Eur. J. Prosthodont. Rest. Dent., Vol.13, No. 2, pp 87–93
Printed in Great Britain

Fracture Mechanics Analysis of an Anterior Resin Bonded Bridge Including the Effects of Tooth Mobility

Nao Shinohara*, David N. Fenner† and P. Brett Robinson‡

Abstract - *The effects of design parameters on crack growth along the adhesive layer in a resin-bonded first incisor/canine bridge are analysed using a finite element (FE) model in which allowance is made for tooth mobility by including elastic supports for the abutment teeth. The energy release rate,* G, *for incipient cracks in the adhesive layer are calculated for various crack lengths, metal frame configurations, frame thicknesses and tooth mobilities. Energy release rates for bridge frame designs with and without wrap round, denoted by* G_w *and* G_o*, respectively, decrease as the metal frame thickness increases. The difference* $\Delta G = G_o - G_w$ *reaches a maximum with respect to the crack length,* a, *in the range* $0.3 < a < 0.6$*mm, depending on the frame thickness. The effect of tooth mobility becomes increasingly important in the FE model as the overall stiffness of the bridge increases. Critical lengths for incipient cracks in the adhesive layer are estimated for a range of factors of safety against the onset of unstable crack propagation.*

KEY WORDS: Fracture mechanics; Resin-bonded bridge; Tooth mobility

INTRODUCTION

A resin-bonded dental bridge, in which the metal frame is bonded to the abutment teeth by an adhesive layer, is an attractive device due to its simple configuration. The strength of the adhesive structure has been studied from several points of view including the bridge geometry[1–7] metal surface treatment[8–12] and the adhesive material used[13,14]. These studies assumed that the adhesive layer provides a perfect bond between the bridge and the abutment teeth and showed that the durability of a resin-bonded bridge under load improved as the frame is made stiffer by increasing its thickness and by adding a wrap-round design feature.

In practice, voids are usually present in the adhesive layer and repeated loading, together with chemical attack, may lead to their coalescence to form micro-cracks. These micro-cracks in turn may develop into a larger macro-crack and eventually, at a certain load level, unstable crack propagation will cause complete failure of the bond between the bridge and the abutments. The onset of this unstable crack propagation is the key event in determining the durability of a resin-bonded bridge.

In previous work by the first author[2,3] FE analysis was used to calculate the energy release rate for incipient cracks in the adhesive layer behind each of the abutment teeth. A two-dimensional FE model was used in which the abutment teeth were assumed to be rigidly fixed and a single point force was applied to the labial surface of the pontic in the labio-lingual direction. The effects of metal frame configuration and thickness on the energy release rate were investigated and suggestions were made for the design of resin-bonded bridges in order to increase their durability.

Clinical experience[15–17] shows that the durability of a resin-bonded bridge is affected by the mobility of the abutment teeth due to the deformation of the periodontal ligament. Tooth mobility is included in the present study by incorporating elastic support for the abutments into a FE model. The effect of this elastic support, together with that of the metal frame configuration and thickness on the energy release rate for incipient cracks in the adhesive layer behind the abutments are investigated for a first incisor/canine bridge.

FRACTURE MECHANICS

The energy release rate, *G,* for a crack propagating in an elastic structure subjected to a constant load *P* (*Figure 1*) is given by[18]

$$G = \delta U / \delta A \qquad (2.1)$$

where *U* is the elastic strain energy stored in the structure, and *A* is the area of the crack. If *U* denotes the displacement of the point at which the load *P* is applied when the crack is of length *a* it follows that the corresponding strain energy U_a is given by

$$U_a = \tfrac{1}{2}\, P\, u \qquad (2.2)$$

After the crack has extended by an infinitesimal amount δa under a constant load *P* the corresponding displacement of the loaded point has increased by an amount δu and the strain energy is now

$$U_{a+\delta a} = \tfrac{1}{2}\, P\, (u+\delta u) \qquad (2.3)$$

The energy release rate for a crack of length *a* can now be approximated as

$$G = (U_{a+\delta a} - U_a)/\delta A = (\tfrac{1}{2}\, P\, \delta u)/\delta A \qquad (2.4)$$

For an incipient crack to extend the energy release rate must exceed a critical value which represents the total energy absorbed per unit of new crack surface formed. The smaller the value of G the greater will be the factor

