Original Article

An Evaluation of the Quality of Orthodontic Attachment Offered by Single- and Double-Mesh Bracket Bases Using the Finite Element Method of Stress Analysis

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Abstract: The objective of this study was to evaluate the influence of bracket base mesh geometry on the stresses generated in the bracket-cement-tooth continuum by a shear/peel load case. A validated three-dimensional finite element model of the bracket-cement-tooth system was constructed consisting of 15,324 nodes and 2971 finite elements. Cement geometric and physical properties were held constant and bracket base geometry was varied, representing a variety of single-mesh configurations and 1 double-mesh design. For the single-mesh designs, increasing wire diameter (100–400 μm) resulted in a decrease in enamel and cement stresses. Increases in wire mesh spacing (200–750 μm) increased the major principal stress recorded in the enamel and adhesive at all wire diameters. Within the bracket, the major principal stress increased significantly at wire spacing above 400–500 μm. However, within the impregnated wire mesh (IWM), the major principal stress decreased as wire space increased. When the double-mesh bracket base was considered, the combined mesh layers resulted in a decrease in the stresses recorded in the most superficial (coarse) mesh layer and an increase in the stresses recorded in the deepest (fine mesh) layer when compared with the single-layer designs in isolation. Modification of single-mesh spacing and wire diameter influences the magnitude and distribution of stresses within the bracket-cement-tooth continuum. The use of a double-mesh design results in a reduction in the stresses recorded in the most superficial mesh. Mesh design influenced stress distribution in this study, primarily by determining the flexibility of the bracket base. (*Angle Orthod* 2001;71:149–155.)

Key Words: Finite element method; Stress analysis; Bracket base

INTRODUCTION

The evaluation of new and current bonding techniques has, to date, relied heavily on bond strength tests that are relatively imprecise and that measure only the weakest component in the system.[1,2] However, as the quality of orthodontic attachment is primarily determined by the magnitude and distribution of the stresses generated within the bracket-cement-tooth continuum, an analysis of the structural behavior of this system under load would provide an insight into the determinants of effective attachment.

The finite element method of stress analysis (FEM) is a computer-aided mathematical technique for obtaining approximate numerical solutions to the abstract equations of calculus that predict the response of physical systems subjected to external influences.[3] FEM allows stress distributions and levels to be evaluated in systems with irregular geometry and nonhomogeneous physical properties. The technique has been applied, with some success, in orthodontic research.

Yettram et al[4] were among the first to employ a two-dimensional finite element model of a maxillary central incisor to determine the instantaneous center of rotation of this tooth during translation. Further studies involving two- and three-dimensional models and nonlinear periodontal

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ligament (PDL) properties have aided understanding of the interaction between moment-to-force ratios and PDL stress distribution during mechanotherapy.[5–16]

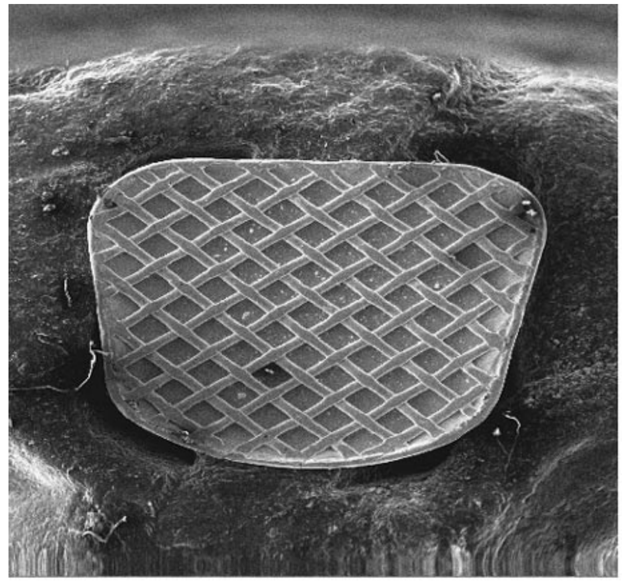
Similarly, finite element models have been employed to evaluate the stress distribution induced within the craniofacial complex during the application of orthopedic forces.[17–22] However, the finite element method has only recently been applied to the evaluation of orthodontic attachment. Katona[23,24] and Katona and Moore[25] have used a two-dimensional finite element model of the bracket-tooth interface to assess the stress distribution in the system when bracket-removing forces are applied. Similarly, Rossouw and Tereblanche[26] have used a simplified three-dimensional finite element model to evaluate the stress distribution around orthodontic attachments during debonding. Katona[27] compared different methods of bracket removal and suggested that different loading methods resulted in significantly different stress patterns. In addition, peak stress concentrations were suggested to be responsible for attachment failure, indicating that mean stress values were of little value in quantifying the quality of attachment.

