Journal of Orthodontics/Vol. 27/2000/39–46

An evaluation of the Stresses Generated in a Bonded Orthodontic Attachment by Three Different Load Cases Using the Finite Element Method of Stress Analysis

JEREMY KNOX, B.D.S., M.SC.D., PH.D., M.ORTH. R.C.S., F.D.S. (ORTH.)

MALCOLM L. JONES, B.D.S., M.SC.D., PH.D., F.D.S., D.ORTH. R.C.S

Department of Dental Health and Development, University of Wales College Of Medicine, Dental School, Heath Park, Cardiff CF4 4XY, U.K.

PIERRE HUBSCH, DIPL.-ING., PH.D.

JOHN MIDDLETON, B.SC., M.SC., F.R.S.A.

Department of Basic Dental Science, University of Wales College Of Medicine, Dental School, Heath Park, Cardiff CF4 4XY, U.K.

BERISLAV KRALJ, DIPL-ING, PH.D.

Welsh Centre for Biomechanics, University College Swansea, U.K.

Abstract. *The objective of the investigation was to develop a clinically valid three-dimensional computer model of the orthodontic bracket-cement-tooth continuum, and determine the magnitude and distribution of stresses generated by three different load cases.*

A three-dimensional finite element model of the bracket-cement-tooth system was constructed consisting of 15324 nodes and 2971 finite elements. The stresses induced in the bracket-tooth interface by a masticatory load, a peel force and a twisting couple were recorded.

The maximum principal stresses resulting from occlusal and 'twisting' forces are distributed toward the lute periphery. Peel forces, applied to the bracket tie wing, are concentrated beneath the bracket stem. Twisting forces result in the highest enamel stresses.

The quality of orthodontic attachment can be explained by the magnitude and distribution of major principal stresses within the cement and impregnated bracket base. Shear and shear/peel forces are most likely to induce crack propagation within the adhesive layer. However, when a twisting action is used to remove orthodontic brackets, enamel failure is most likely. A clearer insight into the complexity of the bracket-cement-tooth system has been provided by numerical and finite element investigations. Further investigations, evaluating the influence of bracket base designs and orthodontic cement physical and geometric properties are indicated.

Index words: Orthodontic attachment; finite element method; stress analysis.

Refereed Scientific Paper

Introduction

Engineering design begins with an attempt to analyse the stresses and strains acting on and within the structure under consideration before producing and testing a prototype. Unfortunately, the development of orthodontic cements and bracket bases has, largely, relied on relatively imprecise *ex vivo* experiments (Fox *et al*., 1991) which measure only the weakest component in the bracket-cement-tooth system. As the quality of attachment is primarily determined by the stresses generated in response to applied load, computer models are ideally suited to provide some insight into the structural behaviour of this system.

Correspondence: Jeremy Knox, Department of Dental Health and Development, University of Wales College of Medicine, Dental School, Heath Park, Cardiff CF4 4XY, U.K.

A number of methods of numerical analysis have been employed in bioengineering, in particular the Finite Element Method of stress analysis (FEM). 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 (Burnett, 1987). FEM has already been broadly applied in orthodontic research. Yettram *et al*. (1972) were amongst the first to employ a two-dimenstional finite element model of a maxillary central incisor to determine the instantaneous centre of rotation of this tooth during translation. Halazonetis (1996) used a similar two-dimensional model to determine periodontal ligament (PDL) stress distribution following force application at varying distances from the centre of resistance of a maxillary incisor. Using more complex three dimensional models Wilson *et al*. (1992, 1994), Tanne *et al*. (1987, 1988a,b) and McGuinness *et al*. (1990, 1991) have studied moment to

0301-228X/00/010000+00$02.00

force ratios and stress distributions during orthodontic tooth movement. Cobo *et al.* (1993) studied periodontal stresses during tooth movement when attachment levels are reduced.

More recent work has attempted to quantify periodontal properties during instantaneous tooth movement (Tanne, 1995; Volp *et al.*, 1996). These studies have allowed the development of more clinically valid three-dimensional FEM models of the tooth/PDL continuum (Middleton *et al.*, 1996; Hickman, 1997; Jones *et al.*, 1998).

In the field of dentofacial orthopaedics, finite element models have been employed to evaluate the stress distribution induced within the craniofacial complex during the application of protraction headgear (Tanne *et al.*, 1988a,b, 1989a,b; Miyasaka-Hiraga *et al.*, 1994), orthopaedic chin cup forces (Tanne, 1993), and conventional headgear forces (Tanne and Matsubara, 1996).

The finite element method has only recently been applied to the evaluation of orthodontic attachment. Ghosh *et al.* (1995) have used three-dimensional FEM models of ceramic orthodontic bracket designs to determine the stress distribution and likely mode of cohesive failure within the bracket when a full dimension stainless steel arch wire is engaged within the bracket slot. Katona (1994, 1997a), and Katona and Moore (1994) 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 (1995) have used a simplified three-dimensional finite element model to evaluate the stress distribution around orthodontic attachments during debonding. Katona (1997b) 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.

