adding a fillet to the root of the bend
Source: (Rucinski, 2015)

High levels of stress can lead to plastic deformation and lasting harm to the snap-fit. Typically, assembly occurs rapidly, preventing visible damage despite momentary stress surpassing elasticity. However, prolonged exposure to high stress and significant deformation will inevitably cause damage to the snap-fit over time (El Otmani & Shin, 2023).

The von Mises criterion assumes that yielding occurs when the distortion energy (also known as the von Mises energy) exceeds a critical value for the material. It is particularly useful for predicting the failure of ductile materials, such as metals, under multiaxial stress states, where the stress distribution is not purely tensile or compressive. Figure 1.4 shows an example of the von Mises stress from the simulation of the cantilever snap-fit. Von Mises stress is a stress measure used in the field of finite element analysis (FEA) and solid mechanics to predict yielding or failure of materials subjected to complex loading conditions and it is named after the Austrian physicist and mathematician Richard von Mises. In this figure, the highest von Mises stress generated is on the base angle due to 90° design as circled in the diagram.

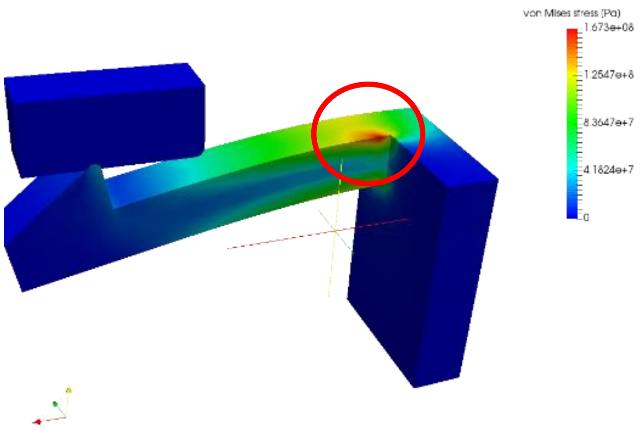


Figure 1.4 Finite Element Analysis of cantilever snap-fit
Source: (Kuzev, A., 2017)

In this research, ABS plastic is utilized, and as with all plastic applications, plastic deformation is inevitable. This phenomenon aligns with Hooke's Law, which establishes that stress applied to an elastic material is directly proportional to the strain produced, given the material remains within its elastic limit ("Hooke's Law | Description & Equation | Britannica," 2024). Nonlinearity in Hooke's Law occurs when materials surpass their elastic limit, leading to deviations from the linear relationship between stress and strain. Consequently, materials may exhibit nonlinear behaviour, such as irreversible plastic deformation, particularly at high stress levels. Superposition, a principle stating that the total response of a system to combined stimuli equals the sum of individual responses, holds significance in Hooke's Law. It enables the analysis of complex systems by considering the combined effects of multiple forces or deformations acting on a material. In this case, A cantilever hook snap-fit typically follows linear behaviour as per Hooke's Law within its elastic limit. However, if the material surpasses its elastic limit, nonlinear behaviour, such as plastic deformation, may occur. But the principle of superposition can only be valid when the linear-elastic behaviour occurs which valid the Hooke's Law and therefore the load is proportional to displacement and the structural geometry should remain stable and experience minimal alteration under the applied load.

1.2 Problem Statement

The snap-fit dimensions (geometrical forms) have a significant impact on mating performance and accuracy. The use of excessive force during assembly can cause the snap-fit to break or crack (Salmanzadeh & Rasouli, 2015). With such comes increased risk in terms of the parts' ability to sustain loads and forces. The solution is to decrease the insertion and retention forces of the snap-fit so that the risk for injuries during assembly and disassembly can be decreased. Thus, that is why it is important to determine which design can contributes the most towards the optimum forces. The most prevalent cause of snap-fit failure is stress concentration caused by a specific angle between the snap-fit beam and the wall to which it is attached as in previous Figure 1.2.

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 (Suri & Luscher, 2000). Among the important design factors that can influence all the problems mentioned previously are the thickness of the features, beam length, beam width, base radius, mounting and dismounting angle. Small interferences between these factors will include the insertion and retention forces, which can influence joint quality. In terms of application, a poor design, on the other hand, can cause discomfort and injury to the fingertips. As a result, determining snap-fit dimensions that reflect insertion and retention forces is crucial. In conclusion, for snap-fit modelling, it is important to ensure the design will not destroy the working of the snap-fit, by reducing the stress concentration that can affect the insertion and retention forces of the snap-fit such as adding a fillet to the root of the bend, and then the tolerance variation must be fixed by implementing the correct design parameters using guidelines for the snap-fit and the 3D printing characteristics. Lastly, the fatigue failure of the snap-fit can be fixed by using the correct material for printing the model. The materials used and the dimensions of the model can give an impact on the insertion and retention forces. As for the simulation for finite element analysis, snap-fits joint modelling has been extensively discussed in a variety of applications. Because snap-fits assemblies are highly non-linear, Finite Element Analysis (FEA) is essential for simulating and predicting the joint quality (K Billal et al., 2014). Among the key challenges such as contact formulation, boundary conditions, and material properties, have been satisfactorily solved. However, there has been little discussion so far about the modelling of snap-fits concerning FEA results. In a typical approach, snap-fit numerical modelling is performed to validate the design by considering response factors such as insertion and retention forces. If the design fails to meet the predetermined requirements, it can be modified. There are no clear rules for modifying design elements to directly reflect insertion and retention forces (*BASF Snap-Fit Design Manual*, 2007). As a result, the process was extensive and time-consuming. To resolve the issue, the design of cantilever hook snap-fit is modelled and simulated to observe the response variables (insertion and retention forces). Recent design modelling tools like the finite element method (FEM) will help to improve accuracy whilst minimizing time and costs associated with product development.

In FEA, when analyzing the stress distribution within a structure or component, the von Mises stress is often used to evaluate the material's yielding or failure criteria such as previous Figure 1.4. It is derived from the stress tensor, which characterizes the state of stress at a particular point within a material. The von Mises criterion is particularly useful for ductile materials, such as metals, where yielding occurs gradually due to the material's ability to deform plastically before fracture. When the von Mises stress exceeds the material's yield strength, it suggests that yielding or plastic deformation might occur in the material. FEA software often uses von Mises stress calculations to help engineers and designers assess the structural integrity and safety of components by predicting potential failure locations or regions where yielding might occur under various loading conditions.

1.3 Objectives

The objectives of the research are as follows:

- To investigate the length, thickness and insertion and retention angles (design factors) of snap-fit joint in relation towards the insertion and retention forces.
- To simulate a non-linear simulation analysis-based on contact surface using Ansys Workbench and Mechanical software.
- To evaluate the performance of the proposed model based on the design factors, insertion and retention forces of cantilever hook snap-fit.

1.4 Scope of Research

The scope of the research are as follows:

- The type of snap-fit focused on this study is the cantilever type.
- Simulation and analysis of the cantilever snap-fit with the insertion and retention forces.
- The material used for the cantilever snap-fit design in this research is ABS.

1.5 Summary

Cantilever hook snap-fit joints are a popular and efficient method for assembling components in various industries, especially in plastic part manufacturing. The key points in the introduction to cantilever hook snap-fit joints include, basic principle, in which these joints involve one part featuring a hook-like protrusion (the "male" part) and another part with a corresponding groove or recess (the "female" part). The hook structure is designed to flex during assembly, allowing it to engage and interlock with the mating component securely. The assembly process involves applying an insertion force to connect the components. In this study, for snap-fit assembly, the contact analysis is non-linear in which non-linear implies that the relationship between the applied forces and resulting deformations is not linear. This suggests that the behaviour of the joint may not follow a simple, straight-line relationship as forces are applied, but rather it may exhibit complex behaviour, including plastic deformation or nonlinear material properties. The hooks flex during insertion, and once the parts are fully engaged, the hooks return to their original position, generating a retention force that holds the joint together. Various parameters influence the performance of cantilever hook snap-fit joints. These include hook geometry, such as hook angle, length, and width, material properties, clearance between mating parts, surface finish, temperature effects, and environmental factors. Optimizing these parameters is crucial for achieving reliable and functional snap-fit connections. Cantilever hook snap-fit joints offer several advantages, including ease of assembly, cost-effectiveness which reducing the need for additional fasteners, design flexibility, ease of disassembly for maintenance or recycling, and potential weight reduction in products.

These snap-fit joints find applications across industries such as consumer electronics, automotive, medical devices, packaging, and more, where rapid assembly, cost efficiency, and reliable connections are essential. Understanding the mechanics, design parameters, and optimization of cantilever hook snap-fit joints is crucial for engineers and designers aiming to create robust and efficient assembly solutions for various products. These joints continue to be a widely used and versatile method for connecting plastic components, offering both practical and economic advantages in manufacturing and product design.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

It is sometimes necessary to produce a complex part that involves the assembly of two or more parts together. Designers must examine the success rate of parts connection for a working unit. For designing and producing complex parts, joining methods can provide a cost-effective and structurally sound solution (LANXESS Corporation, 2006). In this chapter, a detailed explanation of the cantilever hook snap-fit is discussed.

The insertion and retention forces were assessed as variables in this investigation. Thus, research into the data related to these variables is comprehensively discussed on the literature. The materials and design parameters are a major contribution to generating the data for the studied forces. Any changes in parameters or design can affect the efficiency and strength of the cantilever hook snap-fit. The simulation and application of the snap-fit are also explained in this chapter.

2.2 Snap-fits

A snap-fit is a form-fitting joint that is often moulded directly into a plastic part. In an assembly, the features are formed into a part that provides mechanical attachment functionality. The joint determines relative part placement, alignment, and orientation while transmitting service loads, removing degrees of freedom, and/or absorbing tolerance between these parts. Mechanical asymmetry is a crucial characteristic of industrial snap-fits that is caused by the combination of flexibility, frictional contacts, and the geometric structure of the snap-fit parts (Yoshida & Wada, 2020). Snap-fits come in a variety of shapes, but they all share the same property of elastically deforming into an undercut or depression to form a joint. The displacement of flexible elements during assembly and disassembly is the primary criteria for snap-fits (Klahn et al., 2016). Snap-fit may be intended to be separable or inseparable depending on the application.

Snap-fits are the easiest, quickest, and most cost-effective way to connect two pieces. When constructed correctly, snap-fit pieces can be assembled and removed several times without affecting the assembly. Because of their simplicity of disassembly, snap-fits are also the most ecologically friendly form of assembly, allowing components of various materials to be recycled. Although snap-fits can be made from a variety of materials, thermoplastic is the preferred material due to its great flexibility and ability to be readily and inexpensively shaped into complex shapes. Other advantages include its relatively high elongation, low coefficient of friction, and sufficient strength and rigidity to suit the needs of most applications (*BASF Snap-Fit Design Manual*, 2007). Figure 2.1 shows the application of snap-fit in which the type is annular snap-fit, as annular snap-fits in pen and cap designs exemplify a clever use of material properties and geometric design to create a simple, effective, and user-friendly closure mechanism. They leverage the inherent flexibility of thermoplastic materials to provide a secure, reusable connection that enhances the functionality and convenience of everyday items like pens. Meanwhile, Figure 2.2 shows the application of a cantilever hook snap-fit in the remote battery compartment, as cantilever hook snap-fits are an efficient and user-friendly solution for securing battery covers in remote controls. Their simplicity, reliability, and cost-effectiveness make them a popular choice in consumer electronics, enhancing the overall user experience by providing easy access to the battery compartment while ensuring secure closure during use.

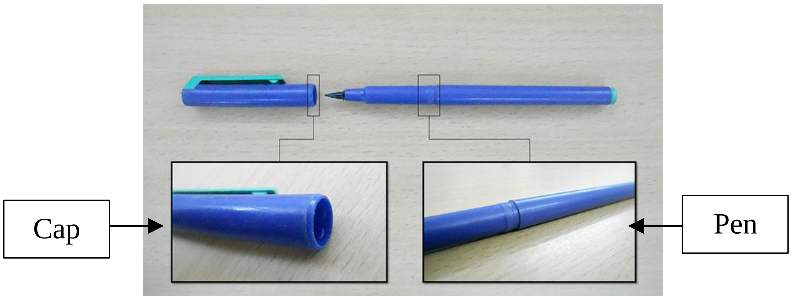


Figure 2.1 Application of snap-fit in pen and cap

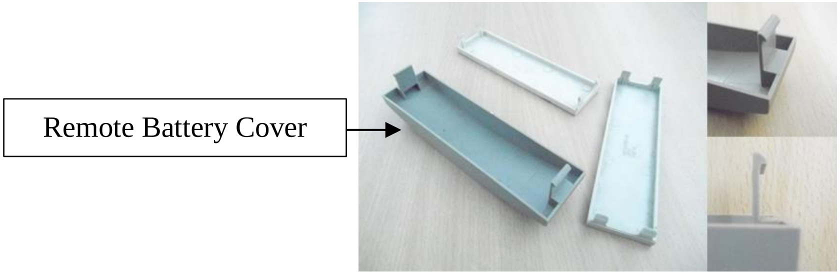


Figure 2.2 Application of snap-fit in remote battery compartment
Source: (Bapat & Verma, 2015)

Figure 2.3 shows the direction of installation of the snap-fit according to Suzamri and Osman Zahid (2021). This motion can also be called the insertion motion. According to Suri & Luscher (2000), there are several alternatives' topologies in snap-fit design that are available to use other than cantilever hook snap-fit. The author mentioned that the cantilever hook is unsuitable as it has low retention force and is likely to have the loss of engagement. The alternatives are shown in Figure 2.4, which are the Post & Dome snap-fit feature, Bayonet & Finger snap-fit feature, Loop-hook snap-fit feature, Trap type snap-fit feature and lastly, Hollow-core snap-fit feature. Post and dome snap-fits involve a post on one part that snaps into a domed recess on another, providing secure, easily detachable connections. Bayonet and finger snap-fits use a pin-and-slot mechanism where a pin on one part is twisted into a slot on another, locking in place; these are common in light fixtures. Loop-hook snap-fits consist of a flexible loop that engages with a hook on the opposite part, often seen in closures for containers. Trap-type snap-fits have a locking tab that snaps into a catch or trap, frequently used in electronic housings. Hollow-core snap-fits involve a hollow protrusion that fits into a corresponding recess, utilizing the hollow section's flexibility to secure the parts, suitable for lightweight and compact applications.

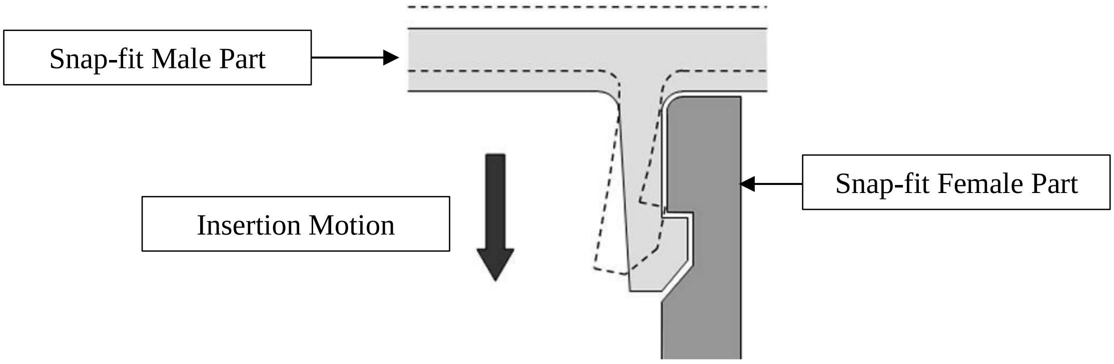
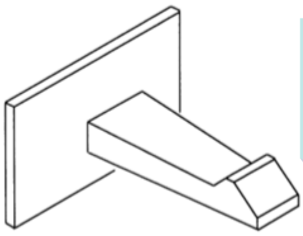
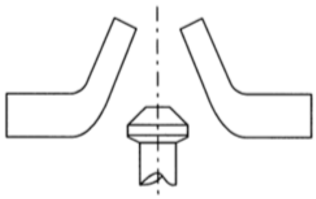


Figure 2.3 Installation of snap-fit

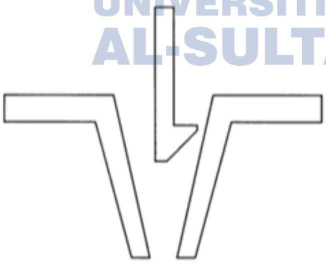
Source: (Suzamri & Osman Zahid, 2021)



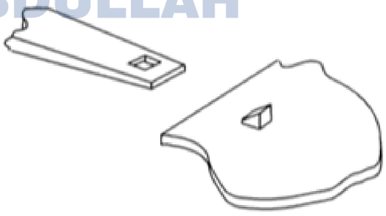
a) Cantilever hook feature



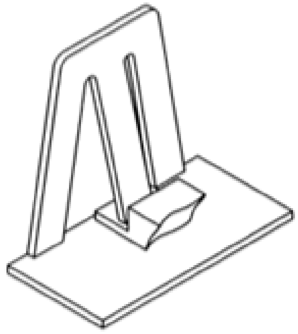
b) Post & Dome snap-fit feature



c) Bayonet & Finger snap-fit feature

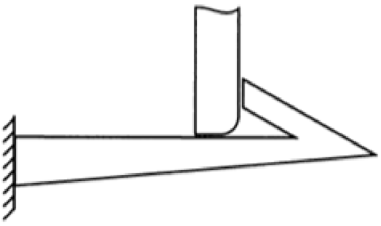


d) Loop-hook snap-fit feature



e) Trap type snap-fit feature

feature



f) Hollow-core hook snap-fit

Figure 2.4 Snap-fits topologies
Source: (Suri & Luscher, 2000)

Current development of snap-fits would be using metamaterials for fabrication. Multistable states in metamaterials were achieved by linking snap-fit units sequentially, while the modular design involved separating the mechanical responses of these connected units in parallel. The mechanical characteristics of individual snap-fit units and metamaterials underwent theoretical, numerical, and experimental analysis. The designed metamaterials displayed impressive impact resistance and absorbed significant energy in demonstrative experiments, suggesting their potential as candidates for shock absorber development. Additionally, these metamaterials can adapt to various non-planar protective configurations, allowing for flexible deployment and easy replacement in complex environments (Xu et al., 2023). However, there is downside to metamaterials usage. 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. Metamaterials often involve specialized materials or complex fabrication techniques, leading to higher production costs compared to traditional materials used in snap-fit designs. This increased cost can limit their widespread adoption, especially in cost-sensitive industries. Some advanced metamaterials might not be readily available in bulk or might have limited accessibility due to their specialized nature, which can hinder their use in large-scale manufacturing of snap-fit components. The unconventional mechanical properties of metamaterials might pose challenges regarding their long-term durability and reliability in snap-fit applications. Understanding fatigue behaviour, creep, and the effects of environmental factors on these materials is essential for ensuring their reliability over time. Integrating metamaterials into snap-fit designs can increase design complexity. Optimizing snap-fit geometries to leverage the unique properties of metamaterials while ensuring reliability and ease of assembly might require sophisticated design approaches.

2.2.1 Basic Mechanisms of Snap-fit

To attach one part to another, the snap-fit mechanism is one of the methods that can be used. Snap-fit consists of a cantilever structure with a hook at one end. The hook's interference with another part that is needed to be assembled can produce a mating force that deflects the cantilever and interlocks the two parts (Chen & Lan, 2012). A beam subjected to a bending load in the form of a cantilever snap-fit beam with a hook is the most frequent structural element in snap-fit joints. Its beneficial snap-fit height (momentary interference) can be changed by modifying the beam's cross-sectional form and, of course, its effective snap-fit length. A typical snap-fit assembly can be shown in Figure 2.5, which consists of a cantilever beam with an overhang at the end of the beam that can attach the unit while also exerting additional strain on the beam. A snap-fit can also be said as a tiny protrusion, like a hook, that deflects during the assembly to catch in a depression on the mating part. A protruding part of one component is deflected during the joining process and catches a feature in the mating component.

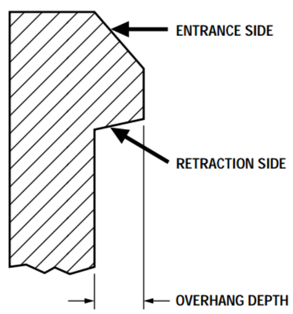


Figure 2.5 Entrance, retraction side and overhang depth
Source: (Axsom, 2020)

Snap-fit can be made separable and non-separable. Figure 2.6 depicts the dismounting and ramping return angle of the snap-fit as it approaches 90°. This makes the cantilever snap-fit unable to retract which causes breaks and failures during detachment due to its non-separable properties. As for Figure 2.7, the dismounting and ramping return angle smaller than 90° which makes the mechanism of the cantilever snap-fit to be separable as the angle of the hook allows the snap-fit to deflect when disassemble and does not cause break or damage to it.

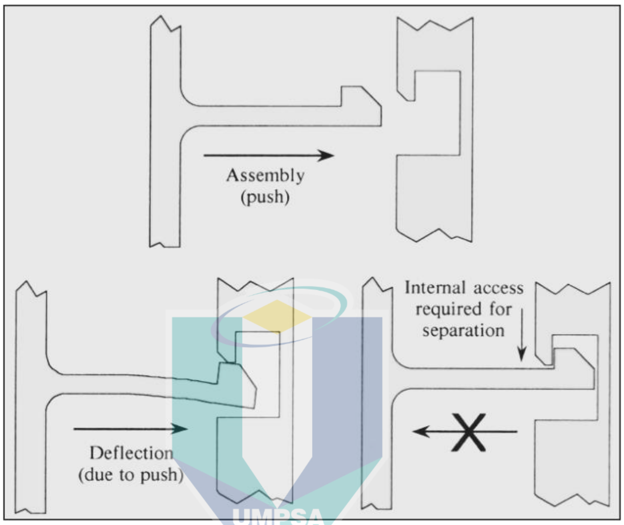


Figure 2.6 Dismounting and ramping return angle approaching 90°

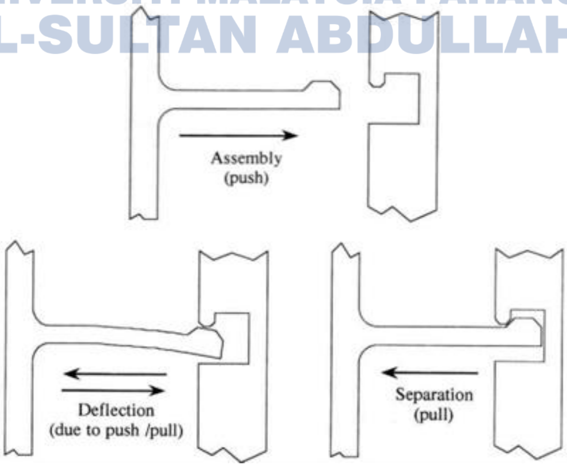


Figure 2.7 Dismounting and ramping return angle smaller than 90°

Source: (*Snap Fit Design*, 2024)

2.2.2 Application of Snap-fits

Snap-fits are categorized as the most common joining method used in the manufacturing industry. Snap-fit can be applied in the making of caster wheels, door handles as in Figure 2.8 and chairs in the office's furniture assembly as it is the most cost-effective method of assembling processes (Dolah et al., 2007). In the automobile industry, there is a lot of use of snap-fit. It can be used in automotive fuse boxes, which is the snap on the sides of the box, door handle bezel that uses cantilever design on the backside and automotive oil filter (*BASF Snap-Fit Design Manual*, 2007).

Figure 2.8 Door handle bezel

Source: (BASF Snap-Fit Design Manual, 2007)

In this research, the application of the snap-fit can be seen in the safety cover for wall plug sockets for homes with children. This is to avoid the lower wall socket to be reachable by children which can lead to harmful situations. Figure 2.9 displays a sample of one of the cover designs. Medical records in The Children's Hospital of Philadelphia and The Johns Hopkins Hospital Baltimore show that the cases of injuries most commonly in the meantime of preparing meals as the children created oral contacts with electrical cords and sockets (Baker, 1989). Previous study by Dundar et. al (2023), regarding electric shock injuries in children in southeast Turkey in which 81% of the children suffers a low-voltage injury resulted from domestic appliances while at home. Meanwhile, study by Byard et al. (2003), in Adelaide Australia, childhood deaths due to electrocution are rare and are more likely to occur when children are playing around electrical wires or equipment, and often result from either faulty apparatus, or a lack of understanding of the potential dangers involved. Most deaths (11/16; 69%) occur in the home environment.

Figure 2.9 Wall socket cover
Source: (*Shopee*, 2023)

2.2.3 Advantages of Snap-fits

Some of the advantages of snap-fits are, snap-fit is the simplest and quickest method to assemble two plastic parts, or plastic parts with other materials as well. It can be assembled and disassembled many times and can be permanent and non-permanent. The disassembly can take place without ruining or affecting the assembly (*BASF Snap-Fit Design Manual*, 2007). Snap-fits solve the problem of creating an inexpensive component that can be quickly and easily joined with another piece (Ajesh et al., 2017).

