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Interfacial stress distribution between bovine dentine and resin composite in dentine bonding systems

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In finite element stress analysis, the principal interfacial stress at a tensile bond strength of 10 MPa during tensile loading was estimated for the resin composite/dentine material including the bonding area with elastic moduli of 0.03, 0.3, 3.0 and 12.0 GPa assumed in this study. Interfacial stress along the resin composite/bonding area interface or bonding area/dentine interface increased with increasing elastic modulus. The interfacial stress distributed non-uniformly and locally at the most sensitive sites, that is, the edge of the resin composite/bonding area interface with the lowest elastic modulus (0.03 GPa) and the edge of bonding area/dentine interfaces with other elastic modulus values (0.3, 3.0 and 12.0 GPa). The maximum value of interfacial stress increased linearly with increasing elastic modulus of bonding area from 0.03 to 12.0 GPa. This study showed that the distribution of interfacial stress was highly non-uniform along the interfaces of the bonded areas in dentinal adhesives.

1. Introduction

Wide variations of bond strength have been demonstrated during shear or tensile bond testing [1, 2]. The critique of bond strength determined by finite element stress analysis showed that the maximum interfacial stress was near the edge of the resin composite/dentine interface, and that the magnitude exceeded the applied tensile bond strength during tensile loading in a calculation case with no bonding area between them (bonding area thickness = 0 μm) [3]. The loading geometry of test samples was different for shear and tensile testing: shear and tensile tests were, respectively, parallel and perpendicular to the direction of the resin composite/dentine interface. The bonding area of different elastic moduli was observed [1–3]. The geometry parameters depended on the nature of the bonding area, such as the thickness and elastic modulus of the bonding area and the type of bonding agent [4–11]. Finite element analysis demonstrated that interfacial stress at the adhesive resin/bonding area interface was not uniform along the interface in the absence of bonding area thickness [3, 12]. This study examines the stress distribution at the interfaces of resin composite/ bonding area and bonding area/dentine with a bonding area thickness of 100 μm and a large variation of elastic moduli of bonding area of 0.03, 0.3, 3.0 and 12.0 GPa, and attempts to clarify the effect of the elastic modulus of the bonding area on the interfacial stress.

2. Materials and methods

The test sample was a cylindrical block of resin composite of 3 mm height and 6 mm diameter bonded to a flat dentine surface. The mean thickness of bonding area was assumed to be 100 μm (as shown in Fig. 1) in the calculation model, in accordance with earlier reports and studies [13–15]. The elastic moduli of the bonding area were estimated at about 1.0–10.0 GPa, using the relation between load change to deflection and elastic modulus value at nano-indentation testing [4, 13, 15]. Thus, the elastic moduli assumed in this model for the bonding area were 0.03, 0.3, 3.0 and 12.0 GPa.

The calculation model used for finite element stress analysis is shown in Fig. 2, and comprises resin composite, bonding area (composite resin/dentine interface) and dentine. This fundamental geometry has previously been reported as a model to express two-dimensional plane strain in x- (along the bonding area/dentine interface) and z-axes (along the tensile loading direction) [3], but the bonding area was not given. The interfacial stress along the interfaces at tensile bond strength was determined during tensile loading of the test model. The mesh was generated using the finite element program developed by Nakatsuka, which was calculated for a section of a cylindrical test sample [17]. 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 (Fig. 2). The distances BC and CH, 40 and 60 μm, were selected to clarify stress distribution at the edge. The choice of mesh size was determined as described in previous reports [17]. A small fillet was applied at the bottom edge of the resin composite to join the interface of the dentine and resin composite, where the interface was not considered.

Elastic moduli of dentine and resin composite used were, respectively, 15.0 and 25.0 GPa, and 5.0 to 25.0 GPa [13].

The assumed elastic moduli had a very large range from the lowest to the largest magnitudes, to clarify the effect of elastic modulus on interfacial stress along their interfaces. The tensile or shear bond strength varied from about 2.0 to 20.0 MPa with a large scatter when the thickness of the bonding area was 10–100 μm [14, 15, 18]. Based on this wide variation in values of bond strength, we assumed the applied tensile bond strength to be 10 MPa in the finite element stress analysis, and the interfacial stress was calculated along the resin composite/bonding area or bonding area/dentine interface. The principal stress as a nominal applied stress was estimated in this model, as defined by Hirth and Lothe [19].

