Chapter 18
Evaluation of Bending Deformation Behavior of a NiTi Archwire at Various Orthodontic Bracket Conditions

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Abstract NiTi archwires are often used in orthodontic tooth treatment nowadays. The goal of this study is to investigate the bending deformation behavior of NiTi archwires in orthodontic brackets under various bending conditions. Using 0.022-in. bracket size, an experimental test setup was designed to bend three brackets, frictionless three brackets, elastomeric ligated three brackets, and five brackets at room temperatures (27 °C). A 0.016-in. NiTi round wire was used for the bending testing. As a frictionless material, polytetrafluoroethylene (PTFE, Teflon) is used. All bending tests have done three different deflections (2, 3, and 4 mm). The bending deformation of the archwire was used to determine and measure binding friction. Apart from frictions, the stainless-steel bracket configuration caused the wire to release the force in a sloping trend as compared to the Teflon bracket in the test. When constrained (ligated) and with the five brackets, the binding friction increases. These findings highlight that the usage of ligature and numbers of brackets has directly affected the bending deformation behavior during orthodontic leveling treatment.

Keywords NiTi shape memory alloy · Bending deformation behavior · Three-bracket bending · Five-bracket bending · Fabricated Teflon bracket

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18.1 Introduction

During orthodontic treatment, the tooth is being moved by the recovery of NiTi's bent archwire, when the wire returns back to its original arch shape. The NiTi shape memory alloy has unique superelasticity behavior that can produce constant force up to 8% stretch elongation (Thompson 2000). Constant and continuous force is needed for optimal tooth movement, at the same time, to reduce unwanted clinical side effects due to higher force (Cobourne and DiBiase 2010; Yee et al. 2009). In the actual treatment, the NiTi archwire is slid along the bracket slot during treatment, producing different bending deformation behaviors. As a result, it is essential to consider the NiTi archwire's bending deformation behavior under various orthodontic bracket conditions.

18.2 Literature

Bending methods determine the bending deformation behavior of NiTi archwires. The different bending methods yield various behaviors and characteristics of the force–deflection curve (Wilkinson et al. 2002). In orthodontics, the three-point bending test is a basic method for determining and analyzing the bending deformation behavior of NiTi archwires (Wilkinson et al. 2002). This bending method should follow the American Dental Association's Specification No. 32 for Orthodontic wires and ISO 15841: Wires for use in orthodontic (Standard 2014). However, the usage of three-point bending is not considered sufficient since this approach neglects the function of the bracket in the actual orthodontic treatment. As a result, few researchers have adapted the three-point bending test into the bracket bending test to simulate the real state of forces applied to the archwire (Elayyan et al. 2010; Nucera et al. 2014; Oltjen et al. 1997). The three-bracket bending imitates the actual bending condition during the orthodontic treatment, while the classical three-point bending test only allows the NiTi archwire to slip free during the bending test.

The bending deformation behavior of the archwire is assessed by examining the force produced at the deflection magnitudes and brackets' distance. The interaction between the archwire and bracket slot causes the gradual force–deflection trend, as well as the magnitude of specific displacement (Meling and Ødegaard 2001). The distance between brackets became the span during the archwire bending, thereby affecting the force–deflection behavior of the NiTi archwire (Badawi et al. 2009). The ligation force from the ligation technique also affects the bending deformation behavior of the NiTi archwire. The frictional resistance of self-ligating brackets, elastomeric-ligated brackets, and stainless-steel ligated brackets was studied, and it was discovered that the self-ligating bracket had the lowest frictional resistance (Leite et al. 2014).

A higher friction coefficient at the archwire–bracket interface was found to be influencing the frictions (Clocheret et al. 2004). The coefficient of friction on the

NiTi archwire and stainless-steel bracket interface was measured and found to be in the range of 0.21–0.27 (Alper Oz et al. 2012). Alternative materials with a lower coefficient are Teflon, and recent evidence of its application shows the potential to reduce the frictions with the lower coefficient of friction (Fraunhofer and Jr 1995; Murayama et al. 2013).