The purpose of this study was to determine the effect of altering the geometry of the bracket base mesh on the quality of orthodontic attachment employing a three-dimensional finite element computer model.

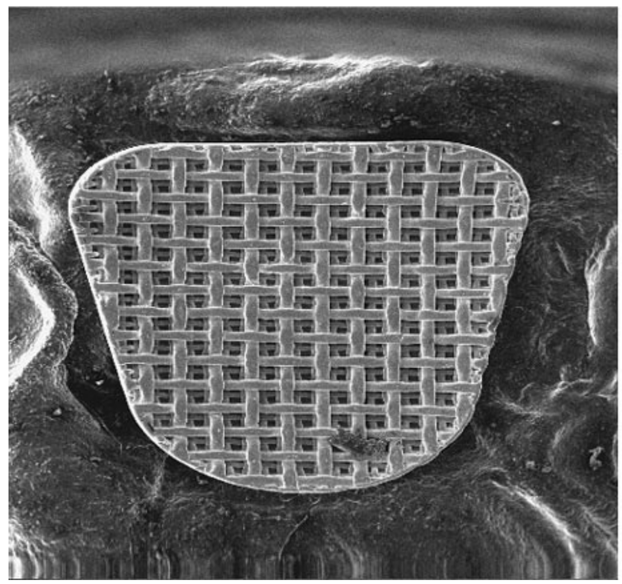
MATERIALS AND METHODS

A clinically valid computer model of the bracket-tooth interface requires the quantification of the physical and geometric properties of each component of the system. The geometric properties of a maxillary first premolar tooth were determined by preparing serial 0.5-mm longitudinal sections of a representative tooth in a Microslice (Malvern Instruments, Malvern, UK). Using digital measurements of the sections, the three-dimensional coordinates of the tooth were recorded and a finite element mesh generated using a commercial mesh-generating program (PATRAN, PDA Engineering, Los Angeles, Calif.). To keep the size of the overall model reasonably small, only the area of enamel local to the orthodontic attachment was modeled. The remainder of the tooth was represented by the appropriate boundary conditions with fixed nodes on the gingival margin and rollers on the cross section, representing the areas of the tooth omitted from the model.

A maxillary first premolar bracket was modeled (Master Series, American Orthodontics Ltd, Sheboygan, Wis). The bracket slot, tie wings, stem, and thin foil base were considered separately from the bracket base mesh as cement impregnation of the base mesh produced a complex, nonhomogeneous area with physical properties that lay somewhere between those of the stainless steel bracket and the cement lute. The cement had an average thickness of approximately 271 μm. The material was considered separately from the impregnated wire mesh (IWM) and was considered to be homogeneous and isotropic.



a.



b.

FIGURE 1. (a) Single mesh base. (b) Double mesh base.

Although none of the materials considered in this model can be considered to be truly (microscopically) homogeneous, all but the impregnated wire mesh base and etched enamel surface are homogeneous at the macroscopic level. The IWM layer consists of a thin (94-μm diameter) stainless steel wire mesh (Figure 1) embedded in orthodontic cement. To determine the physical properties of this macroscopically nonhomogeneous layer, a theory of composite materials was employed to homogenize the layer and represent it as a mechanically equivalent but homogeneous material (Hübsch et al[28,29]).