---

*DDS, PhD
†PhD, DIC, BSc (Eng), ACGI, MIMechE
‡BDS, FDSRCS, PhD, MBA

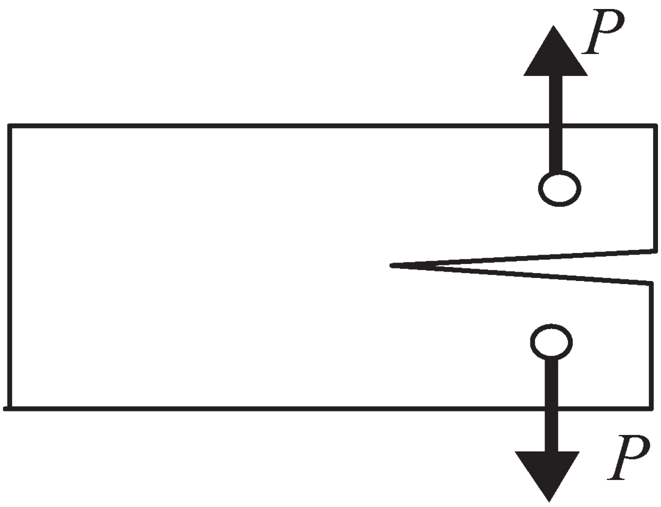

Figure 1. *Energy release rate for a crack propagating in an elastic structure subjected to a constant load P.*

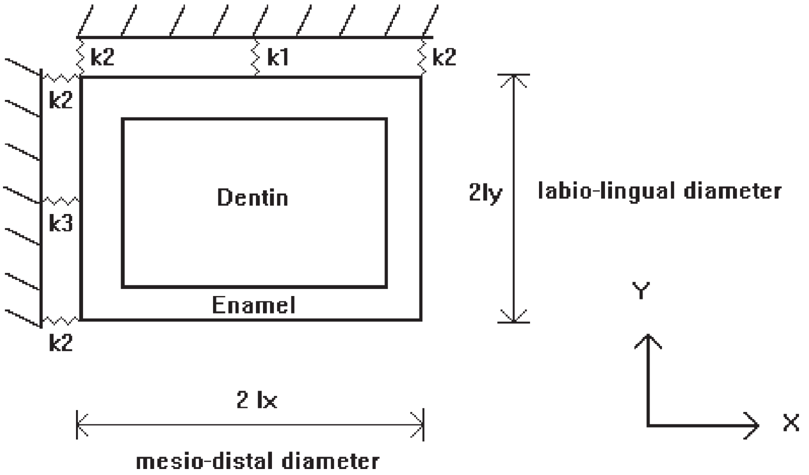

Figure 2. *Modelling of tooth mobility.*

of safety against failure for the structure containing the crack.

MODELLING OF TOOTH MOBILITY

The movement of a tooth under load may be separated into three components[2]: vertical displacement[19], horizontal displacement[20–22] and rotation[23]. Of these three components, the horizontal displacement is the largest and most damaging to the periodontal tissues[24]. In this study displacement in the horizontal plane is analysed using a two-dimensional FE model in which tooth mobility is introduced by means of elastic support in the form of linear springs as shown in *Figure 2*. The abutment teeth and pontic are represented as two-dimensional rectangular solids, with side lengths equal to the mesio-distal diameter, $2l_x$, and the labio-lingual diameter, $2l_y$, of the appropriate tooth.

The resistance to horizontal movement and rotation in the horizontal plane of each abutment tooth is represented by six springs whose combined stiffnesses give the tooth mobilities k_x and k_y in the x and y directions (where x is the mesio-distal direction and y is the labio-lingual direction) and the rotational stiffness k_θ. These mobilities are given in terms of the spring stiffnesses k_1, k_2 and k_3 in the FE model by

$$k_x = k_3 + 2k_2 \qquad k_y = k_1 + 2k_2 \qquad k_\theta = k_2\,(2l_x + 2l_y) \qquad (3.1)$$

Here, k_x, k_y, and k_θ are known from the studies of tooth mobility[21-24] and l_x and l_y are given from the anatomical data of tooth[25]. Solving equations (3.1) for k_1, k_2 and k_3 in terms of k_x, k_y, and k_θ gives

$$k_1 = k_y - k_\theta/(l_x + l_y), \qquad k_2 = k_\theta/[2(l_x + l_y)], \qquad k_3 = k_x - k_\theta/(l_x + l_y) \quad (3.2)$$

FINITE ELEMENT MODEL

A schematic of the bridge geometry, together with the 1mm thick horizontal slice analysed using two-dimensional (2-D) FE analysis, are shown in *Figure 3*. 2D FE analysis gives important information about three dimensional problems (3-D)[26,27]. It makes simpler the contruction of the model which, in this case, is complex and it reduces the initial computing time. For these reasons three-dimen-

