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Finite element sub-modeling analyses of damage to enamel at the incisor enamel/adhesive interface upon de-bonding for different orthodontic bracket bases

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ABSTRACT

This study investigates the micro-mechanical behavior associated with enamel damage at an enamel/adhesive interface for different bracket bases subjected to various detachment forces using 3-D finite element (FE) sub-modeling analysis. Two FE macro-models using triangular and square bracket bases subjected to shear, tensile and torsional de-bonding forces were established using μCT images. Six enamel/adhesive interface sub-models with micro- resin tag morphology and enamel rod arrangement were constructed at the corresponding stress concentrations in macro-model results. The boundary conditions for the sub-models were determined from the macro-model results and applied in sub-modeling analysis. The enamel and resin cement stress concentrations for triangular and square bases were observed at the adhesive bottom towards the occlusal surface under shear force and at the mesial and distal side planes under tensile force. The corresponding areas under torsional force were at the three corners of the adhesive for the triangular base and at the adhesive bottom toward/off the occlusal surface for the square base. In the sub-model analysis, the concentration regions were at the resin tag base and in the region around the etched holes in the enamel. These were perfectly consistent with morphological observations in a parallel *in vitro* bracket detachment experiment. The critical de-bonding forces damaging the enamel for the square base were lower than those of the triangular base for all detached forces. This study establishes that FE sub-modeling can be used to simulate the stress pattern at the micro-scale enamel/adhesive interface, suggesting that a square base bracket might be better than a triangular bracket. A de-bonding shear force can detach a bracket more easily than any other force with a lower risk of enamel loss.

1. Introduction

The bonding strength between a bracket and a tooth must withstand mastication forces, the stresses exerted by arch wires and abuse by the patient. It must also accommodate tooth movement control during orthodontic treatment. The bond strength should allow for bracket de-bonding without causing damage to the enamel surface (Pickett et al., 2001; Brosh et al., 2005; Chen et al., 2008).

Adhesive resins are extensively used to bond orthodontic brackets to enamel. A common recommendation is that phosphoric acid should be utilized to etch the enamel to bond the resin and bracket more tightly. However, most de-bonding interfaces are still found at the enamel/adhesive interface when the bracket is removed. Enamel may be damaged at the moment of de-bonding and can cause staining and plaque accumulation on the rough fractured surface (Meng et al., 1998; Sorel et al., 2000, 2002; Chen et al., 2008). The enamel thickness lost during bracket removal has been estimated to be approximately 150 μm (Shinya et al., 2008).

The enamel/adhesive bonding mechanism has been demonstrated by exploiting a micron level interfacial interaction, such as micro-mechanical interlocking or the use of resin tags that penetrate the etched enamel prism (Buonocore et al., 1968; Faust et al., 1978; Knoll et al., 1986; Hipólito et al., 2005; Shinya et al., 2008). However, the stress transfer mechanism from the resin tags to the enamel substrate under a load that typically dominates the interfacial bond strength remains unclear. Currently *in vitro* failure testing and numerical simulations are limited to accurately

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determine the mechanical response at the enamel/adhesive interface, which exhibits micro-scale morphology.

Bracket detachment is usually caused through shear peeling, tensile forces or torque (Wang et al., 1997; Kapur et al., 1999; Rix et al., 2001) by clinicians. Many studies have focused on the stress distribution at an enamel/adhesive/bracket interface in various detached loading modes, but no comprehensive survey of the enamel damage associated with the micro-interlocking mechanism between resin tags has been carried out (Rossouw and Terblanche, 1995; Knox et al., 2000; Valletta et al., 2007; Chen et al., 2008). A reduction in the size of the brackets and their bases has also been proposed to produce a smaller retentive area, which