The goal of this study is to assess the bending deformation behavior of NiTi archwires when using orthodontic stainless-steel brackets in a various situations. Three brackets, fabricated Teflon five brackets, and ligated bracket were used as an experimental setup to simulate various bending test conditions. The bending tests used friction on brackets to predict the bending deformation behavior of the superelastic NiTi archwire under various wire constraint conditions, whereas a frictionless bending state was achieved using a fabricated Teflon bracket. This in vitro investigation was done at room temperature and dry condition (without saliva). Force–deflection curves plotted are very useful since they show forces over deflection at both conditions of installation of the wire in the bracket (activation phase) and wire recovery after installation (deactivation phase).

18.3 Methodology

The three-bracket bending jig setup is shown in Fig. 18.1a. The jig consists of two bars, the jig base, and indenter, which are made from stainless steel. Stainless steel was used as jig because it is easy to clean and glued bracket and has a good cosmetic appearance. The dimensions of the bar are 7 mm × 7 mm × 30 mm to mimic the size of teeth. The bars were bolted to the jig base with screws. The jig base is attached at an adjustable clamper at the universal tensile machine (UTM, Instron 3367) before testing. A UTM load cell with a maximum static load of 500 N is attached to an indenter with dimensions of 3 mm × 10 mm × 50 mm (resolution 0.01 N). During the bending test, a crosshead speed of 1 mm per minute is employed to provide load. For this investigation, a typical stainless-steel bracket (Natural Orthodontics) with a mini MBT prescription and a 0.022-in. (0.559 mm) size was used. Before glueing brackets to stainless-steel bars with cyanoacrylate adhesive (Selleys), proper alignments are determined using a digital caliper, height gauge (Mitutoyo), and mini bubble level protector (Haccury). The arrangement of the bars and indenter is representing the arrangement of the tooth at the maxillary jaw, canine, first premolar, and second premolar as in the phantom model. A bending span of 15.0 mm was used with an average midpoint within the tooth and an indenter was placed in the middle, 7.5 mm on each side. The elastomeric ligatures (commercial unbranded ligature ties O-ring type) are applied at bracket hooks to hold the NiTi archwire in the bracket slot, during the ligated bracket bending condition.

Three-brackets bending setup the extended to frictionless bending condition by using a fabricated Teflon bracket as shown in Fig. 18.1b. The fabricated Teflon brackets are made by machining a Teflon bar into a small insert and then using the press-fit method to attach it to the stainless-steel square housing. The Teflon

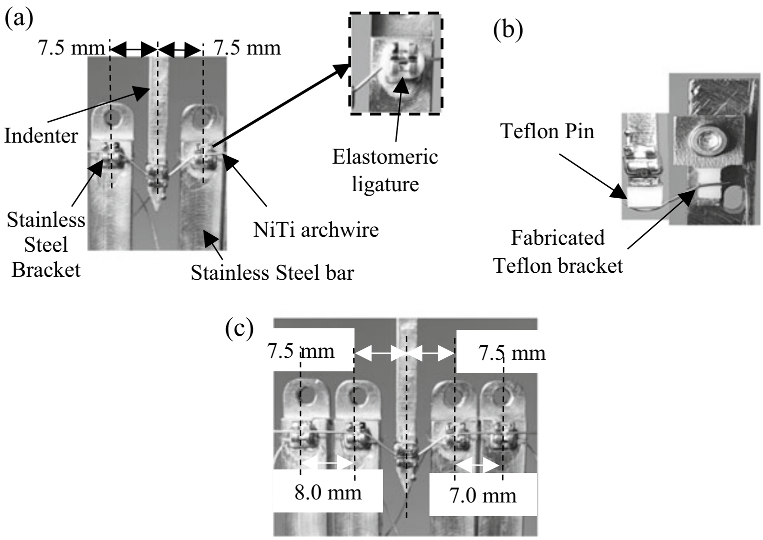


Fig. 18.1 Setup of various condition bending tests; **a** three brackets and extend to elastomeric ligated, **b** fabricated Teflon bracket, **c** five brackets