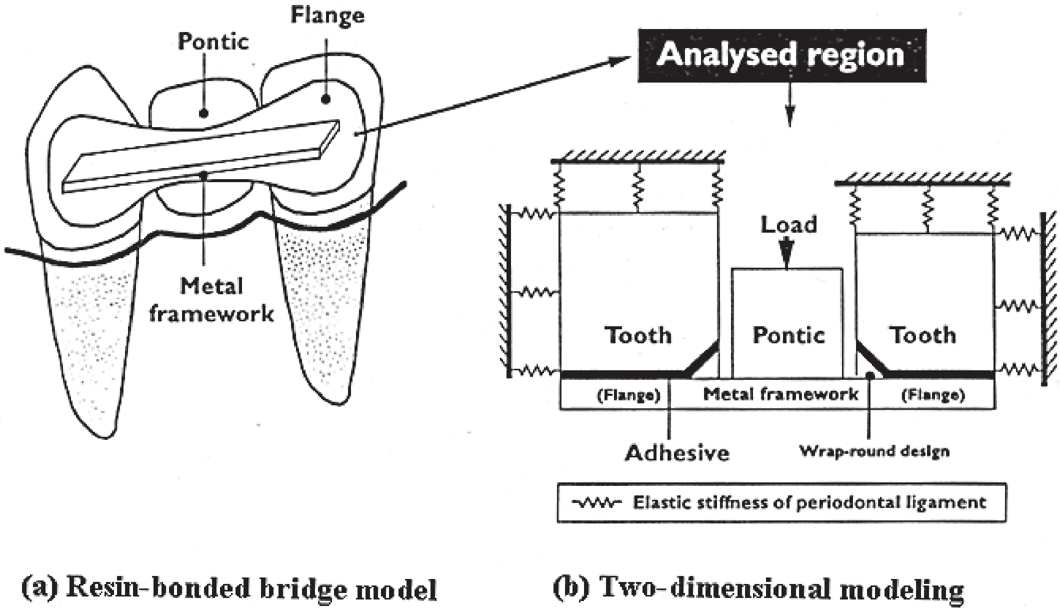

Figure 3. *Resin bonded bridge: a) Schematic, b) 2D model with elastic support.*

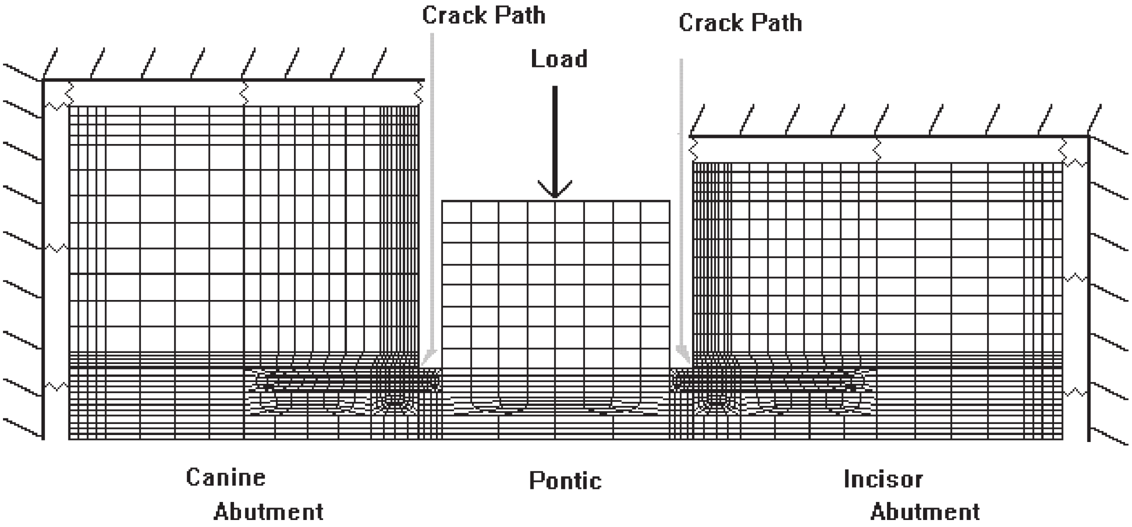

Figure 4. *Finite element mesh for a resin-bonded bridge with a metal framework design without wrap round.*