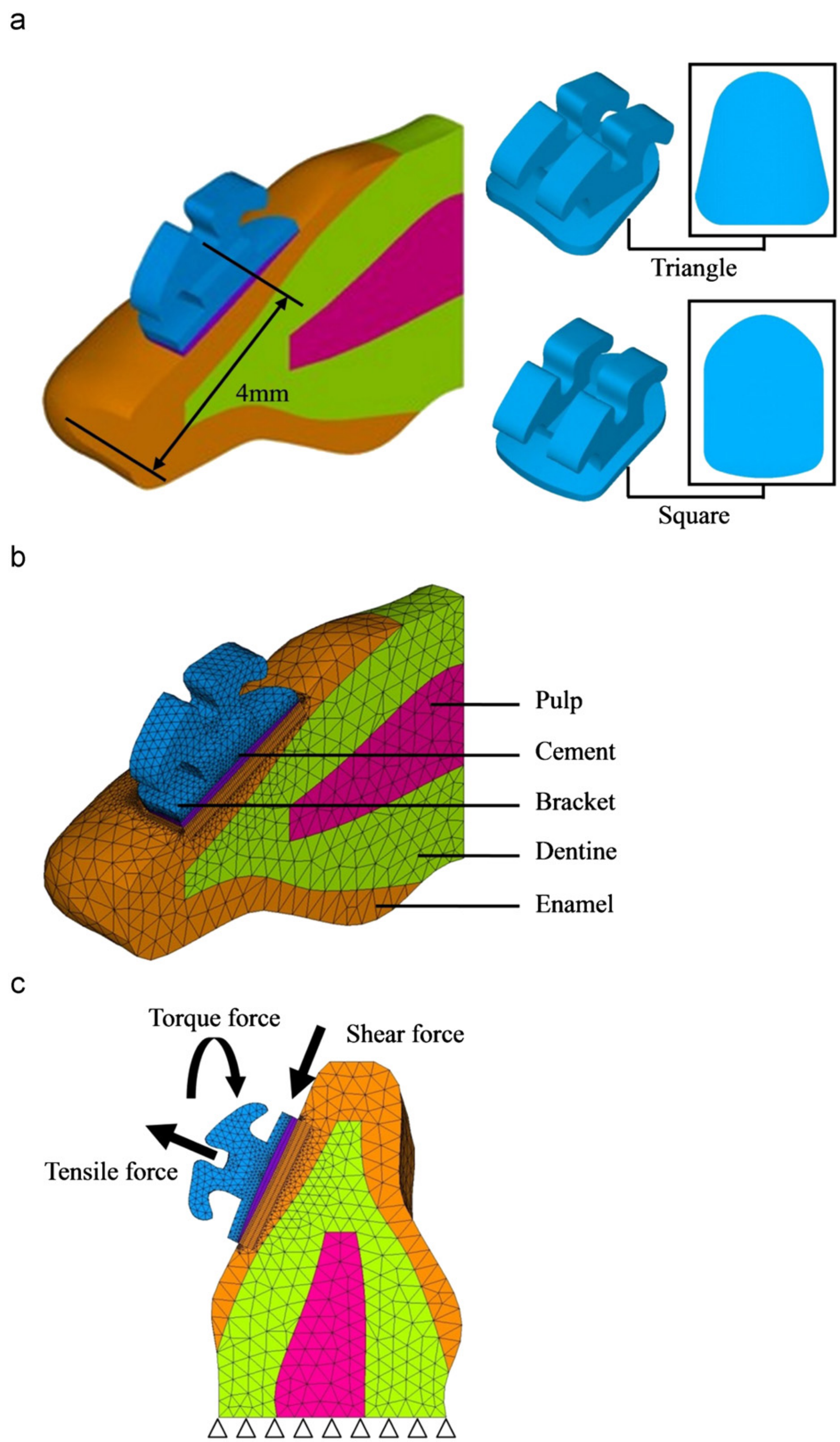

Fig. 1. (a) Section-view of solid models of the incisor tooth, adhesive and orthodontic bracket, and their relative positions. The right part shows the triangular (upper) and square (lower) bracket bases investigated in this study; (b) corresponding FE mesh for the tooth/adhesive/bracket macro-model; (c) boundary and load (shear, tensile and torsional de-bonding forces) conditions applied in the macro-model.