The design of snap-fit can replace the use of bolts and nuts, and there is no need for the use of fasteners (Kahraman & Kahraman, 2023) (Troughton, 2009). Snap-fit joints are the simplest, quickest, cost-effective and efficient in joining parts (Kakade & Patil, 2008). Using snap-fits can significantly reduce costs in manufacturing by simplifying assembly processes and eliminating the need for additional hardware. Snap-fit designs allow for quicker and more efficient automated assembly, reducing labour costs and assembly time. The use of fewer parts also cuts material costs and reduces inventory management complexity. Additionally, snap-fits can be integrated into injection-moulded parts, enabling the production of complete assemblies in a single moulding operation, which lowers production costs. Overall, the reduction in parts, faster assembly, and streamlined manufacturing processes contribute to significant cost savings.

2.2.4 Disadvantages of Snap-fits

Snap-fit can result in a fracture if it does not suit the applications that require impact resistance. This is due to the applied impact load that does not allow enough time for the elastic reaction of a polymer. It can produce full impact shock that can unintendedly deflect the elasticity of the cantilever snap-fit. In the automobile industry, snap-fit is commonly used as an alternative for mechanical joints, cabling joints and car interior lining joints. All of these are assembled manually and the contact area of snap-fits and worker’s fingertips is rather small and that can cause harm to fingertips. This can cause skin pain on the worker’s fingertips (Salmanzadeh & Rasouli, 2015).

2.3 Types of Snap-fits

There are various other kinds of snap-fits that can be used including the popular cantilever snap-fit, torsion snap-fit, and annular snap-fit.

2.3.1 Cantilever Hook Snap-fits

Cantilever hook snap-fits are made up of a cantilever arm with a deflecting hook on the end. Despite their simplicity of construction (the joint is made up of only two pieces), they frequently have advantageous shapes and can be made not only of plastics but also of metals and fibre composites. Other forms of snap-fits include annular snap-fits, which are formed by the mating of concave and convex surfaces, and torsion snap-fits, which are formed by a twisting motion in which these will be discussed in section 2.3.2 and 2.3.3. Figure 2.10 illustrates the cantilever hook snap-fits. Figure 2.11 shows the 3D-printed cantilever snap-fit enclosure.

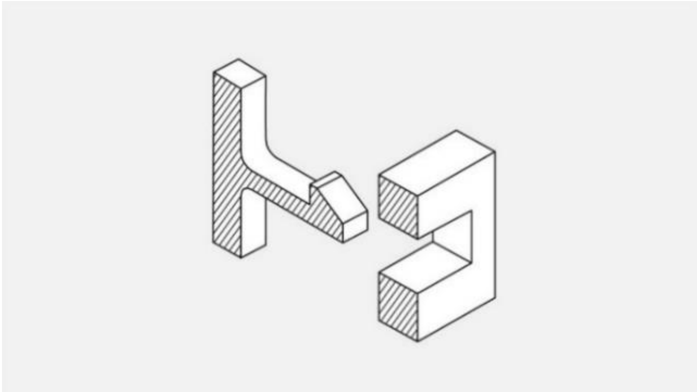


Figure 2.10 Cantilever hook snap-fits

Figure 2.11 A cantilever snap-fit on a 3D-printed enclosure

Source: (*How Do You Design Snap-Fit Joints for 3D Printing? | Protolabs Network*, 2024)

2.3.2 Torsion Snap-fits

Torsion snap-fit joints deflect largely by twisting a bar. Torsion snap-fits are depicted in the figure below. Torsion snap-fit, shown in Figure 2.12 (b), is a straightforward way to make detachable connections. A seesaw mechanism is created by extending the beam hook beyond the axis of the torsion bar. A push on the beam's free end raises the hook and releases the joint (Klahn et al., 2016).

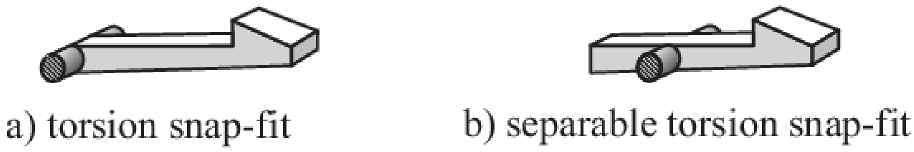


Figure 2.12 Torsion snap-fits
Source: (Klahn et al., 2016)

2.3.3 Annular Snap-fits

Annular snap-fit joints as in Figure 2.13 are frequently used to combine circular or elliptic pieces, such as containers and lids or pens and caps. A ridge around the circumference of one-part latches into a groove in the second part in this form of snap-fit joint. Tensile or compressive hoop stresses arise throughout the assembling process, along with bending. These multiaxial strains might make the proper joint design difficult (Klahn et al., 2016).

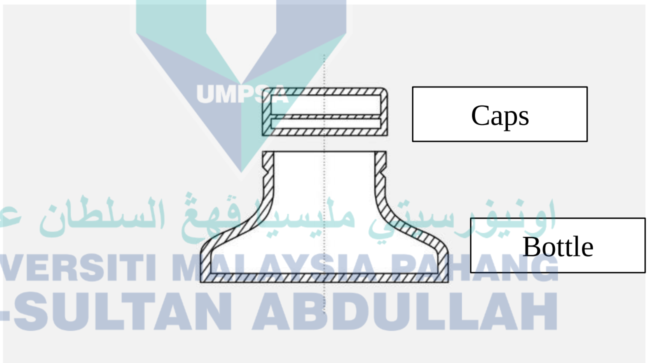


Figure 2.13 Annular snap-fit
Source: (Klahn et al., 2016)

2.3.4 Snap-fits Design Parameters

In snap-fit joints, the cantilever hook-type snap feature is widely employed. The snap-fits primary role is to hold the mating components together, and it must bear vibration and durability pressures. Snap-fits should be created during the assembly process to be easy to assemble and not fail while mating to other components. Snap-fit joints are classified as separable or non-separable based on their design. Non-separable joints needed the part to sustain the loads until failure, whereas separable joints will only withstand the design load. As a result, the design of snap-fits must be capable of generating an efficient interlock fitting. The mounting parts used for demountable joints should be flexible enough to deform elastically even in small spaces. Snap-fits, when properly engineered, may be joined and disjoined repeatedly without causing any damage to the attachment (Ajesh et al., 2017).

The length, width or base, and thickness are the most important parameters that influence snap-fits. The design elements of snap-fits are highly important, and each of them will influence the joint performance and ability to sustain stress during assembly. The key needs of snap-fit design have been characterised as strength, constraint, compatibility, and robustness. Several aspects in the matting process will impact the efficiency and feasibility of the snap-fit design. A good design of snap-fit connectors, like any other contact-aided mechanism, necessitates the precise determination of the design attributes (Kakade & Patil, 2008).

Several design solutions for cantilever hook snap-fits can be identified to predict the joint's insertion and retention forces. These are the feature thickness (Tb), beam length (Lb), beam width (Wb), base radius (Rb), mounting (α), and dismounting angle (β). The forces acquired during the insertion and retention of the snap-fits joint will be affected by changes in the values of these parameters. Figures 2.14, 2.15 and 2.16 illustrate the design parameters of the snap-fits joint.

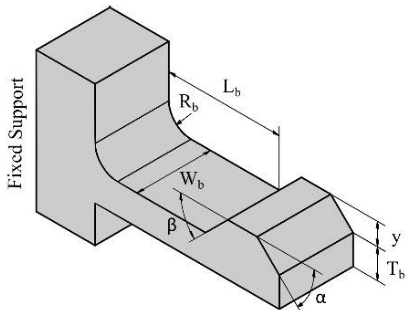


Figure 2.14 Design parameters of cantilever hook snap-fits
Source: (Amaya et al., 2019)

Design parameters for cantilever snap-fit:

Tb	=	Feature thickness
Lb	=	Beam length
Wb	=	Beam width
Rb	=	Base radius
α	=	Mounting angle
β	=	Dismounting angle

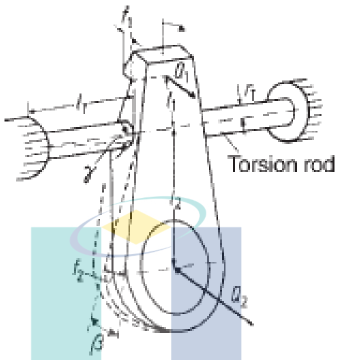


Figure 2.15 Design of torsion snap-fit

Source: (Erhard, 2006)

Design parameters for torsion snap-fit:

l_T	=	Length
r_T	=	Radius
β	=	Angle of torsion
γ	=	Angle of twisting
$l_{1,2}$	=	Length of lever arm
$f_{1,2}$	=	Elastic excursions
$Q_{1,2}$	=	Forces of deflection

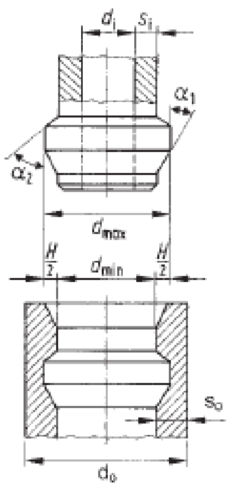


Figure 2.16 Design of annular snap-fit

Source: (Erhard, 2006)

Design parameters for annular snap-fit:

d_{max} = Maximum diameter of snap-fit joint

d_{min} = Minimum diameter of snap-fit joint

d_0 = Outer diameter of outer part

d_i = Inner diameter of inner part

s_0 = Outer wall thickness

s_i = Inner wall thickness

2.4 Parametric Study of Cantilever Snap-fit

There are several important parameters that need to be evaluated to analyse the performance of the insertion, retention forces and locking ratio in the cantilever snap-fit. The manipulated parameters are the feature thickness (Tb), beam length (Lb), beam width (Wb), base radius (Rb), mounting angle (α) and dismounting angle (β).

2.4.1 Beam Thickness (Tb)

The optimum beam thickness for cantilever hook snap-fits is critical for balancing flexibility and strength. 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 optimal thickness depends on the material properties, the required retention force, and the expected load conditions. According to Bonenberger (2017), the beam thickness Tb, as in Figure 2.17, is normally the first parameter and constraint for the feature design. He mentioned that he started on where the hook meets the parent component. The beam extends from the wall in different ways and the most common is 90° protrusion and in-plane. According to Bonenberger (2017), the thickness of the beam should be 50% or 60% of the thickness of the wall. If the beam is lower than 50%, it may cause high residual stress that will weaken the feature.

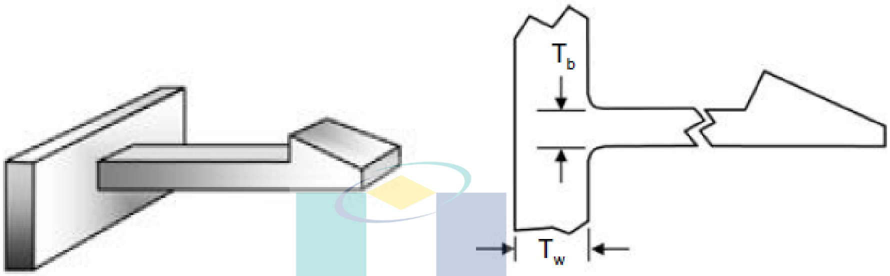


Figure 2.17 Snap-fit Thickness

Source: (Bonenberger, 2017)

2.4.2 Beam Length (Lb)

The optimum beam length for cantilever hook snap-fits balances flexibility and strength to ensure secure engagement and easy release without material fatigue or failure. Ideally, the beam should be long enough to provide sufficient deflection when engaged, minimizing stress concentrations at the base and distributing load more evenly. However, it must not be so long that it becomes overly flexible and compromises retention force. The beam length (Lb) in Figure 2.18 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 (Bonenberger, 2017).

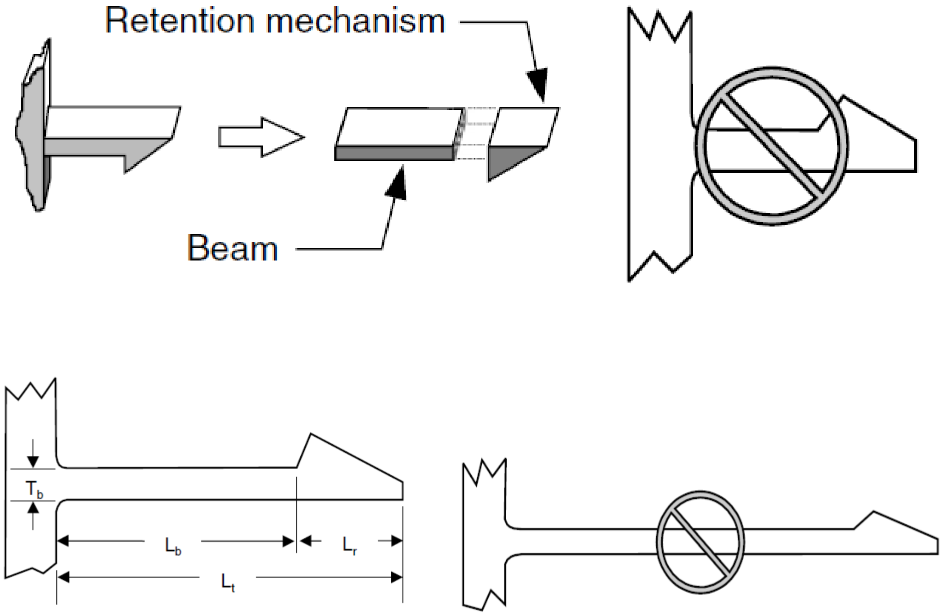


Figure 2.18 Beam length design

Source: (Bonenberger, 2017)

Beams that are shorter than 5 times the beam thickness will result in significant shear effects as well as bending at the base. It can damage and render the analytical calculations less accurate due to its less flexibility which creates higher strains at the base. Higher length-to-thickness ratios is recommended for brittle and harder plastics (Bonenberger, 2017). This means that the length should be optimum as it cannot be too long or too short as it can cause damage or crack towards the snap-fits.

2.4.3 Beam Width (Wb)

Technically, the beam width does not affect the maximum assembly strain, but it affects the forces during assembly and disassembly and the retention strength. The width should be less or equal to the length for the beam theory to apply and as the width is greater than half of the length, the feature will be considered as a plate rather than a beam but minor inaccuracies of the higher beam widths can be generally ignored when involves in calculations (Bonenberger, 2017).

Figure 2.19 Beam width design

Source: (Lee, 2022)

2.4.4 Base Radius (Rb)

The optimum beam base radius 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. Generally, a larger base radius is preferred as it lowers the stress concentration factor, but it must be balanced with the overall geometry and space constraints of the design. By using the ratio of R/h, the optimum reduction for stress concentration seems to be 0.6 since the marginal reduction occurs after this point. However, the 0.6 R/h results in a thick area at the intersection of the snap-fit arm and its base that would cause the thick section to sink or become void due to high residual stress. The internal testing made shows that the radius should not be less than 0.015 in. (0.381 mm) (Snap-Fit Joints for Plastics - A Design Guide, 2013). Figure 2.20 shows the effect of a fillet radius on the stress concentration, the increased value of the fillet contributes to the lower stress concentration factor of the snap.

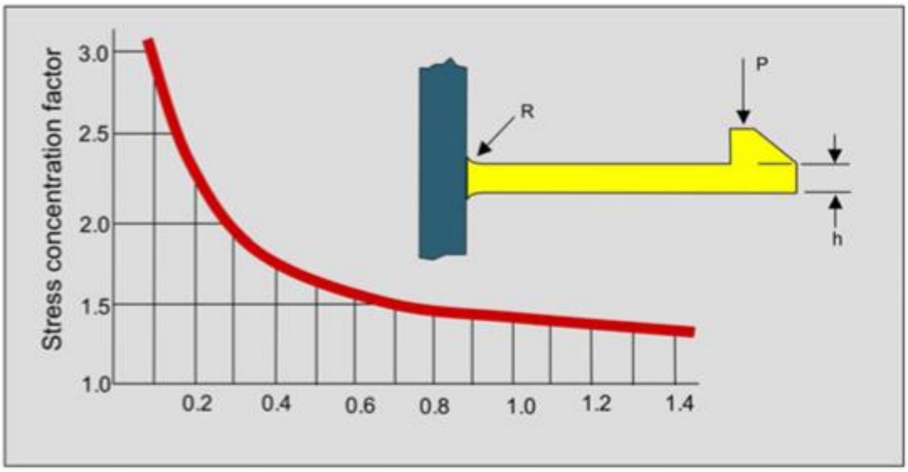


Figure 2.20 Effects of a fillet radius on stress concentration

Source: (*Snap-fit Joints for Plastics: A Design Guide*, 2013).

2.4.5 Mounting / Insertion Angle (α)

The optimum mounting or insertion angle for cantilever hook snap-fits is critical for achieving a balance between ease of assembly and secure retention. This angle determines how easily the snap-fit can be engaged during assembly and how effectively it holds the components together. The mounting angle (α) or the insertion face angle will affect the assembly forces. According to Bonenberger (2017), the steeper the angle, the higher the force required to deflect and engage the hook. He suggested, as shown in Figure 2.21, that the ideal angle should be as low as possible for low assembly force which is 25° to 35° reasonably. 45° or greater can be difficult to assemble and should be avoided.

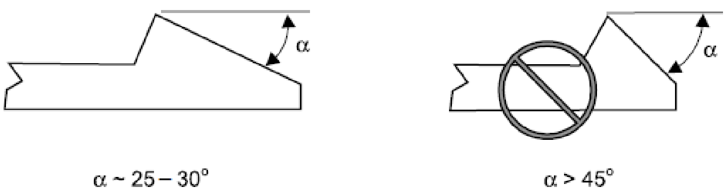


Figure 2.21 Mounting/ Insertion angle

Source: (Bonenberger, 2017)

2.4.6 Dismounting/ Retention Angle (β)

The dismounting angle (β) or the retention face angle in Figure 2.22 will affect the retention and separation behaviour as the steeper the angle, the higher the retention strength and the disassembly force. 35° retention angle is acceptable for a releasing lock where no external separation forces are acting on the mating part. If a low external separation force is expected, the retention face angle will be about 45°, reasonably (Bonenberger, 2017).

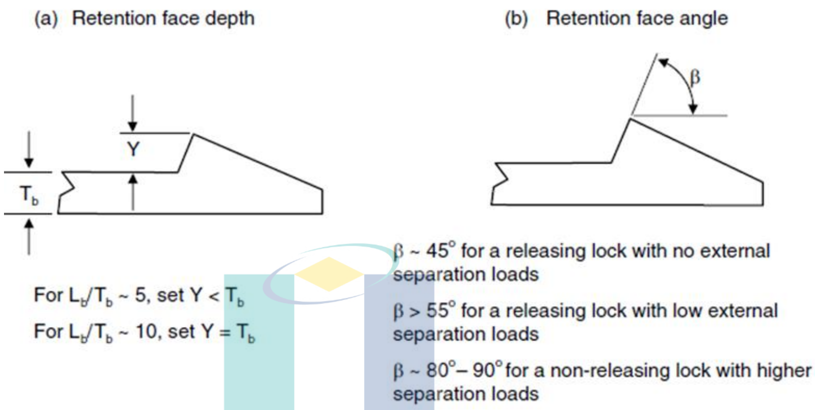


Figure 2.22 Dismounting/ Retention angle of snap-fit
Source: (Bonenberger, 2017)

2.4.7 Geometrical Relationships of the Parameters

Each of the parameters is mostly dependent on each other as the design consideration can affect the functionality and strength of the parts. Thus, Bonenberger (2017) suggests that the dimensions and parameters of the snap-fit design are as shown in Table 2.1.

Table 2.1 Geometrical relationship of the parameters

Variable	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} is the thickness of the wall

2.4.8 Performance of Snap-fits (Insertion and Retention Forces)

The force that must be provided in the direction of insertion while the snap-fit interacts with the matting component is referred to the insertion force. It can be expressed as a single maximum value or as forces versus position with respect to snap-fit characteristics. Retention force is a parameter that must be considered when disassembling a snap-fits joint. Disengagement happens through fracture or irreversible deformation of the two mated pieces if the design is intended to be permanent. The combination of these two pressures results in a locking ratio, which is described as the maximum retention force to the maximum insertion force of snap-fit features. The design specifications of the snap-fits have a significant impact on these forces. The quantity of interference between the joints will indicate the assembly's quality. The insertion force increases as the interference increases. Too little interference results in the loose assembly, whereas too much interference causes difficulty in assembly and increases the likelihood of component failure. Figure 2.23 shows the typical experimental force curve for insertion and retention of the snap-fit from a study made by Suri (2002). The force of retention is higher than the force during the insertion of the snap-fit.

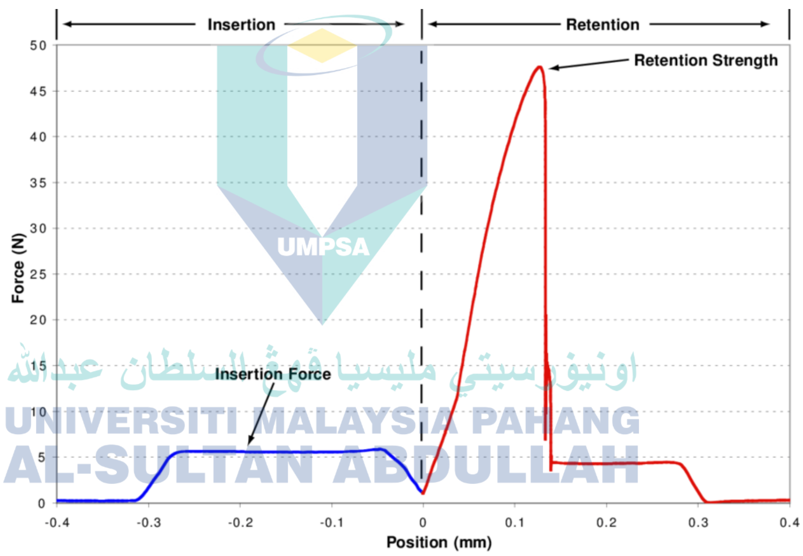


Figure 2.23 Typical experimental force curve for insertion and retention of snap-fit
Source: (Suri, 2002)

2.4.9 Insertion Forces (Fi)

Insertion force (Fi) is the force required to engage a snap-fit in the insertion direction. It can be specified as a single maximum value or as a graph of force versus positive related to the snap-fit feature (Suri & Luscher, 2000).

2.4.10 Retention Forces (Fr)

To disassemble a snap-fit feature, 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. If a snap-fit is intended to be detachable, the retention face angle is set to be less than the critical angle of friction, allowing for disengagement by camming motion (Suri & Luscher, 2000).

2.4.11 Locking Ratio (LR)

A locking ratio can be defined as the ratio of the maximum retention force to the maximum retention force of the snap-fit. The equation 2.1 is shown:

$$LR = \frac{F_r}{F_i} \qquad 2.1$$

According to Suri & Luscher (2000), the locking ratio may be interpreted as the mechanical benefit of the snap-fit feature, and it links the Fr, the favourable characteristic, that is obtained in exchange for Fi, the unfavourable attribute. The benefit of a high locking ratio is that it allows for the strongest final assembly with the least amount of engagement force. Normally, the maximum allowed insertion force for manually assembled parts is limited by ergonomic reasons. As a general guideline, the greatest force that an assembly worker should apply with his hand and thumb throughout an 8-hour working shift is 2N and 0.5N, respectively. A greater LR provides a substantial advantage in assembly efficiency since it requires less engagement force for ergonomic considerations (Suri & Luscher, 2000).

2.5 Simulation of Snap-fits Joining

Snap-fit has the simplest joining method and easy to disassemble depending on the suitability of the application. To analyse the joining before producing the snap-fit, a simulation of joining must be made to determine the strength of the snap-fit. The figure

2.24 below shows the simulation of joining for snap-fit. The boundary conditions can be seen on both the male and the female part of the snap-fit.

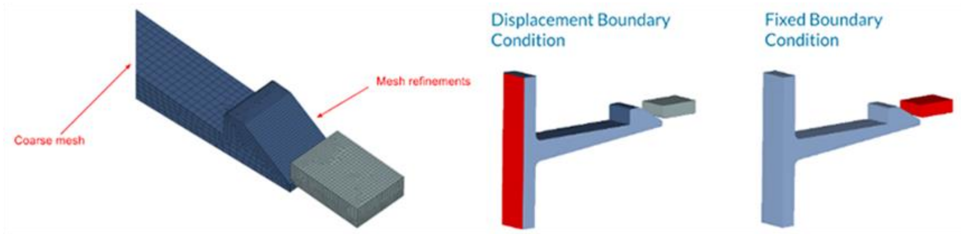


Figure 2.24 Conditions of the snap-fit
Source: (Churazova, 2017)

In finite element analysis, the position of the fixed boundary condition and displacement boundary condition is needed to be set beforehand. According to Figure 2.25, the snap is the displacement boundary condition while the small box against which the body deforms is the fixed boundary. The areas that have the highest stress after the design is simulated, can be clearly visible as shown in Figure 2.26 below.

