IMPROVING THE FORCE DELIVERY TREND OF NICKEL-TITANIUM ARCHWIRE IN ORTHODONTIC BRACKET SYSTEM

By:
NUR AINUL NURINA BT ISHAK LATIFFI
(Matrix no: 128964)

Supervisor:
Dr. MUHAMMAD FAUZINIZAM RAZALI

MAY 2019

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfillment of the requirement to graduate with honors degrees in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering
Enginnering Campus
Universiti Sains Malaysia

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed...
(NUR AINUL NURINA BT ISHAK LATIFFI)
Date ....

Statement 1

This thesis is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Biblography/references are appended.

Signed...
(NUR AINUL NURINA BT ISHAK LATIFFI)
Date ....

Statement 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available outside organizations.

Signed...
(NUR AINUL NURINA BT ISHAK LATIFFI)
Date ....

ACKNOWLEDGEMENT

First and foremost, I am grateful to The Almighty God for giving me the strength, knowledge, ability and opportunity to undertake this final year project and to persevere and complete it satisfactorily.

Next, I would like to give a special gratitude to my supervisor, Dr. Fauzinizam Razali for his guidance and help throughout the whole project. I am thankful for all the contribution in stimulating suggestions and encouragement, helped me to coordinate my project which enables me to carry out the analysis more smoothly especially in writing this thesis.

I would also like to express my gratitude to all lecturers and technical staffs in the School of Mechanical Engineering, Universiti Sains Malaysia, especially to Encik Mohd Nizam Ahmad who have been so helpful and sharing his knowledge gave permission to use all the required equipment and necessary materials to make my progress run more smoothly.to help me achieve my goal.

My acknowledgement would be incomplete without thanking the biggest source of my strength, my family. My parent and siblings for their continuous love, support and encouragemeNt. For those who have directly and indirectly contributed to the accomplishment of this thesis, thank you so much.

Nur Ainul Nurina bt Ishak Latiffi

May 2019

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

NiTi	Nickel Titanium
RS	Resistance to sliding
FR	Classical Friction
BI	Binding
UTM	Universal Testing Machine
RP	Reference Point
RF	Reaction Force

MEMPERBAIKI TREND PENGHASILAN DAYA OLEH DAWAI ARKUS NiTi DI DALAM SISTEM PENDAKAP ORTODONTIK

ABSTRAK

Ortodontik adalah sebuah khusus pergigian yang menumpukan kepada memperbetulkan posisi gigitan, dan kedudukan gigi. Dalam kes ini, rawatan ortodontik digalakkan untuk menukar kedudukan dan membetulkan gigi menjadi lurus dan sebaris secara perlahan lahan dengan menggunakan alatan seperti pendakap gigi. Pendakap gigi biasanya terdiri daripada pendakap yang dilekatkan di atas gigi dan dawai arkus yang dimasukkan di celah pendakap. Kajian ini bertujuan untuk menyiasat pengaruh sistem pendakap ortodontik ke arah daya-defleksi yang berkesan melalui dawai arkus NiTi semasa rawatan pengarasan. Lengkung daya-defleksi oleh lenturan dawai arkus super-elastik NiTi dalam konfigurasi tiga pendakap gigi telah diramalkan oleh model unsur terhingga tiga dimensi telah disatukan dengan menggunakan subrutin bahan dan interaksi sentuh yang menyerupai ujian lenturan tiga pendakap gigi sebenar yang dijalankan menggunakan mesin ujian umum. Kecekapan model ini diperiksa dengan membandingkan ramalan lengkung daya-defleksi dengan keputusan eksperimen dan tiga set pendakap gigi yang berlainan dimensi. Didapati bahawa pendakap gigi yang lebar menghasilkan cerun yang tinggi manakala pendakap yang lebih kecil membantu dalam mengurangkan daya cerunan ketika kitaran penurunan. Selain itu, geseran antara wayar dan pendakap meningkat secara berkadar sebagai fungsi dawai defleksi, justeru pendakap akan mengubah tingkah laku daya tetap oleh dawai arkus NiTi kepada cerun.

IMPROVING THE FORCE DELIVERY TREND OF NiTi ARCHWIRE IN ORTHODONTIC BRACKET SYSTEM

ABSTRACT

Orthodontics is a specialty within dentistry that focus on correcting bites, and the position of the teeth. In such cases, orthodontic treatments are recommended to slowly change the positioning and correcting the teeth to be straighter and more aligned using devices such as braces. Dental braces usually consist of brackets that are bonded to the teeth and an archwire that is inserted into the brackets. This study was designed to investigate the influence of the orthodontic bracket system toward the effective force release by NiTi archwire during orthodontic leveling treatment. The force-deflection curve of superelastic NiTi archwires bends in three-bracket configurations were predicted by three-dimensional finite element model integrated with superelastic user material subroutine and contact interaction that resembled the actual three bracket bending test that conducted using a universal testing machine. The competency of the bending model was examined by comparing the predicted force-deflection curve with the experimental result and three different sets of bracket dimensions. It was found that the wider bracket produce a greater slope while narrow bracket helps in reducing the force slope on the unloading cycle. Besides, the friction between the wire and the bracket increased proportionally as a function of wire deflection, hence the bracket altered the constant force behavior of NiTi archwire material into slope.

CHAPTER 1

INTRODUCTION

1.1 Project overview

Orthodontics is the branch of dentistry to correct teeth and jaws that are in irregular position such as overcrowding of teeth. Orthodontic treatment is a way to improve the appearance of the teeth by straightening or moving the teeth into a better position [1]. The average length of the treatment is from 12 to 24 months depending on the age and the irregularity of the tooth [2]. A typical tooth movement rate was reported to be around 0.25mm per week [3].

The treatment can be done by many sorts of appliances such as the most common type is fixed appliance therapy. The fixed appliance usually consists of small orthodontic brackets cemented to the teeth and connected by an orthodontist archwire which is periodically tightened by orthodontist to gradually shift teeth and jaw [4]. Figure 1.1 shows the main components of the fixed appliance used in malocclusion case of the displaced canine tooth.