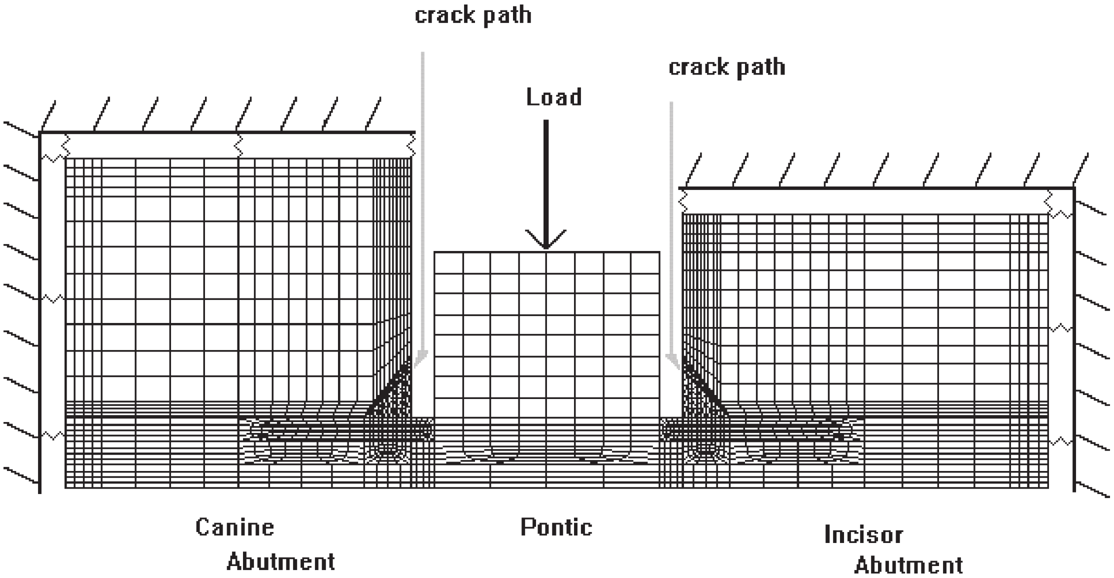

Figure 5. *Finite element mesh for a resin bonded bridge with a metal framework with wrap round.*

Table 1. *Mechanical properties of the materials used in the FE model.*

Material	*Young's modulus GPa*	*Poisson's ratio*
Pt – Au Alloy	134[2–31]	0.32 [32]
Resin	4[32]	0.3 [1]
Enamel	40[2]	0.3 [28–29]
Dentine	14[2,32]	0.3 [3,28–29]
Ceramics	200[28–29]	0.2 [29]

sion finite element analyis was not chosen for this preliminary complex analysis. Finite element models with and without frame wrap round (*Figures 4* and *5*) were analysed to assess the effect of including wrap round in the metal frame design. Frame thicknesses, t_m, of 0.5, 1.0 and 1.5mm where used in each case. The models consist of abutment teeth with enamel and dentine, an adhesive layer of 50μm thickness, a metal frame of Pt-Au alloy and a porcelain pontic. The mechanical properties of the various components in the model[2,3,28–32]are shown in *Table 1*. The load $P = 5$ Kgf is applied to the centre of the pontic in the labio-lingual direction. The first incisor abutment tooth, the pontic and the canine abutment tooth have mesio-distal diameters of 7.8, 4.8 and 7.4 mm, respectively, and the corresponding labio-lingual diameters are 4.8, 4.0 and 6.2 mm, respectively. The frame wrap round is 1mm in length and has a 45° included angle (*Figure 5*).

The elastic strain energy in the model with a constant load P is first calculated for the bridge with no cracks. Cracks of length a between the metal frame and the adhesive layer are then incorporated into the mesh geometry behind each abutment tooth, by separating elements, one by one, along the crack paths. The crack length was varied from 0.1 to 1 mm in steps of 0.1 mm. Values of the strain energy for two adjacent crack lengths were inserted into equation (2.4) to obtain the energy release rate. ABAQUS version 5.4 was used for the finite element analysis.

RESULTS

Effect of metal frame thickness

Figure 6 shows the energy release rate G as a function of crack length for 3 metal frame thicknesses where the abutments have elastic support. For each frame thickness the energy release rates with and without wrap round, denoted by G_w and G_o respectively, were found. In all cases the energy release rate decreases with t_m for a given crack length, and increases with crack length for a given t_m. The rate of change of slope of the energy release rate versus crack length curve is positive for G_w and negative for G_o.

Effect of frame wrap round

The difference $\Delta G = G_o - G_{w,}$ between the energy release rate without and with frame wrap round is shown as a function of the crack length and frame thickness (*Figure 7*). The value of ΔG exhibits a maximum with respect to a in the range $0.3 < a < 0.6$ mm depending on the frame thickness. For a given crack length the effect of adding frame wrap round is greatest for the thinnest frame.

