

Dentine Bonding: Effects of Applied Stress and Thickness on Principal Stress within the Resin Composite/Dentine Interface (FEM Analysis)

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ABSTRACT

The effects of applied stress and interface thickness on nominal principal stress of test bonded samples were examined by their factors related to the quality of the resin composite/dentine interface, based on the finite element method (FEM) analysis. The distribution of stress within the interface was sensitive to their relative elastic moduli and interface thicknesses when an applied stress was loaded. FEM interface analysis model clarified that there appeared non-uniform stress distribution of principal stress during tensile loading at their resin composite/bonding area and bonding area/dentine interfaces in supposing the resin composite/dentine interface as a bonding area.

INTRODUCTION

The maximum value of an interfacial principal stress was near the edge of resin composite/dentine interface in a finite element stress calculation model which had no bonding area thickness¹. FEM analyses were applied to acetabular reconstruction², prosthetic-design analysis³, resin-bonded loaded porcelain inlays⁴, and orthodontic brackets^{5,6}. In the calculation model, the direction of the resin composite/dentine interface as the bonding area with various elastic moduli was important to calculate the

stress distribution along the interface^{1,7}. The thickness and elastic modulus of bonding area and the type of bonding agent affected the magnitude of interfacial stress⁷⁻¹⁴. The interfacial stress at adhesive resin/bonding area interface was defined as follows. It was not uniform along the interface with no bonding area thickness when a uniform loading was added to the interface^{8,15,16}. This study was to examine the effects of applied stress and interface thickness on the maximum principal stress in the bonding area with the thickness of 0.05, 0.1, and 0.2 mm. The stress distribution was calculated by means of the resin composite/dentine interface model which was proposed by Nakatsuka, Wakasa and Yamaki¹⁶.

MATERIALS AND METHODS

Fig. 1 shows the interface model calculated by finite element stress analysis, which was given by Nakatsuka, Wakasa and Yamaki¹⁶. An interface model to calculate principal stress within the resin composite/dentine interface, which has 0.05, 0.1, and 0.2 mm as an interface distance. Test sample had a cylindrical block of resin composite of 3 mm height and 6 mm in diameter, which was bonded to a flat dentine surface¹⁶. The mean thickness of bonding area was assumed to be 0.05, 0.1, and 0.2 mm, according to the earlier reports and our studies¹⁵⁻¹⁸. The elastic moduli of the bonding area were estimated to be about 0.03 to 12 GPa, as reported^{16,19}, because the relation between load change to deflection was written to calculate elastic modulus value at nano-indentation testing⁷⁻¹⁵. In this study, the values of elastic modulus were assumed to be 0.3, 3, and 12 GPa for the resin composite/dentine interface. These values were based on our same model as earlier reports^{8,16}. The effect of Poisson ratio of bonding area on the magnitude of stress distribution was considered, and then

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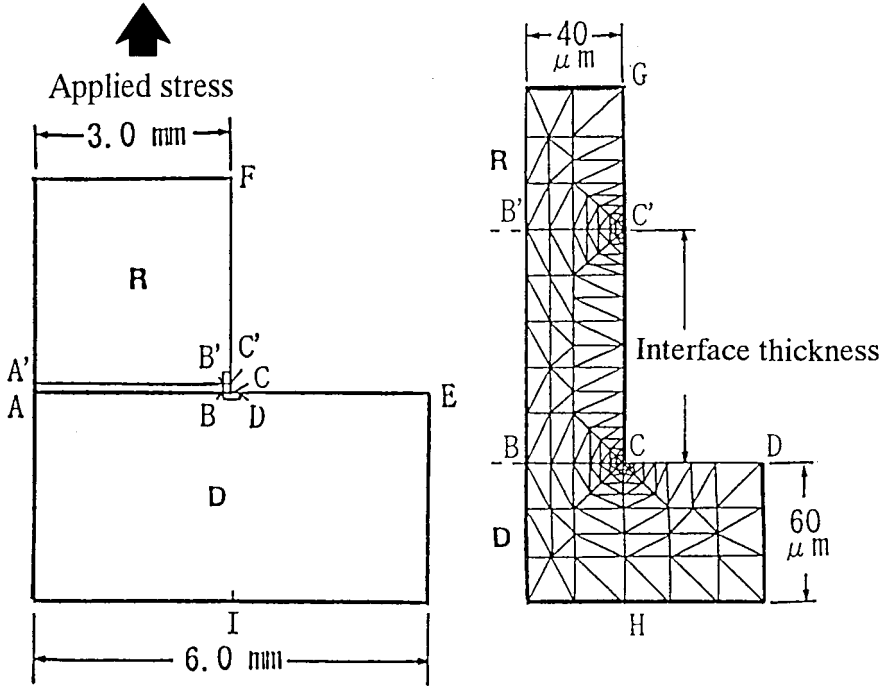


