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Finite-element analysis of NiTi wire deflection during orthodontic levelling treatment

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Abstract. Finite-element analysis is an important product development tool in medical devices industry for design and failure analysis of devices. This tool helps device designers to quickly explore various design options, optimizing specific designs and providing a deeper insight how a device is actually performing. In this study, three-dimensional finite-element models of superelastic nickel-titanium arch wire engaged in a three brackets system were developed. The aim was to measure the effect of binding friction developed on wire-bracket interaction towards the remaining recovery force available for tooth movement. Uniaxial and three brackets bending test were modelled and validated against experimental works. The prediction made by the three brackets bending models shows good agreement with the experimental results.

1. Introduction
Nickel titanium (NiTi) shape memory arch wires are widely used in orthodontic treatment for teeth aligning and levelling. NiTi arch wires progressively replace stainless steel in most orthodontic applications owing to their ability to provide constant and effective force over huge deformation. This ability is attributed to NiTi unique deformation behaviours namely, superelasticity and shape memory effect, which exhibit complete recovery of huge deformation strain upon the release of force. The deformation strain occurs at constant stress plateau and may yield up to 10% strain \cite{1}. On the other hand, stainless steel can only yield a maximum 1% elastic strain, and the force required for this deformation increases as the strain magnitude increases. The huge deformation recovery exhibited by NiTi arch wires provides a substantial advantages for tooth movement, and the constant force produced upon strain recovery is found to be the most effective to encourage tooth movement for the prescribed level and alignment \cite{2}.

Tooth movements can be categorized into six types, referred to translational and rotational kind of movements and each movement has its own recommended force to be applied as provided in table 1. Tooth movement is driven by the recovery force generated by the spring back potential of a deflected arch wire. It is a general consensus that this generated recovery force is reduced due to existence of frictional resistance in a wire-bracket engagement \cite{3}.
Figure 1(a) illustrates the real case of levelling canine on upper maxillary arch. The type of frictional resistances involve after the first arch wire is placed into the brackets slot can be classified into classical friction and binding as shown in 1(b) [4]. Classic friction ($F_L$) is the frictional force generated by conventional ligation ties whereas binding ($F_B$) is the opposing force generated when the arch wire is in contact with the lateral edges of the bracket-slot. The tooth movement will start to proceed if the recovery force ($F_R$) is larger than the frictional resistances.

<table>
<thead>
<tr>
<th>Type of movement</th>
<th>Optimal force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tipping</td>
<td>0.35–0.60</td>
</tr>
<tr>
<td>Translation</td>
<td>0.70–1.20</td>
</tr>
<tr>
<td>Root movement</td>
<td>0.50–1.00</td>
</tr>
<tr>
<td>Rotation</td>
<td>0.35–0.60</td>
</tr>
<tr>
<td>Extrusion</td>
<td>0.35–0.60</td>
</tr>
<tr>
<td>Intrusion</td>
<td>0.10–0.20</td>
</tr>
</tbody>
</table>

Figure 1. Engagement of arch wire and brackets for orthodontic levelling treatment, (a) in-vivo (b) illustration to demonstrate the frictional resistance occurrence at the brackets.

Many researchers have proposed their own constitutive model of shape memory alloys either for superelasticity only [5] or for both shape memory and superelastic behaviour [6]. Seeing this opportunity, some have adopted these attainable constitutive models into commercially finite-element codes to understand and predict the complex response of shape memory alloy devices in advance of any prototyping. For example, this method has been successfully utilized to understand the performance of NiTi alloy as a stent for femoral artery [7], orthodontic wire [8], mechanical damper [9] and micro pump [10].

In this study, a constitutive model of shape memory alloys was implemented using the finite-element analysis software to simulate the bending phenomenon of NiTi wire in a brackets system. The aim was to study the influence of binding friction between arch wire and bracket towards the generated recovery force. The recovery force registered at the middle bracket of numerical and experiment works were recorded for comparison and validation.


2. Methodology

2.1. Shape memory alloy constitutive model

The constitutive model is based on the work of Auricchio, Taylor and Lubliner, with extensive extensions of Rebelo [5]. The model is available as a predefined user material in Abaqus 6.12 (Dassault Systèmes, Providence, RI, USA). This model was chosen for its good agreement with experimental data [7]. The user material data required to calibrate the arch wire model can be obtained from uniaxial behaviour in terms of loading, unloading, reverse loading and temperature effects. Table 2 summarized the user material data used for modelling the superelastic arch wires for both uniaxial and three brackets bending test.

