FEM Analysis of Interfacial Stress Distribution between Bovine and Resin Composite in Dentine Bonding Systems: Effect of Interfacial Elastic Modulus

Akio Nakatsuka, Kunio Wakasa and Masao Yamaki

(Received for publication, March 6, 1996)

ABSTRACT

Stress concentration in cylindrical specimen composed of three different phases (resin, adhesion elastic layer, and dentine) was estimated by FEM (finite element method) analysis. When a uniformly distributed stress of 10 MPa was applied at the top surface of the model, the stress at the central part of the specimen was almost uniform and 10 MPa. Intense stress concentration was found at the region within approximately 0.2 mm from the edge of the interface. Large elastic modulus of elastic layer caused intense stress concentration, and a tensile stress of 91 MPa was obtained at the edge of the elastic layer for E=12000 MPa.

INTRODUCTION

There are mainly three kinds of adhesion techniques in dental field, metal-resin, enamel-resin, and dentine-resin systems. Bonding behavior should be analyzed for each of these bonding systems. On the other hand, it is useful to study general aspect of bonding phenomenon. There are two different types of stress concentrations in the bonding area: type 1) stress concentration due to defects such as voids and inclusions, and type 2) stress concentration due to differences of mechanical properties of materials. Stress concentration of type 2 is essentially different from type 1, because stress concentration of type 2 can not be avoided even when perfect bonding procedure is achieved.

Fig. 1 shows how stress concentration occurs at the interface between two different materials 1 and 2. When tensile stress is applied on the one ends of materials 1 and 2, strains in the direction perpendicular to the loading axis are $\nu_1\sigma/E_1$ and $\nu_2\sigma/E_2$, where E_i is elastic modulus and υ_i Poisson's ratio, respectively[1]. In case that there two materials are connected at the other ends, this strain gap must be compensated by introducing stress concentration at the bonding interface.

In this study, stress distribution in a cylindrical specimen which is composed of three regions (resion, elastic layer, and dentine), and effect of elastic modulus of elastic layer on stress distribution were analyzed numerically by FEM. Van Noort *et al.* studied stress distribution in a similar configuration, although the model did not include an elastic layer[2]. In this analysis, intense stress concentration was found at the edge of the interface between the different regions, and stress concentration intensified with an increase in elastic modulus of the elastic layer.

MATERIALS AND METHODS

A commercially supplied FEM program for axisymmetric elastic stress analysis was used for the model shown in Fig. 2. This model represented a tensile test specimen of resin adhered to a cylindrical dentine piece, which was composed of three regions. Resin part had a radius of 3 mm and a height of 3 mm, and dentine part had a radius of 6 mm and a height of 3 mm. Elastic layer was situated at the interface between the resin part and dentine part, having a thickness of 0.1 mm.

Fine triangular elements were introduced near the edge of the bonding interface because intense stress concentration was expected at this area. Elastic moduli were 3000 MPa for the resin, and 30000 MPa for the dentine respectively. Elastic modulus of the elastic layer were varied

---

Hiroshima University School of Dentistry, Department of Dental Materials (Chairman; Professor Masao Yamaki).

This study was supported in part by "*Biomaterial Combined Analysis System*" and a Grant-in-Aid (C) 07672112.

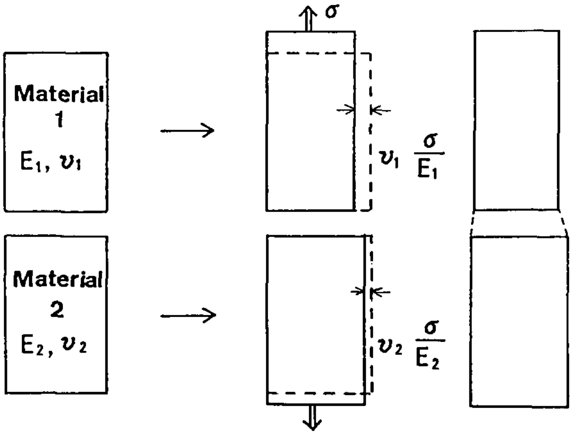

Figure 1 Stress concentration due to the difference of mechanical properties between materials 1 and 2.

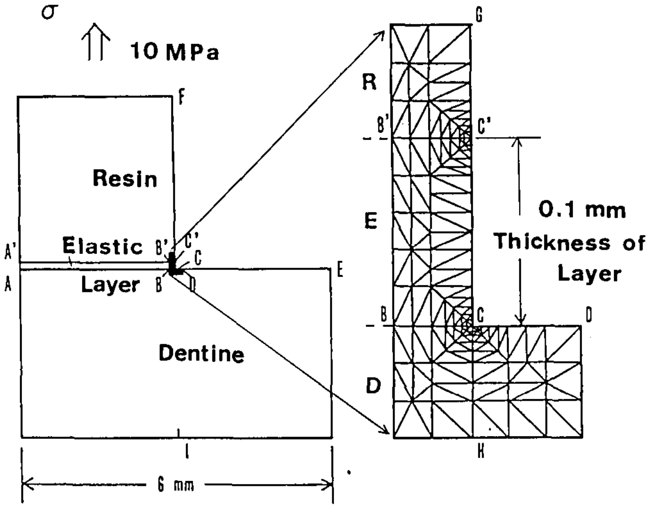

Figure 2 FEM model for analysis.

from 300 to 12000 MPa. Values of Poisson's ratio were assumed to be 0.3 for all regions.