Figure 1 An interface model (a section of test sample shows a half configuration) at tensile loading direction. The section of regions R and D means resin composite and dentine (FC distance = 3 mm). The thickness of bonding area was assumed to be 0.05, 0.1, and 0.2 mm. BC and CH distances are 40 and 60 μm . $GC' = 60 \mu\text{m}$.

Poisson ratio of the interface was assumed to be 0.30 for FEM analysis, based on the values measured (0.25 to 0.35) for unfilled resin reported⁸⁾. The other studies also assumed to be 0.30 as the Poisson ratio for an adhesive resin or a unfilled base resin matrix in the bonding systems^{1,17,20)}. The model included resin composite (R) and dentine (D), and the interface was composed of resin composite resin/dentine interface. In this schematic diagram of test arrangement, the finite element mesh was generated. Upper (A'B'C') and lower interface (ABC) were indicated at the bonding area (B'C' line = 40 μm). The FGH and BCDE edges were respectively written along tensile direction and perpendicular to tensile direction. The stress distribution in the bonding area was calculated along the x-y line, and the sections of the test sample were noted as region R for resin composite and region D for dentine. The elastic moduli were 3 GPa for R, and 30 GPa for D. The stress distribution at respective interface site at tensile bond strength of 1, 5, and 10 MPa which results from the application of a tensile load (A'C' = 3 mm and B'C' = 40 μm). The maximum value of principal stress in the bonding area during tensile loading

was calculated in increasing the assumed thickness value. The small mesh was modelled at the right-angled corner at the interface between the dentine and bonding area and also the resin composite and bonding area. The bonding area has been shown clearly as bonding area which is at the interface by Van Meerbeek et al⁷⁾, ranging from 1 to 10 GPa as the elastic moduli estimated by nano-indentation testing.

RESULTS

Figures 2, 3 and 4 show a change of principal stress within the resin composite/dentine interface with the thickness of 0.05, 0.1 and 0.2 mm, respectively, when the elastic moduli were 12 (left side) and 0.3 GPa (right side). The maximum stress value was observed near dentine site. A non-uniform stress distributed within the interface, in spite of the uniform mode of tensile load. Fig. 5 shows the maximum value of principal stress values at dentine sites with the interfacial elastic moduli of 0.3, 3, and 12 MPa when applied stress values are 1, 5, and 10 MPa. The stress within the resin composite/dentine interface as the maximum values was the constant values

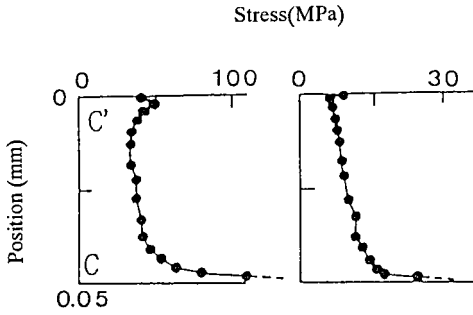


Figure 2 A change of principal stress within the resin composite/ dentine interface (thickness of 0.05 mm) when the elastic moduli were 12 (left side) and 0.3 GPa (right side). Applied stress=10 MPa.