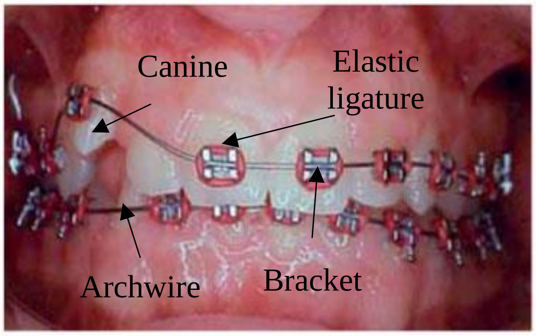


Figure 1.1 Niti archwire traction canine [5]

Orthodontic treatments involve the tooth movement in various directions and orientations at different stages. The major stages of comprehensive treatment are alignment and leveling, correction of molar relationship and space closure, and finishing treatment. Tooth aligning, and leveling is normally the first orthodontic objective during the initial stage. The orthodontist will start with a round light wire that can be bent easily and subsequently will replace it with a thicker wire with a rectangular shape. The use of superelastic NiTi wire is preferred against stainless steel wire during the early stage of orthodontic treatment, with a goal of bringing the teeth into alignment [6].

Orthodontic archwires are used to generate mechanical forces that are transmitted through brackets to move teeth and correct malocclusion, spacing, and/or crowding [7]. The archwire selection should provide the benefit of optimum and predictable treatment results [8] because they are designed to move teeth with light continuous force [9] such as the superelastic NiTi type. Unfortunately, the force is not constant anymore in the bracket configurations due to the effect of friction.

There are a few factors that are believed to influence the frictional force such as bracket geometry, wire sizes and wear of the bracket and archwire [10]. The orthodontic force and friction released from the archwire and brackets will affect the sliding of the wire in the leveling stage [11]. The tooth movement will occur when only forces applied exceed the friction on the wire-bracket interface [12]. Orthodontic archwires used for initial leveling stage must be capable of generating such forces and to do so they need to be flexible and to transmit light forces in a wide range of activation. [13]. The finite element analysis is one of the best tool to evaluate the force delivery trend of the archwire in an orthodontic bracket system to increase the quality of treatment.

Other than that, different force-deflection curves are produced from different bending models [14]. It is important to choose the right bending model, in order to obtain informative data from the deflection of the archwire. Figure 1.2 (a) shows the three point bending force-deflection curve that promote by the manufacturer in their brochure, claim that the flat plateau is produce during the recovery of the tooth and Figure 1.2 (a) shows the actual force-deflection behavior of superelastic wire obtained from three-bracket bending that transformed the flat plateau into a slope curve. The difference obtained is due to the friction at the wire-bracket interface.

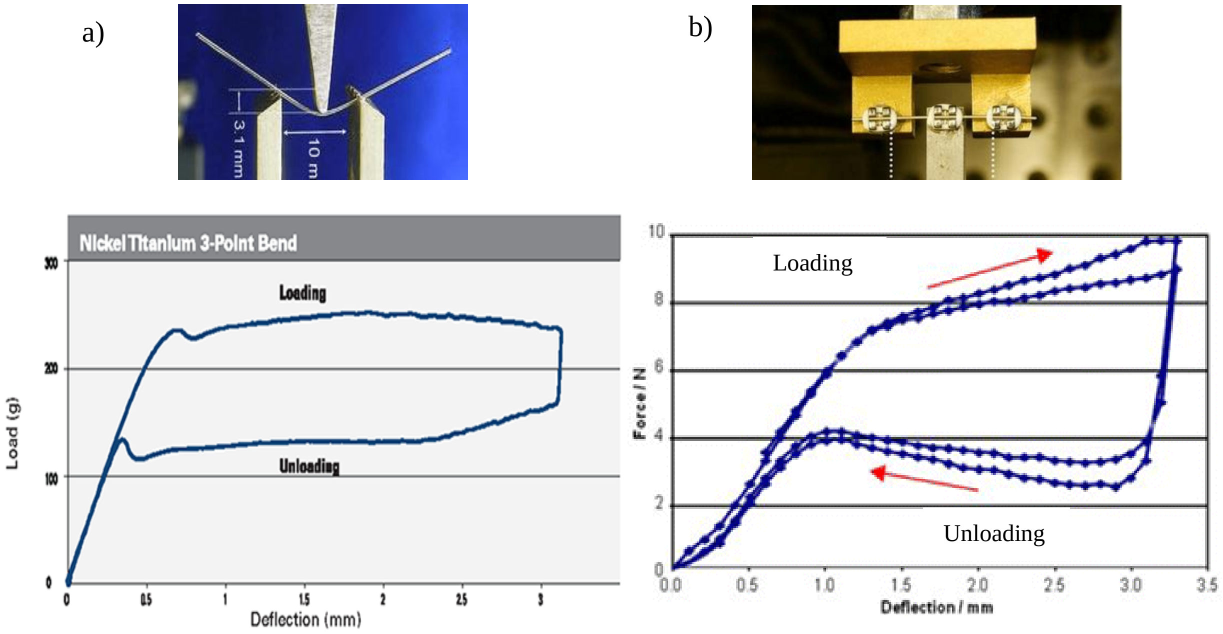


Figure 1.2 Force-deflection curves using in (a) three-point bending; (b) three-bracket bending [15].

1.2 Problem statement

In fixed orthodontic therapy, the teeth are reported to move most effectively upon the application of continuous and light force but the sliding friction introduced by the brackets and archwire contact can potentially affect the force delivered to the teeth and transformed the continuous force into a slope [12].

Frequent change of force magnitude will delay the cell activity involved during the treatment, thus prolong the treatment duration. That is why we are aiming to preserving the constant force behavior. Since the slope is due to the bracket friction, altering the bracket width might help reduces the force slope, hence promotes constant force trend.

1.3 Objective

There are a few objectives that need to be achieved at the end of this project:

1) To design three dimensional NiTi wire-bracket bending model.

2) To reduce the force slope of NiTi archwires by improving bracket design.

1.4 Project scopes

The purpose of this study is to investigate the influence of the orthodontic bracket geometry toward the effective force release by NiTi archwire by observing the force-deflection curve using computation. The analysis model focused on the standard leveling case of a highly displaced canine in a maxillary arch. The experimental and numerical approaches were used in this project. The force-deflection behavior of superelastic NiTi archwires was predicted by three-dimensional finite element model that consists of dental brackets and archwire that resembled the actual three point bending test that conducted using universal testing machine

Superelastic NiTi archwire with a dimension of 0.4 × 0.56 mm was used with three stainless- steel brackets, each with a 0.46 mm slot height and a 3.4 mm width. The coupling of the 0.4-mm archwire with the 0.46-mm slot bracket reflects the standard wire-bracket combination used during the leveling treatment.