A uniform tensile stress of 10 MPa was applied at the top surface of the model, and displacement along the loading direction at the bottom surface of the dentine was fixed to be zero.

RESULTS AND DISCUSSION

The largest values among principal stresses at the centroid of each triangular elements are shown in this paper. It should be noted that these values do not represent stresses at the exact interface.

Fig. 3 and Fig. 4 show stress distributions along ABDE and A'B'C' respectively. Stress concentrations were found at the resin-elastic layer and elastic layer-dentine interfaces. An almost uniform stress of 10 MPa was found at the central part of the specimen, and intense stress concentration was found at the region within approximately 0.2 mm from the edge of the interface. The stress concentration intensified with increase of the elastic modulus of the elastic layer.

Fig. 5 shows stress distribution along FGHI, in the direction across the elastic layer at the surface. Two peaks of stress concentration were found near the edge of the resin-elastic layer and elastic layer-dentine interfaces for E = 300, 5000, and 12000 MPa. The maximum tensile stress of 91 MPa was obtained at the inside corner of the elastic layer for E = 12000 MPa.

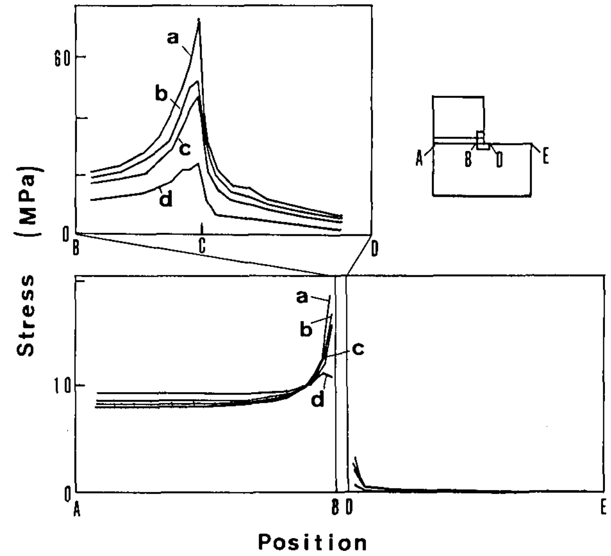

Figure 3 Stress distribution along the elastic layer-dentine interface: a) E=12000 MPa, b) E=5000 MPa, c) E=3000 MPa, and d) E=300 MPa.

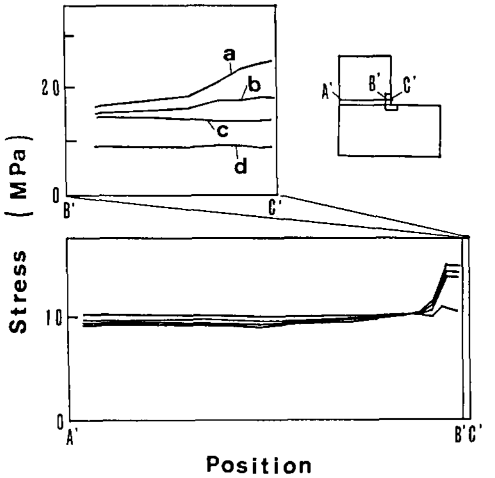

Figure 4 Stress distribution along the resin-elastic layer interface: a) E=12000 MPa, b) E=5000 MPa, c) E=3000 MPa, and d) E=300 MPa.

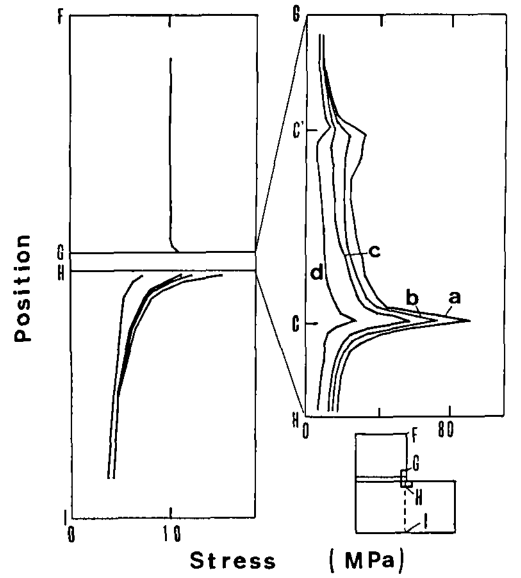

Figure 5 Stress distribution along the direction across the elastic layer: a) E=12000 MPa, b) E=5000 MPa, c) E=3000 MPa, and d) E=300 MPa.

