原　　著

Analytical Model of Shear and Tensile Bond Testing: Definition of Yield Criteria

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ABSTRACT

This study proposed the calculation model of shear or tensile loading to dentine surface which was parallel or perpendicular to the interface (interdiffusion zone), as referred to be bonding area or hybrid layer on bonded dentine surface. This concept for calculation model was based on yield criteria due to equivalent stress, deviation stress and mean stress expressed by principal stress. Thus, an analytical equation predicted the meaning of stress direction and the interface between dentine and resin composite, representing that the magnitude of shear or tensile strength was estimated in dental dentine bonding systems.

INTRODUCTION

Recent studies reported that the value of shear or tensile strength at bond test was given by the calculation models[1−5], and a standardisation method to determine bond strength has been proposed[6]. A finite element stress analysis revealed that the maximum value of an interfacial principal stress was near the edge of resin composite/dentine interface in a calculation case which had no bonding area thickness[7]. The stress direction to the test samples were parallel and perpendicular to the resin composite/dentine interface as the bonding area. It is assumed that the interfacial stress is determined by the nature of the layer, because the strength values depended on the thickness and elastic modulus of bonding area[8−10]. Also, the loading was not uniform along the interface between resin composite and bonding area (adhesive resin)[11,12]. This study is thus to propose the calculation model to predict shear and tensile strength values in the test sample including the layer, i.e. bonding area or hybrid layer when bonded to dentine surface.

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MATERIALS AND METHODS

Figure 1 shows a schematic diagram to indicate the section of a cylindrical block of resin composite with 3 mm height (D) and 6 mm in diameter as a test sample which is bonded to a flat dentine surface in dentine bonding systems (DBSs). Previous studies reported that the mean thickness of bonding area (l) was assumed to be 0.025 to 0.2 mm[11−13]. In this model, the stress distribution in the bonding area was calculated along the 1-axis on the coordinate. This fundamental geometry with no bonding area has been already reported as a model to express a two-dimensional plane strain in x_1-axis (along the bonding area/dentine interface) and x_3-axis (along tensile loading direction)[3]. Van Meerbeek et al, SEM (scanning electron microscopy) study reported that the interdiffusion zone was observed clearly as bonding area which was identified as the interface[13]. To estimate the yield criteria in the layer, the equation is expressed as, according to Jaoul[14],

$$(\sigma_e/\sigma_e^*) + (\sigma_m/\sigma_m^*) = 1 \qquad (1)$$

where σ_e is the equivalent stress and σ_m is the mean stress. Their stresses were defined as

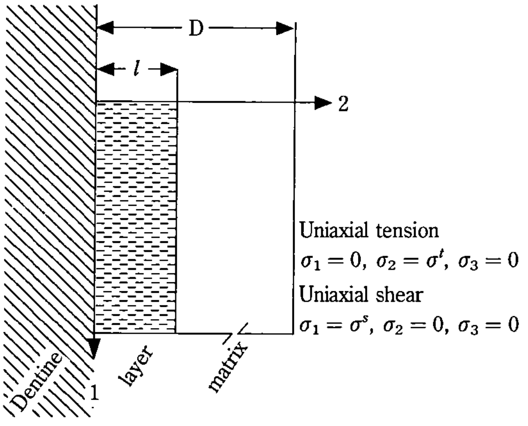

Figure 1 A schematic diagram for a calculation model which indicates a section of cylyndrical test sample at shear or tensile bond loading. The section of regions shows resin composite, layer (bonding area or hybrid layer) and dentine. The coordinate shows a principal stress directions of 1- and 2-axes. The lengths of D and l mean the sample height and thickness of the layer in this study. In the cases of uniaxial tension and uniaxial shear, the stress conditions were given, indicating that the subscript t and s mean tension and shear direction.

$$\sigma_e = (3\sigma'_{ij}\sigma'_{ij})^{1/2},\ \sigma_m = \delta_{ij}\sigma_{ij}/3,\ \sigma'_{ij} = \sigma_{ij} - \delta_{ij}\sigma_{ij}/3 \quad (2)$$

where δ_{ij} is a Kronecker delta and σ'_{ij} is the deviation stress. Thus, the stress condition and yield criteria at uniaxial yield stress (tensile) can be expressed as

$$\sigma_e = \sigma^t,\ \sigma_m = \sigma^t/3$$
$$\sigma_y^t = 1/(1/\sigma_e^* + 1/3\sigma_m^*),\ \sigma_y^t = 3\sigma_y^c/(2\alpha^c + 3) \quad (3)$$

where σ_y^c is the yield stress at uniaxial compression test.

In a case of uniaxial yield stress (shear), the following stress condition can be expressed as, using equations (1), (2), and (3),

$$\sigma_e = \sigma^s,\ \sigma_m = \sigma^s/3$$
$$\sigma_y^s = 3\sigma_y^c/(2\alpha^c + 3) \quad (4)$$

Here $\sigma_y^c > 0$, $\sigma_y^s < \sigma_y^c$, and $\sigma_y^t < \sigma_y^c$ consisted. Using these equations, the ratio of σ_y^s/σ_y^c was calculated with respect to the value of α^c which expressed a relation between shear and compression loading.