The homogenization theory is a well-established tool for the analysis of composite materials (Hollister et al[30]). The

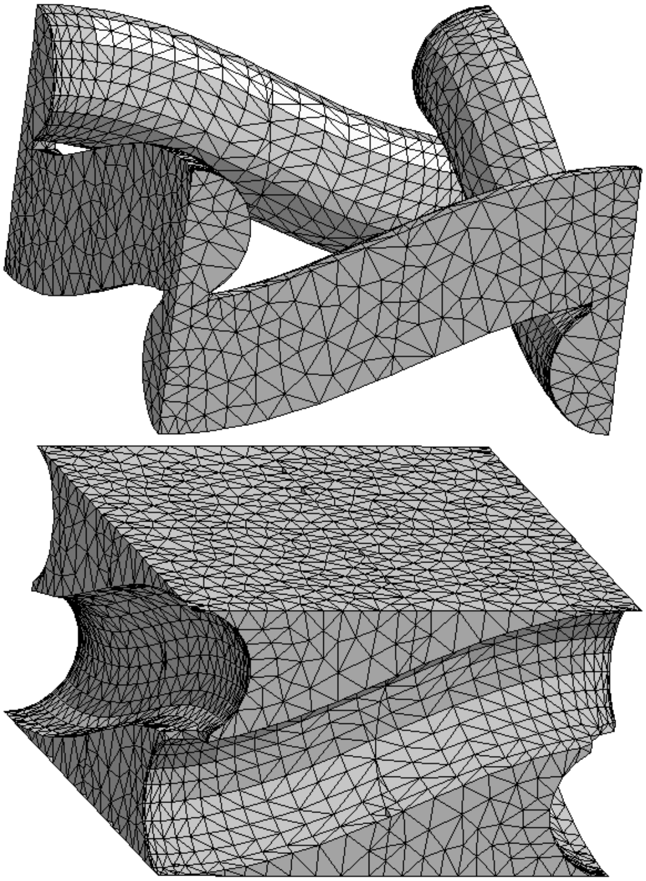


FIGURE 2. Finite element mesh of; (A) Mesh base; (B) Cement unit cells.

TABLE 1. Material Properties Employed[31,32]

Material	Young's Modulus (MPa)	Poisson's Ratio
Enamel	46,890	0.30
Cement	11,721	0.21
Stainless steel	210,000	0.30

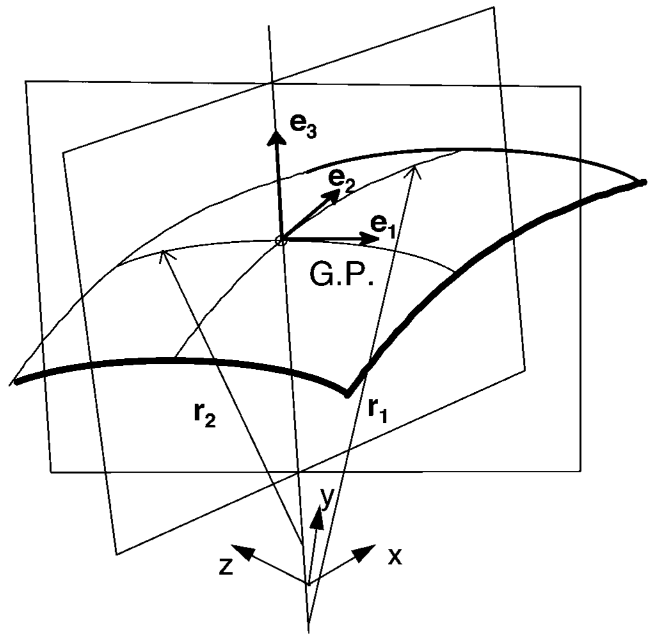


FIGURE 3. Global (x,y,z) and local (e_1, e_2, e_3) co-ordinate systems (r_1-radius in one plane; r_2-radius in the second plane).

application of this theory relies on the microstructure of the material analyzed being locally periodic or self-repeating. A small but representative area (unit cell) of the heterogeneous solid is isolated and the behavior of the unit cell studied under loading conditions equal to those encountered when embedded in the periodic structure. An extrapolation of the results of this process was made to represent the global material.