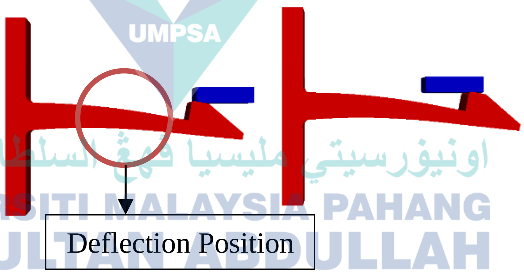


Figure 2.25 Deflection position of the snap-fit

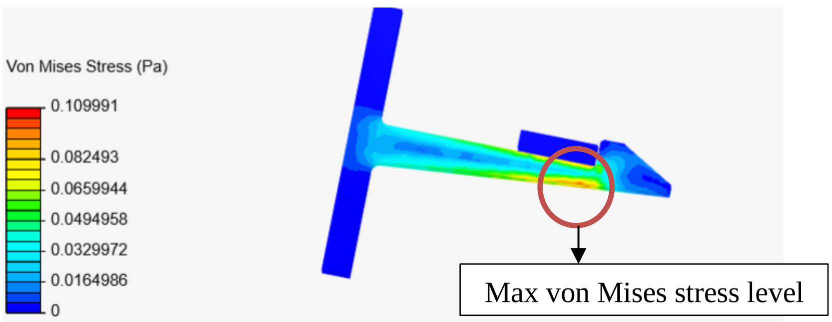


Figure 2.26 Final position of snap-fit with stress

Figure 2.26 showing the concentration level of von Mises Stress generated after the insertion process is completed. Thus, the area in which is in highlighted in red, showing that it has the maximum stress concentration. In this case, force can be higher in that region compared to others.

Another example of snap-fit application can be seen in the production of a 1-gallon plastic container division. According to a case study by Amaya et al. (2019), the study focused on the portioning of a 1-gallon plastic container into 6 parts as shown in Figure 2.27, for printing and posterior joining using Acrylonitrile Butadiene Styrene (ABS) plastic with permanent joints that do not affect the appearance of the container. The hook and the design of the snap-fit for the plastic container follow the geometry of the cantilever snap-fit. The wall's dimensions are 2mm in thickness, 13mm in length, 6mm in breadth, 1mm in base radius, 2mm in retention height, 25° mounting angle and 50° dismounting angle.

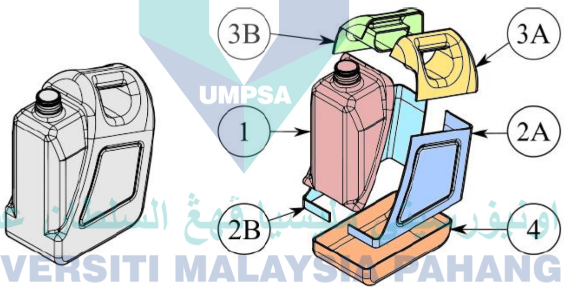


Figure 2.27 Original model and 6-parts division of 1-gallon plastic container
Source: (Amaya et al., 2019)

Figure 2.28 shows the total deformation in the FEA simulation for Part 4 of a 1-gallon plastic container and it shows that the side of the part has the maximum deformation which is 0.00434 mm. In Figure 2.29, it shows the deformation of Part 2A of a 1-gallon plastic container and the maximum deformation of the beam is on the snap of the container.

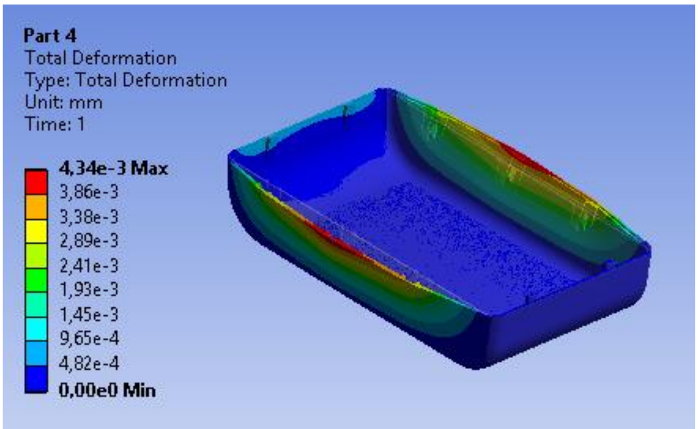


Figure 2.28 Part 4 total deformation in FEA simulation

Source: (Amaya et al., 2019)

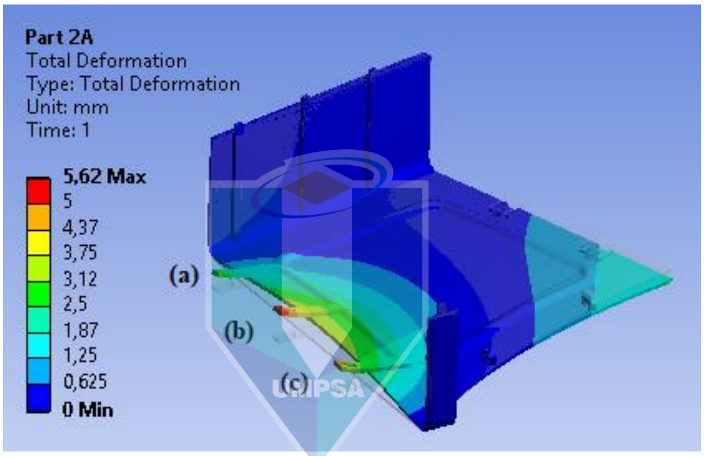


Figure 2.29 Part 2A total deformation in FEA simulation

Source: (Amaya et al., 2019)

2.6 Design for Wall Socket Cover

This research for snap-fit is used in the application for safety wall socket cover and it can be used to avoid injuries for children at home. Figure 2.30 show the design of the socket cover using snap-fit model 1 and it shows the whole design of the cover with the lid and case combined. Figure 2.31 shows the lid of the wall socket cover that includes the snap-fit applications. Then Figure 2.32 shows the wall socket case which will be attached to the wall with a hole at the bottom for the plug’s wire.

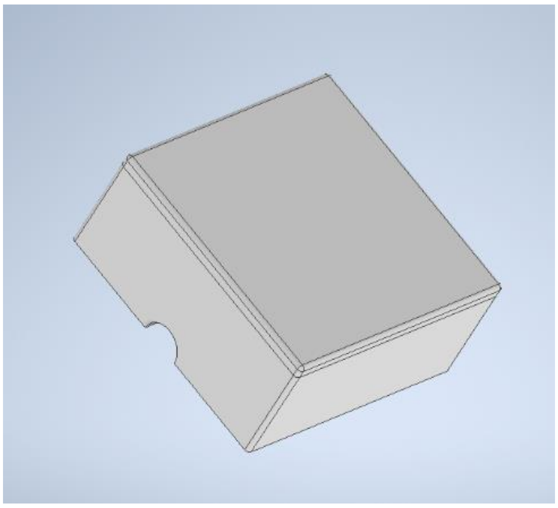


Figure 2.30 Wall socket cover

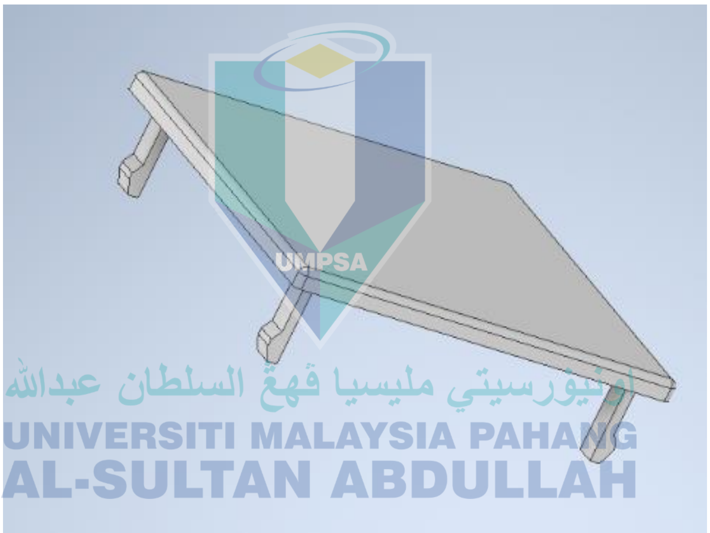


Figure 2.31 Wall socket lid

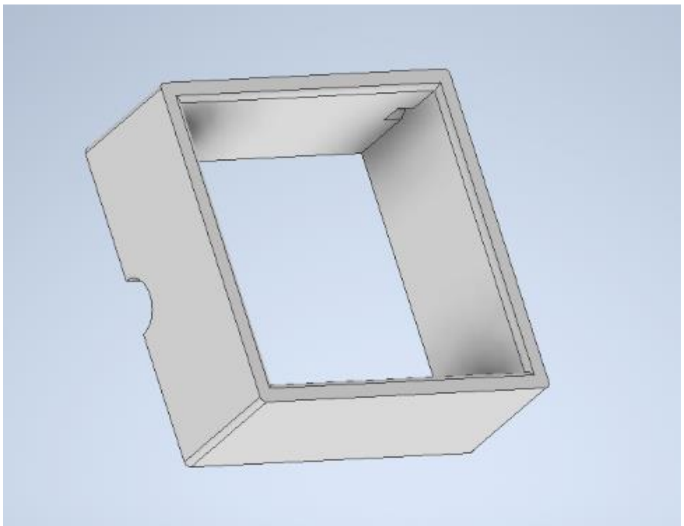


Figure 2.32 Wall socket case

2.7 ABS Material Application

ABS applications can be found in the surroundings, for example, ABS plastics are used to make Lego bricks as in Figure 2.33 and most toys, protective helmets, car dashboards, control panels for household appliances and many more.

Figure 2.33 Lego bricks

2.7.1 Advantages and Disadvantages of ABS

ABS offers excellent mechanical qualities due to its reputation as a tough and long-lasting material. It can withstand higher strain and stress and is heat resistant. For "wear and tear" 3D printing, ABS is an excellent material option. The drawbacks of ABS plastic include its bad odour during printing and its propensity for typical issues like curling and warping brought on by temperature differences between layers of extruded components (Chen, 2019).

2.8 Additive Manufacturing

Additive manufacturing or also known as AM, is the industrial production name for 3D printing, a computer-controlled process that creates three-dimensional objects by depositing materials, usually in layers (*What Is Additive Manufacturing? (Definition & Types)*, 2023). Additive manufacturing processes take the information from a computer-aided design (CAD) file that is later converted to a stereolithography (STL) file. In this process, the drawing made in the CAD software is approximated by triangles and sliced containing the information of each layer that is going to be printed as shown in Figure 2.34. There is a discussion of the relevant additive manufacturing processes and their applications. The aerospace industry employs them because of the possibility of manufacturing lighter structures to reduce weight. Additive manufacturing is transforming the practice of medicine and making work easier for architects (Wong & Hernandez, 2012).

AM provides a cost-effective and time-efficient way to produce low-volume, customized products with complicated geometries and advanced material properties and functionality (Huang et al., 2015). AM can support the production of composite parts along the whole process chain ranging from tooling to post processing (Türk et al., 2017). Non-traditional methods of manufacturing are needed to be developed. Thus, AM plays a vital role in the sufficiency of mass customization in Industry 4.0. Additionally, AM technology is rapidly developing straightforward systems enabling designers to make products faster, despite current technology limitations (Amaya et al., 2019). AM may become a key technology for fabricating customized products due to its ability to create sophisticated objects with advanced attributes (new materials, shapes). Thanks to increased product quality, AM is currently being used in various industries such as aerospace, biomedical, and manufacturing. Although there are still some doubts about its applicability in mass production, the utilization of AM in the industry is on the rise due to new technological advancements (Dilberoglu et al., 2017).

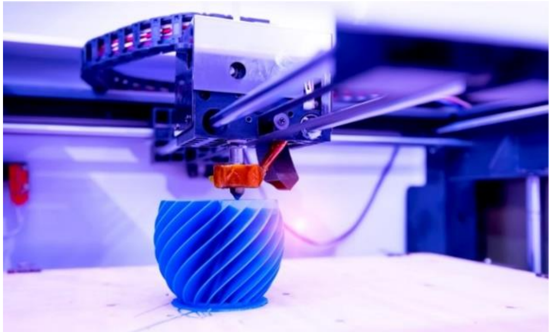


Figure 2.34 3D Printing

2.8.1 3D printing for snap-fit

Traditional snap-fit are usually made using an injection moulding process but other studies have shown that the additive manufactured snap-fits joints have a similar behaviour with the one that fabricated through injection moulding. The developed design rules for injection moulding can also be used in 3D printing (Ramírez et al., 2019). Manufacturing issues can be effectively overcome by implementing AM constraints in the design (Boschetto et al., 2019).

There are several topics that need to be addressed as it affects the performance of the printing and the strength of the printed parts. First, the anisotropic mechanical properties need to be adapted to the design. Figure 2.35 shows the toolpaths in cantilever snap-fit produced by Fused Deposition Modelling (FDM) showing the poor and good toolpaths to place filaments in a snap-fit (Klahn et al., 2016). Anisotropic mechanical properties in FDM mean that printed parts exhibit different mechanical characteristics based on the direction of the applied forces relative to the printed layers, necessitating careful consideration of part orientation and loading conditions during the design process. The filament placement *x*, *y* plane is where the cantilever is oriented. Poor alignment may be shown in the example in Figure 2.35 (a), where the stresses are perpendicular to the filaments. The strong anisotropic direction is aligned with the major stress direction in Figure 2.35 (b), making that orientation more advantageous. Figure 2.36 shows the process of fabrication from the insertion of the solid material filament until it is deposited as semi-molten material that is fed through the nozzle to create parts (Adhiyamaan & Masood, 2012).

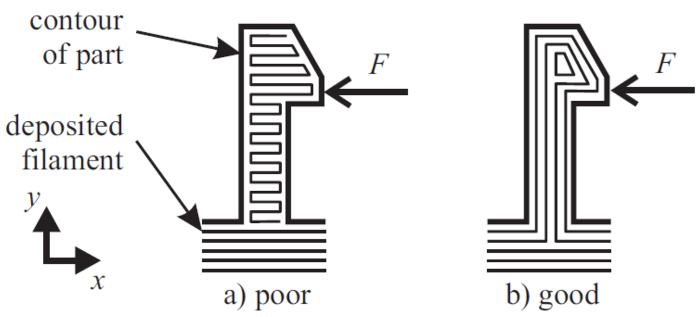


Figure 2.35 Snap-fit toolpaths

Source: (Klahn et al., 2016)

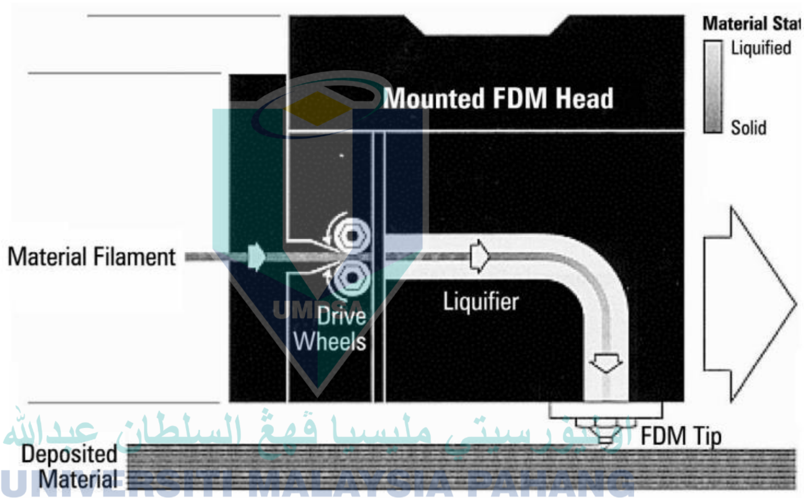


Figure 2.36 Fused deposition modelling

Source: (Ahn et al., 2002)

2.8.2 3D printing for thermoplastics

The design model is created beforehand to produce and fabricate models using 3D printing. Thermoplastics are the best materials to integrate with 3D printers. By using FDM, engineers can make parts using thermoplastics such as ABS, PC and a variety of blends as well as engineered thermoplastics for aerospace, medical, automotive and other applications. Layer-based technology is used in additive manufacturing to translate digital models into plastic components. Automated machines add layer after layer of material directly from CAD files, which makes it simple to build exceedingly complicated parts. The materials are extruded and deposited during the FDM process to produce functioning pieces (Fischer, 2011). There are many considerations before choosing the right printing materials. The stability of the material and its long-term performance is paramount. The mechanical, electrical, thermal and environment properties needed to be considered. Parts created using FDM machines are somewhat similar in terms of the characteristics of the moulded thermoplastics (Ahn et al., 2002).

2.8.3 Advantages and Disadvantages of 3D printing

Advantages	**Disadvantages**
It has flexible design, fast design and production etc. The prototyping process is sped up due to the ability of 3D printing to produce parts in a matter of hours. This makes it possible for each step to be completed sooner. In comparison to machining prototypes, 3D printing is less expensive and faster at producing components since the part may be done in a matter of hours. This makes it possible to complete each design alteration considerably more quickly (*What Is Additive Manufacturing? (Definition & Types)*, 2023). 3D printing is also said to be environmentally friendly as it reduces the amount of material wastage during the process. It is also more accessible as many local services provide the outsourcing for manufacturing works. It saves time and costs compared to traditional manufacturing processes.	3D printing can only be made with limited materials because not all metals and plastics can be temperature controlled enough to allow 3D printing. 3D printing has also limited size as it can only produce small-sized parts due to the small print chambers. Bigger products will need to be printed in smaller parts and joined together after production (*What Is Additive Manufacturing? (Definition & Types)*, 2023).

2.9 Universal Testing Machine (UTM)

Universal Testing Machine (UTM) is a universal tester that can perform various kinds of tests such as tensile test, compression test, bending test, shear test etc. UTM consists of two essential parts which are the loading unit and the control/measuring unit as shown in Figure 2.37.

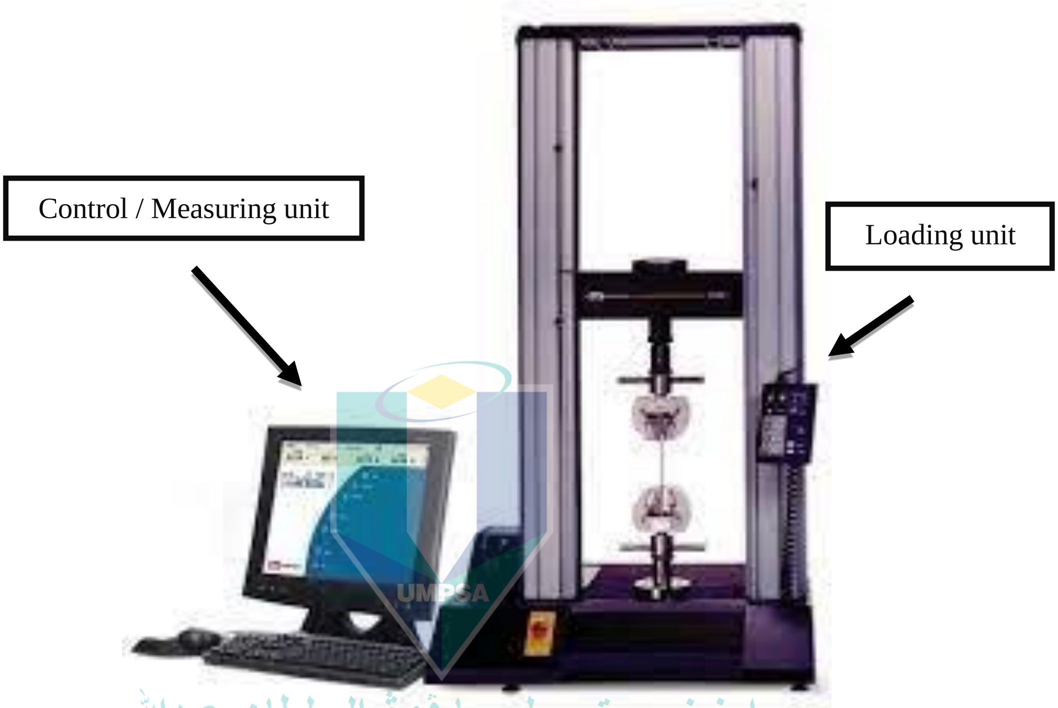


Figure 2.37 Universal Testing Machine (UTM)

Usually, the materials for tests performed using UTM are metals, plastics and most other materials. If the tensile test is conducted, the tensile load pulls the specimen apart and puts the specimen in tension and it is used to determine the mechanical behaviour of materials under static, axial tensile, or stretch loading (Michigan Technological University, 2021). The compression test is a test that will compress the specimen as the forces push towards each other and making the specimen shorter. The data collected on compression test is such as applied load, deformation, deflection and condition of the specimen. The length of the specimen for flexural or bend testing should be 6 to 12 times the width to prevent shear failure. The areas of contact with the material being tested should be designed to prevent excessively high stress concentrations.

Longitudinal adjustments and lateral rotational adjustments are necessary for support and to prevent torsional stresses.

2.9.1 UTM testing for snap-fits

There are several studies showing snap-fits tests using UTM. The assembly and disassembly mechanics of a cylindrical snap-fit has been made by Guo and Sun (2022) showing the compression test made on 3D printed cylindrical snap-fit by using an electronic universal testing machine and controlled by a microcomputer to conduct the assembly as shown in Figure 2.38.

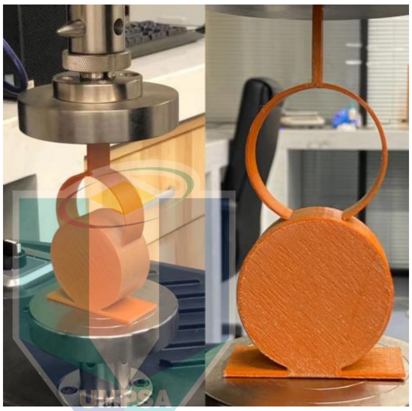


Figure 2.38 Experimental setup for 3D printed cylindrical snap-fit
Source: (Guo & Sun, 2022)

There is also a study made by Wang et al. (2019) regarding the compression performances and failure maps of sandwich cylinders with pyramidal truss cores obtained through geometric mapping and snap-fit method. The test on the sandwich cylinders is made using static uniaxial compressive tests in a 200kN capacity electronic universal testing machine (Wang et al., 2019). A pair of stainless-steel disks with annular grooves were placed at the top and bottom of the sandwich cylinder to achieve a clamped boundary condition as shown in Figure 2.39.

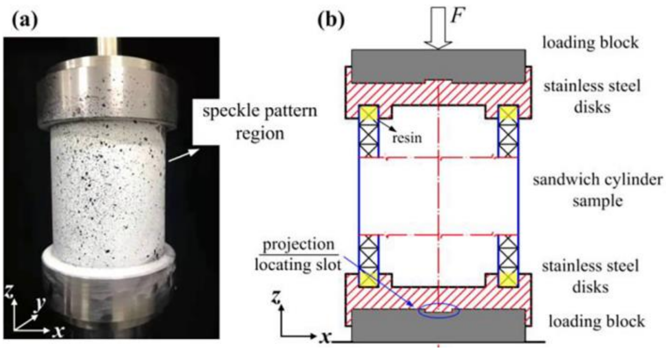


Figure 2.39 Sandwich cylinder test using UTM
Source: (Wang et al., 2019)

2.10 Summary

Snap-fits are mechanical fastening systems used in manufacturing industry to join two or more components. They work by using a small amount of interference or friction to keep the components together, thus eliminating the use of external fasteners. The benefits of using snap-fits include cost savings, faster assembly times, and simpler designs.

This research emphasizes on creating snap-fit based on the parameters stated in the literature. There have been advancements in understanding the mechanics involved in snap-fits. Researchers have utilized various modelling techniques such as finite element analysis (FEA), analytical and empirical approaches to develop accurate numerical models. By doing the FEA, the stress concentration can be measured thus can generate the insertion and retention forces and solving the problems as stated in the problem statements such as the stress concentration and the fingertip injuries. The main parameters that are needed to measure are the insertion and retention forces of the snap-fit. It is important to design a cantilever snap-fit that has a proper dimension as it affects the quality of the performance and the forces that it can sustain. Additive manufacturing is used in this study to fabricate the snap-fits models. The use of 3D printing is in high demand due to its advanced technology manufacturing and rapid prototyping. Then, the use of UTM has been applied to evaluate the forces of snap-fit in experimental analysis as UTM provides a tensile and compression test.

