Evaluation of the stresses generated by altering the bracket mesh base design in the bracket-cement-tooth continuum using the finite element method of stress analysis

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Aim: To analyze the influence of bracket base mesh geometry on the stresses generated in the tooth-cement-bracket continuum by a shear/peel load case and to compare the stress generated by three different loads (masticatory, peel, and twisting) on the bracket mesh base by employing a three-dimensional (3D) finite element computer model. Methods: A validated 3D finite element model of the bracket-cement-tooth system was constructed consisting of 40,536 nodes and 49,201 finite elements. Results: An increase in the diameter of the bracket mesh base wire resulted in a decrease in the stress at the enamel and cement. Increase in wire spacing (200 to 500 mm) increased the stresses in the enamel and cement at all wire diameters, but within the impregnated wire mesh, the major stress decreased with the increase in the wire spacing. Peel load produced comparatively less stress on enamel than masticatory and twisting force. Conclusion: Alteration in mesh spacing and wire diameter influences the magnitude and distribution of stresses within the bracket-cement-tooth continuum. Peel load and twisting load are best to debond the bracket since they produced minimal stress on the enamel, which is suggestive of lower chances of enamel damage. ORTHODONTICS (CHIC) 2012;13:e66–e75.

Key words: bracket mesh base, finite element method, peel load, stress

Orthodontic treatment relies mainly on brackets attached to the teeth, which are the loci of transferring the desired force, and the efficacy of which depends on the bond strength of the bracket. Various factors determine the bond strength of the bracket system and mechanical retentive design of the bracket is among them.¹,² Since most bracket bases do not chemically bond to enamel or resin, efforts have been made to improve mechanical retention with various designs. The increasing demand for more esthetic metal bonded appliances has led to, among other things, a reduction in the size of the brackets and their bases. The smaller retentive area of the bracket base becomes a variable that influences bond strength.³
The magnitude and distribution of the stresses generated within the
bracket-cement-tooth continuum primarily determines the quality of ortho-
dontic attachment. An analysis of the structural behavior of this system under
load would provide insight into the determinants of effective attachment.

Much of the previous research on enhancing the mechanical retention of the
bracket has failed to provide a consensus. Knox et al.3 and Smith and Reynolds6
reported that altering the mesh geometry affects the bond strength of the
bracket. However, Cucu et al.7 have reported contrasting findings.

Nevertheless, there were flaws in the methodology used for studying the
correlation between bond strength and the bracket mesh base design. Ac-
cording to Fox et al.4 the analysis of orthodontic attachment is more or less
associated with ex vivo experiments, which measure only the weakest compo-
nent in the bracket-cement-tooth system. Knox et al.3 noted the quality of orth-
dontic attachment is primarily determined by the magnitude and distribution
of the stresses generated within the bracket-cement-tooth continuum.

Early finite element method (FEM) studies in orthodontics were done to
evaluate the stress distribution induced within the craniofacial complex during
the application of orthopedic forces.8,9 However, the FEM has only recently
been applied to the evaluation of orthodontic attachment, and the earlier stud-
ies used a two-dimensional finite element model of the bracket-tooth interface
to assess the stress distribution in the system when bracket removal forces are
applied.10–12

The force system is currently the major factor that the orthodontist can con-
trol to achieve desirable orthodontic tooth movement. It is clinically useful to
relate tooth movement with orthodontic force systems generated from various
appliances at the bracket on the crown of a tooth.5 Thus, the bracket becomes
the major component through which the forces are transmitted and with this it
becomes important for the bracket attachment to the tooth to be strong. For
the bracket attachment to be strong, the bracket base should be more reten-
tive. There were so many modifications/variations in bracket base mesh. The
in vitro studies on these variables are difficult at best; thus, the development
of an effective model for this system is a worthy goal.

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 using a peel
load case and to compare the stress generated by three different loads (masticatory,
peel, and twisting) by employing a 3D finite element computer model.

METHODS

A computed tomography (CT) scanner (GE) was used to obtain the 0.5-mm
longitudinal section of the maxillary first premolar. These sections were then
transferred to AutoCAD software (Autodesk), which was used to draw the geo-
metric models and determined the geometric properties of the representative
tooth. The model generated was transferred to a finite element package as an
IGES (Initial Graphics Exchange Specification) format. IGES is one of the most
common formats built into all the modeling and finite element packages. This
format is widely used in the engineering community.