inserts have the same slot size as the conventional bracket size. The square housing dimension is matching with the new stainless-steel bar of 10 mm × 7 mm × 30 mm, where the fabricated Teflon bracket was bolted. Teflon pins are fabricated by gluing a small Teflon bar, 3.1 mm × 10 mm × 3 mm on the flat indenter tip. The five-bracket bending setup is shown in Fig. 18.1c. The setup is an extension to the existing three-bracket bending jig. Other bars were installed to the jig with the same brackets was placed, but with a slightly different on tooth line-up. The arrangement of the bars and indenter is representing the arrangement of the tooth at maxillary jaw, lateral incisor, canine, first premolar, second premolar, and first molar, at which the midpoint distance within the tooth is 8.0 mm, 7.5 mm, 7.5 mm, and 7.0 mm to replicate actual tooth conditions.

Alignment activities are performed, to ensure the bending jig which is positioned correctly at the UTM clamper base. A 30-mm NiTi archwire was cut on the straight section and installed on bracket slots as a dummy for alignment. Digital caliper and magnifying glass are used to observe the bending span and that the indenter is in position. The NiTi archwire (G&H Orthodontics) size used is 0.016-in. round. The bending test was performed five times at three deflections of 2, 3, and 4 mm at the beginning to demonstrate the superelasticity behavior of the NiTi wire. After similarities of five times' test results are observed, the tests were performed three times only for every deflection and the best of three results was used for further evaluation.

18.4 Result and Discussion

In the three-bracket configuration, Fig. 18.2 depicts the bending deformation behavior of the 0.016-in. NiTi orthodontic wire. The deformation is linear elastic up to 1-mm wire deflection, and the force plateau remains flat, demonstrating stress-induced martensitic transformation (SIMT) behavior. On the constructed Teflon brackets, the archwire deformation behavior generated a flat force plateau, whereas the stainless-steel back produced a gradient slope. Because Teflon brackets are frictionless, deformation can occur without binding friction, resulting in a flat force plateau, whereas the force gradient in stainless-steel brackets indicates the presence of binding friction between the wire and the bracket tip. The force gradient was positive throughout the activation phase but negative during the deactivation phase, with a small valley deformed during the early stages of strain recovery. The increased binding friction between the wire and the upper surfaces of the bracket's tip causes the formation of a valley on the deactivation curve of the wire on stainless steel. This slows down the wire's retraction to a significantly lower force magnitude. The geometry of the wire bending curvature limits the contact of the wire with the top side bracket's tip once the strain recovery reaches a particular strain value, so the deactivation curve returned to a linear gradient.

An interesting finding was found during the bending test performed in the presence of friction due to the archwire bend at the bracket edge. The friction is clearly shown in Fig. 18.2, namely the binding friction. The binding friction is measured by the force difference of the flat force plateau at the Teflon bracket and the force gradient at the orthodontic bracket. The binding friction measured at 4-mm deflection is 1.142 N on the activation curve and 0.974 N on the linear gradient behavior of the deactivation curve. Discussion on the frictions that occurred will be made later.