Materials and Methods

The development of a valid three-dimensional computer model of the bracket tooth interface, requires the quantification of the physical and geometric properties of each of the system components. The geometric properties of a maxillary first premolar tooth were determined by preparing serial longitudinal sections of a representative tooth. Using computer imaging techniques, the three-dimensional co-ordinates of the tooth were recorded from serial longitudinal sections of a representative tooth, and a finite element mesh generated (15324 nodes each with 3 degrees of freedom, assembled into 2971 20-noded hexahedral elements) using a commercial mesh generating programme (PATRAN - PDA Engineering USA). To keep the size of the overall model reasonably small, only the area of enamel local to the orthodontic attachment was modelled. The remainder of the tooth was represented by the appropriate boundary conditions (Kralj *et al.*, 1996).

A maxillary first premolar bracket was modelled. 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, non-

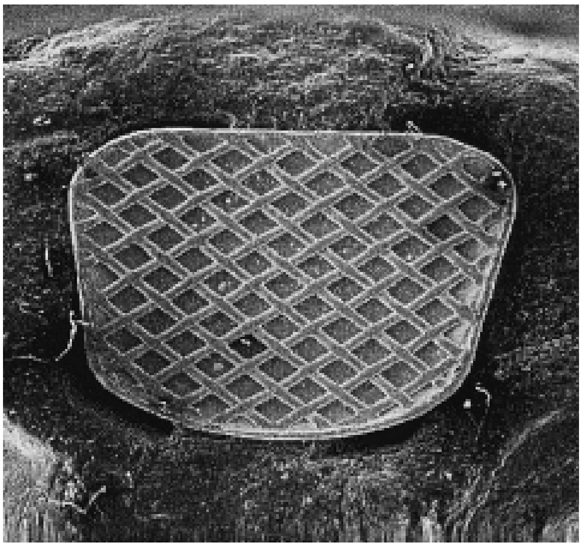

FIG. 1 Mesh base.

homogeneous, area with physical properties which lay somewhere between those of the stainless steel bracket and the cement lute. The cement had an average thickness of approximately 271 μm, and the material was considered to be homogeneous and isotropic.

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 impregnated wire mesh (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 non-homogeneous layer a theory of composite materials was employed to homogenize the layer and represent it with a mechanically equivalent, but homogeneous material (Hübsch *et al.*, 1994, 1996).

The homogenization theory is a well established tool for the analysis of composite materials (Hollister *et al.*, 1991). The application of this theory relies on the microstructure of the material analysed being locally periodic or self-repeating. A small but representative area (unit cell) of the heterogeneous solid is selected and the behaviour of the unit cell studied under load. 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.*, 1994, 1996) were constructed for the bracket base mesh (Figure 2) and orthodontic cement unit cells (Figure 3). 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 modelled. Both the wire and the orthodontic adhesive were considered to be linear elastic, homogeneous, and isotropic materials.

The material parameters used 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 two materials. The

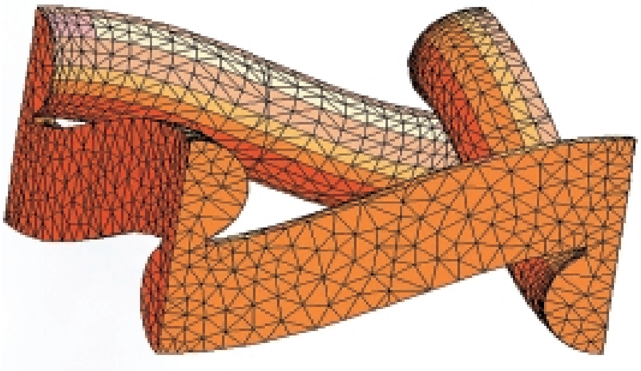

FIG. 2 Finite element model of base mesh part of unit cell.

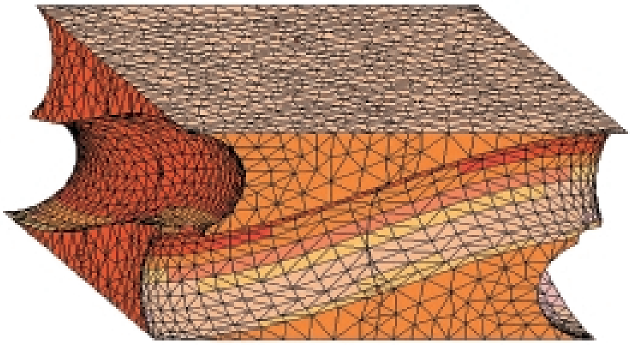

FIG. 3 Finite element mesh of cement part of unit cell.

TABLE 1 *Material properties employed*

Material	Young's Modulus (MPa)	Poisson's ratio
Enamel	46890	0·30
Cement	11721	0·21
Stainless steel	210000	0·30

impregnated wire mesh layer (IWM) was assumed to have transversely isotropic mechanical properties in planes parallel to and perpendicular to the mesh base. This demanded the introduction of elements with orthotropic properties in this region, i.e. material properties which differ in each of the three dimensions. In addition, the IWM is a double curved structure resulting in changes in the material property principal axes relative to the global co-ordinates (Figure 4).

Appropriate material properties were calcualted by applying a transformation of the material principal axes into the global co-ordinate direction at each Gauss point of the FE model of the IWM (Kralj *et al*., 1996). The material properties of the IWM are presented in Table 2.