**Table 2.** User material data for constitutive model of superelastic arch wire (T=26°C).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_A)</td>
<td>Austenite elasticity</td>
<td>44000 (MPa)</td>
</tr>
<tr>
<td>((\nu_A))</td>
<td>Austenite Poisson’s ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>(E_M)</td>
<td>Martensite elasticity</td>
<td>26000 (MPa)</td>
</tr>
<tr>
<td>((\nu_M))</td>
<td>Martensite Poisson’s ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>(\varepsilon_L)</td>
<td>Transformation strain</td>
<td>0.06 %</td>
</tr>
<tr>
<td>(\delta\sigma/\delta T)_L)</td>
<td>Loading</td>
<td>6.7 (MPa C(^{-1}))</td>
</tr>
<tr>
<td>(\sigma_{SL})</td>
<td>Start of transformation loading</td>
<td>377 (MPa)</td>
</tr>
<tr>
<td>(\sigma_{EL})</td>
<td>End of transformation loading</td>
<td>445 (MPa)</td>
</tr>
<tr>
<td>(T_0)</td>
<td>Reference temperature</td>
<td>26 (°C)</td>
</tr>
<tr>
<td>(\delta\sigma/\delta T)_U)</td>
<td>Unloading</td>
<td>6.7 (MPa C(^{-1}))</td>
</tr>
<tr>
<td>(\sigma_{SU})</td>
<td>Start of transformation unloading</td>
<td>145 (MPa)</td>
</tr>
<tr>
<td>(\sigma_{EL})</td>
<td>End of transformation loading</td>
<td>118 (MPa)</td>
</tr>
<tr>
<td>(\sigma_{SCL})</td>
<td>Start of transformation stress in compression</td>
<td>377 (MPa)</td>
</tr>
<tr>
<td>(\varepsilon_{LV})</td>
<td>Volumetric transformation strain</td>
<td>0.06 %</td>
</tr>
</tbody>
</table>

2.2. Experimental

2.2.1. Uniaxial test

The uniaxial test was conducted on a rectangular superelastic arch wire with a dimension of 0.4 mm x 0.55 mm manufactured by Masel Enterprises. The stress-strain curve was recorded using Instron 3367 universal testing machine at room temperature of 26°C. The gauge length of the wire was set to 20 mm, and the wire was pulled up to 1.5 mm elongation with a displacement rate of 1 mm/min. The stress–strain curve was recorded for comparison with the proposed numerical model of superelastic NiTi wires. The test was conducted by following the ISO 15841: Dentistry-Wires for use in orthodontics.

2.2.2. Three brackets bending test

Three brackets bending test was conducted on the same wire batch over a three brackets apparatus. As shown in figure 2, the apparatus was set up by aligning three brackets corresponding to the lateral incisor, canine, and first premolar, which portray a levelling treatment on upper-right maxillary arch. The bracket used was a conventional type with 0.5 mm slot height and 0.7 mm slot width (MTX Bracket-Roth RX). This bracket was chosen due to the zero torque and angulations on its design. No elastomeric module was installed in order to eliminate the influence of conventional friction towards the recovery force.
The central bracket which represents the canine bracket was mounted on the crosshead of the universal testing machine. The adjacent brackets which represent the lateral incisor and the first premolar were mounted on the fixed support of the three brackets apparatus. The distance between the midpoint of every mounted bracket was set to be 7.5 mm. Tests were performed by loading and unloading the wire up to 4 mm at a displacement rate of 1 mm/min, and the environment temperature was 26°C. Since no elastomeric ligatures were used for bracket engagement, a 0.1 mm pre-deflection was applied to the wire to ensure good positioning within the bracket's slot.

Figure 2. Three points bending test resembling three brackets.

2.3. Finite-element simulation

2.3.1. Uniaxial test
Numerical uniaxial test was modelled over the same testing parameters as described in section 2.2.1. A total of 1872 linear hexahedral elements (C3D8) were created for modelling the superelastic wires with the element size of 0.10 mm. The model was elongated to 1.5 mm by applying a displacement control of 1 mm/min at one end of the wire. The uniaxial load was measured from the reaction force generated on the other fixed end of the wire model.