Figure 18.3 illustrates the bending deformation behavior of the 0.016-in. NiTi orthodontic archwire at 3-mm deflection under all bending conditions. The bending

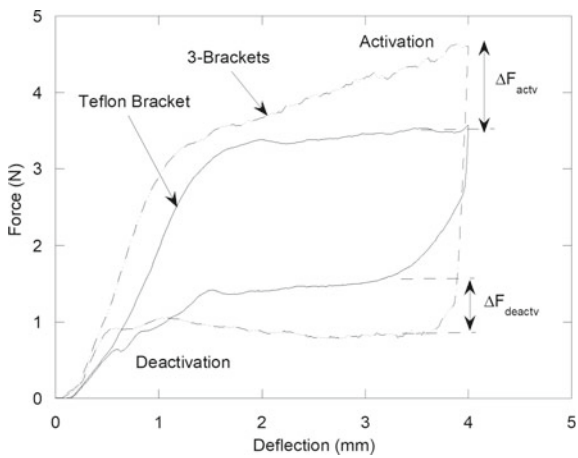
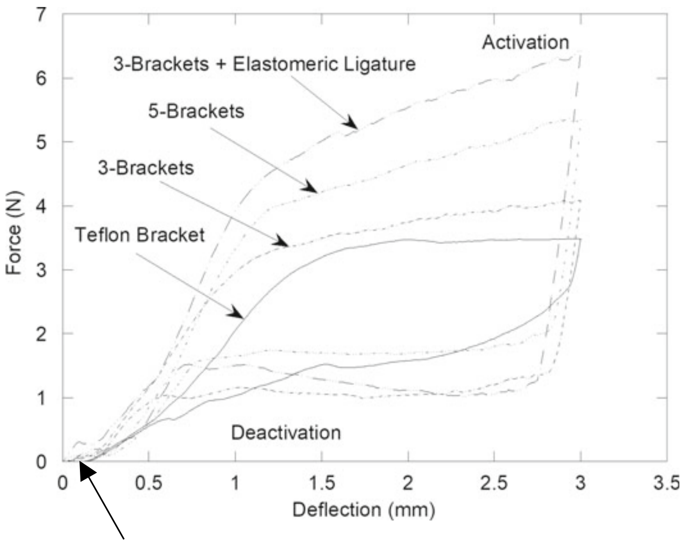


Fig. 18.2 Bending deformation behavior of 0.016-in. orthodontic NiTi archwire

deformation trend on all force–deflection curves is the same but has a different magnitude of forces. The usage of stainless-steel bracket always shows a force increase in gradient slope compared with the flat force plateau (frictionless) at Teflon bracket. Meanwhile, the ligated three-bracket bending produced the highest bending force, slightly higher than the five-bracket bending conditions, at both the activation and deactivation phases. Table 18.1 shows the binding frictions at bending conditions.

Frictions that occurred during the bending tests are identified into two types: sliding friction and binding friction as clearly shown in Fig. 18.3. The sliding friction occurred when the wire slides in the bracket slot during the bending test, while binding friction occurred when the wire is bent in the bracket slot during incremental deflections. From the force–deflection curve, the binding friction starts after around 0.2-mm deflection at most bending tests but started immediately on the ligated three-bracket bending. At the initial bending test condition, the wire slid at the bracket tip at the beginning and start making contact with the top lateral bracket tip. Once the contact was established, the wire starts to bend to a short load slope as shown



Binding frictions start here

Fig. 18.3 Bending deformation behavior of the 0.016-in. NiTi archwire at all bending conditions

Table 18.1 Binding friction measured at all bending conditions at 3 mm deflection

	Binding friction (N) at three different brackets' configuration		
Deformation phase	Three brackets	Three brackets + ligature	Five brackets
Activation	1.142	3.577	2.671
Deactivation	0.974	1.291	0.988

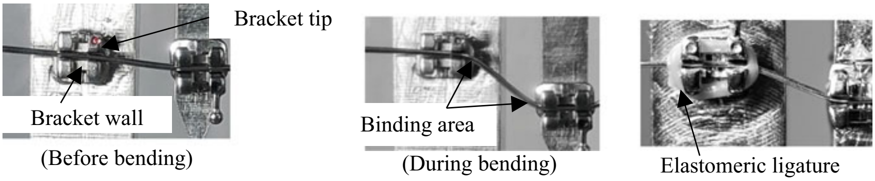


Fig. 18.4 Binding area and wire bent in the bracket

in Fig. 18.4. When the load is continuously applied and the wire deflection angle is more than the critical contact angle, the pure binding friction occurred.