CHAPTER 3

METHODOLOGY

3.1 Introduction

For this chapter, a detailed explanation of the methodology is given and the flowchart summarizes the research framework. The methodology is divided into 4 phases which are: Phase 1, design parameters and geometrical modelling of the cantilever hook snap-fits joint. Phase 2 is the modelling of retention and insertion forces using implicit Finite Element Method (FEM) analysis. Implicit and explicit FEM are two different computational approaches used to solve problems involving complex structures and materials under various conditions. Implicit FEM is typically used for static, steady-state, and slowly varying dynamic problems. It involves solving a set of simultaneous equations at each time step, which can be computationally intensive but stable and accurate for small time increments. Explicit FEM, on the other hand, is suited for highly dynamic, transient events such as impacts, explosions, and crash simulations. It calculates the state of the system at each time step directly without solving a system of equations, making it faster for very short time steps but potentially less stable for longer time steps. Implicit methods generally require fewer, larger time steps, while explicit methods use many small-time steps to capture the dynamics of rapidly changing systems. Phase 3 is to compare the numerical results (FEA) with the experimental works. Meanwhile, Phase 4 is the analysing the results and data acquired in cantilever hook snap-fits design. Any changes in parameters or design can affect the efficiency and strength of the cantilever hook snap-fit. To examine the forces related, Finite Element Analysis or FEA method is done to generate the number of forces that can be applied to the snap-fit. The equipment used to test the insertion and retention forces of the cantilever hook snap-fit is laid out and the application of each piece of equipment is explained.

3.2 Flowchart

The flowchart or framework is created to show the process of the work that is needed to be done so that it can be done with the right step within the right timeline. The process flow of conducting this research is shown in the Figure 3.1.

For Phase 1, which is the design parameters and geometrical modelling of the cantilever hook snap-fits joint, the first step is to analyse and find the parameters that are measured in the research. For this research, the important parameters are the insertion and retention forces. The thickness of the features (Tb), beam length (Wb), base radius (Rb), mounting (α) and dismounting angle (β) are the important characteristics that most influence the cantilever type of snap-fits. Thus, this gives 16 different models that can be investigated and designed. The first stage of the research is to convert all the parameters into a CAD model.

The focus of Phase 2, modelling of retention and insertion forces using Finite Element Method (FEM) Analysis, is to simulate the insertion and retention forces generated while executing the matting operation of the snap-fit. ABS is the material of choice for modelling. Then, continue with the simulation analysis with different design parameters. The model would predict insertion and retention force curves based on the design parameters used in the CAD model. The model is then tested with a different set of parameters. Any changes to the design parameters are expected to affect the value of the insertion and retention forces. These results will be analysed further to determine the relationship between the design parameters and the response variables (insertion and retention forces).

The next phase of the research, which is Phase 3, is to compare the numerical results (FEA) with the experimental works. The impact of parameters such as snap-fit geometry, friction and wear of surfaces in contact and manufacturing variability would be investigated. The experiment would be carried out by creating a test fixture that includes a snap-fits component, a sliding mechanism, load cells and other measuring devices. The last phase would be analysing the results and data acquired. This is to finalize the results that are obtained from the research and can be documented properly and correctly.

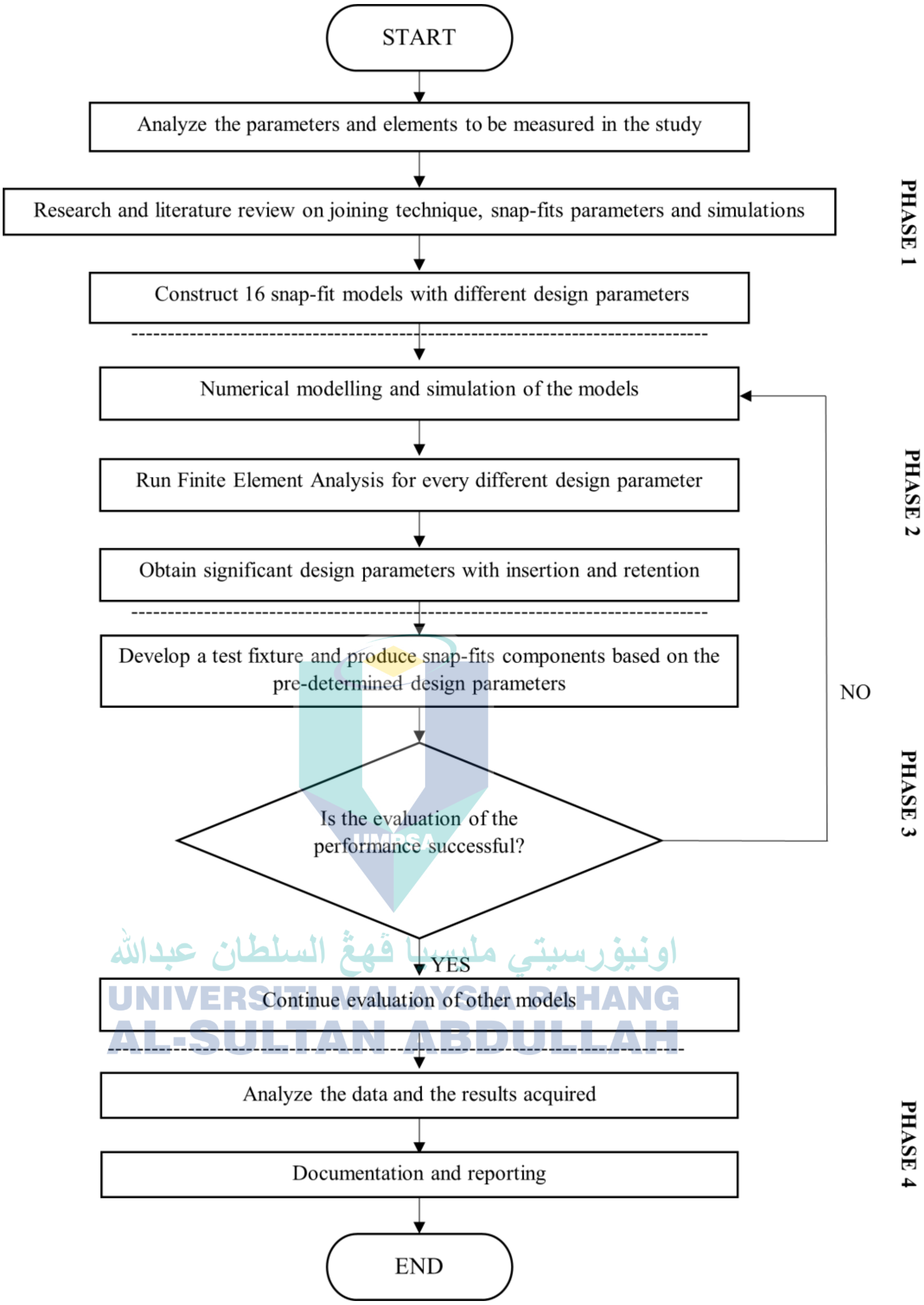


Figure 3.1 Flowchart of the research

3.3 Design parameters

In this research, several parameters need to be set as they affect the cantilever hook snap-fits analysis. The parameters mentioned are categorised to constant parameters and variable parameters. Figure 3.2 shows the proposed design and deflection mechanism dimensioning from the literature.

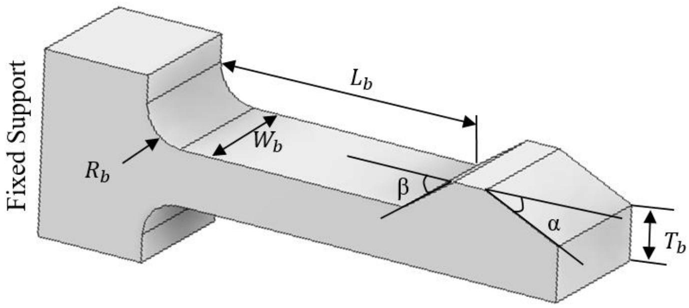


Figure 3.2 Design parameters of cantilever hook snap-fits

Source: (Amaya et al., 2019)

Design parameters for cantilever snap-fit:

Tb	=	Feature thickness
Lb	=	Beam length
Wb	=	Beam width
Rb	=	Base radius
α	=	Mounting angle
β	=	Dismounting angle

3.3.1 Constant Parameters

A constant parameter is a parameter that is not manipulated and stayed the same for the whole experiment. Hence, the constant parameter in this research is the area of the hook of the cantilever hook snap-fits. The number is chosen based on the size of the plug outlet as referred to literature review or Chapter 2.2.2 and 2.6. It is important to make sure that this parameter is constant throughout the research. In this research, the constant parameters are as Table 3.1 following the guideline from Bonenberger (2017):

Table 3.1 Constant parameters

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

3.3.2 Manipulated Parameters

Several parameters are manipulated to obtain several design parameters and models to be evaluated. The parameters are as Table 3.2.

Table 3.2 Testing model parameters

α	**β**	$\boldsymbol{T_b}$	$\boldsymbol{L_b}$	**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 mm	15 mm	5
			30 mm	6
		3.6 mm	18 mm	7
			36 mm	8
30°	35°	3 mm	15 mm	9
			30 mm	10
		3.6 mm	18 mm	11
			36 mm	12
	45°	3 mm	15 mm	13
			30 mm	14
		3.6 mm	18 mm	15
			36 mm	16

3.3.3 Design Software (Autodesk Inventor)

Autodesk Inventor was used to model the cantilever hook snap-fit design for this study, as illustrated in Figure 3.3. It is a software program that offers resources for 3D product design and production. Tool integration for machine design, presentations, rendering, simulation, sheet metal, frame design, tube and pipe design, cable and harness design, and other tasks is possible with Inventor. (*Inventor Software | Get Prices & Buy Official Inventor 2023 | Autodesk*, 2021).

Figure 3.3 Autodesk Inventor

3.3.4 Flow for Designing

The flow for designing parts in Inventor software is shown in Appendix B. The process starts by opening the Autodesk Inventor software. After the software runs, to begin design, "Part" is selected on the main page and it opens a new page showing the design tools. Click on "Start 2D Sketch" and choose the axis to begin the sketch. The axis must be assigned with the consideration of printing movement. Typically, lateral movement is assigned to *x*-axes and *y*-axes, meanwhile for *z*-axis corresponds to vertical motion (Carolo, 2020). There are many tools that can be used to design a snap-fit such as line, rectangle, fillet and so on. After the design of the snap-fit is drafted, the dimension feature is used to insert the accurate dimension values that are used in the research. The work on 2D sketch is continue until all the dimension values are inserted. If the sketch is completed, click on "Finish Sketch". Then the sketch is extruded which makes it 3D. Finally, after everything is done, the design can be saved as .ipt, .stp and .stl files to be used in ANSYS and 3D printer.

3.3.5 Design Model for Snap-fits

Snap-fit models are drafted using Autodesk Inventor and the parameters of the design followed the guidelines discussed in Chapter 2.4 and Chapter 3.3. The snap-fit model design and sketch can be seen in Figures 3.4 and 3.5. The parameters of the models designed in this research which has been made according to suggestion and formulation made by Bonenberger (2017) which has been validated by research from Amaya et al. (2019) can be seen from previous Table 3.2.

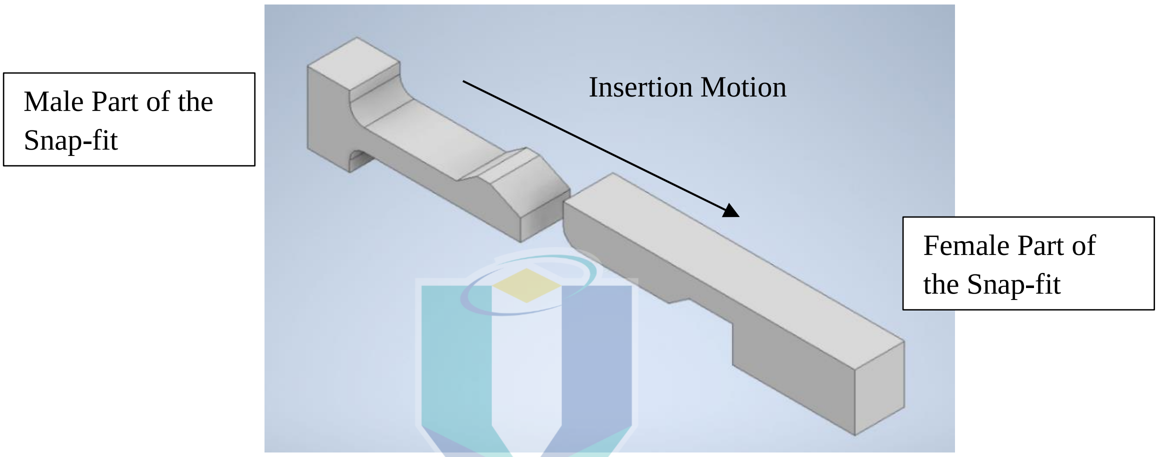


Figure 3.4 Snap-fit model 1 design in Inventor

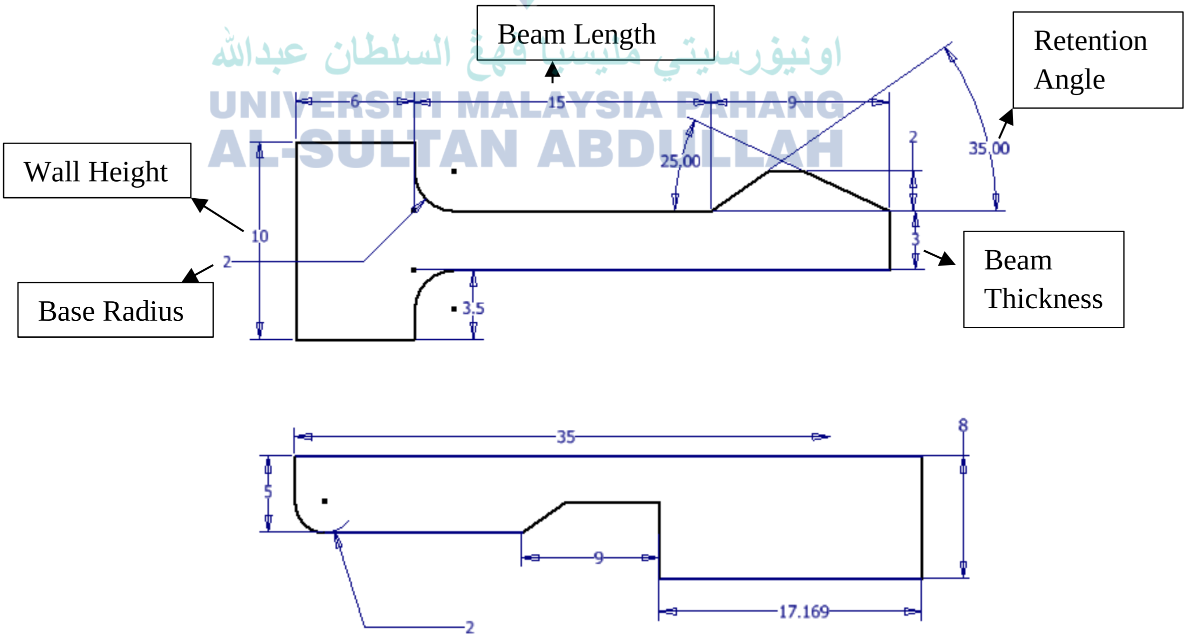


Figure 3.5 Sketch for snap-fit model 1 in Inventor

16 sets of design parameters are chosen with the different manipulated variables starting from the insertion angle, retention angle, the thickness of beam and the length of beam. Each of the different parameters has been set to either the lowest boundaries or highest boundaries or a mix of both as in Table 3.2. Thus, a thorough investigation can be carried out to identify which design suits the most and functions well.

3.4 Material

Acrylonitrile Butadiene Styrene, also known as ABS, is a typical thermoplastics polymer used for injection moulding and 3D printing. The popularity of this material is attributed to its advantages, which include affordability and low production costs. ABS offers several mechanical qualities that make it the ideal material for usage, including impact resistance, structural strength, and stiffness. Additionally, it is resistant to chemicals and works well in both hot and low temperatures. It has excellent capabilities for electrical insulation. The coefficient of friction of ABS is in the range of 0.11 to 0.46. In this research, the coefficient that is used is 0.4 as the simulation stated that the coefficient of friction is larger than 0.2 and 0.4 is a suitable value to avoid convergence error during simulation. ABS polymers consist of three monomer units which are acrylonitrile, butadiene and styrene (Vishwakarma, 2017) as shown in Figure 3.6.

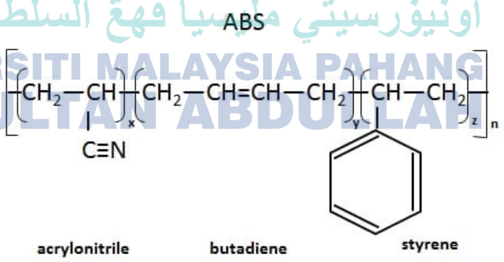


Figure 3.6 ABS Chemical Structure

Source: (*ABS Recycling in Vancouver / Burnaby - Reclaim Plastics*, 2023)

3.4.1 Properties of ABS

The mechanical and thermal properties and the print settings for 3D printer are shown in the Table 3.3. The properties are according to the information by Polymaker

Polylite ABS 3D printing filament as shown in Table 3.3 and 3.4 (*PolyLite™ ABS – Polymaker*, 2022) and ANSYS Engineering Data Sources for Plastic, ABS. Figure 3.7 showing the example of ABS filament in 3D printing. Young's modulus and tensile strength are both important mechanical properties of materials, but they describe different aspects. Young's modulus, or the modulus of elasticity, measures a material's stiffness and is defined as the ratio of stress (force per unit area) to strain (deformation) within the elastic limit of the material. It indicates how much a material will deform under a given load within its elastic range. Tensile strength, on the other hand, is the maximum stress a material can withstand while being stretched or pulled before breaking. While Young's modulus tells us how easily a material deforms elastically, tensile strength indicates the material's ability to resist breaking under tensile loading. Together, they provide a comprehensive understanding of a material's mechanical behavior under stress.

Table 3.3 Mechanical properties of ABS

Mechanical Properties	
Young’s Modulus	2174 MPa
Density	1050 kgm^{-3}
Tensile Strength	29.6 MPa
Bending Strength	72.8 MPa
Charpy Impact Strength	12.6 kJ/m^2

Table 3.4 Print settings for ABS

Print Settings	
Nozzle Temperature	240˚C
Printing Speed	55mm/s
Bed Temperature	85˚C
Bed Surface	BuildTak®, PEI sheet with ABS slurry
Cooling Fan	LOW for better surface quality

Figure 3.7 Polymaker Polylite ABS 3D Filament

3.4.2 Printing Performances

Due to its light weight and stiffness, ABS is a well-liked material that may be extruded or injection moulded. When opposed to PLA, ABS is less friable and can withstand greater temperatures since it has strong mechanical qualities. All home, professional, and commercial printers that employ FDM technology frequently use ABS.

ABS plastic needs a heated bed as it does not stick to the print surfaces which can break prints. If it is poorly heated, it can warp dramatically and deformed. If the setting is right, ABS filament will generate a good result as the filament oozes and strings lesser than others and it gives the model a smooth finish (Chen, 2019).

3.5 Finite Element Analysis (FEA)

Finite Element Analysis or FEA method is a numerical technique that maintains the complexity of the problems, like varying shapes, boundary conditions and loads, but the solutions obtained are approximate. This method has been receiving much attention because of its diversity and flexibility as an analysis tool. The fast improvements in computer hardware technology and slashing of the cost of computers have boosted this method since the computer is the basic need for the application of this method.

The FEA originated as a method of stress analysis in the design of aircraft. It started as an extension of the matrix method of structural analysis. Now, this analysis can be used extensively in many aspects, such as fluid flow, heat transfer, analysis of beams, plates and many more (Bhavikatti, 2015). There are a lot of software that can be used to perform this analysis such as ANSYS and Autodesk Inventor.

In this research, non-linear FEA is used as non-linear analysis accounts for material non-linearity, large deformations, geometric non-linearities, and other complex behaviours. It considers changes in material properties, contact interactions, large displacements, and large strains that might result in non-linear relationships between stress and strain. Non-linear analysis in ANSYS is used in scenarios involving plastic deformations or yielding of materials, large displacements or rotations that may alter the structure's behaviour significantly, non-linear materials like elastomers or composites with complex stress-strain behaviour, contact problems where parts interact in a non-linear manner due to friction, large sliding, or separation. Finite Element Analysis (FEA) flow involves a systematic process to simulate and analyze the behavior of structures and materials under various conditions. The FEA process typically begins with defining the geometry of the model, followed by discretizing it into smaller elements (meshing). Material properties and boundary conditions (constraints and loads) are then assigned. The system of equations derived from the governing physical laws is solved, resulting in outputs such as displacements, stresses, and strains. Non-linear FEA addresses scenarios where the relationship between applied forces and displacements is not proportional, encompassing material non-linearities (such as plasticity, hyperelasticity), geometric non-linearities (large deformations), and boundary non-linearities (contact problems). These require iterative solving techniques due to their complex, non-linear nature.

3.5.1 Flow for Simulation in ANSYS

The flowchart for simulation in ANSYS can be found in Appendix C. To begin the simulation, first, the ANSYS Workbench software is opened and the "Static Structural" function is selected from the left side of the main page. Then click on "Engineering Data" to select materials to use, which in this study, is ABS. After selecting the material, click on "Geometry" and import geometry from Inventor in .stp file. Then, click on "Model" and select "Edit" to edit properties and functions for the simulation. The windows forwarded to ANSYS Mechanical software.

The connections are made to ensure the contact surfaces are correct. The selected face of the snap-fit must be accurately selected to obtain a good simulation. The contacts are inserted manually by selecting the faces of the cantilever snap-fit to connect to the female part. “Contact” is set up for snap-fit meanwhile “Target” is the female part of which the snap-fit will be inserted to. The value of coefficient friction for ABS is inserted which is 0.4, the most suitable value for simulation to avoid convergence error. In Finite Element Analysis (FEA) of ABS snap-fits, a friction coefficient between 0 and 1 represents the level of resistance to sliding between contact surfaces during engagement and disengagement. A lower coefficient, closer to 0, indicates smoother interaction with less resistance, facilitating easier assembly and disassembly of the snap-fit components. Conversely, a higher coefficient, closer to 1, signifies greater resistance, which can enhance the retention force but may require more force to assemble or disassemble, potentially leading to higher wear on the contact surfaces. Accurately modeling this coefficient is crucial for predicting the performance, durability, and ease of use of ABS snap-fits in practical applications. Then, the “Formulation” function in the “Advance” option is changed to “Augmented Lagrange”.

To create the mesh, the “Mesh” function is selected and the “Method” for meshing is inserted which is “Tetrahedrons”. Then, choose the snap element order as “Quadratic” and the other part as “Linear”. Then, insert meshing sizes from the “Sizing” function in “Mesh” and let the default setting. Using quadratic elements in FEA is justified when high accuracy is needed, especially in areas with complex stress gradients or curved boundaries, as they provide better precision with fewer elements due to their higher-order interpolation. Quadratic elements can more accurately represent deformations and stress distributions, making them ideal for detailed stress analysis and capturing subtle effects in the material response. Conversely, tetrahedral mesh elements are justified for their versatility and ease of automatic generation, particularly in complex geometries where conforming a mesh might be challenging. Tetrahedral elements can quickly adapt to intricate shapes and are computationally efficient for a broad range of applications, especially when linear analysis is sufficient or when combined with higher-order formulations for increased accuracy. Thus, the choice between quadratic and tetrahedral elements depends on the specific requirements of accuracy, geometry complexity, and computational efficiency in the FEA project.

The next step is to proceed with the “Analysis Setting” option by inserting the value of step controls into 2 steps and substeps to desired value (Suzamri & Osman Zahid, 2021). Change the “Force Convergence” to “On” in “Nonlinear Controls” and then change “Nonlinear Data” and “Nodal Forces” to “On” in “Output Controls”. Select “Static Structural” and appoint the “Fixed Support” to the female part and “Displacement” for snap-fit. Change the X component to “Tabular” and insert the values of the displacement. The Y and Z Components are set to “Constant” because it moves in constant value. Next, select “Solution” and insert “Total Deformation” follow by selecting the “Probe” and choose “Force Reaction”. Choose the boundary condition which is the “Displacement” that is appointed previously. Lastly, click on “Solution” and choose “Solve”. Then the simulation will run successfully if there are no mistakes or errors occur. If not, the input values of step controls and afterwards need to be checked thoroughly. After finished assessing and simulating, the value of force reaction which is insertion and retention forces and deformation value is obtained. The process ends.

3.5.2 Properties for Simulation

There are several properties in ANSYS that can be set up beforehand, such as the units that are used, meshing techniques, analysis settings and more. Thus, below shows all properties that can be set up as for an example in Table 3.5 is the units used in ANSYS during simulation.