Effect of tooth mobility

Figure 8 shows the energy release rate as a function of crack length for 3 metal frame thicknesses where the abutments have rigid support. The energy release rates for rigid and elastic support are denoted by G_r and G_e, respectively, and the ratio $\lambda = G_e/G_r$, as a function of crack length, is shown in *Figure 9*. The value of λ is less than 1 and decreases as t_m increases from 0.5mm to 1.5mm. The value of λ for a frame without wrap round is relatively insensitive to crack length, whilst the value of λ for a frame with wrap round shows a significant increase with a. The general conclusion to be drawn here is that when tooth mobility is ignored the energy release rate for an incipient crack is over-estimated. The effect of tooth mobility becomes increasingly important in the model as

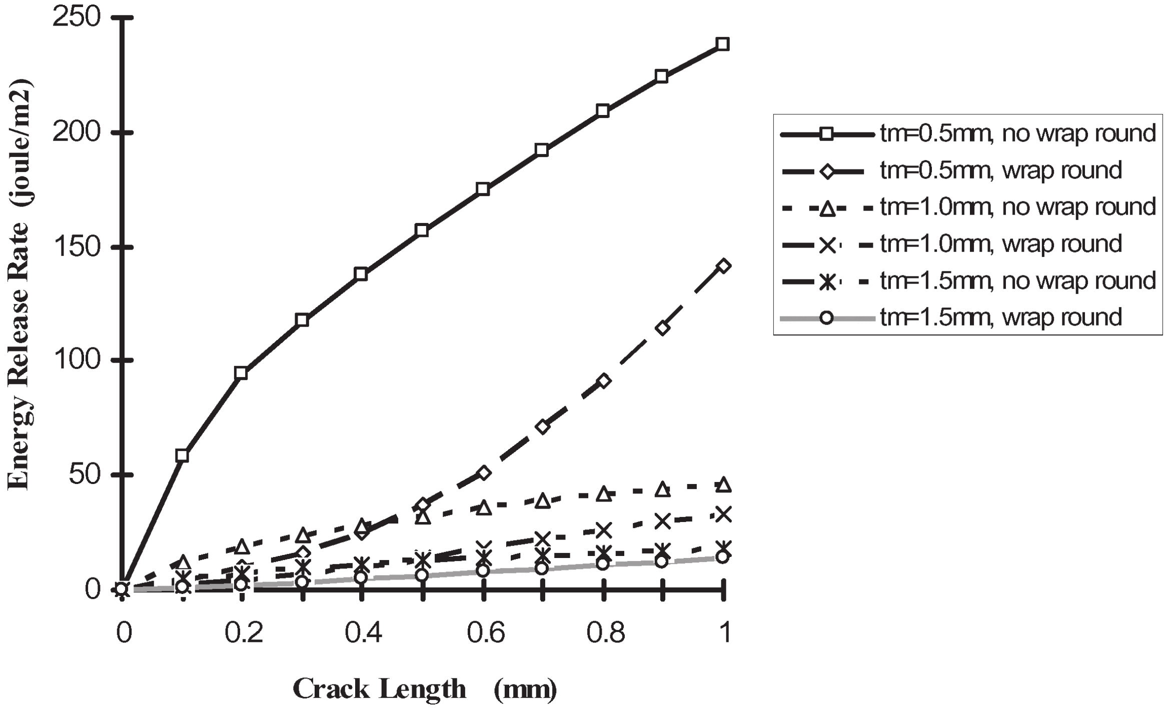

Figure 6. *Energy release rate for a metal frame design with and without wrap round, for abutments with elastic support.*

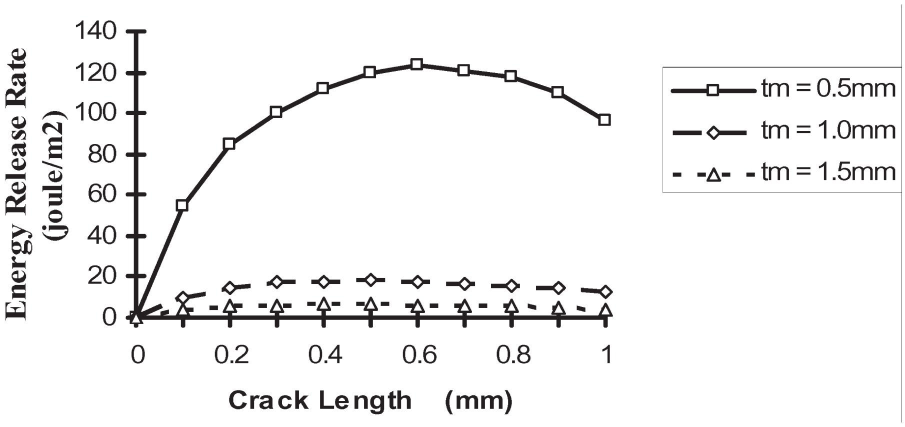

Figure 7. *Energy release rate difference, $\Delta G = G_o - G_w$, for a metal framework design with and without wrap round.*