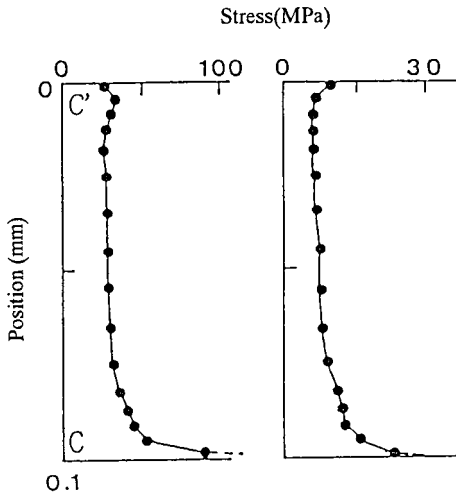


Figure 3 A change of principal stress at each site of the interface (0.1 mm) when the elastic moduli were 12 (left) and 0.3 GPa (right). Applied stress=10 MPa.

at the most sensitive dentine sites. The interfacial stress at lower interface (bonding area/dentine interface) had the maximum value at each elastic modulus value. Fig. 6 shows the maximum stress (σ_{MAX})/applied stress (σ_A) with three elastic moduli, indicating that there appeared an increased trend with increased elastic moduli. The σ_{MAX} corresponded to the maximum principal stress and the difference $|\sigma_1 - \sigma_2|$ between the principal stress, σ_1 and σ_2 .

DISCUSSION

The x and y sites are respectively resin composite and

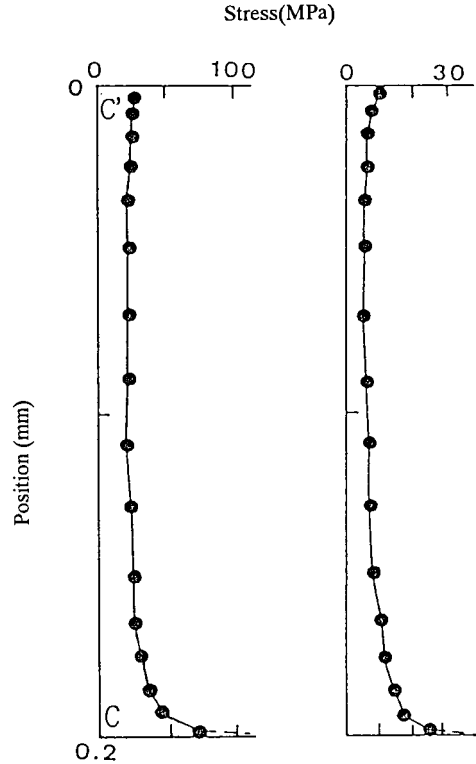


Figure 4 A change of principal stress within the interface (thickness of 0.2 mm) when the elastic moduli were 12 (left) and 0.3 GPa (right). Applied stress=10 MPa.

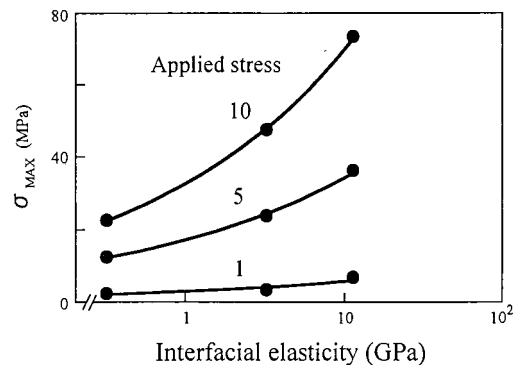


Figure 5 The maximum value of principal stress values with the interfacial elastic moduli of 0.3, 3, and 12 GPa when applied stress values are 1, 5, and 10 MPa.

dentine sites (Fig. 1). The fundamental geometry with no interface as a bonding area at resin composite/dentine interface is a model to express a two-dimensional plane strain in x_1 -(along the bonding area/dentine interface) and

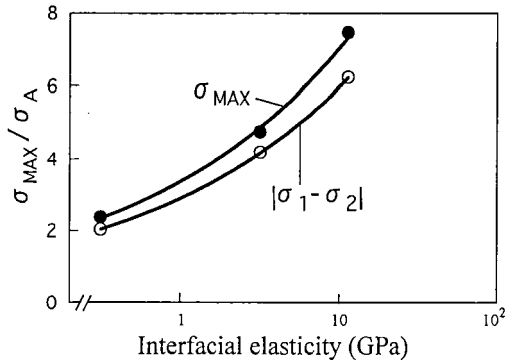


Figure 6 The relation between maximum stress (σ_{MAX})/ applied stress (σ_A) with three elastic moduli. The σ_{MAX} corresponded to the maximum principal stress and the difference $|\sigma_1 - \sigma_2|$ between the principal stresses, σ_1 and σ_2 .