The complete 3D finite element model of the bracket-cement-tooth system (Figure 5) consisted of 15324 nodes and 2971 finite elements. To keep the size of this complex model within reasonable limits, only the relevant areas of the tooth were modelled, the remainder being substituted by the appropriate boundary conditions.

Three load cases (Figure 6) were selected to represent masticatory forces (shear), a 'peel' force (similar to that

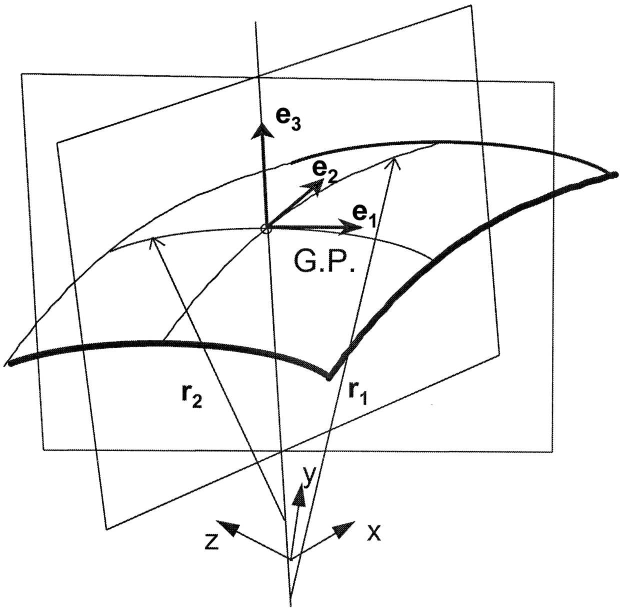

FIG. 4 Global (x, y, z) and local (e_1, e_2, e_3) co-ordinate systems (r_1–radius in one plane; r_2–radius in the second plane).

TABLE 2 *Material properties of homogenized IWM*

Property	In plane value	Out of plane value
Youngs Modulus [E]	40162 MPa	24944 MPa
Shear modulus [G]	11116 MPa	10793 MPa
Poissons ratio	0·09	0·30

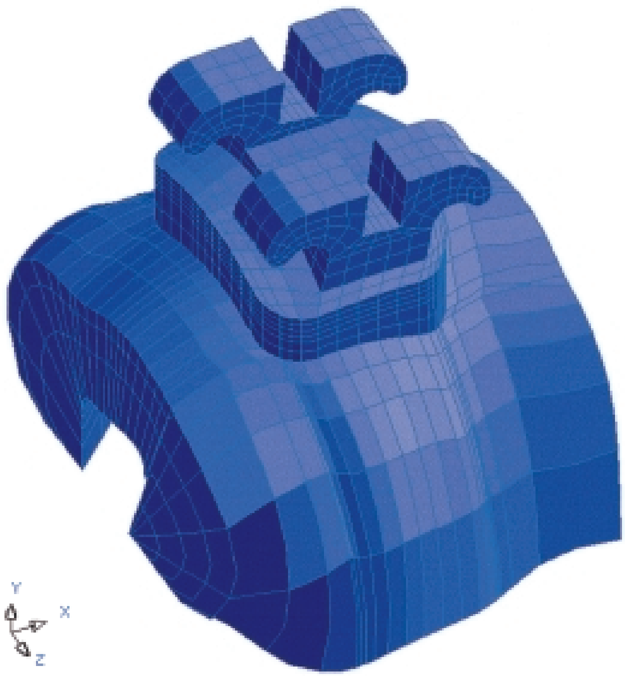

FIG. 5 Finite element model of the bracket-cement-tooth interface.