Using digital measurements of these sections, the 3D coordinates of the
tooth were recorded, and a finite element mesh was generated using a com-
mmercial mesh-generating programmer (ANSYS 7.0). To keep the size of the
overall model reasonably small, only the area of enamel near the orthodontic
attachment was modeled (Fig 1). The remainder of the tooth was represented
by the appropriate boundary conditions with fixed nodes.
Using an electronic slide vernier caliper, the measurements of the maxillary first premolar bracket were made, and the model of the bracket was generated (Fig 2). The data from the previous literature was used for generation of the cement layer and impregnated wire mesh (IWM) (Fig 3). A thickness of approximately 271 μm was kept for the cement layer, and IWM was considered as cement embedded in the wire base mesh. Per the recommendation of the previous study on the bracket mesh base, the cement layer and bracket mesh wire were kept linear, elastic, homogenous, and isotropic. The theory of composite material was applied to generate the properties of the IWM layer.

The material parameters used in the computations are similar to those used in previous studies, which comprised the Young modulus and Poisson ratio. For enamel, it was defined as 46,890 and 0.30, respectively; for brackets, it was 210,000 and 0.3, respectively; and for cement, it was defined as 11,721.
and 0.21, respectively. The material properties of the cement were of glass-ionomer cement, and the Young modulus and the Poisson ratio hold good even for the composite cements.\textsuperscript{14,15} The complete 3D finite element model of the bracket-cement-tooth system consisted of 40,536 nodes and 49,201 finite elements (Fig 4). To keep the size of this complex model within reasonable limits, only the relevant areas of the tooth were modeled. The remainder were substituted with appropriate boundary conditions. To evaluate the stress generated by altering, the geometry of bracket mesh base peel load was used. Keeping the wire spacing constant at 300 \( \mu \text{m} \), the wire diameter was varied from 100 to 400 \( \mu \text{m} \) for comparison of stresses generated by different types of forces. The necessary peel force/masticatory/twisting force was applied to the bracket model at appropriate model positions (Figs 5 to 7). The force value taken for analysis was 1 N.
RESULTS

The influence of altered mesh base design on the stresses induced in the bracket-cement-tooth system by a peel force are presented in Table 1 and Figs 8 to 11. The stresses generated in different layers in the tooth-cement-bracket continuum varied from 1.19 to 9.85 MPa. Stresses generated at the enamel varied from 1.19 to 1.182 MPa for different wire diameters and spacings. IWM layer stresses varied from 3.49 to 3.479 MPa, whereas cement stresses ranged from 0.4999 to 0.1549 MPa, but the bracket stresses remained at 9.444 MPa. The stress generated in all layers remained constant compared with the cement layer (see Table 1).

The stresses generated in the tooth-cement-bracket continuum due to the three different loads (masticatory, peel, and twisting force) are shown in Table 2. The stresses generated from peel force varied from 1.200 to 1.170 MPa in enamel. For IWM stresses, they varied from 3.480 to 3.491 MPa, and for the brackets, it varied from 9.444 to 9.700 MPa for the peel force. For the masticatory force, the stresses generated in the enamel remained constant for different wire diameters at...
2.247 MPa. For IWM stress, it was 4.781 MPa, and for brackets, it was 9.617 MPa. In the case of twisting forces, the stresses generated also remained constant for different wire diameters. In case of enamel stresses, it was 0.452 MPa; for IWM, it was 4.140 MPa; and for brackets, it was 6.500 MPa. The stresses generated at the cement layer for all the forces remained in the range of 0.1012 to 0.7541 MPa, which was comparatively low in comparison to the other layers of the continuum. Figures 12a to 12c show the pattern of stress generation in the different layers of tooth-cement-bracket continuum.
DISCUSSION

The FEM has become a powerful tool for the numeric solution of a wide range of problems. The FEM utilized for this study is a product of the computer age, and the application of this method to solve practical problems requires the use of computer analysis. Credability of finite element analysis in analyzing the internal stress-strain levels has been already proven by various studies.\textsuperscript{3,10,12,13} Considering relative ease with which modeling of different objects is possible with FEM, it is the tool of choice to generate the tooth-cement-bracket continuum. This study utilized the bonded orthodontic bracket, which was subjected to a range of forces, such as tensile/peel, masticatory, and twisting load, during elective bracket removal. After this, the stresses generated were obtained in the form of graphs.

![Fig 12a](image1.png)  Stress generation in bracket due to twisting load.

![Fig 12b](image2.png)  Stress generation in IWM due to twisting load.

![Fig 12c](image3.png)  Stress generation in enamel due to twisting load.
The increase in the wire diameter from 100 to 400 μm in the tooth-cement-bracket continuum generated greater stress at the bracket level, followed by the IWM, enamel, and cement layers. However, for all the wire diameters, the stresses generated remained constant for the IWM and bracket body, suggesting little influence of diameter of mesh base wire on the IWM and bracket body (see Table 1). An increase in wire diameter increased the rigidity of the bracket base, resulting in the applied load being distributed more evenly over the total bonded area of the bracket base. Both findings were in accordance with the results of Knox et al, who used FEM analysis to evaluate the stress generation in the bracket mesh base. In the study of Merone et al, who compared the R system with the conventional bracket base system, the R system was shown to have better retention since it allowed transfer of torsional stress more uniformly to the substrate.