Fig. 6 shows relationship between the maximum principal stress and elastic modulus of the elastic layer. Stress concentration intensified with increase of elastic modulus. These results suggest that a low elastic modulus is desirable for the elastic layer to reduce stress concentrations. However, there is a tendency that materials with low elastic moduli have small tensile strengths.

In the process of fracture, atoms are separated each other against interatomic attractive force, and fracture starts when stress caused by external load exceeds the maximum interatomic attractive stress σ_M (σ_{max})$^{3)}$. As shown in Fig. 7, σ_M has nearly the same order of magnitude as elastic modulus. Furthermore, actual strengths are generally between E/100 and E/1000 because of defects in the materials.

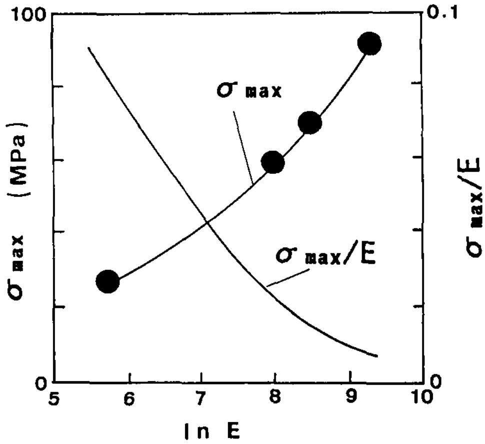

Figure 6 Relationship between the elastic modulus of the elastic layer and maximum stress values.

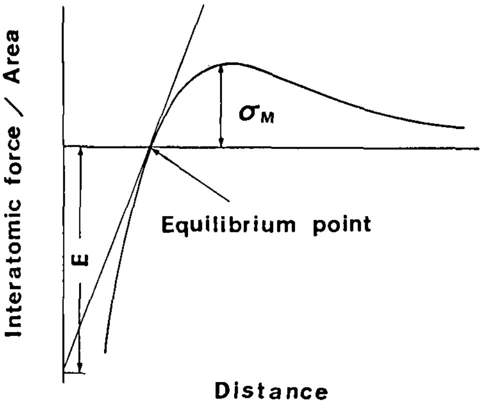

Figure 7 Schematic drawing of interatomic force-distance curve.

Thus, the ratio of maximum stress in the elastic layer to the elastic modulues, σ_{max}/E, roughly gives the possibility of fracture. Relationship between E of elastic layer and σ_{max}/E is shown in Fig. 7. It shows that large elastic modulus causes intense stress concentration and value σ_{max}/E decreases at the same time. Value σ_{max}/E is 0.01 when E is about 8000 MPa, and at this point fracture occurs if the tensile strength of the elastic layer is E/100. Thus, large elastic modulus, more than 8000 MPa would be necessary for the elastic layer in this model to prevent fracture.

According to the fracture mechanics, fracture of a material starts when stress intensity factor $K_I = k\sigma a$, where a is a crack size, σ a stress value at a place far enough from the crack tip, and k a constant, reaches a certain value K_{IC}. Then, if identical defects uniformly distribute in the test specimen, the point where fracture starts is expected to be the place where the maximum stress value is obtained, at the edge of the elastic layer-dentine interface for this model. However, crack size has a distribution in acutual test specimens.

Possibility that large sized crack locates in the region where intense stress concentration is found is small, because area fraction of this region to the entire interface area is small. Fig. 5 shows that when E = 3000 MPa, for example, stress reaches 20 MPa at about 0.025 mm from the edge of the interface. Then, an area where stress value exceeds 20 MPa is 0.47 mm^2, while the area of entire interface between elastic layer and dentine is 28.3 mm^2. This suggests that fracture does not always start at the edge of the interfece. Thus, it would be important to consider the effects of distributions in crack size and position, and thus a statistical approach is expected⁴⁾.

Furthermore, stress distributions are affected by Poisson's ratio, geometry, and thickness of the layer as well as the elastic modulus⁵⁾.

SUMMARY

Stress concentration in the elastic bonding layer of resin bonded to dentine specimen model was studied by FEM.

1. Stress concentration occured at the internal edge of the elastic layer, while the stress at the central part of the model was uniform.
2. Stress concentration intensified with an increase of elastic modulus of elastic bonding layer.

REFERENCES

1) Timoshenko, S.P. and Goodier, J.N.: *Theory of Elasticity*, 3rd edn, McGraw-Hill, New York, pp 8-9, 1973.
2) Van Noort, R., Cardew, G. and Howard, I.C.: An examination of the interfacial shear and tensile stresses in restored teeth using finite element analysis. *J. Dent.* 16, 286-293, 1988.
3) Richards, C.W.: *Engineering Materials Science*, Wardsworth Publishing Company Inc, San Francisco, pp 57-64, 1961.
4) Ban, S. and Anusavice, K.J.: Influence of test method on failure stress of brittle dental materials. *J. Dent. Res.* 69, 1791-1799, 1990.
5) Bogy, D.B.: The problem of edge-bonded elastic quarter-planes loaded at the boundary. *Int. J. Solids Structure* 60, 1287-1313, 1970.