The true flexural behaviors of the archwire was evaluated by bending test in three brackets system. This bending test was repeated for three times, to validate the consistency result of the force-deflection curve. The finite element model was developed using Abaqus Version 6.13. The generated outputs from the numerical model simulation were compared against the experimental of three bracket bending results for validation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will provide the review from previous researches that are related to this final year project. It begins with an overview of the fixed appliance components, general description of force delivery mechanism used during levelling treatment, friction encountered during sliding. Then, the variables influencing the binding friction and the archwire forces of superelastic NiTi wires in bracket configurations, are discussed.

2.2 Fixed appliance therapy

Orthodontic treatment is a way of moving or straightening teeth, to improve the appearance of the teeth by using fixed appliance therapy, where the appliances that are attached to the teeth cannot be removed by the patient. The fixed appliances are indicated when accurate tooth positioning are required [4]. Figure 2.1 shows the main components of the fixed appliance used. The brackets are bonded directly to the front of each tooth with bonding glue. Once they're secured onto all of the necessary teeth, the orthodontist will attach an archwire to the bracket, and secured inside the slot with the help of the rubber bands on top of it.

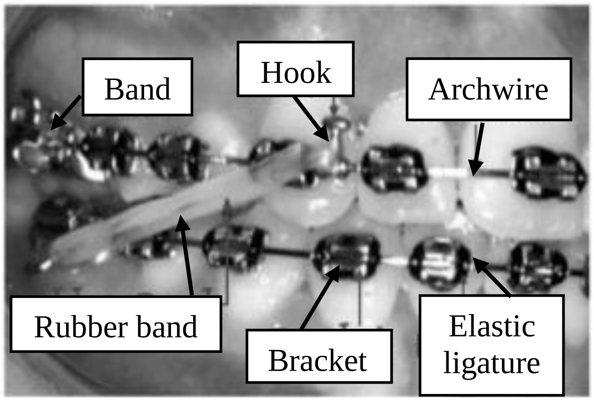


Figure 2.1 Representation of brackets, archwire, elastic ligature [9]

There are various types of bracket and archwire which made this therapy more popular for orthodontic treatment. Figure 2.2 shows the different design and shapes of the brackets that are available for the treatment. Basically, the differences between bracket types are in term of the slot height and the bracket width. The two most commonly used bracket slot sizes are 0.018 x 0.025 inch (0.46 x 0.64 mm) and 0.022 x 0.028 inch (0.56 x 0.071 mm). The bracket slot size is of importance in clinical orthodontics because it influences the “play” between the archwire and bracket slot [16], which indicates the degrees of the archwire rotation within the bracket before its edges come into contact with the slot wall. The larger 0.022-inch slot width produces lighter orthodontic force than the .018-inch slot and may provide more comfortable orthodontic force at the start of treatment [17]. For brackets width may vary from 2.4mm to 3.4mm, with wider bracket specified for wider teeth.

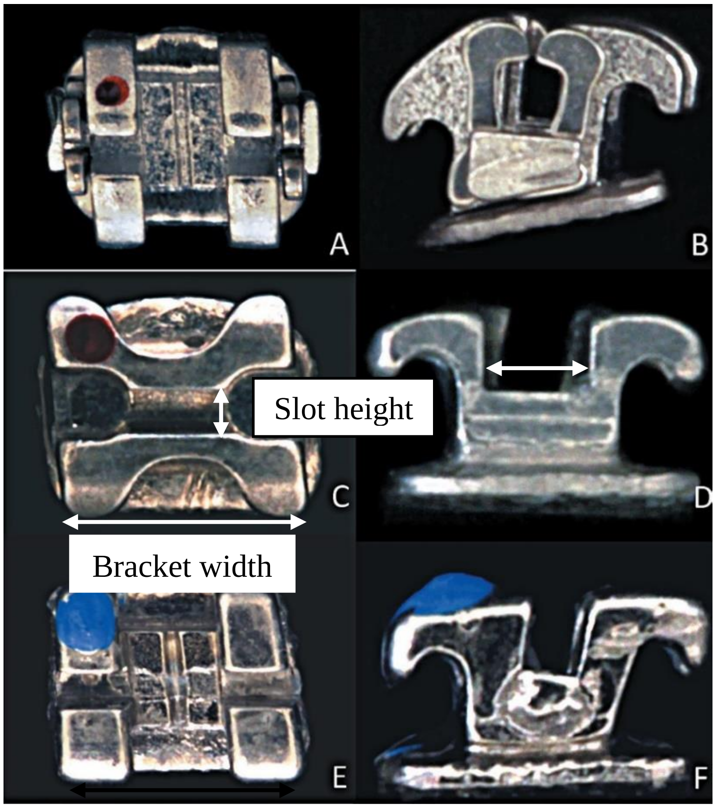


Figure 2.2 Three types of stainless steel brackets, : (A-B) Passive self-ligating bracket; (C-D) Modified slot bracket design. (E-F) Conventional bracket [18]

The distance of bracket position between the midpoints teeth with the adjacent teeth is defined by the interbracket distance. The typical distances between a man's permanent maxillary teeth are illustrated in Figure 2.3. The figure shows that the distance between the middle teeth which represent the canine with the adjacent tooth is 7.5mm.

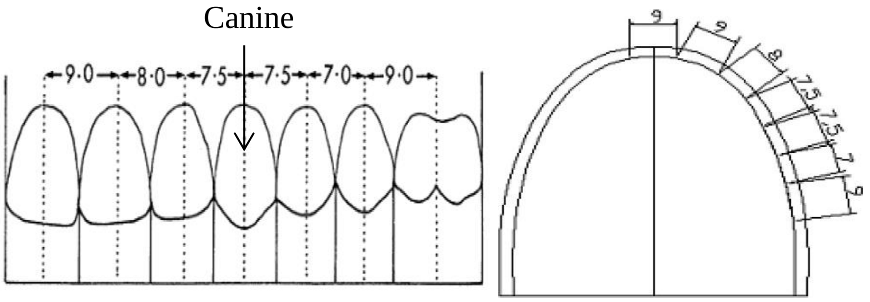


Figure 2.3 Standard midpoint distances between maxillary teeth in (mm) [19]

Orthodontic archwires are specifically designed for the application of force on a tooth during the treatment. Selection of these archwires plays a vital to optimize the biological environment for tooth movement and minimize patient's discomfort. There are many types of orthodontic wires, designed in similar shape of dental arch that can be used with dental braces as a source of force in correcting irregularities in position of the teeth. The shape of archwires has evolved from square, round and rectangular to recent bevelled surfaces [20] but the most common shape are the round and rectangular archwires. Figure 2.4 illustrated the shape of the archwires. Round archwires are normally used to align and level irregular teeth at the initial stage of treatment because it proved to minimize binding between the bracket and archwire [21]. Nowadays, many orthodontists start to place the large dimension rectangular NiTi archwires with the intent to minimize the dumping of the incisor as teeth level and align by controlling the torque [22-23]. Other than that, the purpose would be to provide three-dimensional tooth movement control, thereby developing controlled force level from the start of treatment.