The enamel and cement stresses recorded are gradually decreasing, with maximum stress recorded with 100-μm diameter and minimum with 400 μm. A possible reason for this can be attributed to the increase in surface area as the wire diameter increased, which produced an even distribution of forces. As we increased the wire spacing, the reverse of the above took place for both enamel and cement, with stresses increasing abruptly for wire spacing 200 to 500 μm at all diameters of the wire. The reason is that the number of wire units will be decreased and the wire spacing will be increased, thus resulting in a decrease in the surface area of the mesh. In the studies conducted by Knox et al and Bishara et al, both of whom compared the stress generated in single- and double-mesh bracket bases, comparable bond strengths and bracket failure modes were found.

An increase in wire spacing (200 to 500 μm) increased the stress recorded in the enamel and cement at all wire diameters. Stresses generated in brackets at different wire spacings and different wire diameters were similar, suggesting that alteration in mesh base had no influence on the stress generation at the bracket level. Contrasting reports have been reported by Knox et al, who found significant increase in stress at brackets at wire spacings above 400 to 500 μm. However, within the IWM, the major principle decreased as the wire space increased.

Apart from factors such as wire diameter and spacing of bracket mesh base, researchers have identified a number of variables that might exert their influence on the bond strength of the bracket, such as weld spots, weld spurs, location of weld spots, and air entrapment.

Keeping the wire spacing 300 μm, the wire diameter varied from 100 to 400 μm to get the stresses for masticatory and twisting forces apart from the peeling force. By comparing these three different load cases, we see that stresses generated at all the layers of the tooth-cement-bracket interface remained high in case of peel load, except for enamel. For stresses generated at the IWM, the brackets and enamel were low in cases of twisting force, thus suggesting that the peel force and twisting force are better for bracket debonding. Comparatively, twisting force was better for debonding since it produced minimal enamel damage compared with the peel load (see Table 2). The stresses produced by the masticatory load on the enamel were double in comparison to the twisting force, indicating the chances of enamel breakage. According to Chen et al, there were no significant differences in enamel fracture with different debonding forces (shear, torsion, and tensile force).

The stresses generated at the cement layer remained low for the different forces, and the stresses progressively reduced as the mesh wire diameter increased. Increased diameter of the wire increased the rigidity of the wire, which enabled the mesh to take the entire load so the fragile cement layer was spared the vigor of different forces.
The results of this study suggest that clinicians are supposed to be conscious of the possibilities of the damage on the enamel produced by the masticatory debonding forces and as far as possible avoid such situations by using bite blocks, variations in bracket positioning, and certain debonding procedures. Whatever the variation in the bracket mesh, the stresses produced on the enamel by the masticatory forces were more than all the other forces, indicating that the bracket mesh variation has no influence on the masticatory forces, especially in relation to enamel. The mesh design did make a difference in the production of stresses as one can appreciate varying amounts of stresses at the cement layers at various wire diameters.

The cement layer seems to be the weakest link since the stress levels in the cement layer can be affected by changes in wire mesh geometry (see Table 2). The safest way to break the cement and not the enamel during debonding is to use a twisting force.

The variation in the bracket mesh base failed to influence the stresses generated by twisting force on the different layers of the tooth-cement-bracket continuum, since the stresses produced were constant for all wire diameters (see Table 2). The stresses generated by the peel force varied for different layers and different wire diameters of the mesh, which was more evident for enamel since one can notice that as the wire diameter increased, stresses reduced (see Table 2). Thus, variation in the bracket mesh base influenced the peel forces more in comparison to the masticatory and twisting forces.

An investigation on debonding force and its influence on the bond strength showed that the different debonding sites, such bracket base, ligature groove, and occlusal bracket wings, produced statistically significant differences in the shear bond strength. This factor needs to be considered whenever stress generation in bracket base during debonding is studied. Other factors such as the direction of the debonding force also influence the shear bond strength.

CONCLUSION

Alterations in the bracket mesh base by varying wire diameter and spacing produced varying amounts of stresses within the bracket-cement-tooth system. The peel/tensile and twisting forces are better for debonding purposes since they produced less stress at the enamel level, thus reducing enamel breakage. Thus, by varying the design of the mesh base, we can produce the desired bond strength and stress at the enamel level.

Further studies need to be done in the orthodontic attachment area related to bracket base mesh designs since there are relatively few studies in this regard. This study can be used as a reference for further investigations.

This paper addressed the finite element model analysis to study the influence of alteration in mesh design. Nevertheless, it also addressed the protection of enamel and the safest way to remove brackets, as we have utilized the most commonly used debonding forces.

ACKNOWLEDGMENT

We are indebted to Mr Ragavendra, MS, for his guidance in building up the FEM model.
REFERENCES