x_3 -axes (along tensile loading direction)¹¹. The interfacial stress along the interfaces at tensile bond strength of 10 MPa was determined during tensile loading to the test model. The bonding area has been shown clearly as bonding area which is at the interface by Van Meerbeek et al⁷, ranging from 1 to 10 GPa as the elastic moduli estimated by nano-indentation testing. An earlier report of Van Noort et al exhibited that non-uniform interfacial stress occurred in a resin composite/dentine model with no bonding area¹⁵. It is reported that the interfacial stress is affected by elastic modulus of bonding area. The interfacial stress at lower interface (bonding area/dentine interface) had the maximum value for respective elastic moduli (Figs 2, 3, 4).

We discuss the bonding mechanisms of various etched-dentine adhesive systems, whose different types of conditioners, primers and adhesive resins are used. It is important to consider the finding of hybrid layer at the dentine/resin composite interface, which was first proposed by Nakabayashi et al²⁰, showing that it is the primary bonding mechanism of most dental bonding systems. In the dental adhesive system, the primer agent is applied after the dentine conditioner is rinsed off. The primer wets and penetrates the collagen-mesh network, to increase the wettability of the dentinal surface. Then, adhesive (bonding) resin is applied to it and penetrates the primed dentine. The visible light-cured or chemically-cured resin copolymerized with primer to form an intermingled layer of collagen and adhesive resin. The copolymerized region on the hybrid layer is the bonding area

as a resin composite/dentine interface²⁰. The magnitude of bond strength were considered by such a factor as test geometry, loading configuration and stiffness of bonding area^{16,17}. The resin composite/dentine interface was important in considering a bonding mechanism^{1,16,17,19,21}. The fact is important that the stress distribution along the resin composite or dentine interface site is not uniform when applied stress is loaded uniformly during bond test. The maximum stress values occurred at the edge of resin composite site or dentine site. The bonding resins in commercial dentine bonding systems had the wide varied elastic moduli in a range of below 1 to 20 GPa¹⁸.

Dentine adhesive systems (etching, primer and adhesive or bonding agent) were estimated by shear or bonding test, and only bond strength values were discussed on the adhesive properties. The elastic modulus values calculated by hardness measurement were ranging from 1 to 10 GPa¹⁸. The elastic moduli of bonding area were affected by the quality of bonding agent as an adhesive resin. The Interfacial stress as the maximum at resin composite/bonding area or bonding area/dentine interface had different trends in a variation of elastic moduli^{19,21}. The change of principal stress was obtained with different thickness of bonding area, and the tensile interfacial stress was the maximum at dentine site of the bonding area. The maximum value was constant at respective values of interface thickness with 0.05, 0.1, and 0.2 mm.

The results suggest that interfacial stress at dentine site (bonding area/dentine interface) is more than at resin composite site (resin composite/bonding area interface), because the maximum value of principal stress was obtained only at dentine site of the interfaces with 0.05, 0.1, and 0.2 mm (thickness). The effect of interfacial elastic modulus on principal interfacial stress at tensile bond strength of 10 MPa was clarified in estimating it for the resin composite/dentine interface (elastic moduli of 0.3, 3 and 12 GPa). Interfacial stress along resin composite/bonding area interface or bonding area/dentine interface had an increased trend with increasing elastic modulus. The interfacial stress distributed non-uniformly and locally at the most sensitive sites, as indicated at the edge of bonding area/dentine interfaces with three elastic modulus values. Maximum value of interfacial stress increased gradually with increasing the elastic modulus of bonding area from 0.3 to 12 GPa, as indicated by the difference between two principal stresses (Fig. 6).

CONCLUSION

This study concluded that the nominal principal stress of test bonded samples was influenced by the thickness of the resin composite/dentine interface. The distribution of stress within the interface was sensitive to the quality of the interface between resin composite and dentine, that is, elastic modulus and interface thickness. Using the interface model, finite element stress analysis model showed non-uniform stress distribution of principal stress during tensile loading at their upper and lower interfaces.

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