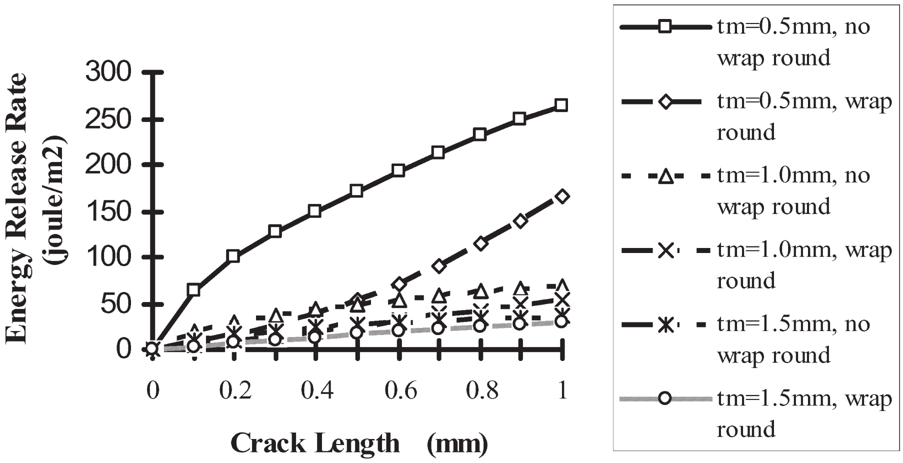

Figure 8. *Energy release rate for a metal frame design with and without wrap round, for abutments with rigid support.*

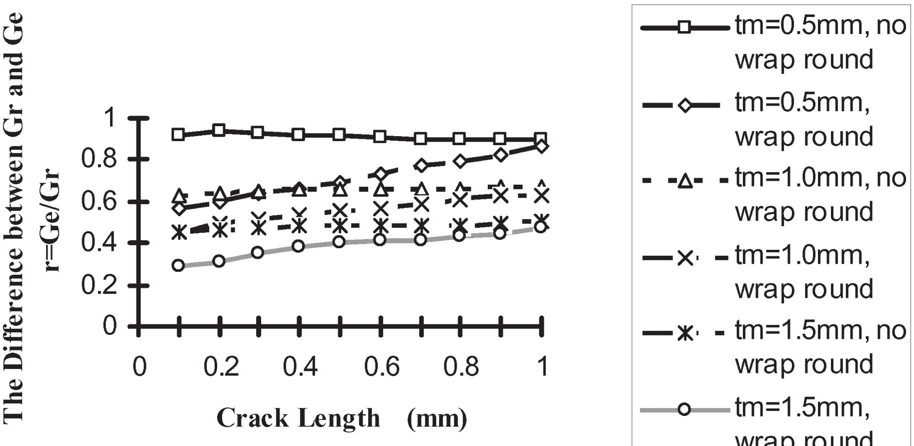

Figure 9. *Effect of tooth mobility for a metal framework design with and without wrap round.*

the overall stiffness of the bridge increases i.e. as the frame thickness is increased, wrap round is added or the crack length is reduced.

DISCUSSION

In the case of brittle fracture a crack will propagate when the energy release rate reaches a critical value, G_{crit}, equal to the specific surface energy γ. For a material that is quasi-brittle G_{crit} is understood to include the energy dissipated during plastic deformation of the material adjacent to the crack tip. To account for the reduction in surface energy that may occur in a dental environment due to chemical attack and thermal changes a factor of safety, η, is used in the fracture criterion given by

$$G_{crit} = \gamma/\eta \tag{6.1}$$

where γ is taken to be 40 J m^{-2} [31].

Figure 10 shows the variation of G_o and G_w with crack length where values of G_{crit} with η = 1, 2 and 3 are superimposed for comparison. The critical lengths of incipient cracks in the adhesive layer of a bridge without or with frame wrap round, and for a range of values of t_m and η, are shown in *Table 2*. For a given frame thickness the