Figure 2.4 Round, rectangular and square shape of NiTi archwire [24].

2.3 Ideal force for tooth movement

It is very important to apply the appropiate amount of force to the malposed tooth during orthodontic treatment to ensure a continuous tooth movement. Tooth movements can be categorized into six types, based on translational and rotational kind of movements and a different force level is recommended for each one as provided in Table 2.1. The relationship between the tooth movement rate and amount of force applied during orthodontic treatment has been considered as a practical tool in identifying the optimal force magnitude. The movement of teeth that occur during orthodontic treatment is dependent on the amount of force by the archwire [25]. An optimal orthodontic force was claimed to promote a maximum rate of tooth movement without tissue damage, and with maximum patient comfort. The application of excessive force during the treatment would cause a delay in the tooth movement [2].

Table 2.1 Types of tooth movement [11].

Type of movement	Force (N)
Tipping	0.35-0.60
Translation	0.70-1.20
Root Movement	0.50-1.00
Rotation	0.35-0.60
Extrusion	0.35-0.60
Intrusion	0.10-0.20

2.4 Orthodontic treatment: levelling stage

There are three major stages of comprehensive treatment. The first stage is alignment and levelling of the teeth, followed by correcting the bite and ended by closing the space or gaps between the teeth during the final stage [17]. The type of archwire that most frequently recommended for the initial stages of the orthodontic treatment is the superelastic NiTi type

[25], since this material offers an exceptionally wide activation range at lower and more constant force. Most orthodontist studies on orthodontic treatment have considered the first stage treatment which is leveling stage as their case study.

The movement of the teeth depends on the force produced by the archwire and the friction resisting the sliding movement. During this procedure, the bracket comes into contact with the wire, promoting friction between their surfaces. The friction between the bracket and orthodontic wire may reduce in half the force used to move the tooth [26]. After realizing the importance of contact friction during levelling therapy, researchers started to incorporate brackets into the experimental setting of bending studies. Figure 2.5 illustrates the modified three-bracket bending test that conducted using a universal testing machine.

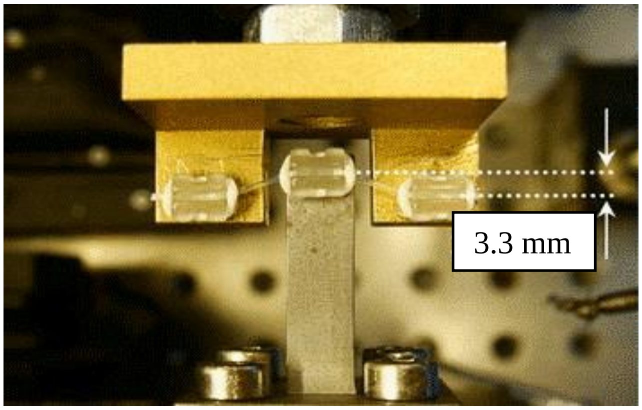


Figure 2.5 NiTi archwire bent on modified three-bracket bending setup [27]

2.5 Classification of friction of force during sliding

Friction is explained as a force that delays or resists the relative motion of two objects that in direct contact with each other and its direction is tangent to a common interface between both surfaces [28]. There are two types of friction, static, which largest friction recorded before relative motion occurs between contacting surfaces, and kinetic, which occurs during the sliding motion of one surface over another [29]. The static friction is more significant than the kinetic because the tooth movement is not continuous. The investigators who measured both of friction found that kinetic friction value is almost always lower than the static friction [30].

In fixed orthodontic therapy, the friction is generated from contacts between the wire, bracket slot, and the ligature surface [31]. During the retraction of the teeth at leveling and alignment stage, friction is one of the factors in sliding mechanics as the wire must slide through the bracket slots and the tooth movement only occur when the force applied to exceed the friction on the bracket-wire interface [29]. Therefore, it is essential to understand the impact of friction between the bracket and wire to control resistance to sliding (RS) to provide more efficient and predictable results, thereby increasing the quality of the treatment [32].

Kusy and Whitley [33] illustrated that the RS in archwire guided tooth movement is because of three parts, which are classical friction (FR), binding (BI) and notching (NO). The FR occurs between the archwire and the brackets when there is clearance between their surfaces. Then, the BI is described as the point where the archwire starts to bind against the bracket edges and when the clearance between the archwire and the bracket slot disappears. The critical angle was calculated as the angle at which FR is no longer exists and the binding dominates the situation. Kusy and Whitley [34] have included bracket width, wire size, and bracket slot to derive the equation 2.1 that determines the critical contact angle (θ_c). The critical contact angle (θ_c) is defined as the angle at which the clearance between the dental bracket and archwire first disappears. The studies have concluded that, for all bracket-archwire combinations, the critical contact angle decreased as bracket width, and wire size increased. To ensure that the contact angle during the sliding movement is within the boundaries of the critical angle, the bracket width should be small. Figure 2.6 shows the parameter related to determine the critical contact angle during the sliding of the archwire along a tipped bracket.

$$\theta c = \frac{57.32\ [1 - \left(\frac{wire\ size}{slot\ height}\right)]}{\frac{slot\ width}{slot\ height}} \qquad \text{Equation 2.1}$$

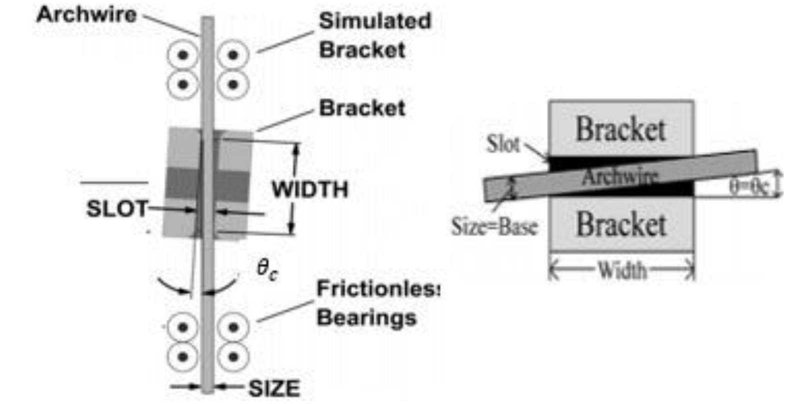


Figure 2.6 The schematic representation of the critical angle for binding, with respect to the tipping angle of the bracket [35].