Table 3.5 Units used in ANSYS

Unit Systems	Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Table 3.6 shows the contact regions setting for male and female parts of the snap-fits. Figure 3.8 shows the parts of the snap-fits in which green part is the male part named “Model 1-FreeParts|Solid 1” meanwhile the grey part is the female part named “Model 1-FreeParts|Solid 1 [2]”. The name of the models depends on what type of model that is investigated. If Model 2, then the name is Model 2.

Table 3.6 Contact region settings

Object name	Frictional-Model 1-FreeParts|Solid 1 to Model 1-FreeParts|Solid 1 [2]
State	Fully Defined
	Scope
Scoping Method	Geometry Selection
Contact	7 Faces
Target	6 Faces
Contact Bodies	Model 1-FreeParts|Solid 1
Target Bodies	Model 1-FreeParts|Solid 1 [2]
	Definition
Type	Frictional
Friction Coefficient	0.4
Scope Mode	Manual
Behaviour	Program Controlled
Trim Contact	Program Controlled
Suppressed	No
	Advanced
Formulation	Augmented Lagrange
Small Sliding	Program Controlled
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness Factor	0.1
Update Stiffness	Each Iteration
Stabilization Damping Factor	0
Pinball Region	Program Controlled
Time Step Controls	None

Table 3.6 Continued

Geometric Modification	
Interface Treatment	Add Offset, No Ramping
Offset	0 mm
Contact Geometry Correction	None
Target Geometry Correction	None

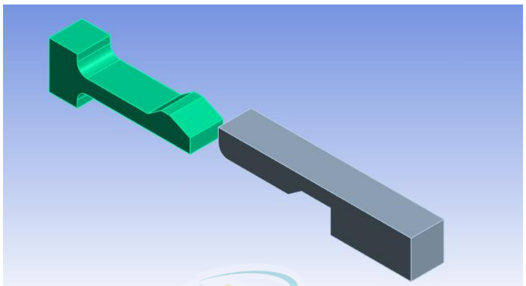


Figure 3.8 Snap-fits model

Table 3.7 showing the mesh controls or the mesh properties in ANSYS. The type of mesh used is Tetrahedrons.

Table 3.7 Mesh controls in ANSYS

Object Name	Patch Conforming Method	Patch Conforming Method 2	Body Sizing	Refinement
State	Fully Defined			
Scope				
Scoping Method	Geometry Selection			
Geometry	1 Body		2 Bodies	13 Faces
Definition				
Suppressed	No			
Method	Tetrahedrons			
Algorithm	Patch Conforming			
Element Order	Quadratic	Linear		
Type			Element Size	
Element Size			Default (3.8962 mm)	
Refinement				1

Table 3.8 shows the static structural setting in ANSYS meanwhile Table 3.9 shows the analysis settings in ANSYS. The analysis settings consist of some parts that needed modification such as the changes of status from "No" to "Yes" as some of it are observed and calculated. Other that are not manipulated stays the same or set on "Program Controlled" so that it can auto generate.

Table 3.8 Static structural settings in ANSYS

Object Name	Static Structural
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22°C
Generate Input Only	No

Table 3.9 Analysis Settings in ANSYS

Object Name	Analysis Settings
State	Fully Defined
Step Controls	
Number of Steps	2
Current Step Number	2
Step End Time	2 s
Auto Time Stepping	On
Define By	Substeps
Carry Over Time Step	Off
Initial Substeps	20
Minimum Substeps	10
Maximum Substeps	25
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Quasi-Static Solution	Off
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	On
--Value	Calculated by solver
--Tolerance	0.5%

Table 3.9 Continued

Nonlinear Controls	
--Minimum Reference	1.e-002 N
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Output Controls	
Stress	Yes
Surface Stress	No
Back Stress	No
Strain	Yes
Contact Data	Yes
Nonlinear Data	Yes
Nodal Forces	Yes
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Result File Compression	Program Controlled

3.5.3 Simulation of Snap-fits

Simulation of snap-fits is made in ANSYS software. Figure 3.9 shows the meshing of the snap-fits Model 1. The meshes are refined in the contact surfaces. Thus, the results for insertion and reaction are obtained from the graph and tabular data will be discussed in Chapter 4. Tetrahedral mesh is used as the benefit of a tetrahedral mesh lies in its capability to effectively approximate the surface contour (Mehmert, 2023). The benefits of employing a tetrahedral mesh in ANSYS for snap-fit contouring include improved accuracy in capturing complex surface features and better representation of the intricate geometry involved in snap-fit designs. In ANSYS simulations, especially when dealing with contact problems involving ABS material, setting a friction coefficient of 0.4 is a commonly used workaround to mitigate force convergence issues.

Force convergence errors often arise in finite element analyses due to unrealistic or challenging contact conditions, where the contact surfaces tend to stick and slide intermittently, causing the solver to struggle in achieving convergence. When simulating contact or sliding interactions involving ABS material, specifying a friction coefficient of 0.4 can help stabilize the simulation and facilitate convergence by providing a conservative estimate in which the chosen value of 0.4 represents an assumed average friction behaviour for ABS materials in contact. It is not an exact value for all cases but rather a practical approximation that tends to work reasonably well for many simulations involving ABS. This coefficient tends to promote less sliding between contacting surfaces, making the analysis more manageable numerically. It limits excessive slippage and stick-slip behaviour that might otherwise impede convergence. By reducing the likelihood of extreme sliding or sticking behaviour between contact surfaces, the solver is better able to converge to a solution, preventing divergence or convergence issues during the simulation. The outcomes of Finite Element Analysis (FEA) are notably influenced by the meshing methodologies employed in the analysis, along with the element type and its size. The quantity of elements holds greater significance than the specific size of each element during meshing, as the element's length is more contingent on the part being meshed. Conducting a mesh convergence study aids in assessing the precision of the FEA solution (Patil & Jeyakarthikeyan, 2018).

Figure 3.9 Tetrahedral meshing of the cantilever hook snap-fit Model 1

Before simulation, the position of displacement and the fixed support must be assigned beforehand. Thus, Figure 3.10 shows the displacement that has been assigned on the “male” part of the snap-fits and also in Figure 3.11, the fixed support has been located on the “female” part of the snap-fits.

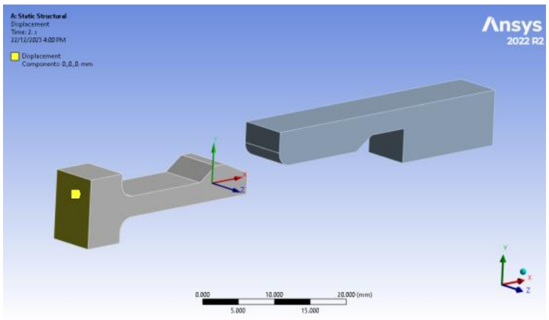


Figure 3.10 Displacement of snap-fits Model 1

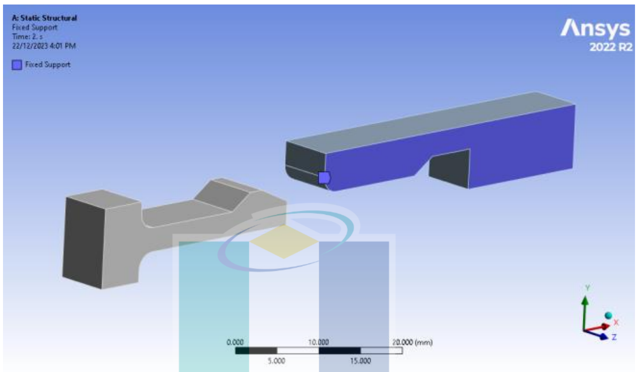


Figure 3.11 Fixed support on snap-fits Model 1

3.5.4 Insertion and Retention Forces

The design strategy is founded on the recommendations given in the literature research. To assess differences in the insertion and retention forces, it is necessary to manipulate the cantilever hook snap-fit design parameters. Below shows formula for insertion force in equation 3.1 (Suzamri & Osman Zahid, 2021).

$$F_i = P \times \frac{\mu + \tan(\alpha)}{1 + \mu \tan(\alpha)} \quad (3.1)$$

The terms "µ" and "α" in equation 3.1 denote the insertion angle and the coefficient of friction, respectively. The maximum deflection of the beam and the force of deflection may be determined using the design parameters of the cantilever hook snap-fit, as illustrated in Table 3.10 and 3.11, because the bending force P is initially unknown.

Table 3.10 Maximum deflection and force of deflection of rectangle design

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 E_s = Secant Modulus		l = Length of Beam a = Upper width	h = Beam Thickness b = Bottom width

Table 3.11 Maximum deflection and force of deflection of trapezoid 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 E_s = Secant Modulus		l = Length of Beam a = Upper width	h = Beam Thickness b = Bottom width

Below shows the formula for retention forces (Suzamri & Osman Zahid, 2021):

$$F_r = P \times \frac{\mu + \tan(\beta)}{1 + \mu \tan(\beta)} \quad 3.2$$

The terms "µ" or coefficient of friction and "β" or retention angle are used in equation 3.2.

3.6 Equipment

Several pieces of equipment are required in this study to perform the test analysis and distinguish the values given by simulation and hardware testing. A 3D printer and a universal testing machine were used.

3.6.1 3D Printer

3D printing services are widely used in today's technology since they are a quick and easy way to generate prototypes, tools and functional final products. 3D printing is a process for constantly generating three-dimensional structures layer by layer until the product is fully constructed. However, there is a vast variety of machines and built-in quality, as well as price. Ultimaker Cura, Simplify3D, Slic3r and IdeaMaker are a few examples of 3D printers. For this research, Ultimaker Cura is used for 3D printing for cantilever snap-fit.

3.6.2 Ultimaker Cura

Ultimaker Cura is a popular 3D printing software because it is simple to interface with CAD software and includes configurable settings for precise control. Ultimaker Cura provides a selection of high-quality 3D printers, software, materials and support.

The flow on using 3D printer and software is shown in Appendix D. There are numerous procedures that require to be done to print the model in 3D printer. First, open “Ultimaker Cura” software and upload .stl file model into the software, as an example in Figure 3.12. Click on the model and adjust the scale (if needed) and click “Prepare” and select the material for the snap-fit. Need to be reminded that the nozzle for Ultimaker S5 printer is 0.4mm. The printing properties can be adjusted in print settings as in Table 3.12 following the properties of ABS material, such as the temperature of bed, diffused filaments and temperature of printing. As shown in Figure 3.13, the infill pattern is concentric and the infill density is 100% to prevent snap-fits from breaking. This pattern is the best option for printing because other patterns can lead to unsatisfactory results. Slice the model into the shape shown in Figure 3.14 and send the information to the printer.

The information is transferred into the Ultimaker S5 3D Printer as shown in Figure 3.15 and to begin printing, choose a file to print from the selection that appears. Adjust the setting on the printer and set the material used which is ABS. Load the ABS filament into the printer if the filament is not yet loaded and after that, the printing can start. The nozzle will find the offset and start printing. The monitor shows the time consumed for the printer to print the model. and lastly, the printer finish printing the model and the model can be unloaded from the printer bed.

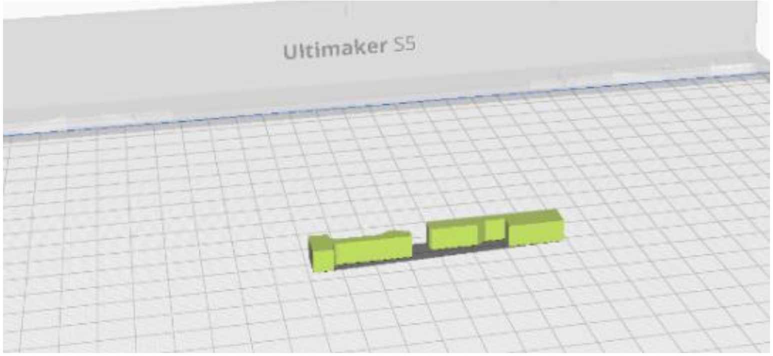


Figure 3.12 Ultimaker Cura 3D software

Table 3.12 Ultimaker Cura print settings

Print Settings	Value
Layer Height	0.1 mm
Wall Thickness	0.8 mm
Wall Line Count	2
Horizontal Expansion	-0.01 mm
Top Thickness	1.0 mm
Top Layers	10
Bottom Thickness	1.0 mm
Bottom Layers	10
Infill Density	100 %
Infill Pattern	Concentric
Printing Temperature	240 °C
Build Plate Temperature	85 °C
Print Speed	55 mm/s
Fan Speed	2.0 %

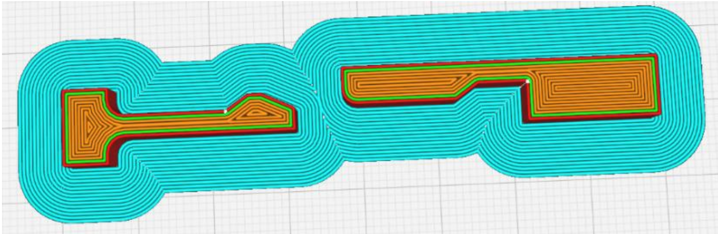


Figure 3.13 Concentric infill pattern

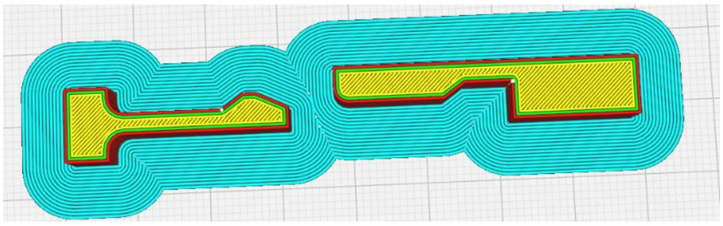


Figure 3.14 Sliced model

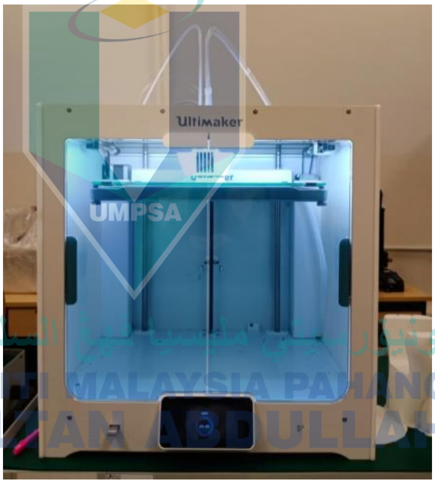


Figure 3.15 Ultimaker 3D Printer

3.6.3 Fabrication of Snap-fits Models

Prior to conducting the experiment, the snap-fits required to be printed. So, the 3D printer machine by Ultimaker is used to print the snap-fits as in Figures 3.16 and 3.17. Then, all the 16 models have been fabricated as in Figure 3.18.

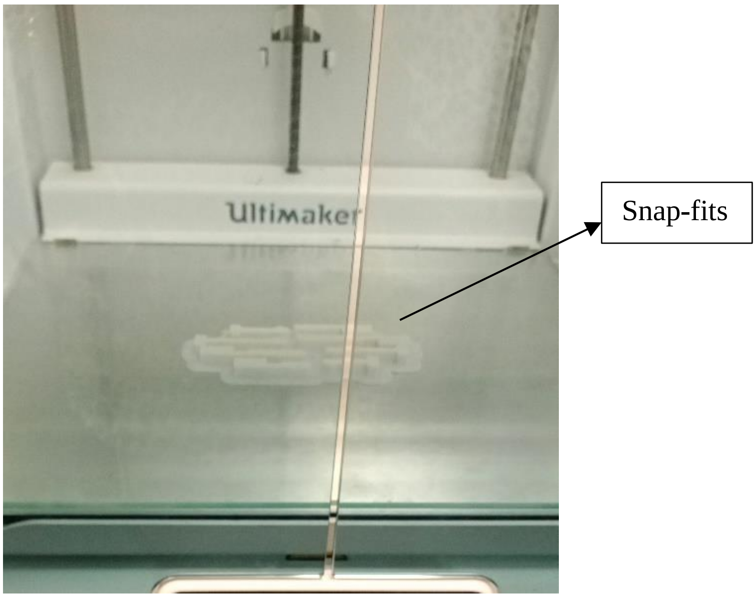


Figure 3.16 Print process of snap-fit in Ultimaker 3D Printer

Figure 3.17 Printed snap-fits

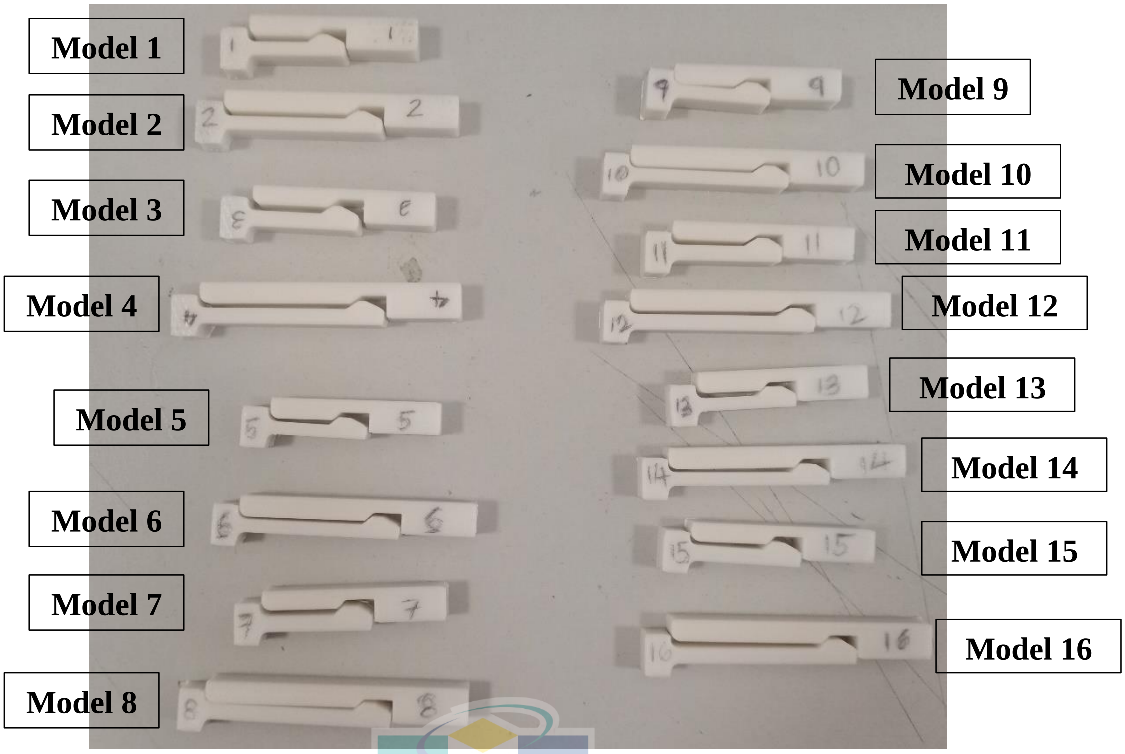


Figure 3.18 16 Models of Snap-fits

3.6.4 Universal Testing Machine (UTM)

Universal Testing Machine (UTM), Figure 3.19, is used to test the mechanical properties (tension, compression etc.) of a given test specimen by exerting tensile, compressive or transverse stresses (Praneeth & Anand, 2022). The machine has been named so because of the wide range of tests it can perform over different kinds of materials. It can perform various tests such as peel test, flexural test, tension test, bend test, friction test, spring test and others. UTM can generate the forces of insertion and retention of the snap-fit (Victoradmin, 2021). The increase of the forces may lead to injuries to the worker's/user's hand during the insertion or extraction process as observed from study by Salmanzadeh and Rasouli (2015) following the workers' epidermis deformation upon installing snap-fits. Thus, this is how the UTM machine can be related to the force of humans in real applications.

The universal testing machine that is used in the research is Instron 3369 model in cobalt blue. The specifications of the UTM are given in Table 3.13.

Table 3.13 Instron UTM specifications

Model Number	3369
Load capacity	50 kN
Maximum speed	500 mm/min
Minimum speed	0.005 mm/min
Maximum force at full speed	25 kN
Maximum speed at full load	250 kN
Return speed	500 mm/min
Total crosshead travel	1122 mm
Total vertical test space	1193 mm
Space between columns	420 mm
Height	1582 mm
Width	756 mm
Depth	707 mm
Weight with typical load cell	141 kg
Maximum power requirement	700 VA

The experimental test that is conducted for this research would be the tension and compression test. The compression test will be resulting in insertion force and the tension test will result in retention force. The results will be compared with the simulation from ANSYS. The snap-fits are clamped on both grips of the UTM and then the test is run using Instron Universal software in Figure 3.20.

Figure 3.19 Universal Testing Machine (UTM)

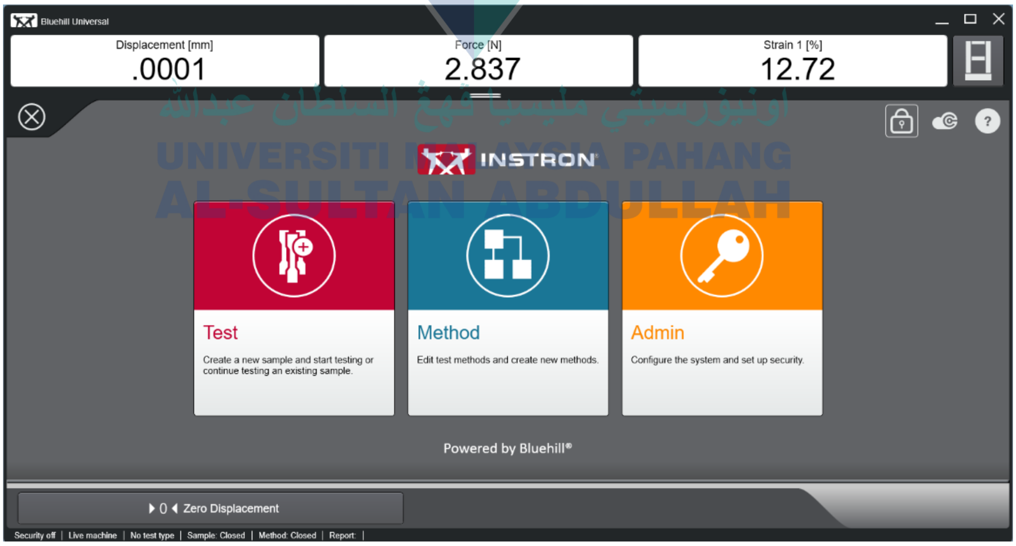


Figure 3.20 Instron Universal software

3.6.5 Flow on using UTM

Appendix E shows the flowchart for Instron Universal and UTM. To start the testing on the universal testing machine, first, open the Instron Universal software and then click on "Method" as in Figure 3.21 and create a method by choosing a tension/compression method depending on the tests made. Select the method file and search for the material used. Then choose the tension/compression method (tension for retention force, and compression for insertion force) and click on "Specimen" and insert the parameters of the models in the space provided such as the type of specimen, length, width and so on. Select "Control" and click on the test and choose the control mode. After that, proceed with selecting the end of the test and choose criteria for the end of the test.

Click on "Calculation" to choose the type of calculation that is measured such as the load, stress or strain. Click on "Results" and select the results that are observed. The results are mainly linked with the calculation previously, if the load is chosen, then the results of the load can be obtained. Select "Graph" and choose the definitions for the *x* and *y* axis for example *x* axis for time and *y* axis for load. Click the raw data to select channels to be set up for the raw data table. Set up the report format to pdf and select the output path.

Choose "Test" and review all the information before starting the test and set live display to view the loads and select balance loads to make sure the display of the load is 0 N before starting. Set the mechanical stops to the limit of the load.

Load the sample to UTM as in Figure 3.22 and click next on the software and insert the specimen label to "Specimen 1" for the first model. Click next and start the test. After the test is finished, the results are obtained as in Figure 3.23 and then click finish sample and save the documents. Thus, the results can be seen in the document saved. Figure 3.24 showing the example of graph obtained from compressive test on UTM and the insertion force can be obtained from the graph and table generated. Figure 3.25 shows the example of graph obtained from tensile test showing the values of the retention forces.