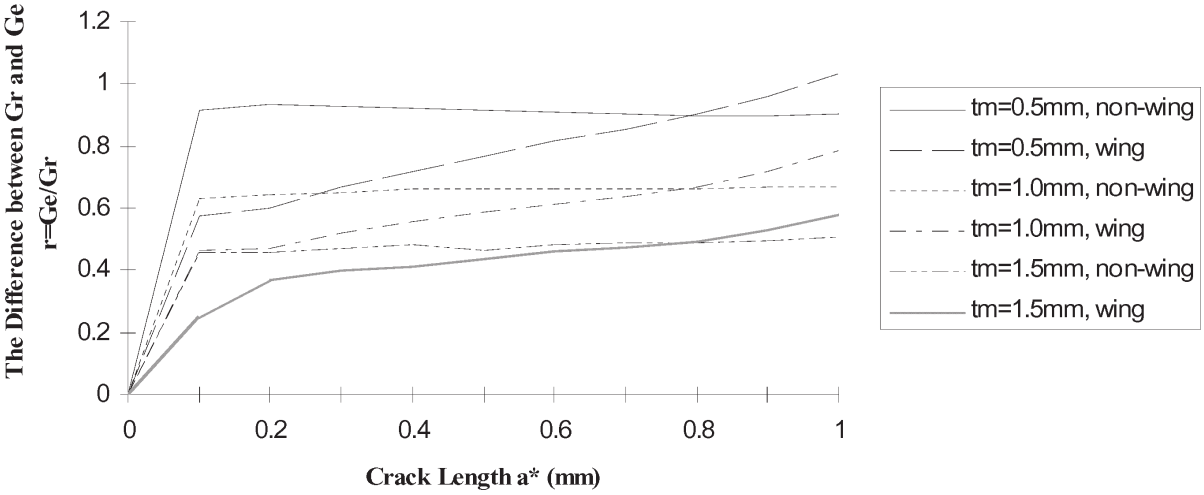

Figure 10. *Comparison of $G_{0(w)}$ and G_{crit} for metal frame design with and without wrap around and abutments with elastic support.*

Table 2. *Critical crack length in mm for metal framework (a) without wrap round and (b) with wrap round.*

(a)	*Metal framework thickness, t_m, mm*		
Safety Factor η	0.5	1.0	1.5
1	0.07	0.74	>1.0
2	0.04	0.22	>1.0
3	0.03	0.12	0.52

(b)	*Metal framework thickness, t_m, mm*		
Safety Factor η	0.5	1.0	1.5
1	0.53	>1.0	>1.0
2	0.34	0.65	>1.0
3	0.27	0.50	0.94

critical crack size decreases with increasing factor of safety and for a given factor of safety the critical crack size increases with frame thickness.

CONCLUSION

Fracture mechanics has been applied to the crack problem for a resin-bonded dental bridge. The effect of various design parameters on the energy release rate for a crack between the metal frame and the adhesive layer has been investigated and the critical lengths of incipient cracks in the adhesive layer have been estimated.

The energy release rate decreases with increasing frame thickness and when a wrap round feature is added thereby making crack propagation less likely. For a given crack length the effect of adding the wrap round shape is greatest for the thinnest frame.

Tooth mobility becomes increasingly important in the model as the overall stiffness of the bridge increases. If tooth mobility is ignored and the abutments are assumed to have rigid support the energy release rate for an incipient crack is overestimated. This simplified model will therefore underestimate the strength of the bridge and hence lead to a bridge design with an enhanced factor of safety.

The influence of frame thickness and wrap around design on the fracture strength of a bridge has important clinical implications. During the preparation and fabrication of an adhesive bridge there are various factors which may result in a framework of reduced thickness. Probably the most important of these is the operator's conservative approach which can lead to under-preparation of the abutment teeth. This will result in the technician fabricating a framework with insufficient bulk. Framework thickness is also jeopardised in patients with a complete bite. Although the importance of a wrap around design is recognised by clinicians there may be a reluctance to incorporate it into a frame design because of aesthetic considerations.

The fracture strength of a bridge is dependent on the stiffness of the frame that in turn depends not only on the frame geometry but also on the elastic properties of the frame material. If an alloy or material of reduced elastic modulus is employed there will be a corresponding reduction in fracture strength of the bridge.

ADDRESS FOR CORRESPONDENCE

Dr. David Fenner, Department of Medical Engineering, King's College London, University of London, Strand, London WC2R 2LS, UK.E-mail: david.fenner@kcl.ac.uk

REFERENCES

1. Caputo, A.A., Gonidis, D. and Matyas, J. Analysis of stresses in resin bonded fixed partial dentures. *Quintessence Int.,* 1986; **17:** 89–93.
2. Shinohara, N. and Takao, Y. Crack growth analysis along the adhesive layer of resin-bonded bridge based upon the energy release rate concept. *Reports of Research Institute for Applied Mechanics, Kyushu University,* 1988; **35:**1–11.
3. Shinohara, N. Fracture mechanics analysis of the durability of resin-bonded bridge – the effect of resin-bonded bridge design parameters on crack growth along adhesive layer. *Dent. Mater. J.,* 1988; **7:** 62–73.
4. Northeast, S.E., van Noort, R. and Shaglouf, A. Tensile peel failure of resin-bonded Ni/Cr beams: an experimental and finite element study. *J, Dent.,* 1994; **22:** 252–256.
5. Hansson, O. and Bergström, B. A longitudinal study of resin-bonded prostheses. *J. Pros. Dent.,* 1996; **76:**132–139.
6. Eshleman, J.R., Janus, C.E. and Jones, C.R. Tooth preparation designs for resin-bonded fixed partial dentures related to