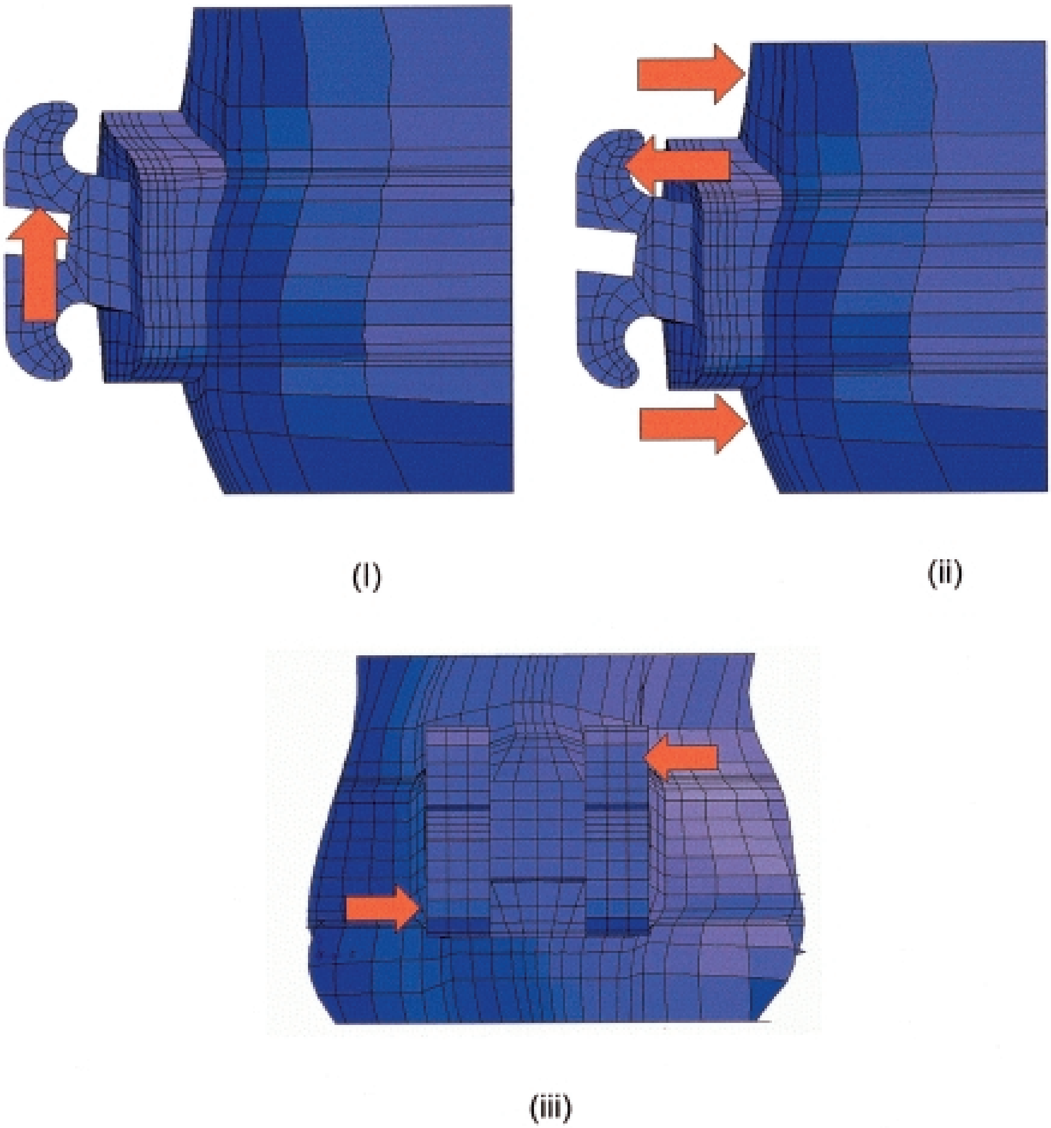

FIG. 6 Load cases: (i) masticatory load, (ii) peel force, (iii) twisting couple.

prescribed by a LOCI, lift off de-bonding instrument; North West Orthodontics, Seattle, Washington, U.S.A.) and the twisting force, similar to that used by some clinicians to remove brackets.

Results

All of the results presented are for unit loads. An insight is given into the stress distribution within the bracket-cement-tooth system and, assuming that all materials behave elastically, the location of initial failure can be predicted.

The maximum principal stresses are illustrated in all areas of the bracket tooth system. However, attention should be focused on the enamel, cement, and IWM areas as these primarily determine the quality of attachment. Stress concentrations are highest within the bracket wings and stem, but these are not considered critical due to the strength and ductility of stainless steel. In all analyses, maximum principle stress distributions are demonstrated as these are most likely to initiate crack propagation within the brittle cement, enamel and IWR layers. Figures 7–9 demonstrate the major principal stresses in the bracket-cement-tooth continuum resulting from the different load cases.

Discussion

Figure 7 presents the maximum principal stresses resulting from the application of a shear force to the occlusal surface of the bracket stem. It can be appreciated that the peak stress concentrations are distributed towards the periphery of the cement/IWM layer and underlying enamel surface. At first glance, it might appear that a masticatory load presents a case of shear loading. Unfortunately, pure shear almost never occurs and this is reflected in the stress