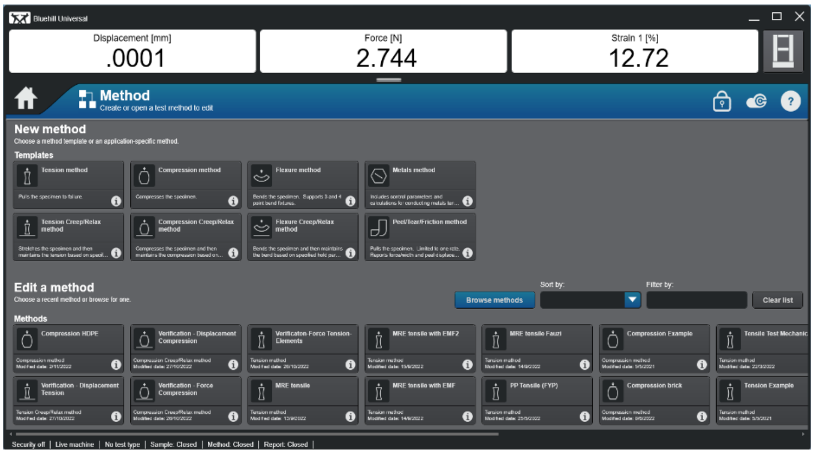


Figure 3.21 Method page on Instron

Figure 3.22 Example snap-fit loads on UTM

Figure 3.23 Example of compressive test results

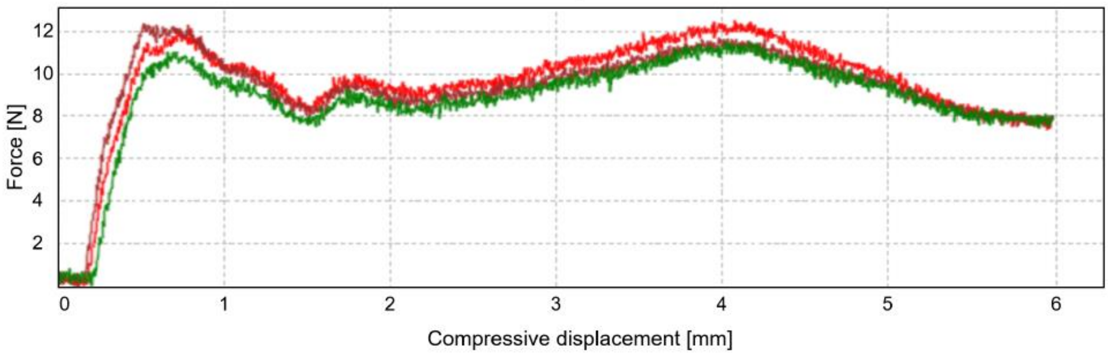


Figure 3.24 Example of compressive test graph for insertion force

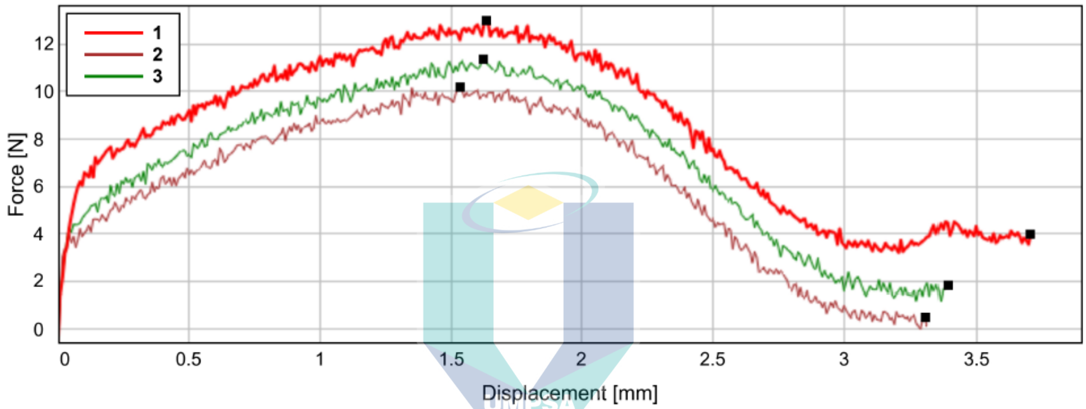


Figure 3.25 Example of tensile test result for retention force

3.7 Regression Analysis

Regression analysis is a technique for determining the connection between variables. Normally, an investigator aims to determine the influence of one variable on another. To investigate such concerns, the investigator collects data on the underlying factors of interest and uses regression to determine the quantitative effect of the causative variables on the variable under consideration. Regression analysis assists in mitigating the impact of other variables, aiming to approach the genuine and average causal effect of a specific factor (Arkes, 2023). The regression formula is as equation 3.3.

$$Y_i = f(X_i, \beta) + e_i \qquad 3.3$$

Where,

Y_i = dependent variable

f = function

X_i= independent variable

β = unknown parameters

e_i= error terms

The experimental insertion and retention are done 3 times to obtain the average value of the forces in the snap-fits. The values are then added and divided into three to get the average/mean as in equation 3.4.

$$Mean = \frac{Value\ 1 + Value\ 2 + Value\ 3}{3} \qquad 3.4$$

A calculation has been made on seeking the differences of value if the length is increased by 0.5mm. The equation 3.5 can be seen below:

$$F_D = \left(\frac{F_1 - F_2}{l_b}\right) \div 2 \qquad 3.5$$

Where;

F_D = Force differences

F_1 = Force of the first model

F_2 = Force of the second model

l_b = Length of the beam

Percentage error is calculated to determine the accuracy of the data provided from the simulation and the experiment. Thus, the percentage of the error is calculated by subtracting the observed value and the true value, then dividing by the true value and multiply it with 100% to obtain the percentage value as in equation 3.6.

$$\% \, error = \left| \frac{V_O - V_T}{V_T} \right| \times 100\% \qquad 3.6$$

3.8 Summary

The process of formulating a numerical model for the insertion and retention forces of cantilever hook snap-fit joints involves several key steps. Researchers manipulate specific factors such as insertion angle, retention angle, length, and thickness of the snap-fit joints. These parameters are essential as they significantly affect the functionality and behaviour of the snap-fit connections. After determining the parameters, a numerical simulation is performed using ANSYS Finite Element Analysis. This simulation employs nonlinear analysis, focusing on contact surfaces to accurately model the behaviour of the snap-fit joints under various conditions (Venkatesh et al., 2019). It helps predict and understand the forces involved during insertion and retention processes. The next step involves fabricating the snap-fit joints using additive manufacturing (Torossian & Bourell, 2015), in this case, the software used and 3D printer used is Ultimaker Cura. ABS material, a common thermoplastic known for its strength and durability, is utilized for the fabrication process. This phase aims to produce physical snap-fit components based on the parameters and simulation results obtained earlier. Once the snap-fit components are fabricated, an experimental setup is arranged utilizing a Universal Testing Machine. This machine allows for controlled tests to be conducted, including both tensile and compression tests on the fabricated snap-fit joints. These tests provide real-world data on how the snap-fit joints perform under different loading conditions, verifying and validating the accuracy of the numerical model and simulation results.

Overall, this comprehensive approach integrates theoretical modelling, numerical simulation, 3D printing technology, and experimental testing. It enables a thorough understanding of the behaviour and performance of cantilever hook snap-fit joints, offering insights into their insertion and retention forces under varying parameters and real-world conditions. This multi-step process contributes to advancements in optimizing the design and functionality of snap-fit connections in engineering applications.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results and the outcomes of the simulation and experimental for insertion and retention forces of snap-fits are discussed. Then the calculation on the regression analysis is calculated and further discussed.

4.2 Simulation of Snap-fits

Before performing experimental analysis, simulation in ANSYS is done to generate the insertion and retention forces of the snap-fits. Thus, the force reaction of the snap-fits shows the maximum insertion and retention forces. Table 4.1 shows the simulation figures and the graph that is generated showing which peak is the maximum insertion forces and maximum retention forces along with their values. Negative values from the simulation graph showing that the snap-fits are in retention state. The results can also be seen in appendix F.

Table 4.1 Simulation insertion and retention of the snap-fits

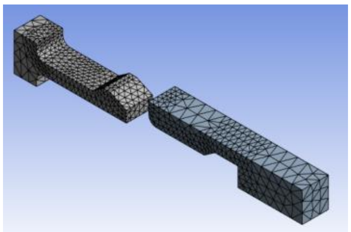
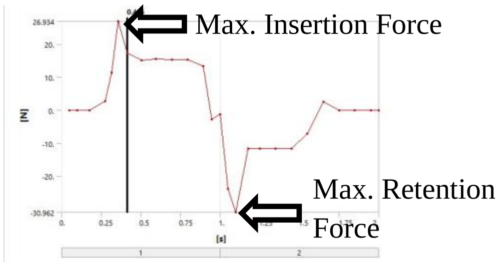
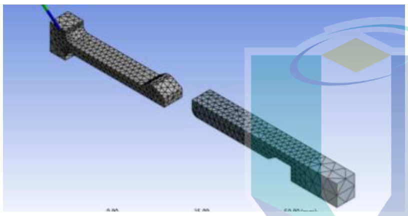
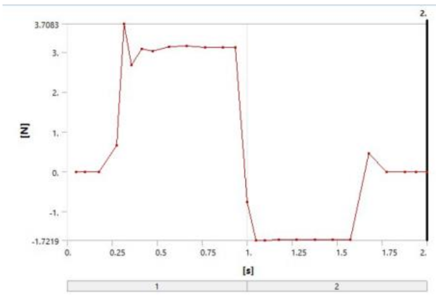
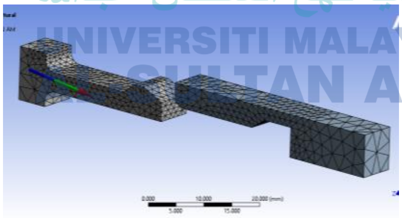
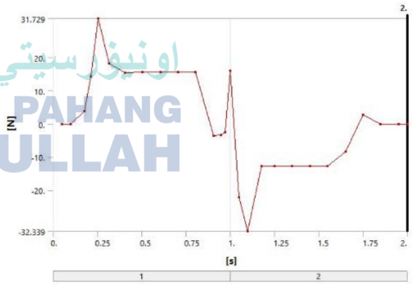
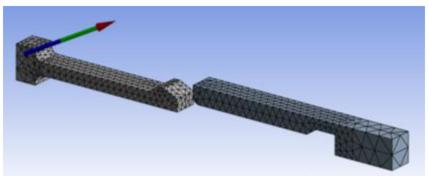
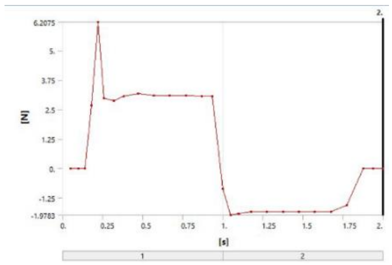
Model	Simulation Figures	Simulation Graph
1		 Insertion: 26.9340 N Retention: 30.9620 N
2		 Insertion: 3.7083 N Retention: 1.7219 N
3		 Insertion: 31.7290 N Retention: 32.3390 N
4		 Insertion: 6.2075 N Retention: 1.9783 N

Table 4.1 Continued

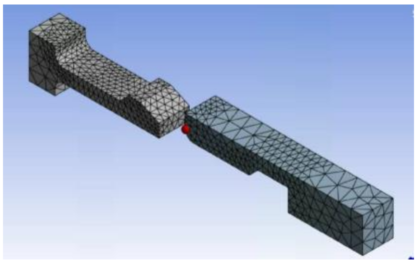
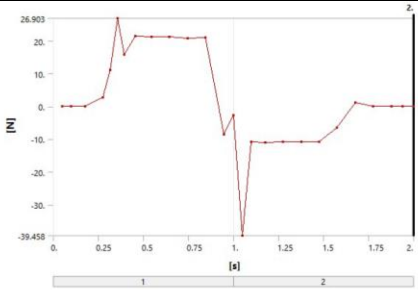
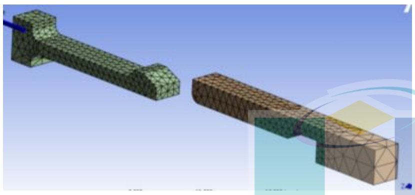
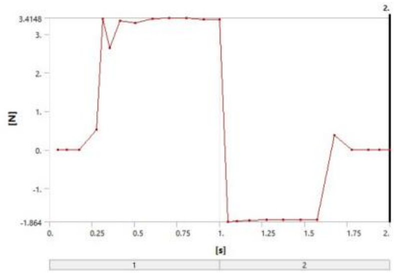
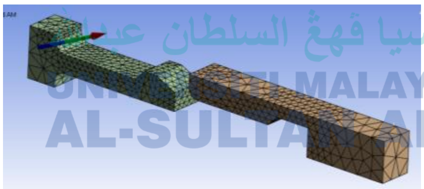
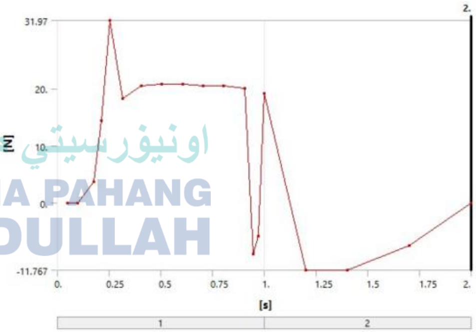
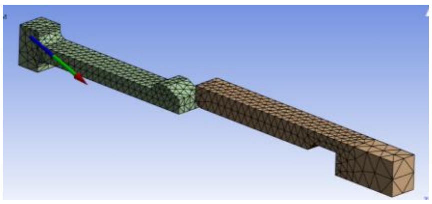
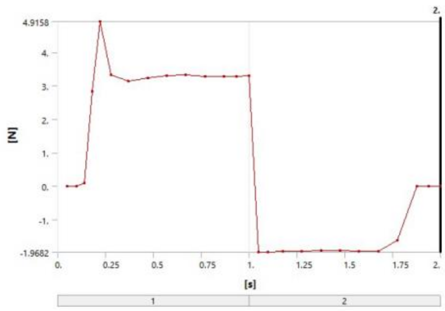
Model	Simulation Figures	Simulation Graph
5		 Insertion: 26.9030 N Retention: 39.4580 N
6		 Insertion: 3.4148 N Retention: 1.8640 N
7		 Insertion: 31.9700 N Retention: 11.7670 N
8		 Insertion: 4.9158 N Retention: 1.9682 N

Table 4.1 Continued

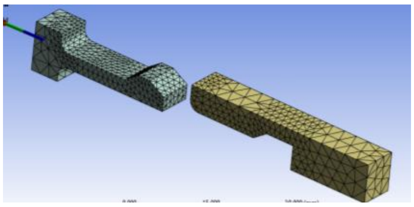
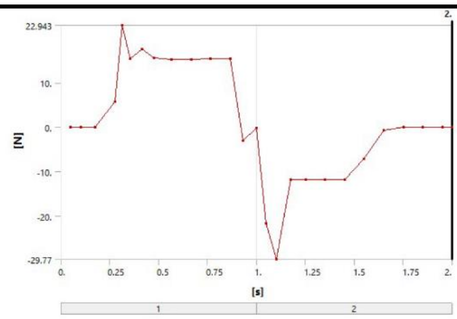
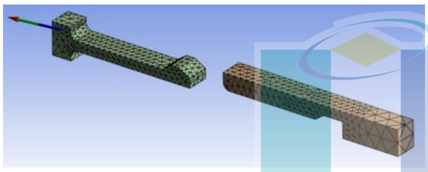
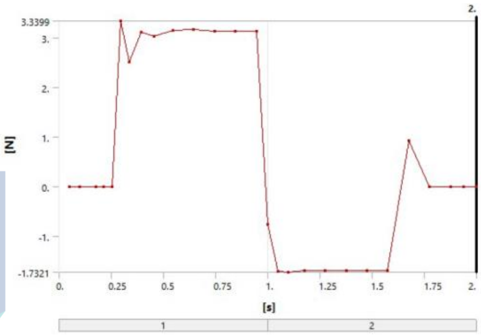
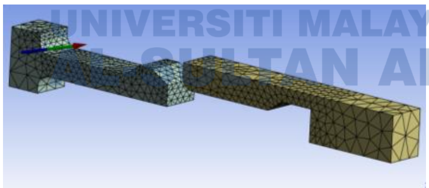
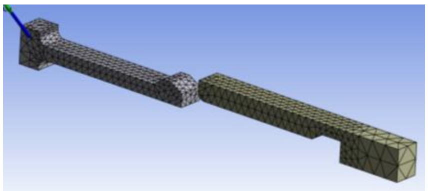
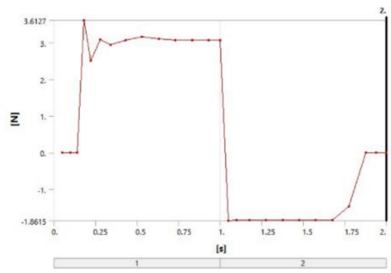
Model	Simulation Figures	Simulation Graph
9		 Insertion: 22.9430 N Retention: 29.7700 N
10		 Insertion: 3.3399 N Retention: 1.7321 N
11		 Insertion: 25.4850 N Retention: 32.2090 N
12		 Insertion: 3.6127 N Retention: 1.8615 N

Table 4.1 Continued

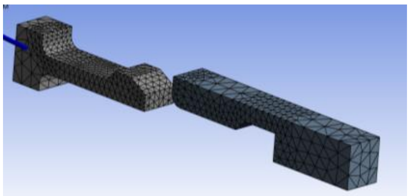
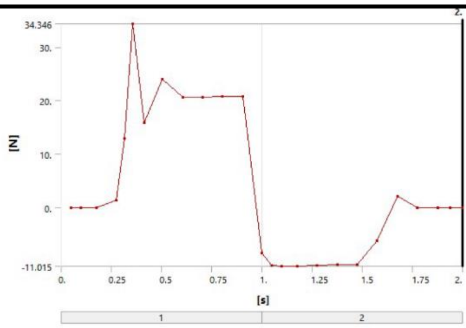
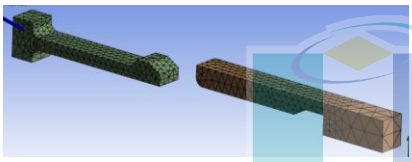
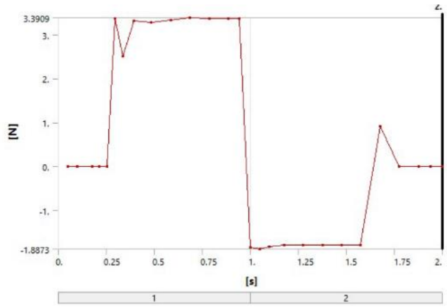
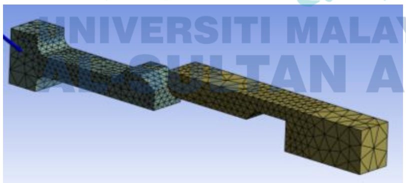
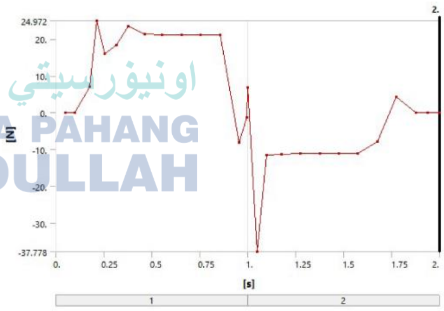
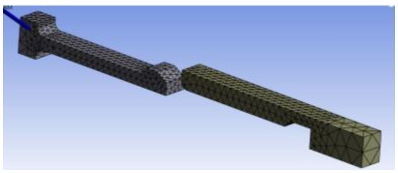
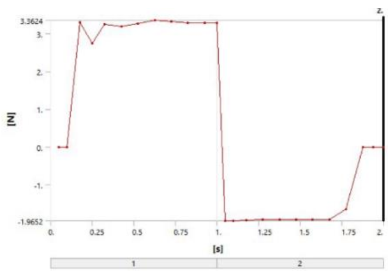
Model	Simulation Figures	Simulation Graph
13		 Insertion: 34.3460 N Retention: 11.0150 N
14		 Insertion: 3.3909 N Retention: 1.8873 N
15		 Insertion: 24.9720 N Retention: 37.7780 N
16		 Insertion: 3.3624 N Retention: 1.9652 N

Figure 4.1 shows the trends of the results from the simulation analysis. The odd numbered models such as model 1,3,5,7,9,11,13,15 have high insertion and retention forces if compared with even numbered models such as model 2,4,6,8,10,12,14,16 which have low insertion and retention forces. Also, trends showing that odd numbered models shows that most of the retention forces have tendency to become higher than the insertion forces. Meanwhile, for even numbered models, the insertion forces have higher values than the retention forces. In this case, it can be said that the length of the beam plays important roles in determining the number of forces needed to be assembled and disassembled as the forces starts to vary when the beam length is manipulated. Higher length of the beam contributes to the lower forces of the snap-fits and this can be validated by study made by Abdul Manan et al. (2022), showing that having a beam length that is longer in cantilever hook snap-fits mechanism requires a lower number of forces during insertion and retention. That is why as can be seen in Figure 4.2, the trends of the simulation results are similar and can be compared. The values of forces are different as the values for manipulated variables are different such as the thickness of the beam, insertion and retention angle and the length of the beam. But the study is done using the same design which is cantilever hook snap-fits. Models of snap-fits made by Abdul Manan et al. (2022) only consists of 8 models since the insertion angle and the retention angle only have two conditions which are "Lower angle" and "Higher angle" meanwhile in this study consist of 4 conditions which are (25° insertion & 35° retention, 25° insertion & 45° retention, 30° insertion & 35° retention, 30° insertion & 45° retention). Thus, this research comes out with 16 different models. The highest value of insertion force is portrayed by Model 13 with the value of 34.3460N meanwhile the lowest insertion force is portrayed by Model 10 with the value of 3.3399N. The highest value of retention force is by Model 5 with the value of 39.4580N and the lowest value is by Model 2 with the value of 1.7219N.

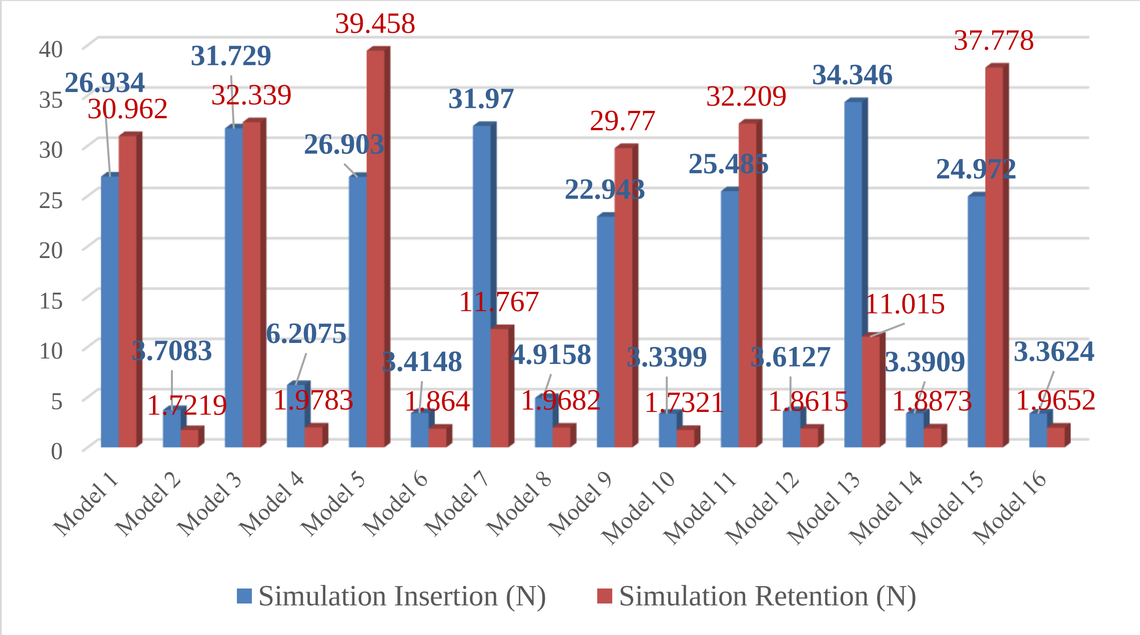


Figure 4.1 Trends of simulation results

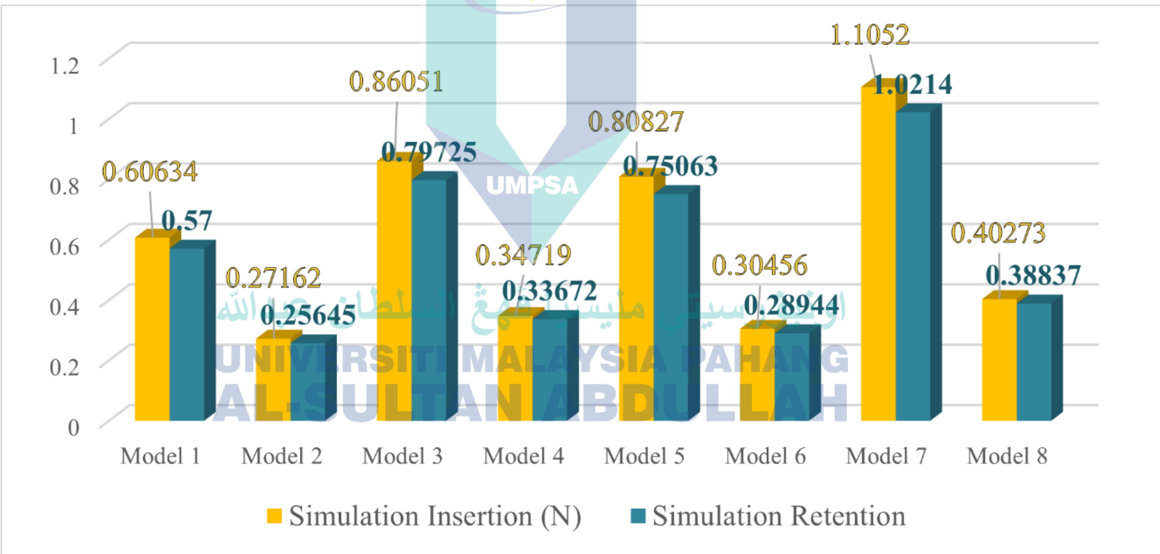


Figure 4.2 Trends of simulation results
Source: (Abdul Manan et al., 2022)

4.3 Experimental of Snap-fits

After simulation, then the research continues with the experimental analysis using UTM. Several tests are made which are the compressive test for insertion force and tensile test for retention force. All the 16 models are tested one by one and each of the models are tested 3 times to gain average value since experiment analysis tends to have external factors that can interrupt the results such as inaccurate measuring equipment, calculation error, and more. Figure 4.3 shows the trends of the results from the experimental analysis. The odd numbered models such as model 1,3,5,7,9,11,13,15 have high insertion and retention forces if compared with even numbered models such as model 2,4,6,8,10,12,14,16 which have low insertion and retention forces. Also, trends showing that odd numbered models shows that most of the retention forces have tendency to become higher than the insertion forces. Meanwhile, for even numbered models, the insertion forces have higher values than the retention forces. The trends and the results are approximate or almost similar to the ones in the simulation. The highest value of insertion force is portrayed by Model 13 with the value of 32.1764N meanwhile the lowest insertion force is portrayed by Model 16 with the value of 3.2341N. The highest value for retention force is shown by Model 5 with the value of 41.1443N and the lowest is by Model 2 with the value of 1.6573N.