Microscopic examination determined the smallest repeatable units of the IWM and finite element models (Hübsch et al[28,29]) were constructed for the bracket base mesh and orthodontic cement unit cells (Figure 2). The bracket base wires were considered to be prismatic bars of circular cross-section running in perpendicular sinusoidal courses. Where the wires crossed and were welded, rigid links of half the wire diameter were modeled. Both the wire and the orthodontic adhesive were considered to be linear elastic, homogeneous, and isotropic materials.

When the double-mesh bracket base was considered (Figure 1), homogenization became more difficult as unit cells became difficult to identify. In addition, the ratio of wire spacing between the 2 layers was not always an integer, leading to potentially large meshes. In the current study, each layer was homogenized separately before introducing them into the overall FE model as 2 different (homogeneous) materials.

The material parameters used[31,32] in the computations are shown in Table 1. It was assumed that there were no air voids within the body of the cement, that cement penetration of the bracket base undercut was complete, and that there was a perfect bond between the 2 materials. The IWM layer was assumed to have isotropic mechanical properties in the plane of the mesh base and different mechanical properties in the plane perpendicular to the mesh base. This demanded the introduction of elements with orthotropic properties in these regions, ie, material properties that differ in each of the 3 dimensions. In addition, the IWM is a double curved structure, resulting in changes in the material property principal axes relative to the global coordinates (Figure 3). Appropriate material properties were calculated by applying a transformation of the material principal axes into the global coordinate direction at each Gauss point of the FE model of the IWM (Kralj et al[33]).

The complete three-dimensional finite element model of the bracket-cement-tooth system (Figure 4) consisted of 15,324 nodes and 2971 finite elements. To keep the size of this complex model within reasonable limits, only the relevant areas of the tooth were modeled, the remainder being substituted by the appropriate boundary conditions.

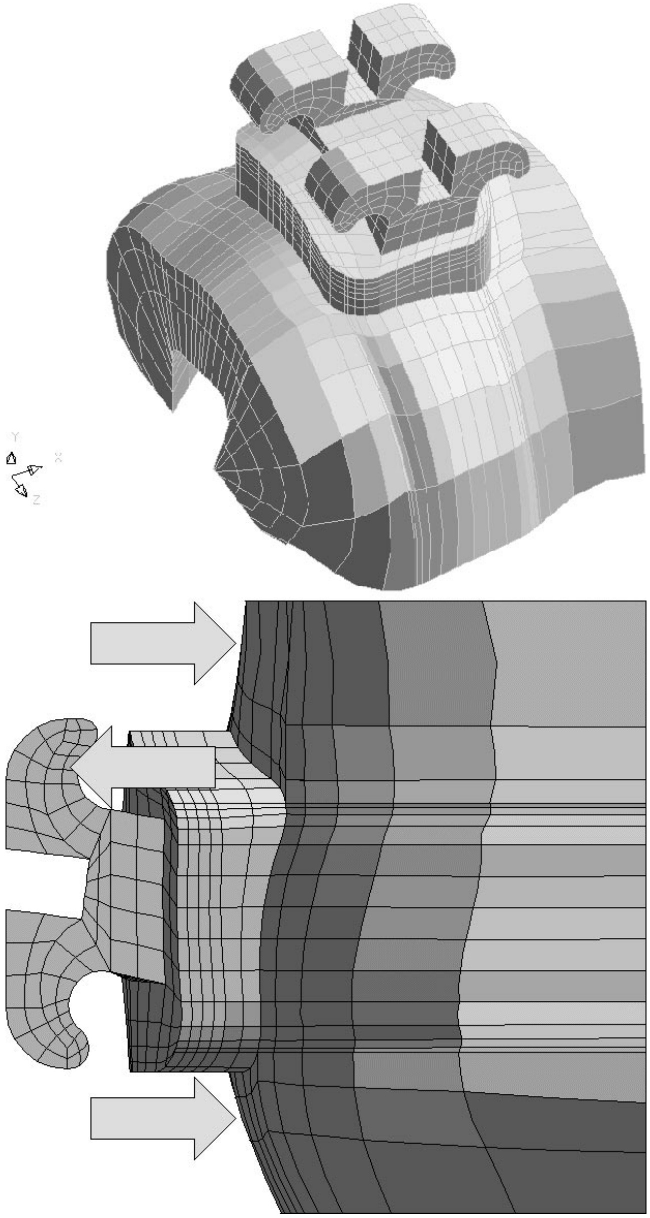


FIGURE 4. (A) Three dimensional finite element model of the bracket-cement-tooth interface; (B) Tensile/peel load case.