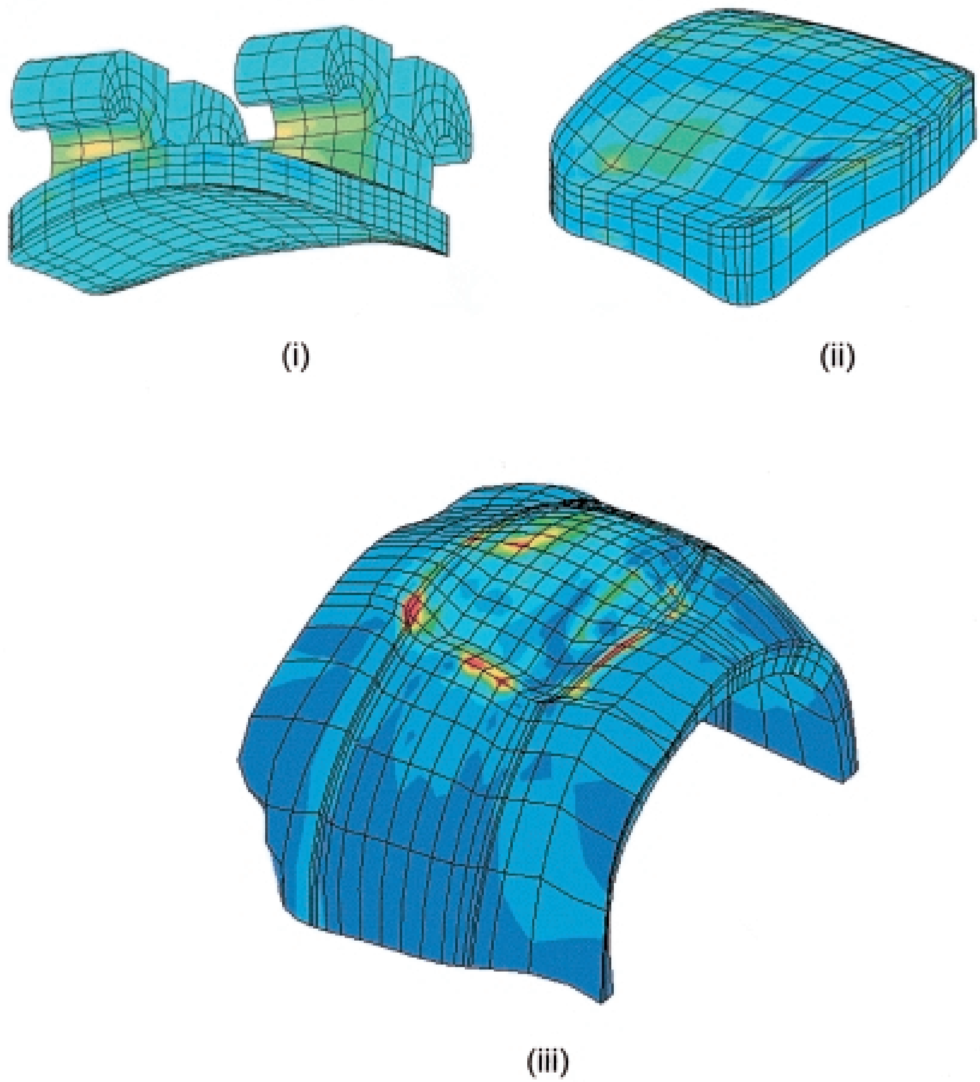

FIG. 7 Maximal principle stress distribution due to masticatory loads (i) Bracket, (ii) IWR-cement sandwich, (iii) enamel.

distribution recorded here. The shear stress is largest under the middle of the bracket while the normal stress increases as the margins are approached. The normal stress is compressive under the gingival half of the bracket and tensile under occlusal section. Some relief of these normal stresses is achieved through flexing of the bracket base. However, maximum stresses are recorded at the bracket, cement and enamel margins.

Figure 8 shows the maximum principle stress distribution resulting from a peel force applied under the bracket tie-wing. Clearly, the peak stress is located under the bracket wing which is being loaded. This is due to the load-transfer mechanism through the relatively stiff bracket stem. Because the bracket base is relatively flexible, very little load is transferred from the bracket stem to the periphery of the foil. Instead, the load is channelled straight down from the body of the bracket and the adhesive into the tooth,

The force couple, presented in Figure 9, results in stress concentrations at the lute periphery, particularly in the enamel. As the ratio of maximum principle stress to ultimate tensile strength approaches 1 within a material, the likelihood of material failure increases. At values below this the material has some residual strength. Knowing the ultimate tensile strength values for each material and the level and distribution of major principle stress within the bracket-tooth interface allows the site of attachment initial failure to be predicted for each load case. Of primary concern during braket removal is the maintenance of enamel integrity. Table 3 shows the predicted site of failure for bracket removal by masticatory loads, 'lift off device' and twisting couple. In each case only the enamel and

TABLE 3 *Predicted site of failure for three load cases, 1·0 indicates failure, less than 1·0—there is still reserve strength*