2.3.2. Bending test
The bending simulation of the wire was performed using quadratic hexahedral elements with reduced integration (C3D20R). This element was chosen because it reduces the effect of shear locking phenomenon during bending, thus better prediction of wire stiffness can be done [11]. A convergence analysis was performed for choosing the appropriate elements size by considering the value of load–displacement response as the convergence criteria. The model was considered to be converged when the maximum difference as compared to experimental result was smaller than 0.3 N. A total of 4180 quadratic hexahedral elements were created for modelling the superelastic wires with the element size of 0.10 mm.

The brackets were defined as a rigid non-deformable body. A 1 mm/min vertical displacement control was applied on the reference point of the central bracket, while the adjacent brackets were set to be fixed. Contacts with a coefficient of friction of 0.28 were defined between arch wire and bracket's surfaces to permit the interaction between the parts. No boundary conditions were applied to the arch wire in order to allow the wire to slide freely through the bracket's slot. The displacement and bending load measured on the set reference point of the central bracket was recorded for comparison with the experimental data.
3. Results and discussion

3.1. Material properties validation

Figure 3 shows the stress-strain curve of uniaxial test obtained from the experimental and numerical works. The experimental result shows that the arch wire was deformed elastically up to 1.4% of strain, followed by a constant stress plateau on both loading and unloading cycles and yielded a ~6% of transformation strain. The wire shows a good superelastic behaviour indicated by the small residual strain of 0.2% recorded at the end of the test. The deformation behaviour generated from the numerical method shows a similar behaviour with the experiment. They exhibited good agreement in loading and unloading plateau, transformation strain, elastic strain and residual strain. Thus, the material data proposed in table 1 can be considered valid and reliable to be used in defining the material properties of the superelastic arch wire used in this study.

![Stress-strain curve of uniaxial test of superelastic arch wire.](image)

Figure 3. Stress-strain curve of uniaxial test of superelastic arch wire.

3.2. Finite-element analysis

Figure 4 illustrates the deformation of arch wire in the three brackets system at the beginning of shape recovery. The colour contour distinguished the vertical displacement of the wire and brackets. The highest vertical displacement was recorded at the middle element of the wire (blue colour), where the reference point of the central bracket was set to move by 4.0 mm in downward direction. Surface contacts were introduced at the top and bottom edges of the fixed brackets as the arch wire accommodated the deflection. At these contact areas, binding frictions were developed and resisted the sliding of arch wire throughout the loading and unloading cycle.
3.3. Finite-element result

Figure 5 shows the load-deflection curve of the superelastic wire bent to 4.0 mm in the three brackets system. The wire shows a good superelastic behaviour with a complete displacement recovery at the end of the test. It can be seen that the load deflection curve derived from numerical method is in good agreement with the experimental result. This identical load-deflection curve indicated that the numerical model managed to predict the influence of binding friction on the bending behaviour of NiTi arch wire in the bracket system.

The load registered during unloading cycle is the main interest of this study as it determines the recovery force available to draw the unlevelled canine. Referring to figure 5, the lowest unloading load was registered at 3.3 mm deflection with a value of 1.3 N. In order to be levelled with the adjacent teeth, the canine needs to be extruded from the periodontal ligament. Based on table 1, this 1.3 N is far above the recommended force level for extrusive tooth movement. However, note that the classical friction is absent in this study due to no elastomeric ligature was installed. Lower unloading load are expected to be registered once classical friction and real oral temperature are put into consideration.

In addition, it is interesting to note that the load plateaus recorded during loading and unloading are no longer at constant levels, as compared to figure 3. The load required to elongate the wire beyond the elastic region increased linearly on loading, but at a much lower slope than its elastic modulus. On the other hand, on unloading the load plateau of reverse transformation yielded a moderate increase of load level before full recovery was achieved. This suggests that the magnitude of binding friction was developed proportionally with arch wire deflection. At high deflection, higher loads are needed to bend the arch wire, while lesser loads are transmitted to the bracket once the wire recovers. This gradient pattern of the load-displacement curve has also been reported in other literatures [3,12,13], claimed to be cause of the delay in loading and unloading cycle, thus implied existence of binding friction.
4. Conclusion
The implementation of superelastic constitutive model with finite element enabled the prediction of bending behaviour of NiTi arch wire in the three bracket system. Upon bending, binding frictions were introduced at the lateral edges of the brackets. Binding frictions influences the load-deflection curves by increasing the load plateau during loading and unloading cycle.

Acknowledgement
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[11] Sun EQ 2006 Shear locking and hourglassing in Msc Nastran, Abaqus, and Ansys in Msc software users meeting (Chicago, Illinois)