A single-load case, representing a tensile/peel force (Figure 4), was considered.

RESULTS

The maximal principal stress distribution due to a tensile force applied to the mesio-gingival wing of a maxillary premolar bracket is presented in Figure 5.

The influences of altered mesh base design on the stresses induced in the bracket-cement-tooth system by a tensile/peel force are presented in Figures 6 through 9. The comparison of single- and double-mesh bases is presented in Figure 10. Major principal stresses were recorded since these give an indication of the location of failure when the ultimate strength of the material is exceeded. Minor principal stresses were also recorded. However, in all cases, these were compressive and noncontributory to the performance of the bracket-cement-tooth system.

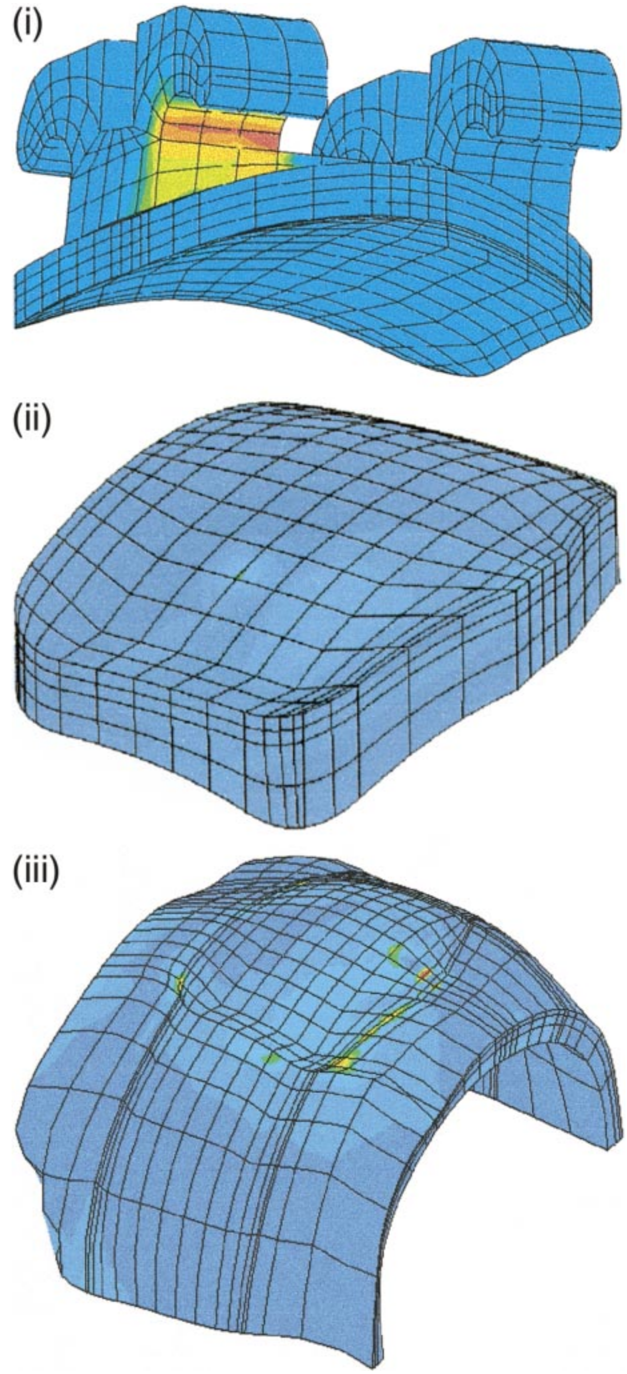


FIGURE 5. Maximal principle stress distribution due to "lift off device" applied to mesio-gingival wing; (i) bracket; (ii) IWR-cement sandwich; (iii) enamel.