2.6 Force-deflection behavior during levelling

NiTi archwires are commonly used in the early stages of orthodontic treatment because they release light constant forces that are appropriate for alignment and levelling. The fixed appliance therapy at leveling stage involves bending of archwire to some extent of deflection. Many studies have been conducted to understand force-deflection behaviours of the archwire material, and a few orthodontists have concluded that ideal orthodontic material is the one that gives a high elastic limit, and constant low forces over a wide range of activation [22].

An ideal archwire should provide light and constant forces capable of producing an adequate biological response in the periodontal ligament to achieve the most efficient tipping tooth movement [36]. Figure 2.7 shows the comparison of force-deflection curves of stainless steel, beta-titanium and nickel-titanium archwires of the same size, obtained from a three-point bending test. The figure demonstrates that the NiTi archwire exerts constant force compare to the stainless steel and beta-titanium archwires that elastically increased to a higher force level as the deflection increased. Therefore, the light and constant force of NiTi archwires make it widely used for initial alignment and physiological reasons.

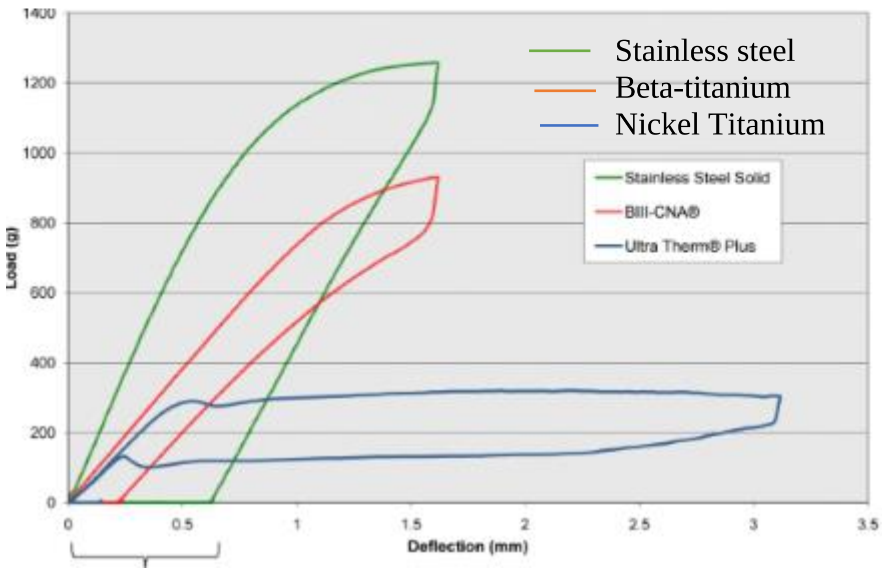


Figure 2.7 Force-deflection comparison between NiTi, Stainless steel, and beta-titanium archwires[16].

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will present both the experimental setup and numerical approaches used in this project. The experimental of the tensile test was conducted first, to determine the material properties needed for the numerical model. From the properties obtained from the experimental, a finite-element of three-bracket bending were modelled following the actual test set-up that consist of brackets and rectangular archwire to obtain the force-deflection curve of NiTi archwire.

3.2 Experiment testing

3.2.1 Tensile Test

The tensile experiment was performed over an universal testing machine (Model 3367, Instron) that equipped with a 30-kN load cell to determine the material properties of the rectangular NiTi orthodontic archwire. Figure 3.1 shows the tensile test setup. The orthodontic wire specimen was set to 50 mm that obtained from the straight-end section of the archwire, with 20mm gauge and 15 mm at each end for gripping. The tensile test was perform following the ISO 15841: Dentistry-Wires for use in Orthodontics. During the test, the specimen was stretched to 1.7 mm (8.5% strain) and unloaded back to initial value at rate 1.0 mm/min and were carried out at room temperature of 27 °C.

The tensile result was described in terms of stress-strain curve, that will be used for the selection of superelastic material parameters. Furthermore, the data of the stress-strain curve were logged using Bluehill v2.0 software.

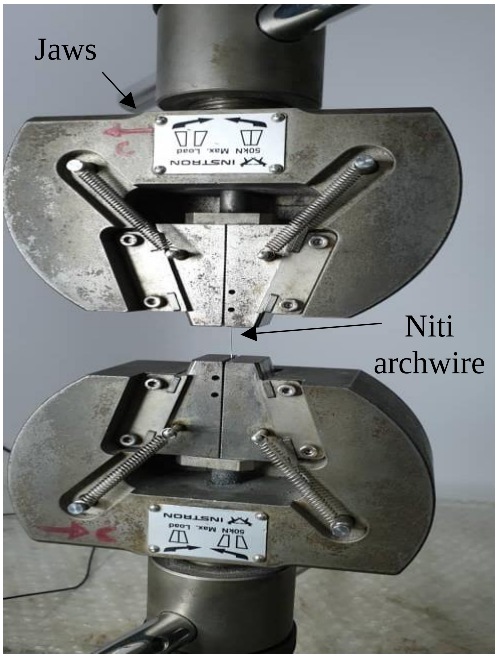


Figure 3.1 Tensile test setup of NitI archwire

3.2.2 Three-bracket bending test

The three brackets bending test is considered a good method to predict the force deflection characteristics of archwire-bracket configurations, as described in [37]. This test was set up by aligning three brackets, where the middle bracket was mounted on the movable indenter and the adjacent brackets were mounted on the fixed support. The three brackets configuration corresponding to the lateral incisor, canine and first premolar to represent the levelling treatment on the maxillary arch. The test was performed on the same universal testing machine. The brackets considered for this test were 0.018-inch (0.46mm) slot universal bracket with zero angulation and torque with the width of 3.4mm. The wire specimen was cut into 30 mm length, from the straight section of the archwire.