RESULTS AND DISCUSSION

To clarify a change of principal stress in the bonding area at tensile bond strength, a loading direction was indicated in Figure 2. The principal stress as a nominal applied stress was estimated in this mode[1,11]. A change of principal stress in the bonding area with the thickness of bonding area was given as reported already[15]. The result predicted that the maximum stress values was observed near dentine site and a non-uniform stress distributed in the bonding area during a uniform mode of tensile load. This result agreed with an earlier report of Van Noort et al that non-uniform interfacial stress occurred in a resin composite/dentine model with no bonding area[3]. The calculation model which gave the stress values at dentine sites showed the stress inside the bonding area as the maximum values was the constant values of about 26 MPa at the most sensitive dentine sites[15,16]. This result suggests that interfacial stress is affected by elastic modulus of bonding area. An earlier study reported that an interfacial stress value at the upper resin composite/bonding area interface was the maximum for the lowest value, while the interfacial stress at lower bonding area/dentine interface had the maximum value for given elastic modulus values[15].

Figure 3 shows the stress ratio σ_y^s/σ_y^c with respect to α^c value in DBSs, by using equation (4). The bonding mechanism of various etched DBSs is proposed by the hybrid layer (resin-impregnated layer) or interdiffusion zone (the interface between dentine and adhesive resin), although different types of conditioners (etchant), primers and adhesive (bonding) resins are applied in dental DBSs. A formation of hybrid layer between dentine and resin composite, which was first described by Nakabayashi et al[16], is proposed as a primary bonding mechanism of

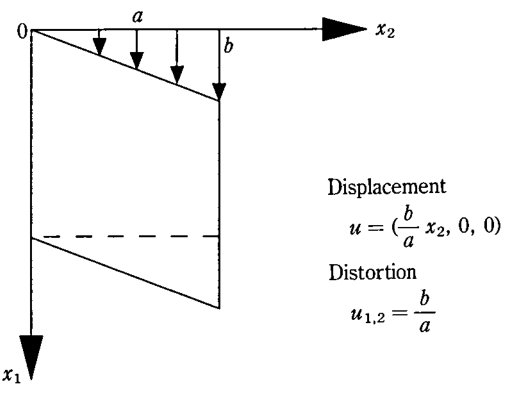

Figure 2 An example of shear loading; the displacement and distortion were defined on x_1- and x_2-axes.

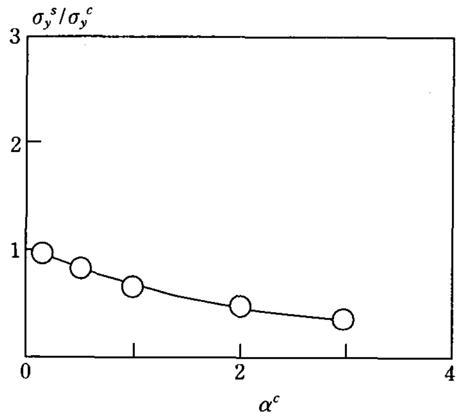

Figure 3 The α^c and σ_y^s/σ_y^c relation was given in the case of shear loading, according to equation (4) in the text. The strength value was obtained using the result[14]. See text for key.

dental DBSs. A primer agent in DBSs is used after the *conditioner* is rinsed off. The role of a primer agent is known as follows. The primer wets and penetrates the collagen-mesh network, to increase the wettability of the dentinal surface. Adhesive resin is applied to it and penetrates the primed dentine. The 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 between resin composite and dentine, which is first described by Van Meerbeek et al[13]. The factors which affected the magnitude of bond strength were test geometry, loading configuration and stiffness of bonding area[13,15−17]. The bonding area at resin composite/dentine interface was important in considering a bonding mechanism[1,13,15]. The nano-indentation evaluation of bonding resins in commercial DBSs had the wide range of 1.0 to 20.0 GPa as elastic modulus[4].

The DBSs, including etching, primer and bonding agent, were estimated by shear or bonding test, to determine only bond strength values as an adhesive property. Previous studies reported that the elastic modulus values were calculated by hardness measurement, ranging from about 1.0 to 10.0 GPa[3,4,16], showing that the magnitude of elastic moduli of bonding area affected the nature of bonding area as an adhesive resin. The types of adhesive resins with varied elastic modulus should be tested to confirm our calculation results, and this result suggests that an interfacial stress as the maximum at resin composite/bonding area or bonding area/dentine interface has the different trends in a variation of elastic moduli. Using an analytical calculation model to predict the nature of bonding area between them, the stress distribution is estimated, and a finite element stress analysis is effective when applied during shear or tensile bond test of the resin composite/dentine interface. As indicated by a schematic diagram (Figure 1), the stress during bond test worked to a composite material including a resin composite (resin matrix and filler), the layer (resin composite/dentine) and dentine. This suggests that the inhomogeneous deformation occurs plastically in the layer, i.e. the interface which is called to be *eigenstrain*[18].

CONCLUSIONS

This study clarified that the method for bond testing of shear or tensile was modelled as indicated by a schematic diagram to predict the distribution of interfacial stress along the interfaces of bonded area in DBSs. Based on yield criteria expressed by equivalent stress, deviation stress and mean stress, the meaning of shear or tensile loading was defined clearly. As suggested, the molophology of test sample dimension was very important in estimating the distribution of stress in the bonding area which was supposed to be sensitive to their relative elastic moduli of bonding area.

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