DISCUSSION

Bonded orthodontic brackets are subjected to a range of forces during function and removal. A single tensile/peel-

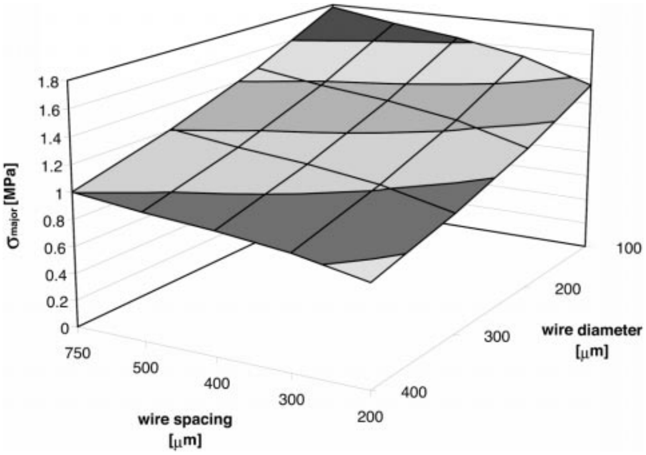


FIGURE 6. Variation of major principal stresses in enamel.

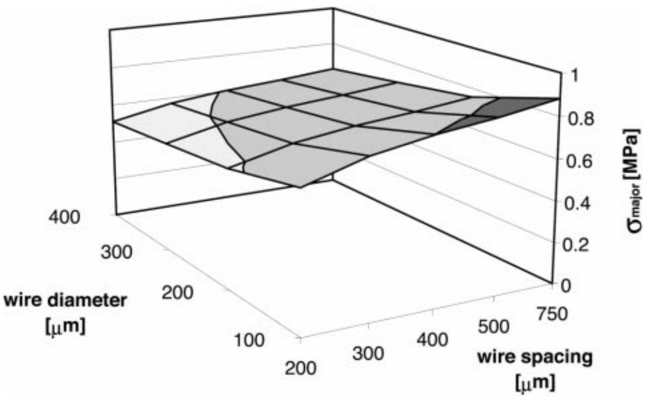


FIGURE 7. Variation of major principle stresses in cement.

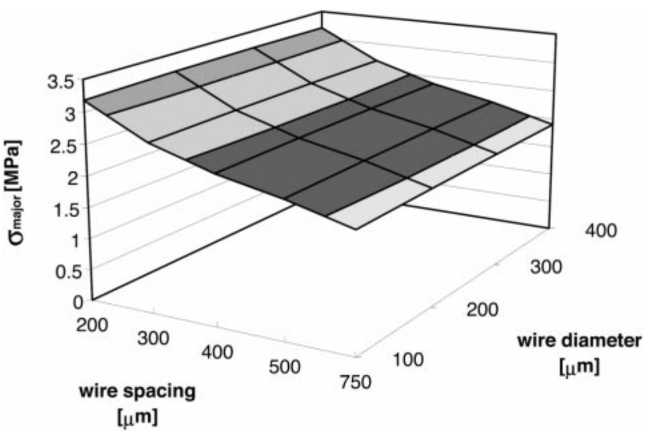


FIGURE 8. Variation of major principle stresses in IWM.

load case was selected in this study to represent the type of force applied during elective bracket removal.[34]

For a single-mesh base, wire diameter changes between 100–400 μm appeared to have little influence on the major principal stresses within the IWM and bracket body. However, increasing wire diameter resulted in a decrease in enamel and cement stresses. An increase in wire diameter

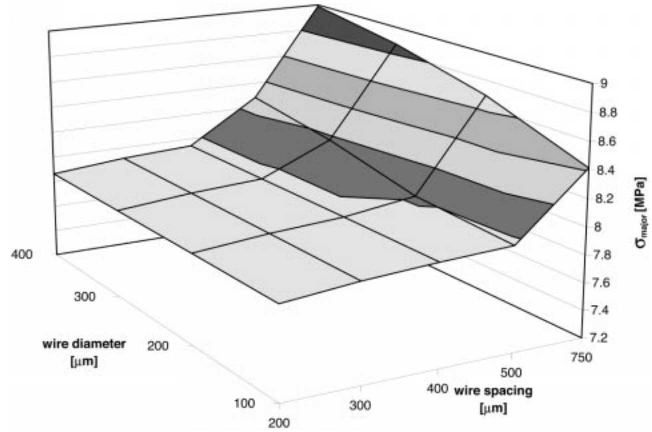


FIGURE 9. Variation of major principle stresses in the bracket.