Then, the NiTi archwire was inserted through the slots of the brackets. The distance between every bracket was set to 7.5mm. The test was initiated by deflecting the archwire specimen to 4.0 mm, at a displacement rate of 1.0 mm/min. Then, the force was unloaded to is original position with similar speed. The test was carried out in a heating chamber at a temperature of 37°C to stimulate the temperature of the human body as shown in Figure 3.2. Throughout the test, the real-time force-deflection curve data were also logged using Bluehill v2.0 software. The force-deflection plot of NiTi specimen upon 4.0 mm bending on three brackets system was validated by comparing with the numerical result.

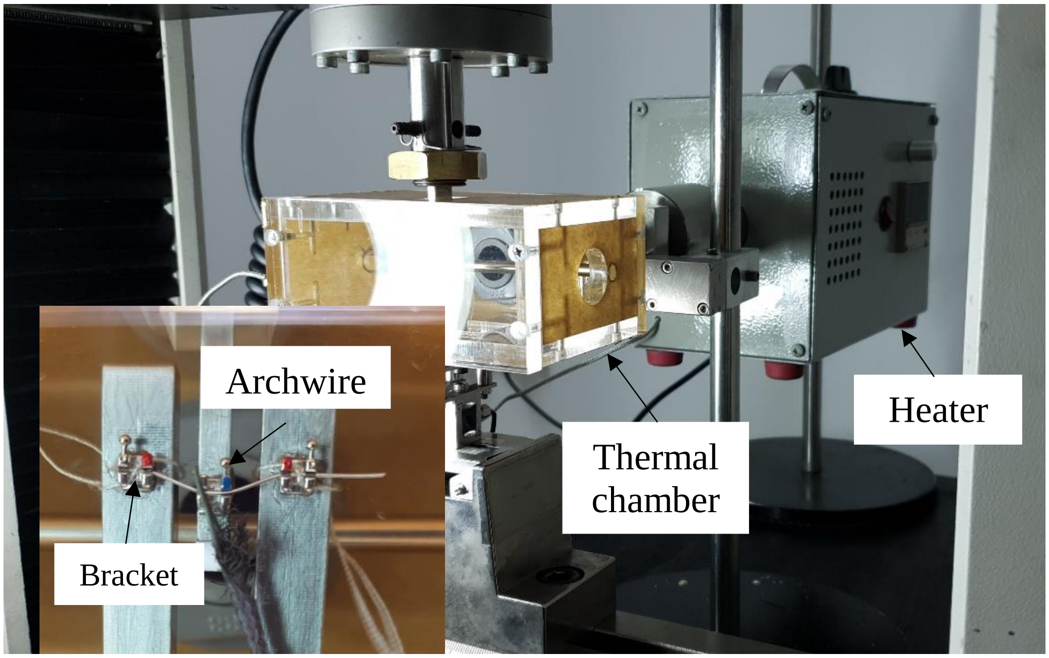


Figure 3.2 Three-bracket bending test setup,

3.3 Development of three bracket bending model

In this study, a series of finite-element archwire bending simulations were executed. This part explains how the analysis of the three-dimensional finite element model was completed using Abaqus version 6.13. This software package has a variety of products designed for any types of applications within its own suite such as Abaqus/CAE is used to create models (including boundary condition, assigning loads, step time, interaction, etc), analysis, job management and result visualisation. For this project, Abaqus/Standard and an implicit solver were utilized for all simulations.

The development process of the finite element model used in Abaqus are:

1. Create archwire and bracket model
2. Define the user material subroutine
3. Assembly the part
4. Meshing
5. Boundary condition and step time definition
6. Save as cae file
7. Initialize the run

3.3.1 Material Parameters

A built-in subroutine user material (UMAT/Nitinol) was employed in Abaqus 6.13. This subroutine is based on Aurrichio constitutive model [38]. This UMAT/Nitinol subroutine was activated by specifying 14 material parameters listed in Table 3.1.

Table 3.1 User material data for constitutive model of superelastic archwire measured from the uniaxial stress-strain curve (T=26°C)

Parameter	Description	Value (unit)
E_A	Austenite elasticity	40 (GPa)
(V_A)	Austenite Poisson's ratio	0.33
E_M	Martensite elasticity	20 (GPa)
V_M	Martensite Poisson's ratio	0.33
(ε_L)	Transformation strain	0.065
$(\delta_\sigma/\delta T)_L$	Loading	6.7 (MPa/°C)
σ_{SL}	Start of transformation loading	330 (MPa)
σ_{EL}	End of transformation loading	390 (MPa)
T_O	Reference temperature	27 (°C)
$(\delta_\sigma/\delta T)_U$	Unloading	6.7 (MPa/°C)
σ_{SU}	Start of transformation unloading	150 (MPa)
σ_{EU}	End of transformation unloading	90 (MPa)
σ_{SCL}	Start of transformation stress in compression	396 (MPa)

Figure 3.3 shows the uniaxial stress-strain curve of NiTi archwire at 27°C. The starting and ending of transformation loading and loading were labelled on the figure. Besides, the transformation strain value was measured from the offset of the straight line of elastic martensite.

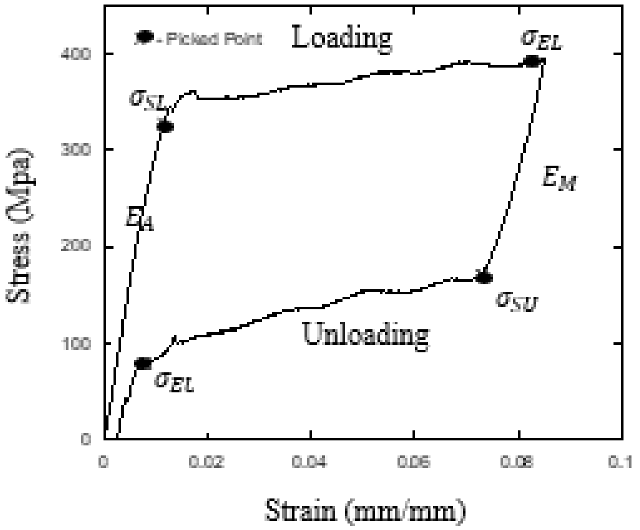


Figure 3.3 Illustration of selected points on the NiTi archwire specimen stress-strain curve

3.3.2 Generation of part, assembly, boundary condition and meshing.

The finite element model consisted of two major parts, namely bracket and NiTi archwire. The bending simulation was performed by considering three different sets of bracket dimension. The dimension of each set and the total number of element is listed in Table 3.2. The bracket was modelled by using a bilinear rigid quadrilateral element (R3D4) with actual bracket slot dimensions of 0.46 × 3.4 × 0.63 mm $(H \times L \times W)$ and defined as a rigid non-deformable body. On the other hand, the archwire part was model using 8-node linear brick elements with reduced integration (C3D8R). The mesh for the bracket and archwire part displayed in Figure 3.4.