	Masiticatory load	LODI	Twisting force
Enamel	0·57	0·42	1·0
Adhesive	1·0	1·0	0·86

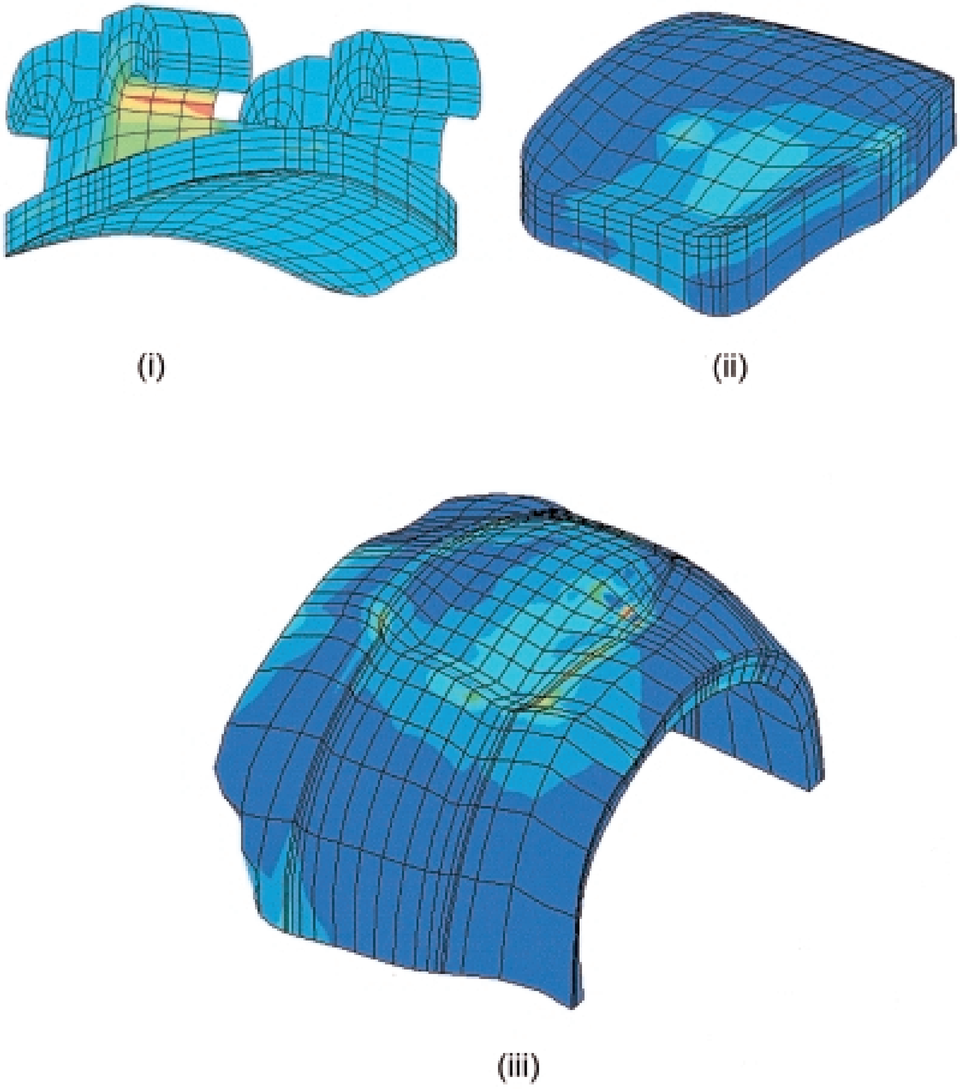

FIG. 8 Maximal principle stress distribution due to 'lift off device' applied to mesio-gingival wing (i) Bracket, (ii) IWR-cement sandwich, (iii) enamel.

cement are considered. These results show that masticatory loads and 'lift off devices' are most likely to induce crack propagation within the adhesive layer. Care must be taken, however, when a twisting action is used to remove orthodontic brackets as enamel failure is likely.

Katona (1994, 1997a), and Katona and Moore (1994) 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. The stress induced by the application of shear force was found to be strongly influenced by the location of applied force (Katona, 1994; Katona and Moore, 1994). In addition, suggestions were made that the use of tensile forces to remove orthodontic brackets would result in a reduced risk of enamel fracture when compared to shear/peel forces (Katona, 1997a). Rossouw and Tereblanche (1995) used a simplified three simensional finite element model to evaluate the stress distribution around orthodontic attachments during de-bonding. Their conclusions differed from those of Katona (1994, 1997a) in that enamel damage was suggested to be mroe likely when tensile forces were applied, rather than shear-torque.

The current investigation demonstrated that shear and shear/peel forces are most likely to induce crack propagation within the adhesive layer. However, when a twisting action is used to remove orthodontic brackets, enamel failure is most likely. It is interesting to note that a 'wrench' was supplied for the removal of some of the early ceramic brackets by twisting. As can be appreciated, the use of a finite element model during the design of these brackets would have revealed that this method of bracket removal was inappropraite.

Conclusions

1. The quality of orthodontic attachment can be explained by the magnitude and distribution of maor principal stresses within the cement and impregnated bracket base.