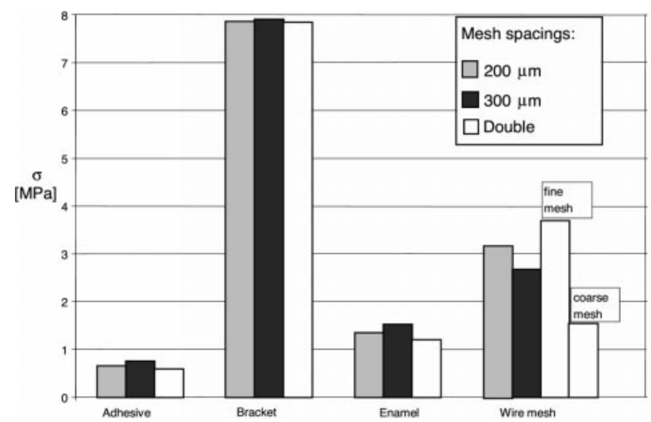


FIGURE 10. The variation of major principle stresses with mesh design.

increases the rigidity of the bracket base, resulting in the applied load being distributed more evenly over the total bonded area of the bracket base. Given a constant load, this would result in the peak stress decreasing in the adhesive and enamel.

Increases in wire mesh spacing (200–750 μm) of single-mesh bases increased the major principal stress recorded in the enamel and adhesive at all wire diameters. Within the bracket, the major principal stress increased significantly at wire spacing above 400–500 μm. However, within the IWM, the major principal stress decreased as wire space increased. Increasing the mesh spacing results in a reduction of the bending stiffness of the bracket base. This results in increased enamel and adhesive stresses and increased bracket stresses (when $>$400 μm) because the applied load was not efficiently transferred to the periphery of the bracket base, reducing the area of adhesive and enamel available for load transfer.

The total strain occurring in the bracket base is governed by the total stiffness of the whole system (bracket body, bracket base, mesh, adhesive, and tooth). Therefore, reducing the stiffness of the IWM has only a small influence on the total stiffness of the system and therefore on the strain. If a reduced IWM bending stiffness opposes a relatively constant strain, the stress in the IWM will tend to decrease.

When the double-mesh bracket base is considered, the combined mesh layers resulted in insignificant changes in stress levels in the bracket, adhesive lute, and enamel. The most obvious influence of the double layer was seen in the stresses recorded in the impregnated wire mesh layers. The most superficial (coarse) mesh layer experienced decreased stresses whereas the stresses recorded in the deepest (fine mesh) layer were increased when compared with the single-layer designs in isolation. The finer mesh is stiffer than the coarse mesh because it incorporates a higher volume fraction of wire. When a soft material is placed alongside a stiffer material, the stiff layer will attract most of the bending stress. This is explained by the strain occurring parallel to the bracket base being equal in both the soft (coarse) mesh and the stiff (fine) mesh along their interface (if this was not the case, there would be relative displacement and gap formation between the meshes). As a consequence, the equal strain causes higher stresses in the stiffer material and the stiff material effectively shields the stress from the soft material.

In the double-mesh design, the relatively coarse outer mesh is shielded from the applied load by the increased stiffness of the deeper mesh layer. In addition, there is more of a gradient in stiffness from the bracket base to the fine mesh and ultimately the coarse mesh resulting in a less abrupt change in physical properties, and this reduces stress concentration at the adhesive interface.

CONCLUSIONS

The quality of orthodontic attachment is primarily determined by the stress distribution generated in response to applied load in the cement and impregnated wire mesh areas of the bracket-cement-tooth system. Alterations in wire diameter and spacing in the single-mesh bases have been shown to effect stress distributions within the bracket-cement-tooth system. These changes are largely a product of altered flexibility of the bracket base. The combination of 2 mesh layers has been demonstrated to reduce stresses in the most superficial mesh layer.

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