Table 3.2 Total number of element used for each model part

Set	Description	Part	No of Element
1	3.4 mm (BW) × 0.46 mm (SH)	Bracket	10,647
2	3.1 mm (BW) × 0.46 mm (SH)	Bracket	10,003
3	2.8 mm (BW) × 0.46 mm (SH)	Bracket	9084
	0.40 mm (H) × 30 mm (L) × 0.56 mm (W)	Rectangular wire	57,582

*H=height, L=length,W =width, BW=bracket width, SH=slot height

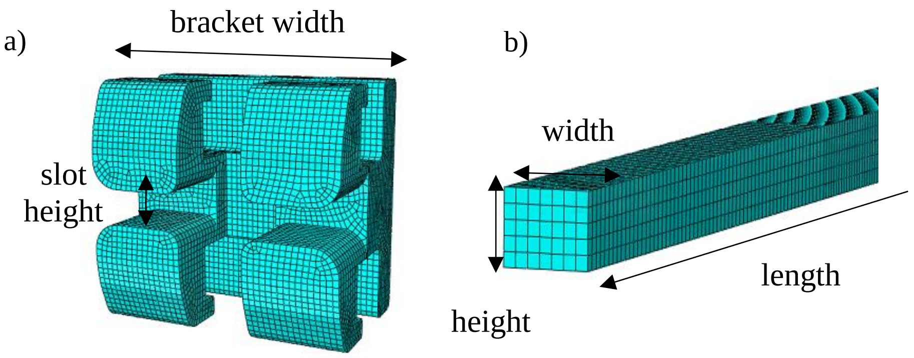


Figure 3.4 Mesh considered on a) bracket b) archwire

Then, to define the analysis model, the bracket and wire part were assembled. The distance between the bracket was set to 7.5mm from its midpoint to ensure it symmetrically positioned. Each part of the bracket was assigned to its own reference point (RP), namely RP-1, RP-2, and RP-3, corresponding to the middle, the left, and the right bracket position, respectively shown in Figure 3.5. The RP help to make sure that any motion or constraints are applied to the entire bracket. The middle bracket was offset downward by a distance of 0.06mm to remove the gap between archwire and the top surface of the bracket, prior to the initiation of the bending. Then, the archwire and positioned inside the three bracket slot.

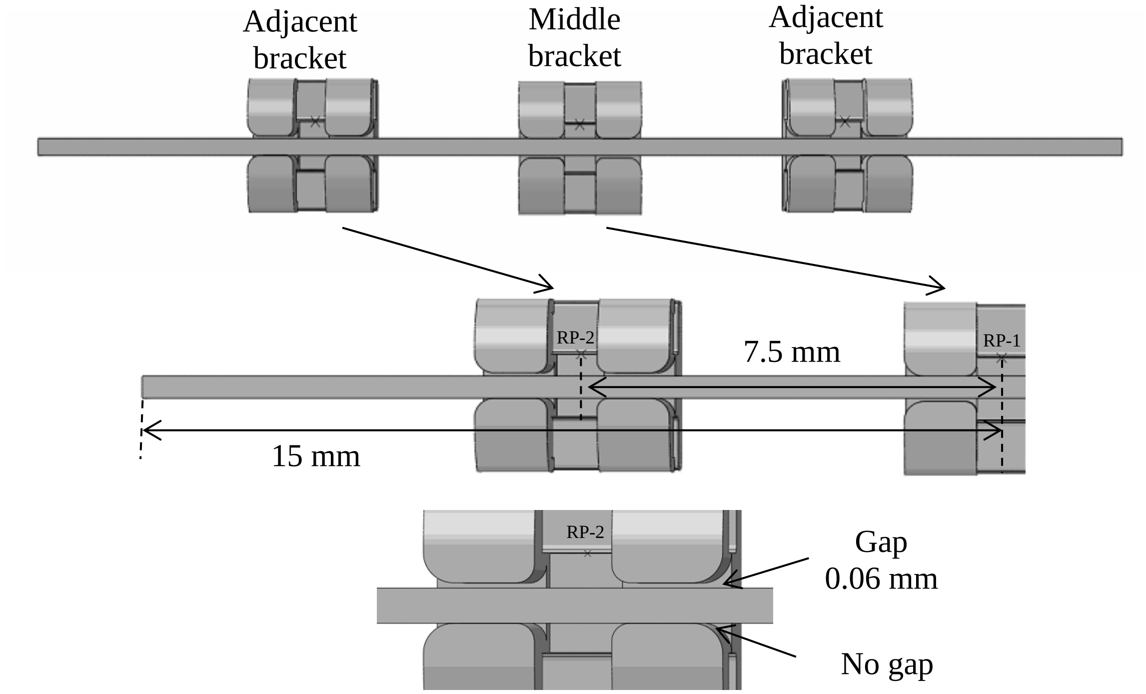
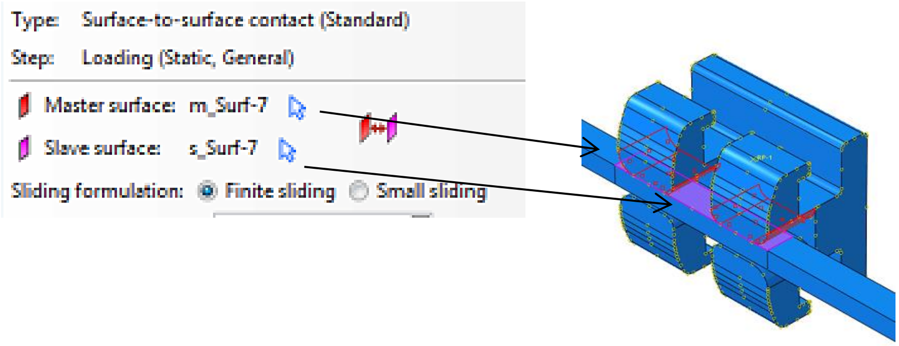


Figure 3.5 Assemble position of bracket and wire part

Next, the contact between the wire and brackets surfaces was defined by surface-to-surface discretization. This type of discretization provides a smoothing effect on the pressure distribution across the contacted surface between the bracket and the wire, by averaging out the penetration resistance between the slave and master nodes. The surface of the bracket was selected as the master surface (the red region) while the surface of the wire was defined as slave surface (the pink region) as shown in Figure 3.6. Contact with a coefficient of friction of 0.20 was defined between bracket's surface and archwire in order to allow the wire to slide freely through the bracket's slot.