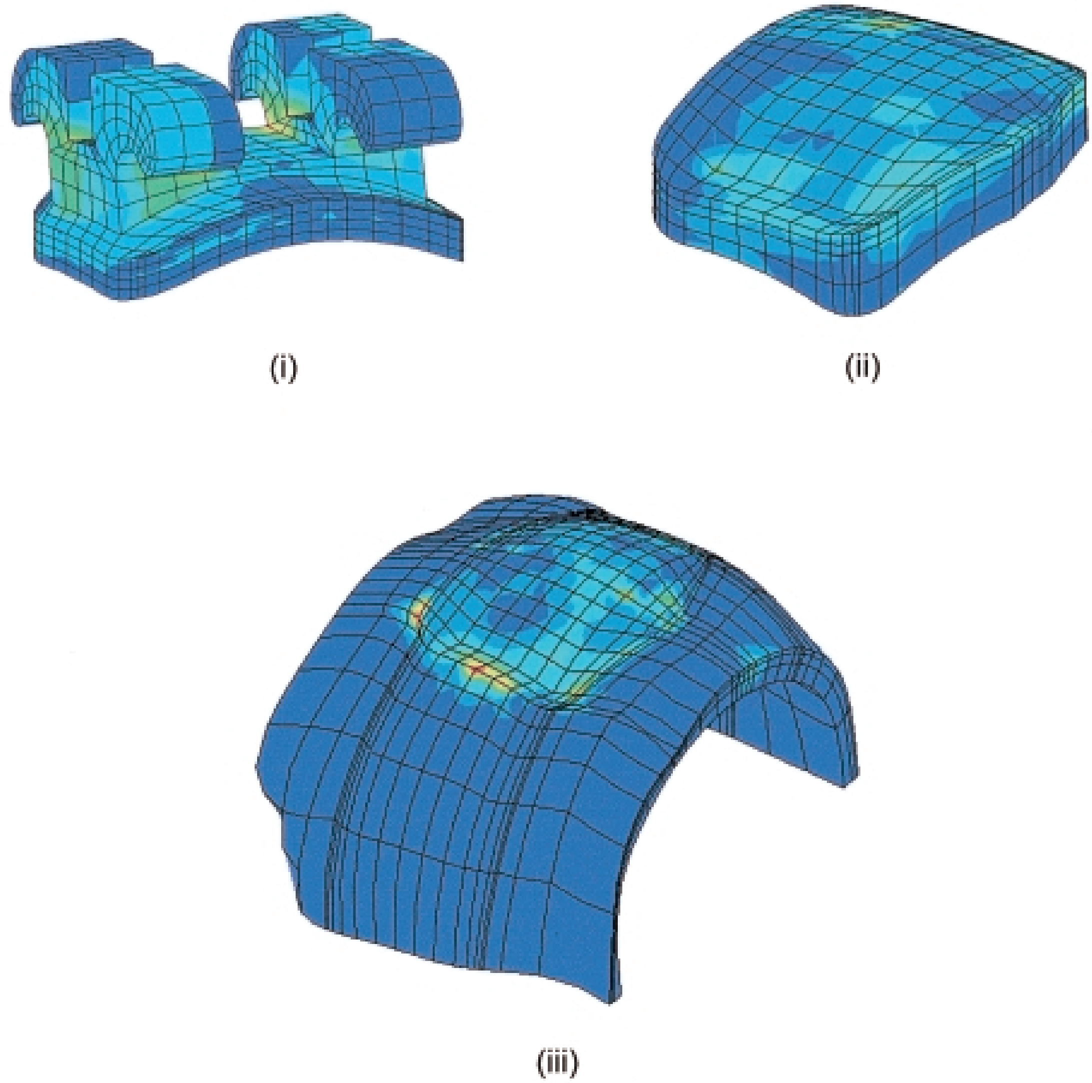

FIG. 9 Maximal principle stress distribution due to twisting couple (i) Bracket, (ii) IWR-cement sandwich, (iii) enamel.

2. Shear and shear/peel forces are most likely to induce crack propagation within the adhesive layer. However, when a twisting action is used to remove orthodontic brackets, enamel failure is most likely.
3. A clearer insight into the complexity of the bracket-cement-tooth system has been provided by numerical and finite element investigations.
4. Further investigations, evaluating the influence of bracket base designs and orthodontic cement physical and geometric properties are indicated.

Acknowledgements

This project was funded by The Welsh Scheme for Development of Health and Social Research. The dimensions of the maxillary premolar bracket were provided by American Orthodontics Ltd, Sheboygan, U.S.A.

References

Burnett, D. S. (1987)
Finite Element Analysis—From Concepts to Applications,
Addison-Wesley Publishing Co., Massachusetts.

Cobo, J., Sicilia, A., Argüelles, J., Suárez, D. and Vijande, M. (1993)
Initial stress induced in periodontal tissue with diverse degrees of bone loss by an orthodontic force: tridimensional analysis by means of the finite element method,
American Journal of Orthodontics and Dentofacial Orthopaedics,
104, 448–454.

Fox, N. A., McCade, J. F. and Buckley, J. G. (1994)
A critique of bond strength testing in orthodontics,
British Journal of Orthodontics, **21,** 33–43.

Ghosh, J., Nanda, R. S., Duncanson, M. G. and Currier, G. F. (1995)
Ceramic bracket design: An analysis using the finite element method,
American Journal of Orthodontics and Dentofacial Orthopaedics,
108, 175–182.

Halazonetis, D. J. (1996)
Computer experiments using a two dimensional model of tooth support,
American Journal of Orthodontics and Dentofacial Orthopaedics,
109, 598–606.

Hickman, J. (1997)
A validated finite element method study of maxillary incisor tooth movement,
MScD dissertation, University of Wales.

Hollister, S. J., Fyhrie, D. P., Jepsen, K. J. and Goldstein, S. A. (1991)
Application of homogenisation theory to the study of trabecular bone mechanics,
Journal of Biomechanics, **24,** 825–839.

Hübsch, P. F., Knox, J., Middleton, J. and Jones, M. L. (1994)
A 3D finite element investigation of fixed orthodontic brackets,
In: *Proceedings of The Second World Congress of Biomechanics*, Vol. 1, Blankevoorte & Koolos 69.

Hübsch, P. F., Knox, J., Jones, M. L. and Middleton, J. (1996)
Global and local behaviour of the stress field at the base of an orthodontic bracket,
In: *Computer Methods in Biomechanics and Biomechanical Engineering*, (eds Middleton, Jones & Pande) 361–369.