enamel thickness. *J. Pros. Dent.*, 1988; **60:**18–22.
7. Burgess, J.O. and McCartney, J.G. Anterior retainer design for resin-bonded acid-etched fixed partial dentures. *J. Pros. Dent.*, 1989; **61:** 433–436.
8. Livaditis, G.J. and Thompson, V.P. Etched castings: an improved retentive mechanism for resin-bonded retainers. *J. Pros. Dent.*, 1982; **47:**52–58.
9. Ohno, H., Araki, Y. and Endo, K. A new method for promoting adhesion between precious metal alloys and dental adhesives. *J. Dent. Res.*, 1992; **71:**1326–1331.
10. Kohli, S., Levine, W.A., Grisius R.J. and Fenster, R.K. The effect of three different surface treatments on the tensile strength of the resin bond to nickel-chromium-beryllium alloy. *J. Pros. Dent.*, 1990; **63:**4–8.
11. Tanaka, T., Nagata, K., Takeyama, M., Atsuta, M., Nakabayashi, N. and Masuhara, E. 4-META opaque resin – a new resin strongly adhesive to nickel-chromium alloy. *J. Dent. Res.*, 1981; **60:**1697–1706.
12. Krueger, G.E., Diaz-Arnold, A.M., Aquilino, S.A. and Scandrett, F.R. A comparison of electrolytic and chemical etch systems on the resin-to-metal tensile bond strength. *J. Pros. Dent.*, 1990; **64:**610–617.
13. Kondo, Y., Yamashita, A., Suzuki, K., Omura, I. and Yamauchi, J.I. Studies on the pre-treatment of dental alloy for adhesive restorations 4. The adhesive durability of adhesive resin to various dental alloys treated with composite plating. *Shika Zairyo Kitai,* 1989; **8:** 572–579.
14. Livaditis, G.J. Etched-metal resin-bonded intracoronal cast restorations. Part 1: The attachment mechanism. *J. Pros. Dent.*, 1986; **56:**267–273.
15. Marinello, C.P., Kerschbaum, T.H. and Heinenberg, B. *et al.* First experiences with resin-bonded bridges and splint – a cross-sectional retrospective study, Part II. *J. Oral Rehab.*, 1988; **15:**223–235.
16. Shaw, M.J. and Tay, W.M. Clinical performance of resin-bonded cast metal bridges (Rochette Bridges). *Br. Dent. J.*, 1982; **152:** 378–380.
17. Gilmour, A.J.M. Resin-bonded bridges: a note of caution. *Br. Dent. J.*, 1989; **167:**140–141.
18. Wilson, W.K. Finite element methods for elastic bodies containing cracks. In: Sih, G.C. (Eds): *Method of Analysis and Solutions of Crack Problems.* Noordhoff: Leyden, 1973; 484–515.
19. Picton, D.C.A. A study of normal tooth mobility and the changes with periodontal disease. *Dent. Practit.*, 1962; **12:**167–170.
20. Mühleman, H.R. Tooth mobility 1. The measuring method: initial and secondary tooth mobility. *J. Periodont.*, 1954a; **25:** 22–29.
21. Mühleman, H.R. Tooth mobility 2. The role of interdental contact points and activation on tooth mobility. *J. Periodont.*, 1954b; **25:** 125–127.
22. Mühleman, H.R. and Zander, H.A. Tooth mobility 3. The mechanism of tooth mobility. *J. Periodont.*, 1954; **25:**128–137.
23. Goto, T. The experimental study of physiological mobility of teeth. *Shikagakuhou,* 1971; **7:**1415–1444.
24. Lindhe, J. *Textbook of Clinical Periodontology.* Munksgaard: W.B Saunders, 1980.
25. Wheeler, R.C. *An Atlas of Tooth Form.* Philadelphia: WB Saunders 1963.
26. Huiskes, R. and Chao, E.Y.S. A survey of finite element analysis in orthopaedic biomechanics: the first decade. *J. Biomechanic.,* 1983; **16:**385–406.
27. Meijer, H.J.A., Starmans, F.J.M. and Steen, W.H.A. A three dimensional finite element studyon two versus four implants in an edentulous mandible. *Int. J. Prosthodont.,* 1994; **7:**271–279.
28 Craig, G.C. *Restorative Dental Materials.* St Louis: C.V. Mosby 1997; 406.
29. Anusavice, K.J. In: Phillips' *Science of Dental Materials.* Skinner and Phillips *Dental Cements for Bonding Application.* Philadelphia: Saunders, 1996; 552–582.
30. Tetelman, A.S. and McEvily, A.J. *Fracture of Structural Materials.* NY Wiley. 1967: 47–52.
31. William, J. and O'Brien, ?. *Dental Materials and Their Selection* 3rd edn Quinntessence Publishing Co Inc., 2003; 312.
32. Shinohara, N. Mechanics analysis of the Durability of Resin – Bonded Bridges. The effect of Resin Bonded Bridge Design Parameters on Crack Growth along Adhesive layers. *Dent. Mat. Sci.*, 1988; **7:**62–73.