Type: Surface-to-surface contact (Standard)
Step: Loading (Static, General)
Master surface: m_Surf-7
Slave surface: s_Surf-7
Sliding formulation: ● Finite sliding ○ Small sliding

Figure 3.6 Middle bracket's master and slave surfaces selection

The bending simulation involves two general steps, known as activation and deactivation. These steps define the deformation and the recovery of the archwire, in terms of the application and the removal of the bending load. For both steps, the initial time increment was set to 0.01s, with the minimum and the maximum admissible time increment sizes set to 0.00001 and 1s.

The boundary conditions applied at each reference point that has been assigned to the brackets are summarized in Table 3.3. The middle bracket was set to move only 4.0mm in y-direction. The adjacent bracket, all degree of freedom were constrained to zero, to avoid any displacement of these brackets during the bending course. There is no boundary condition was specified in the wire model, to let the wire deform and slide freely during the bending. The bending environmental temperature was kept constant, at 37°C which is oral temperature. Lastly, the force deflection of the archwire during the bending was obtained by calculating the vertical reaction force (RF2) and the displacement (U2) with respect to the middle brackets (RP-1)

Table 3.3 Boundary conditions applied on each reference point

Boundary Condition Name	Set	Boundary Condition	
		Activation	Deactivation
Left Bracket	RP-2	Encastre	Encastre
Middle Bracket	RP-1	U1=U3=0; U2=-4.0	U1=U3=0; U2 modified to 0
Right Bracket	RP-3	Encastre	Encastre

*Encastre= fix in all direction

3.4 Design of experiment

In this study, the three bracket bending was designed to investigate the quantitative effect of the binding on the NiTi archwire's force delivery behaviour. This is address the variety of bracket sizes and archwire that available for orthodontic treatments. The simulation was performed by considering three different bracket width (3.4mm, 3.1mm, and 2.8mm) This analysis was carried out at a single bending setting; with the deflection of 4.0 mm and the inter-bracket distance of 7.5 mm. The coefficient of friction at the wire-bracket interface was set to 0.20 and the simulation was conducted at 37°C. The flow of work in this study is summarized in Figure 3.7.

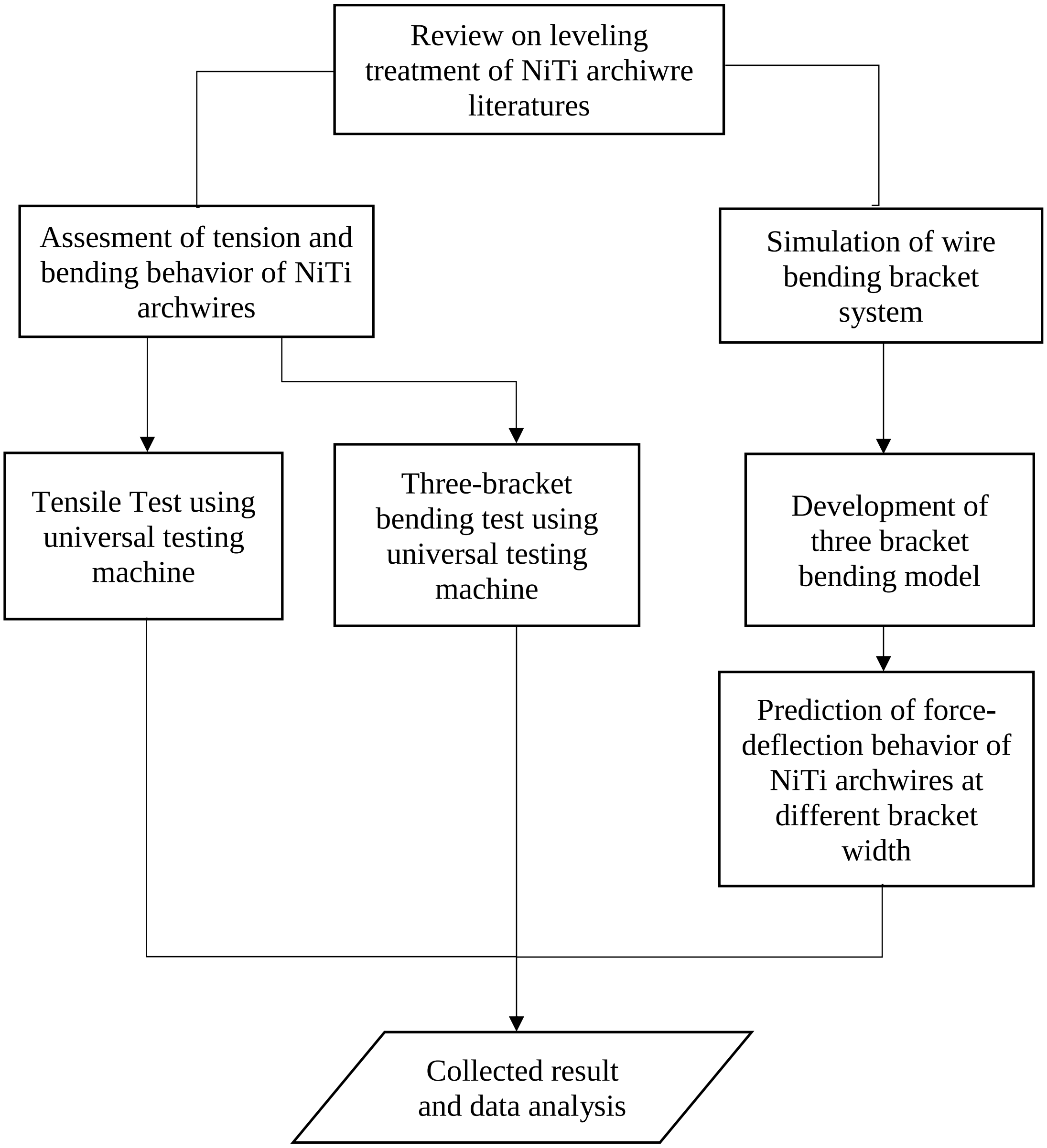


Figure 3.7 Summary of the work