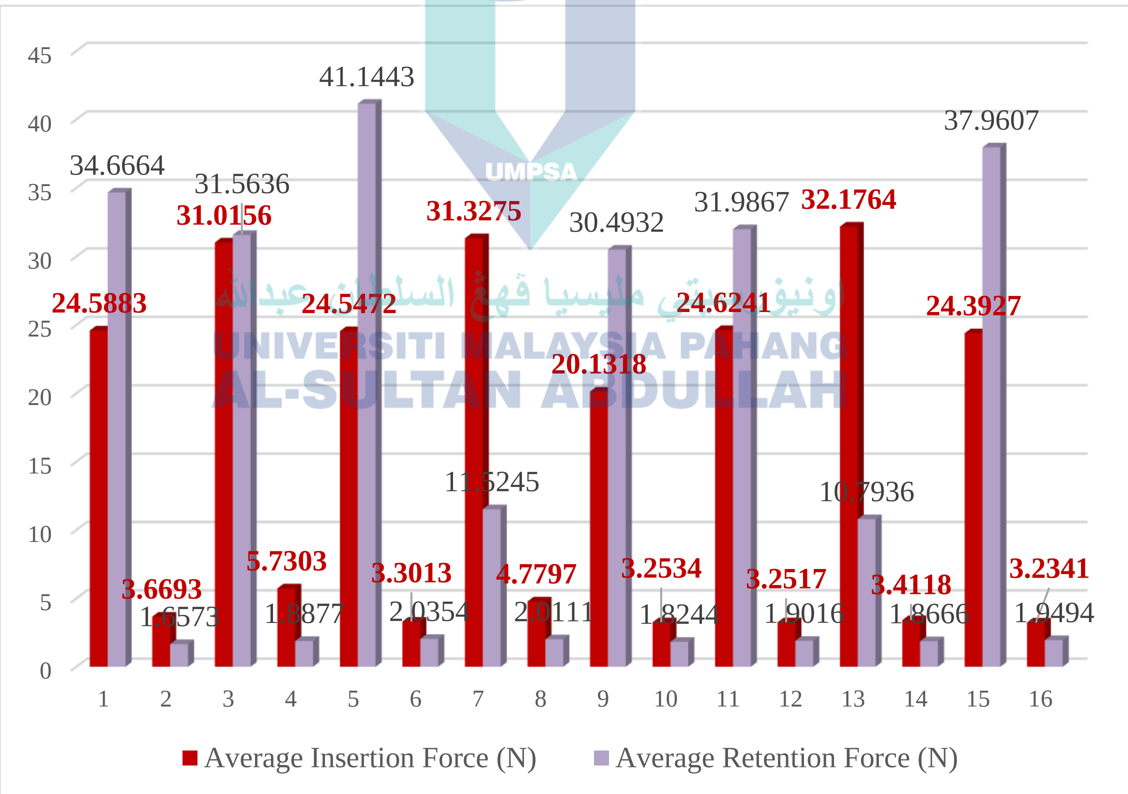


Figure 4.3 Experimental results of the snap-fits

4.4 Regression Analysis on Snap-fits Variables

A regression analysis is performed to determine how one variable has an impact on another. The most influential factors can be seen and clearly identified using this approach. The summary output for regression statistics and its results for the correlation between simulation insertion and beam length are shown in Figure 4.4. The correlation coefficient and coefficient of determination for the snap-fits for other variables are shown in Table 4.2.

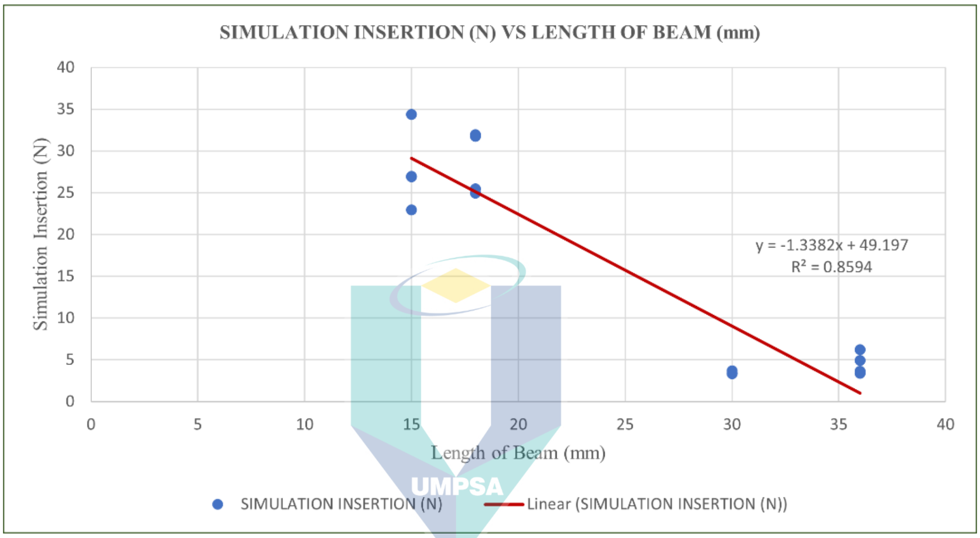


Figure 4.4 Regression line for simulation insertion vs length of the beam

The correlation coefficient and coefficient of determination are both statistical measures used to describe the relationship between two variables in a dataset. However, they represent different aspects of this relationship. The correlation coefficient quantifies the strength and direction of the linear relationship between two continuous variables. It ranges between -1 and 1, where +1 indicates a perfect positive linear relationship (as one variable increases, the other variable increases). -1 indicates a perfect negative linear relationship (as one variable increases, the other variable decreases). 0 indicates no linear relationship between the variables.

The coefficient of determination, often denoted as R-squared, is a measure used in regression analysis that represents the proportion of the variance in the dependent variable that is predictable from the independent variable. It ranges from 0 to 1, with 0 indicating that the independent variable does not explain any variability in the dependent variable. 1 indicating that the independent variable(s) completely explain the variability in the dependent variable. R-squared is the square of the correlation coefficient (r), meaning that it shows the proportion of variance shared between the two variables. The variable that affects the simulation and experimental for both forces is the length of the beam as it shows the most significant value for correlation and determination.

As observed in Table 4.2, the length of the beam is highly affected the insertion force (experiment) with the value of -0.9327 for correlation coefficient, which if the value of the correlation coefficient between two variables is -0.9327, it indicates a very strong negative linear relationship between the variables. Meanwhile, the regression value is 0.8700 which means that the length of the beam is affecting the experimental insertion as the value is approaching 1 or if the coefficient of determination (R-squared) is 0.8700, it means that approximately 87% of the variance in the dependent variable can be explained by the independent variable in the regression model.

The difference between a correlation coefficient and the regression is, the correlation coefficient is made to identify the patterns in things whereas the regression is used to identify the strength of the model or how the model fits the observed data.

Table 4.2 Correlation coefficient and coefficient of determination of the variables

Variables		Correlation Coefficient	Coefficient of Determination
Simulation Insertion	Insertion angle	0.0723	0.0052
	Retention angle	0.0470	0.0022
	Thickness of beam	0.0367	0.0013
	Length of beam	- 0.9270	0.8594
Experimental Insertion	Insertion angle	0.0765	0.0058
	Retention angle	0.0085	0.0001
	Thickness of beam	0.0266	0.0007
	Length of beam	- 0.9327	0.8700
Simulation Retention	Insertion angle	0.0160	0.0003
	Retention angle	0.1037	0.0108
	Thickness of beam	0.0144	0.0002
	Length of beam	- 0.8402	0.7060
Experimental Retention	Insertion angle	0.0417	0.0017
	Retention angle	0.1166	0.0136
	Thickness of beam	0.0045	0.0000
	Length of beam	- 0.8364	0.6996

A calculation has been made on seeking the differences of value if the length is increased by 0.5mm. For example, Model 1 and Model 2 are taken to be compared. Thus, the calculation is made for simulation and experimental insertion and retention. The summarized results can be seen in Table 4.3:

Table 4.3 Differences of forces for 0.5mm length

Model	Differences for 0.5mm of length (F_D)			
	Insertion		**Retention**	
	Simulation	**Experimental**	**Simulation**	**Experimental**
1 2	0.77419 N	0.6973 N	0.9747 N	1 N
3 4	0.7089 N	0.7024 N	0.8434 N	0.8243 N
5 6	0.7829 N	0.7082 N	1.2531 N	1.3036 N
7 8	0.9018 N	0.8454 N	0.3062 N	0.2973 N
9 10	0.6534 N	0.5626 N	0.9346 N	0.9556 N
11 12	0.6835 N	0.6679 N	0.9484 N	0.9406 N
13 14	1.0318 N	0.9588 N	0.3043 N	0.2976 N
15 16	0.6753 N	0.6612 N	1.1192 N	1.1254 N

Percentage of error is also calculated as it helps assess the accuracy of measurements or experimental results by comparing them to a known or expected value. It quantifies how much a measured or calculated value deviates from the true or accepted value. Scientists and researchers use percentage error to gauge the precision and reliability of experimental data. It helps in understanding the margin of error or uncertainty associated with measurements, experiments, or modelling outcomes. Understanding the percentage error is crucial in decision-making processes, especially when assessing risks, making predictions, or implementing changes based on measured or calculated values. In this research, the percentage of errors can be seen in Figure 4.5.

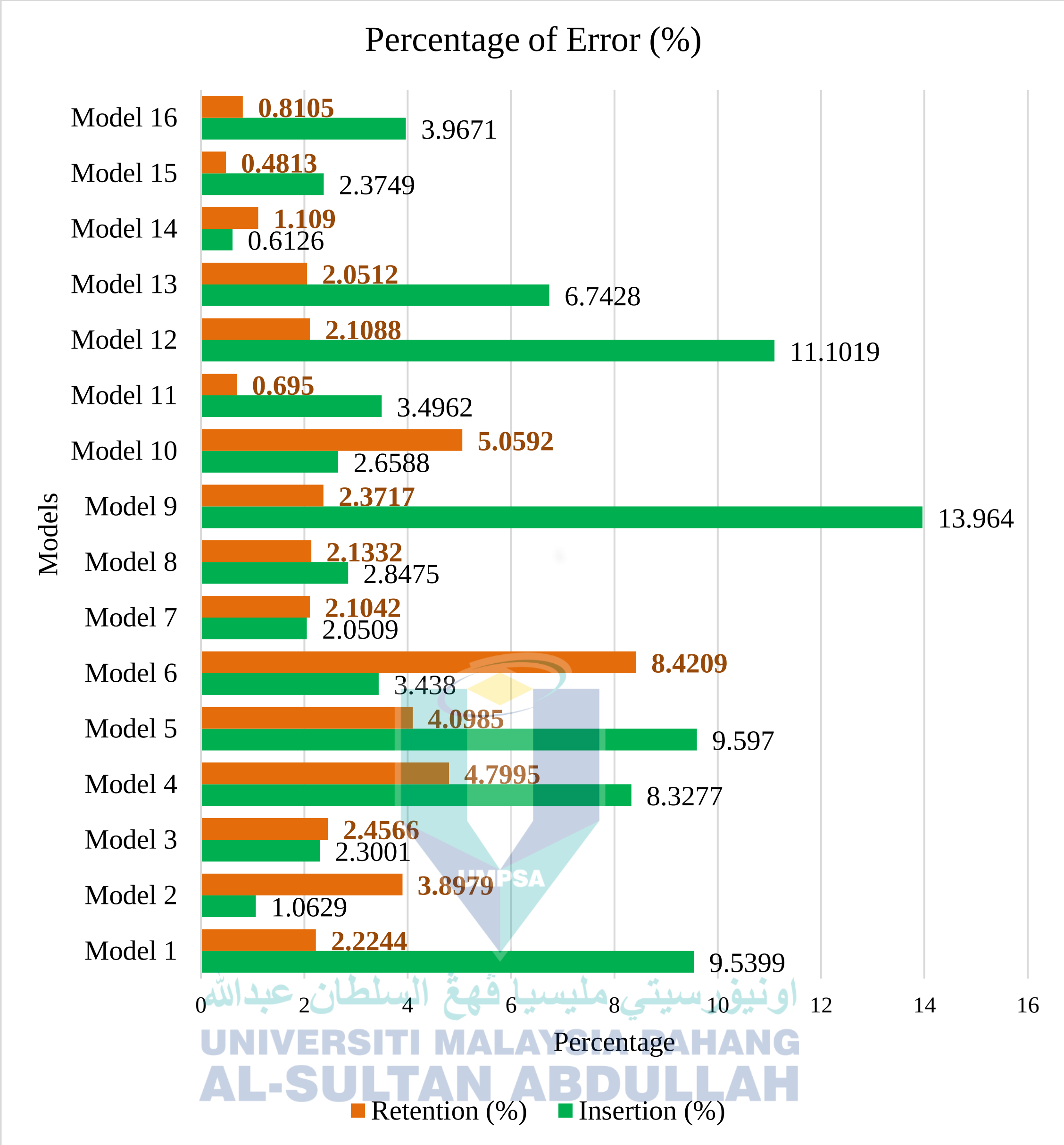


Figure 4.5 Percentage of error

Here, Models 14 and 15 produced the most accurate results for insertion and retention forces, respectively, out of the 16 models, each of which displayed a different percentage error value. The percentage error must be as close as much to 0% to be concluded as accurate and precise data. High percentage of error means that the estimated value is farther away from the known value. Error can happen due to many reasons such as inaccurate measuring equipment or calculation error. Specific percentage values for acceptable errors might not be universally defined, striving for accuracy and minimizing errors in both simulation and experimental analysis is essential. This ensures that the simulated results align closely with the real-world behaviour of the snap-fit joints. Validation of simulation results against experimental data and rigorous testing can help in determining the acceptable level of error for a particular application or industry. The amount of error that can be considered acceptable depends on the experiment but the margin must be 10% and below (Helmenstine, 2016) as the lower the percentage of error, the more accurate the result is.

4.5 Discussion on the Results

The higher forces that are needed to manually assemble and disassemble snap-fits, will cause injury to the fingertips of the workers. According to Salmanzadeh & Rasouli (2015), in the results of the simulations for various force amounts, a linear correlation between the maximum compressive stress and the total deformation of skin was observed with a high correlation coefficient (about 0.985). Figure 4.6 shows the results of the research by Salmanzadeh & Rasouli (2015). The male group exhibits higher maximum compressive stress and total skin deformation compared to the female group. This difference primarily arises from the smaller size of women's thumbs within the selected age groups, being approximately 14 percent smaller than men's thumbs in the same age brackets. Additionally, the outer layer thickness of women's skin, which serves as a protective barrier, is 20 percent thinner than that of men. Table 4.4 shows the results of simulations with respect to the model with various force amounts. It shows that the maximum compressive stress and the total deformation of the skin is increased by enhanced compressive force. This statement can relate with this research as the compressive test has been made to measure the insertion force of the snap fits and validates that the higher force of the snap-fits can increase the risk of having injuries. Thus, a proper design of cantilever hook snap-fits needs to be made as to avoid this problem. This research also contributes to suggest the best design to provide a low insertion and retention forces on the snap-fits. Research by Salmanzadeh & Rasouli (2015), mentions about the compressive stress which aligns with the compressive force. This means that if the compressive force increase, then the compressive stress increase in which causes dermis stress and skin deformation. Thus, by lowering the force, it can reduce the stress that is needed to be applied when assembling the snap-fits.

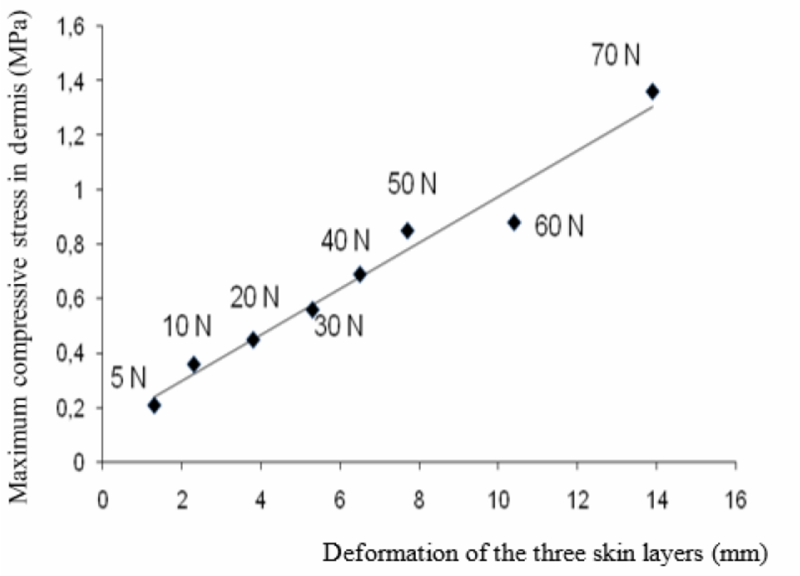


Figure 4.6 Correlation between the maximum compressive stress in the dermis and the total deformation of the skin

Table 4.4 Results of simulations with respect to the model with various force amount

Force	5	10	20	30	40	50	60	70
Maximum compressive stress in dermis (MPa)	0.21	0.36	0.45	0.56	0.69	0.85	0.88	1.36
Deformation of the three skin layers (mm)	1.3	2.3	3.8	5.3	6.5	7.7	10.4	13.9

Source: (Salmanzadeh & Rasouli, 2015)

The differences between insertion and retention forces of cantilever hook snap-fits and the forces that can lead to fingertip injuries are significant in ergonomic and safety considerations. Insertion force refers to the amount of force required to assemble or insert the snap-fit components together initially. It is important for ensuring a secure connection but should be within a manageable range to prevent excessive strain during assembly. Retention force, on the other hand, is the force required to disassemble or separate the snap-fit components once they are engaged. This force needs to be sufficient to maintain the connection under normal operating conditions but should also allow for easy removal when necessary. Higher insertion forces such as in this research, 32.1764N for Model 13 in experimental analysis, can contributes to the larger deformation of skin layers of the fingertips. This is how the previous research and this research can be linked.

In contrast, the forces that can lead to fingertip injuries are typically much lower than both insertion and retention forces. Even relatively low forces, such as those encountered during repetitive tasks or sudden impacts, can cause injuries such as strains, bruises, or cuts to workers' fingertips. Therefore, while designing snap-fit connections, it is crucial to optimize insertion and retention forces to balance assembly security with ease of use, minimizing the risk of injury from repetitive or sudden force applications to workers' fingertips. Ergonomic assessments and testing can help ensure that these forces are within safe limits for the intended user interactions.

CHAPTER 5

CONCLUSION

5.1 Conclusion

Snap-fit is one of the easiest ways to connect or join two pieces or parts together. Snap-fit is often moulded directly into the parts and does not need any external joining method to complete a product. In this research, the aim is to first, investigate the length, thickness and insertion and retention angles (design factors) of the snap-fit joints in relation towards the insertion and retention forces. Thus, in this study, the parameters for the snap-fit are set to investigate the effect of different parameters on the insertion and retention forces of the snap-fits. 16 models have been created with different lengths, thicknesses and insertion and retention angles. This research shows that the length of the beam has the most significant impact towards the insertion and retention forces for both simulation and experimental.

Secondly, the objective is to simulate a non-linear simulation analysis-based contact surface using Ansys software. The simulation of the 16 models has been done foremost in Ansys by using the Augmented Lagrange formulation with the material that is set which is ABS material. Thus, the results for simulation for 16 models are obtained with the highest value of insertion force obtained from Model 13 with the value of 34.3460N. Meanwhile, the highest retention force is generated from Model 5 with a value of 39.4580N. The lowest force value for insertion is by Model 10 with the value of 3.3399N and the retention is from Model 2 with the value of 1.7219N. The data are mostly influenced by the length of the beam which is analysed using regression analysis. This data has been validated by existing literature by Abdul Manan et al. (2022), which is that longer beam length contributes to the lower forces of the snap-fits as the comparison on the results are similar, as the length of the beam increase, the insertion and retention forces during simulation is decrease.

Lastly, this study aims to evaluate the performance of the proposed numerical model based on the design factors, insertion and retention forces of cantilever hook snap-fits. After the simulation is carried out, all 16 models are printed using 3D printing Ultimaker and then tested using UTM. The highest force for experimental insertion is by Model 13 with a value of 32.1764N and for retention is by Model 5 with a value of 41.1443N. The lowest forces are by Model 16 for insertion and Model 2 for retention with the values of 3.2341N and 1.6573N, respectively. After experimental analysis, the results between simulation and experimental are compared to see the similarities and differences of both when tested. The experiments are then being compared with previous research made which is by Salmanzadeh & Rasouli (2015), which stated that increase of force used to assemble the snap-fits will increase the compressive stress, and this means that the risk of injuries towards the fingertips of the assembly workers will increase. Thus, the lower the forces need to assemble the snap-fits, the lower skin deformation due to compressive stress gained by the workers. Thus, it is better to take Model 16 as the optimum design for snap-fits as the insertion and retention force is low due to its longer beam which is 36mm and this length is still suitable for wall socket cover application, and the retention angle is higher which makes the grip stronger. It is advisable to pick snap-fits with a lower insertion force compared to retention force. If the retention force is higher than the insertion force, the strength of the grip of the snap-fit is better. The optimum value of the snap-fit length of the beam depending on the application of the snap. Thus, there is a guideline in determining the parameters as shown from research by Bonenberger (2017).

In this investigation, there are several sources of error. First, the percentage error of the snap-fits simulation compared to the experimental. As a result, Model 9 has the highest percentage error of 13.9640% for insertion and Model 6 with 8.4209% error for retention. The high percentage of errors can be caused by measurement instrument, the environment.

Next would be the effects of each parameter upon the simulation and experimental results for insertion and retention forces. It can be seen, only the length of the beam has a significant impact on the insertion and retention forces. Other parameters do not have a strong influence on the forces.

Then, for a future research, there are several suggestions as below:

- It is suggested having permanent snap-fits performances to be evaluated.
- Besides separable, the inseparable snap-fits also need to be investigated on the insertion forces and the retention forces to be able to see the forces that it can withstand.
- The most basic types of snap-fits can be used which is the cantilever hook snap-fits or also can try with different types of snap-fits such as the torsional or annular snap-fits.