A different condition happens when bending performed with elastomeric ligature is tight at the bracket tip as shown in Fig. 18.4. When applying the elastomeric ligature, the wire is pulled to the bracket wall and slid at the bracket wall and then bracket tip. Sliding on an extra bracket surface produced a slightly higher sliding friction compared to wires without ligation that is very small. The magnitude of binding friction is also the highest compared to the other bending conditions due to the effect that the ligation pulled the wire to the bracket wall. The elastic force from the elastomeric ligature causes both sliding and binding frictions to occur during the bending test.

The bending deformation behavior of the NiTi wire in the bracket application is influenced by binding frictions. Table 18.1 summarizes the binding frictions measured at 4-mm deflection of all bending conditions during the activation and deactivation phases. Ligation effects were increasing the binding friction significantly. Higher binding friction contributes to lengthening the treatment process when only lower forces are used to induce tooth movement. The recovery force generated from the NiTi wire's superelasticity behavior was primarily used to overcome binding friction, with the remainder of the force being used for tooth movement. Referring to Fig. 18.4, if without or minimum magnitude of binding friction, all recovery force from superelasticity behavior can be used to induce tooth movement. When the tooth received enough and a continuous amount of force induced, the tooth movement will be fast and treatment time will be shorter. The clinician needs to do some adjustments due to a lower force will require more clinic visits by patient.

The deactivation phase of the NiTi archwire is the treatment phase on orthodontic treatment because the wire superelasticity behavior was maximally used to the tooth, while during the activation phase, the wire is bent by the clinician when installing the wire into the bracket slot. Referring to Fig. 18.4 and Table 18.1, a higher force is used during the activation phase and produced a higher binding friction due to higher force when using a stainless bracket. However, if using the frictionless bracket, installation and recovery forces are flat plateau over deflections because the force is only used to overcome the internal resistance during phase transformation, not to overcome frictions. This constant load will reduce pain on the patient during the wire installation process and also during treatment.

Although ligation was significantly affecting the performance of the NiTi archwire in the orthodontic treatment and produced higher frictions, it is still being used due to economic cost. Braces cost with elastomeric ligature is the lowest among other braces options. Degradation of the elastomeric force over time in the oral condition is another factor that accepts elastomeric ligature application in orthodontic treatment. Higher frictions only occur at the early stages of treatment and will reduce over time.

Due to binding friction, the NiTi archwire performance is not fully utilized for tooth movement. Superelasticity behavior that produces good recovery force was used to overcome frictions rather than to induce tooth movement. A self-ligating bracket is the best solution to reduce frictions and allow the superelasticity behavior of the NiTi archwire to be fully utilized during the orthodontic treatment. Minimum binding friction at this bracket is due to the fact that the archwire are not a constraint and pulled to slide at the bracket wall. Mostly, the archwire will slide on the bracket tip during the treatment. However, the use of a self-ligating bracket is costly due to the bracket itself which is expensive and requires extra works by the clinician during wire installation.

18.5 Conclusions

In this work, the aim was successfully achieved to evaluate the bending deformation behavior of the NiTi archwire at various bending conditions, in the orthodontic treatment. The following conclusions can be highlighted at the end of this study:

a. Bending deformation behavior is influenced by frictions generated. Higher friction causes the archwire to deflect less, while lower friction causes the wire to deflect more, at the same magnitude of force applied.
b. Elastomeric ligature is major in affecting the bending deformation behavior. Higher frictions occurred during the application of this ligature, compared with the five-bracket bending and three-bracket bending.
c. Superelasticity behavior of NiTi wire is not fully utilized due to frictions that occurred in the orthodontic treatment, as illustrated at various bending conditions.

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