Jones, M. L., Middleton, J., Hicklman, J., Volp, C. and Knox, J. (1999)
The development of a validated model of orthodontic movement of the maxillary central incisor in the human subject,
Russian Journal of Biomechanics, **1–2,** 36–44.

Katona, T. R. (1994)
The effects of load location and misalignment on shear/peel treating of direct bonded orthodontic brackets—a finite element model,
American Journal of Orthodontics and Dentofacial Orthopaedics, **106,** 395–402.

Katona, T. R. (1997a)
Stresses developed during clinical de-bonding of stainless steel orthodontic brackets,
Angle Orthodontist, **67,** 39–46.

Katona, T. R. (1997b)
A comparison of the stresses developed in tension, shear peel and torsion strength testing of directly bonded orthodontic brackets,
American Journal of Orthodontics and Dentofacial Orthopaedics, **112,** 244–251.

Katona, T. R. and Moore, B. K. (1994)
The effects of load misalignment on tensile load testing of direct bonded orthodontic brackets—a finite element model,
American Journal of Orthodontics and Dentofacial Orthopaedics, **105,** 543–551.

Kralj, B., Jones, M. L., Knox, J. and Middleton, J. (1996)
3D Modelling of orthodontic brackets,
In: *Computer Methods in Biomechanics and Biomechanical Engineering*
(ed. Middleton, Jones & Pande) 370–381.

McGuiness, N. J. P., Wilson, A., Jones, M. L. and Middleton, J. (1990)
A stress analysis of the periodontal ligament under various orthodontic loadings,
European Journal of Orthodontics, **13,** 231–242.

McGuiness, N. J. P., Wilson, A., Jones, M. L., *et al.* (1991)
Stress induced by edgewise appliances in the periodontal ligament—a finite element study,
Angle Orthodontist, **62,** 15–21.

Middleton, J. Jones, M. L. and Wilson, A. (1996)
The role of the periodontal ligament in bone remodelling: the initial development of a time dependent model,
American Journal of Orthodontics and Dentofacial Orthopaedics, **109,** 155–162.

Miyasaka-Hiraga, J., Tanne, K. and Nakamura, S. (1994)
Finite element analysis for stresses in the craniofacial sutures produced by maxillary protraction forces applied at the upper canines,
British Journal of Orthodontics, **21,** 343–349.

Rossouw, P. E. and Tereblanche, E. (1995)
Use of the finite element analysis in assessing stress distribution during de-bonding,
Journal of Clinical Orthodontics, **29,** 713–717.

Tanne. K. and Matsubara, S. (1996)
Association between the direction of orthopaedic headgear force and sutural responses in the nasomaxillary complex,
Angle Orthodontist, **66,** 125–130.

Tanne, K., Sakuda, M. and Burstone, C. J. (1987)
Three dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces,
American Journal of Orthodontics and Dentofacial Orthopaedics, **92,** 499–505.

Tanne, K., Koenig, H. A. and Burstone, C. J. (1988a)
Moment to force ratios and the centre of rotation,
American Journal of Orthodontics and Dentofacial Orthopaedics, **94,** 426–431.

Tanne, K., Miyasaka, J., Yamagata, T., *et al.* (1988b)
Three dimensional model of the human craniofacial skeleton: method and preliminary results using finite element analysis,
Journal of Biomechanical Engineering, **10,** 246–252.

Tanne, K., Hiraga, J., Kakiuchi, K., *et al.* (1989a)
Biomechanical effect of anteriorly directed extra-oral forces on the craniofacial complex: a study using the finite element method,
American Journal of Orthodontics and Dentofacial Orthopaedics, **95,** 200–207.

Tanne, K., Jiraga, J. and Sakuda, M. (1989b)
Effects of directions of maxillary protraction forces on biomechanical changes in craniofacial complex,
European Journal of Orthodontics, **11,** 382–391.

Tanne, K., Lu, Y. C., Tanaka, E. and Sakuda, M. (1993)
Biomechanical changes of the mandible from orthopaedic chin cup force studied in a three dimensional finite element model,
European Journal of Orthodontics, **15,** 527–533.

Tanne, K., Inoue, Y. and Sakuda, M. (1995)
Biomechanical behaviour of the periodontium before and after orthodontic tooth movement,
Angle Orthodontist, **65,** 123–128.

Volp, C. R., Western, E. R. N., Knox, J., Jones, M. L. and Williams, K. R. (1994)
A method of evaluating dynamic tooth movement.
International Symposium on *Computer Methods in Biomechanics & Biomedical Engineering*. Pages 461–470.

Wilson, A. N., Jones, M. L. and Middleton, J. (1992)
The effect of the periodontal ligament on bone remodelling,
Recent Advances in Computer Methods in Biomechanics and Biomechanical Engineering
Books and Journals International, 150–158.

Wilson, A. N., Middleton, J., Jones, M. L. and McGuinness, N. J. (1994)
The finite element analysis of stress in the periodontal liagment when subject to vertical orthodontic forces,
British Journal of Orthodontics, **21,** 161–167.

Yettram, A. L., Wright, K. W. and Houston, W. J. B. (1972)
Centre of rotation of a maxillary central incisor under orthodontic loading,
British Journal of Orthodontics, **4,** 23–27.