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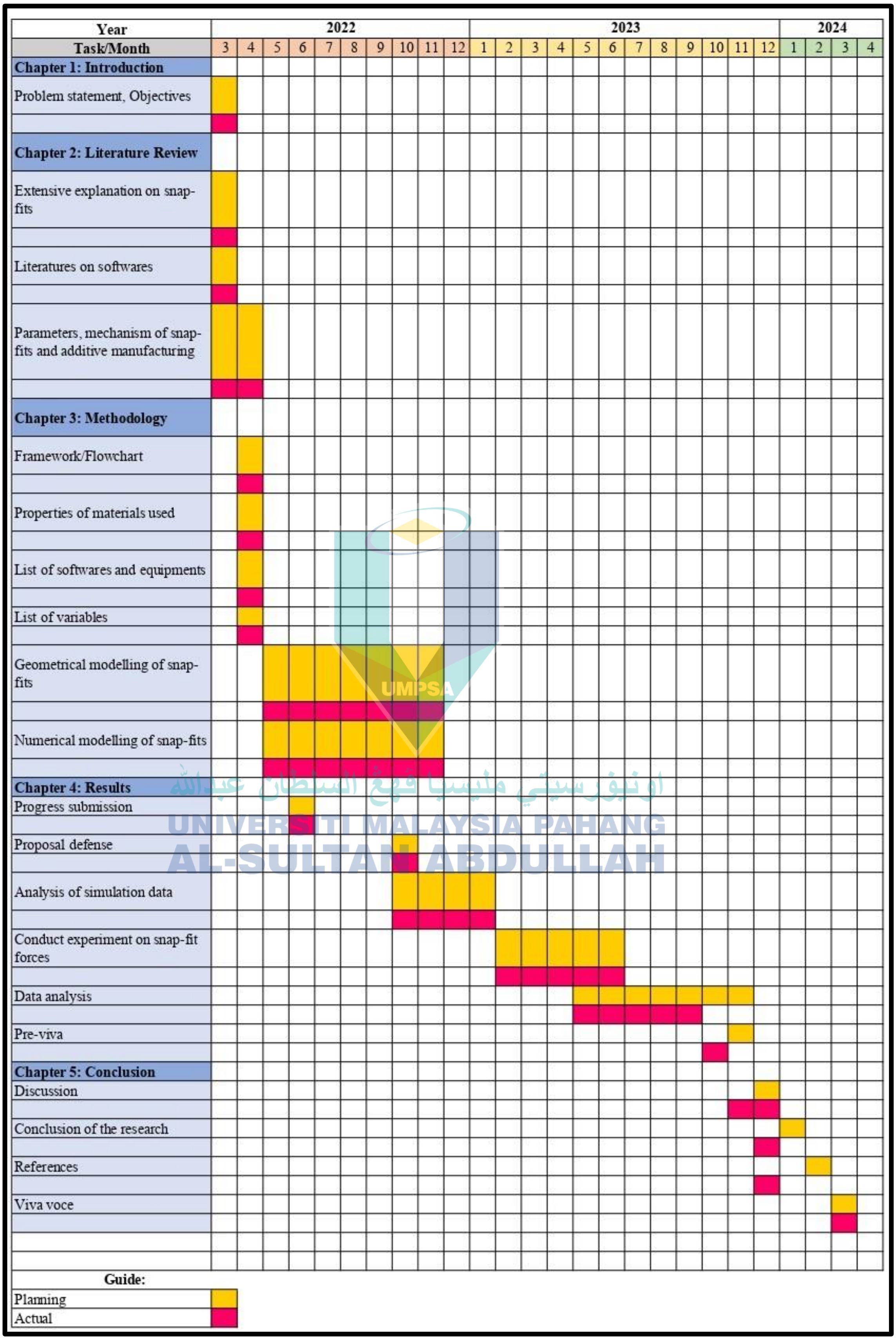
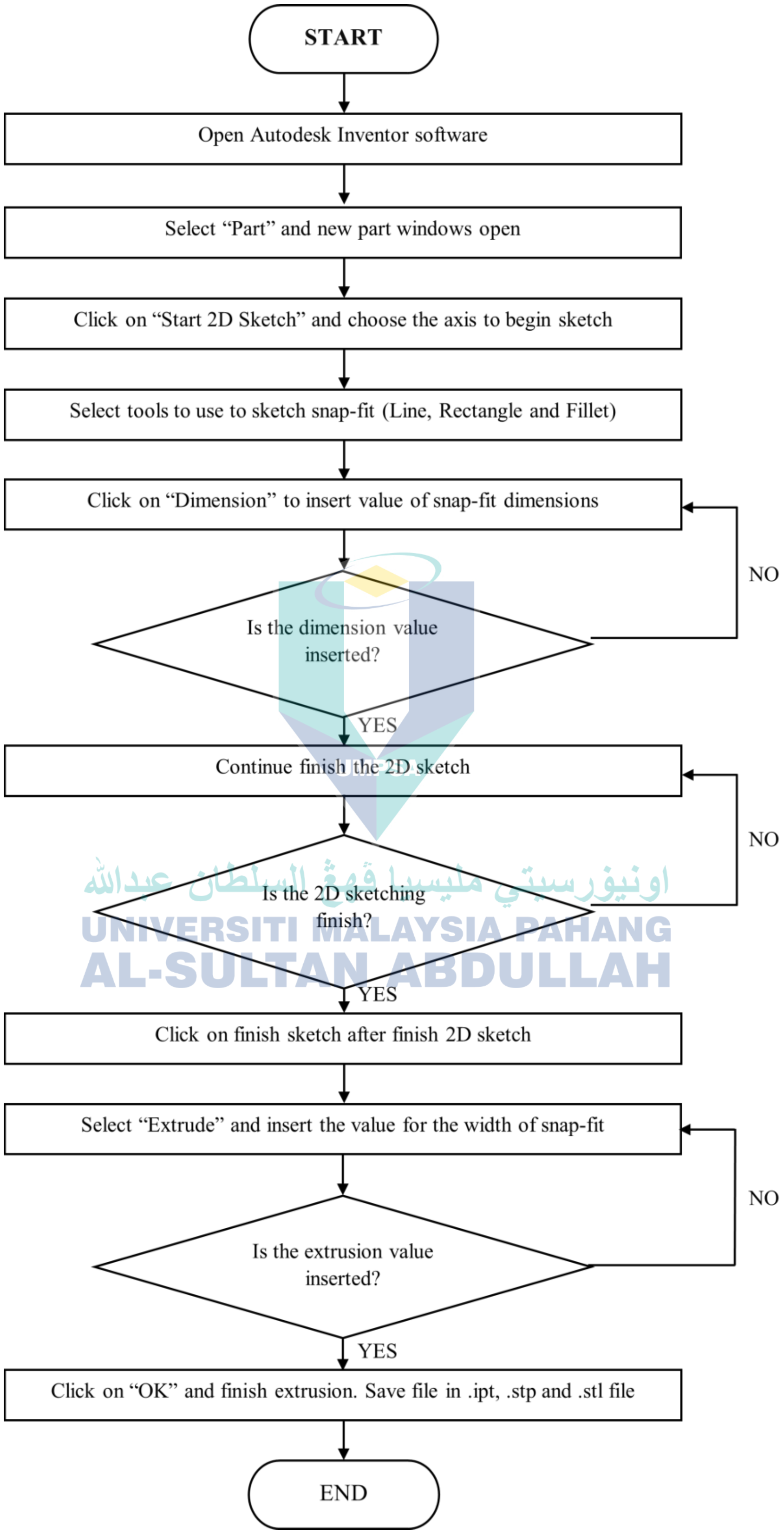
APPENDICES

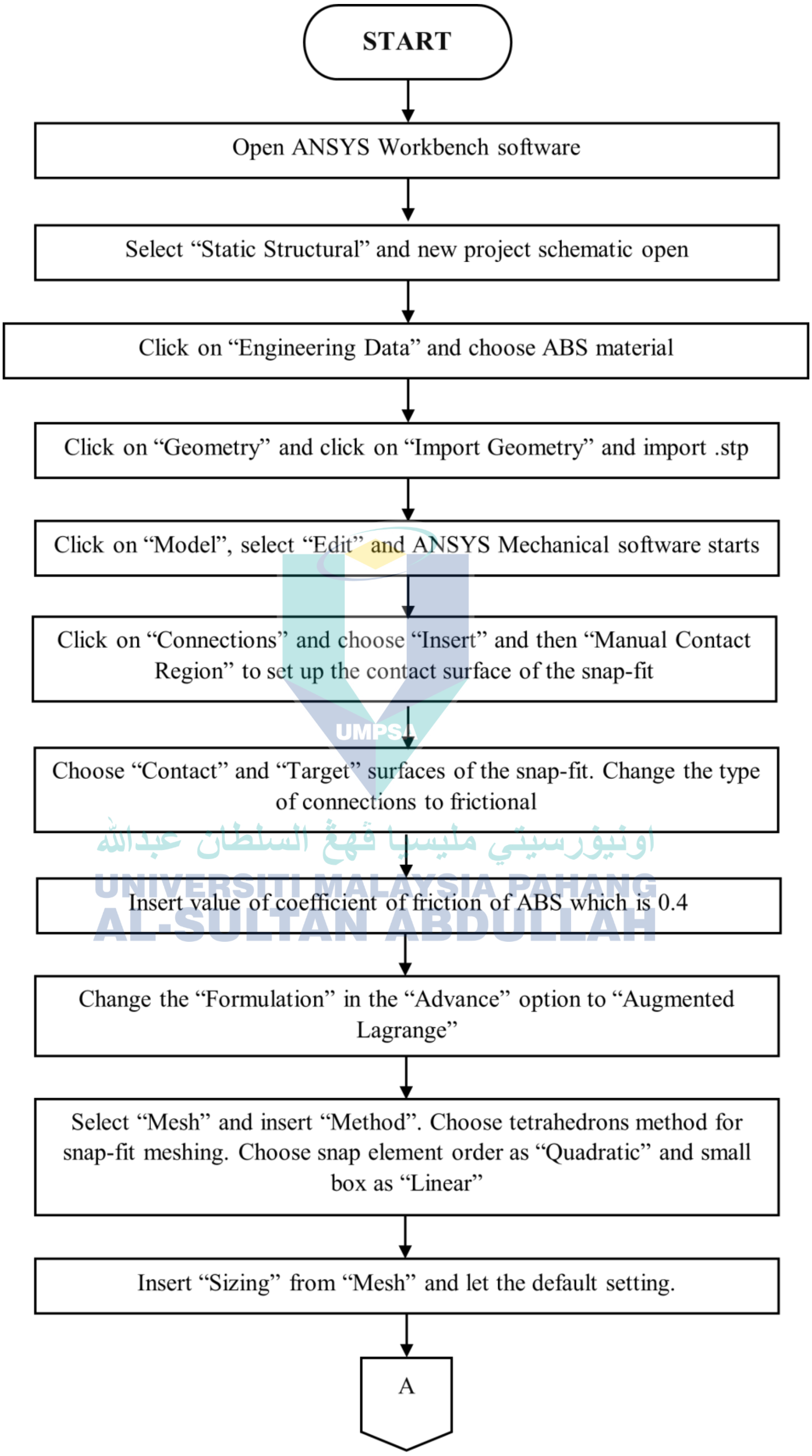
Appendix A: Gantt Chart

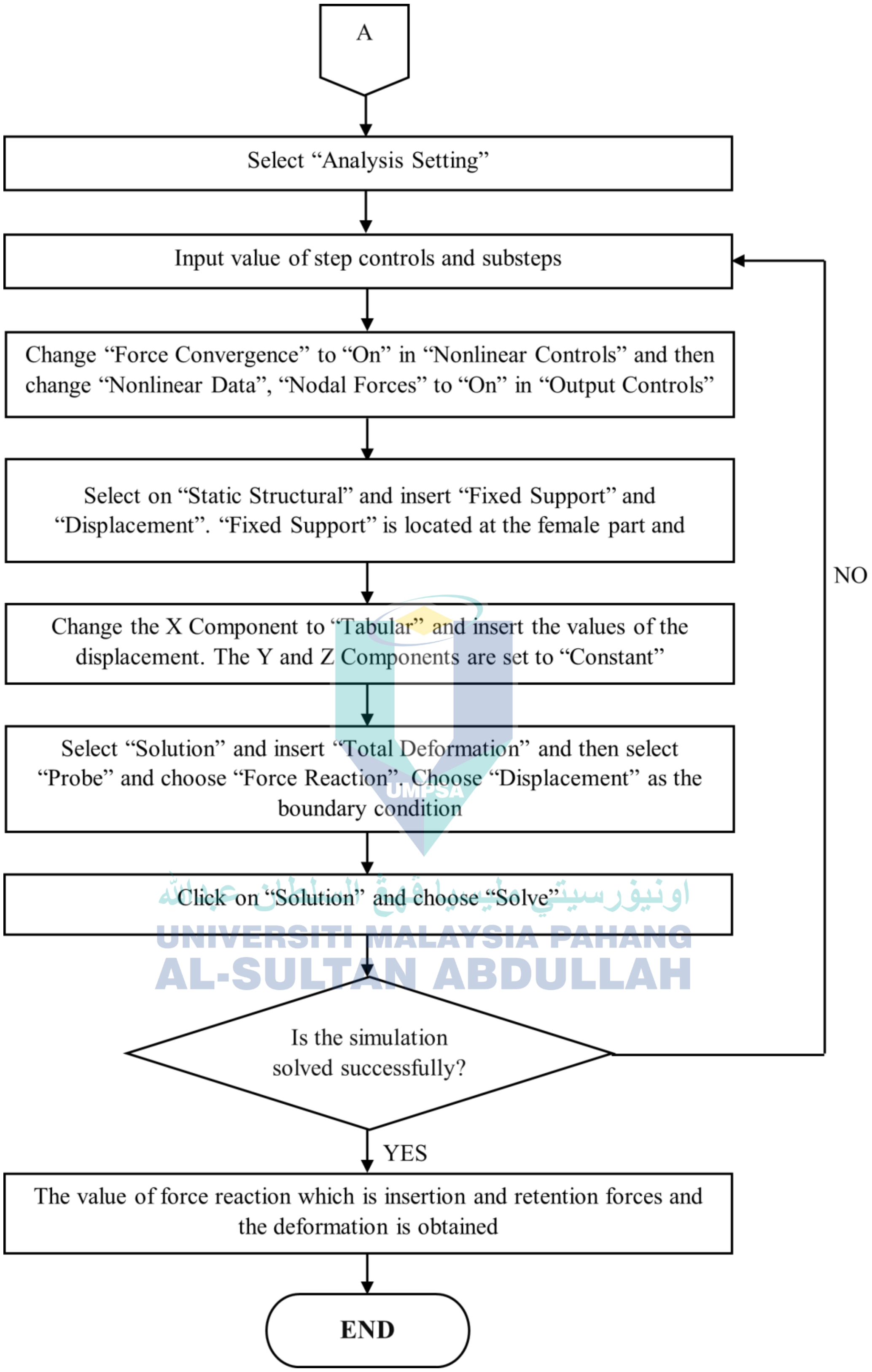


Appendix B: Flowchart for Autodesk Inventor

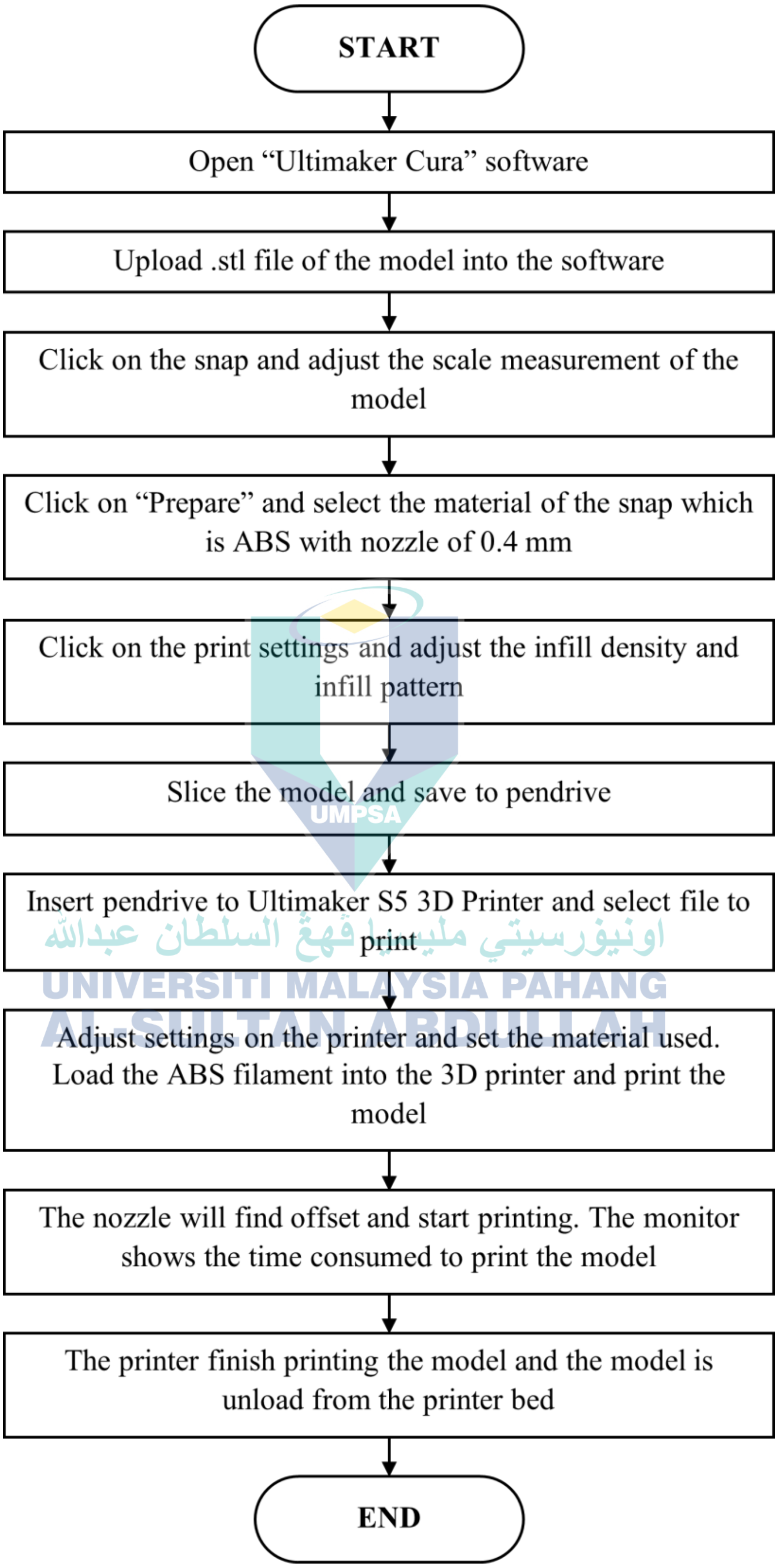


Appendix C: Flowchart for ANSYS Simulation

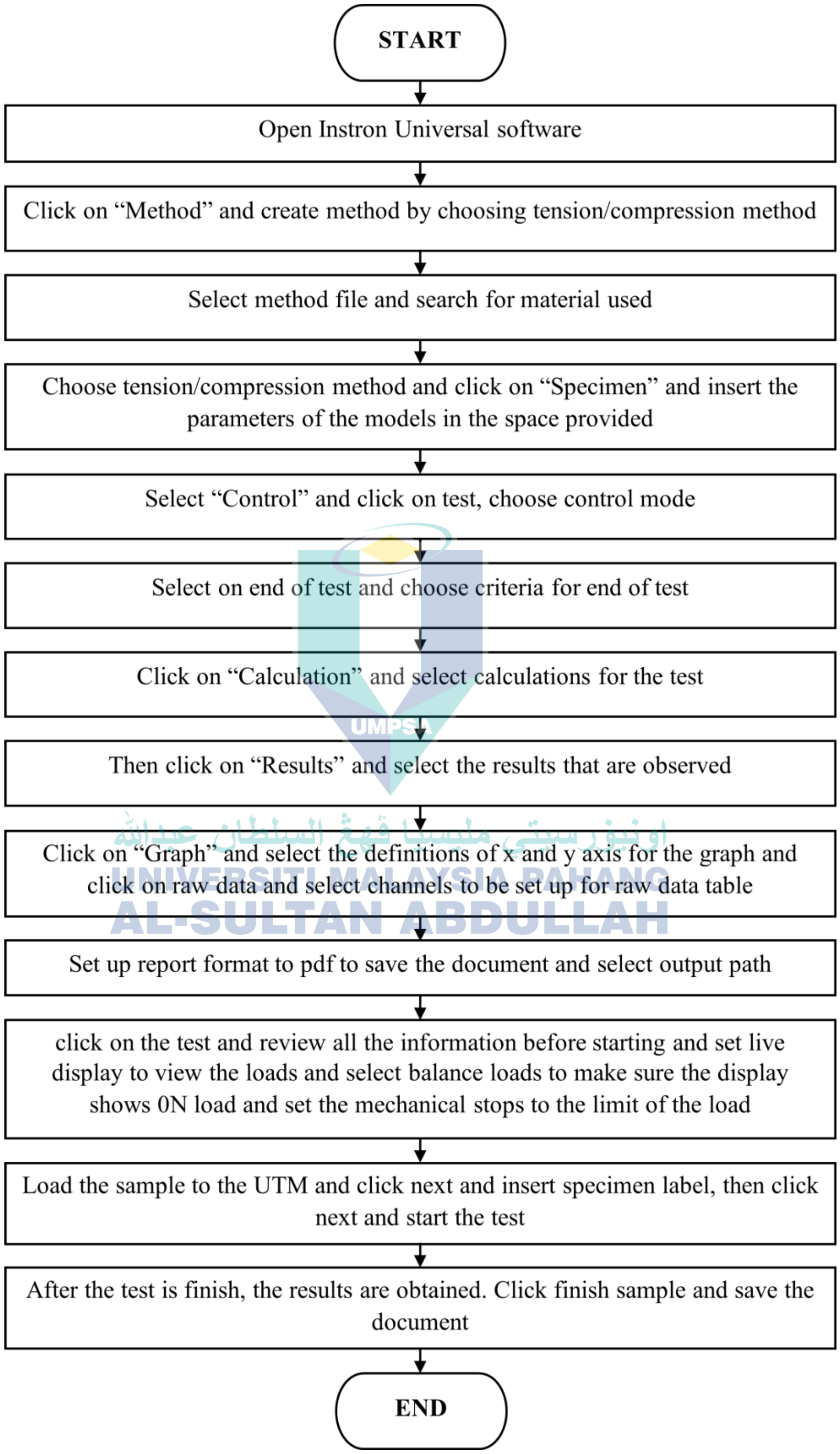



A
Select "Analysis Setting"
Input value of step controls and substeps
Change "Force Convergence" to "On" in "Nonlinear Controls" and then change "Nonlinear Data", "Nodal Forces" to "On" in "Output Controls"
Select on "Static Structural" and insert "Fixed Support" and "Displacement". "Fixed Support" is located at the female part and
Change the X Component to "Tabular" and insert the values of the displacement. The Y and Z Components are set to "Constant"
Select "Solution" and insert "Total Deformation" and then select "Probe" and choose "Force Reaction". Choose "Displacement" as the boundary condition
Click on "Solution" and choose "Solve"
Is the simulation solved successfully?
NO
YES
The value of force reaction which is insertion and retention forces and the deformation is obtained
END

Appendix D: Flowchart for Ultimaker Cura



Appendix E: Flowchart for using UTM



Appendix F: Table of results for simulation and experimental insertion and retention forces

Constant Variable			**Manipulated Variables**				**Observed Forces**				**Model No.**
							Insertion, F_i		Retention, F_r		
$\boldsymbol{W_b}$	$\boldsymbol{T_w}$	$\boldsymbol{R_b}$	**α**	**β**	$\boldsymbol{T_b}$	$\boldsymbol{L_b}$	Simulation	Experimental	Simulation	Experimental	
3.5 mm	3 mm	1 mm	25°	35°	3 mm	15 mm	26.9340 N	24.5883 N	30.9620 N	31.6664 N	1
						30 mm	3.7083 N	3.6693 N	1.7219 N	1.6573 N	2
					3.6 mm	18 mm	31.7290 N	31.0156 N	32.3390 N	31.5636 N	3
						36 mm	6.2075 N	5.7303 N	1.9783 N	1.8877 N	4
				45°	3 mm	15 mm	26.9030 N	24.5472 N	39.4580 N	41.1443 N	5
						30 mm	3.4148 N	3.3013 N	1.8640 N	2.0354 N	6
					3.6 mm	18 mm	31.9700 N	31.3275 N	11.7670 N	11.5245 N	7
						36 mm	4.9158 N	4.7797 N	1.9682 N	2.0111 N	8
			30°	35°	3 mm	15 mm	22.9430 N	20.1318 N	29.7700 N	30.4932 N	9
						30 mm	3.3399 N	3.2534 N	1.7321 N	1.8244 N	10
					3.6 mm	18 mm	25.4850 N	24.6241 N	32.2090 N	31.9867 N	11
						36 mm	3.6127 N	3.2517 N	1.8615 N	1.9016 N	12
				45°	3 mm	15 mm	34.3460 N	32.1764 N	11.0150 N	10.7936 N	13
						30 mm	3.3909 N	3.4118 N	1.8873 N	1.8666 N	14
					3.6 mm	18 mm	24.9720 N	24.3927 N	37.7780 N	37.9607 N	15
						36 mm	3.3624 N	3.2341 N	1.9652 N	1.9494 N	16