3. Results

Fig. 1 shows an example of bonding area which is described as the interface between resin composite (upper) and bovine dentine (lower) when the dentine bonding system (primer and bonding agents) of Light Bond (Tokuyama, Yamaguchi, Japan) was applied. This has also been shown clearly as the bonding area which is at the interface by Meerbeek *et al.* [4], ranging from 1.0 to 10.0 GPa as the elastic moduli estimated by nano-indentation testing.

Fig. 2 shows a schematic diagram of the test arrangement to generate the finite element mesh used for stress analysis. Upper (A′B′C′) and lower interface (ABC) are indicated at the bonding area (B′C′ line = 40 μm), and FGH and BCDE edges are, respectively, along the tensile direction and perpendicular to the tensile direction. The stress distribution was calculated at the edges GC′CH and BCD (GC′ = 60 μm, C′C = 100 μm and CH = 60 μm), and the sections of the test sample were noted as region R for resin composite, region E for bonding area and region D for dentine.

Fig. 3 shows the stress distribution with the maximum value at the respective interface site at a tensile bond strength of 10 MPa, which results from the application of a tensile load along the upper A′B′ or B′C′ edge in Fig. 2 (A′C′ = 3 mm and B′C′ = 40 μm). The stress distribution during tensile loading had increased magnitudes along A′B′ and an increased trend at the edges with increasing assumed elastic moduli of 0.03 (d), 0.3 (c), 3.0 (b) and 12.0 GPa (a).

Fig. 4 shows the values at lower sites ABDE or BCD of bonding area for each elasticity value 0.03–12.0 GPa, representing that greater values at the edge site C than 10 MPa were given with increasing elastic modulus. AC, BD and CD lines are, respectively, 3 mm, 100 μm and 60 μm. Interfacial stress values at AB and CD interfaces were about 10–30 MPa, and about 10–70 MPa when the elastic modulus ranged from 0.03 to 12.0 GPa. There was a compressive stress at the dentine surface with the lowest elastic modulus

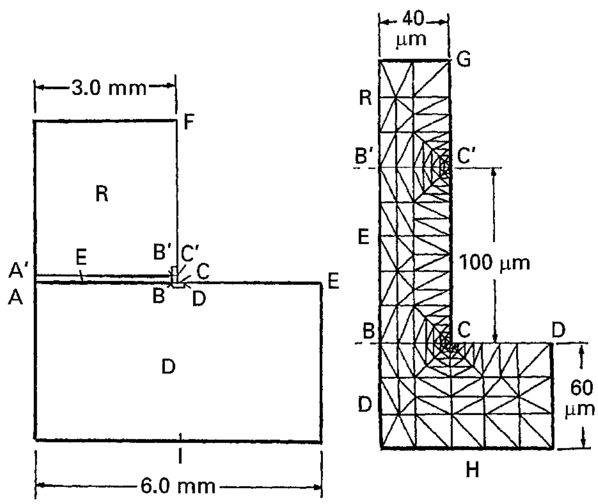

Figure 2 Calculation model (section of test sample shows a half configuration) in the tensile loading direction. In the finite element mesh for the stress distribution which was generated, the regions R, E and D denote the resin composite, bonding area and dentine (FC distance = 3 mm). The thickness of the bonding area was assumed to be 100 μm. BC and CH distances are 40 and 60 μm; GC′ = 60 μm.

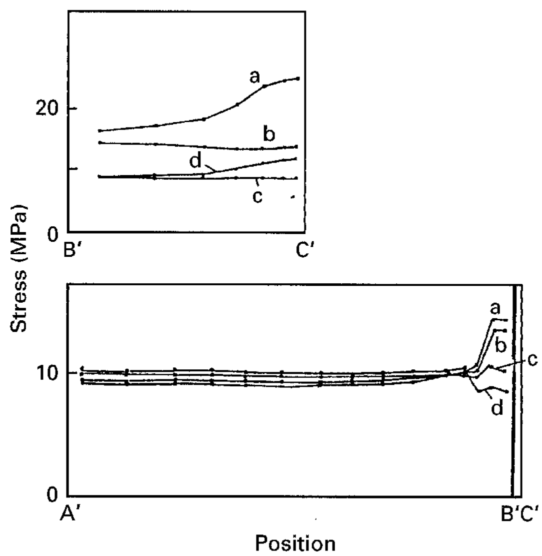

Figure 3 Effect of elastic modulus in the bonding area on the stress distribution at a tensile bond strength of 10 MPa. At B′C′ and A′B′ interfaces of the bonding area, the stress distribution was written. Symbols a, b, c, and d denote 12.0, 3.0, 0.3, and 0.03 GPa elastic moduli. A′B′C′ and B′C′ distances are 3 mm and 40 μm.

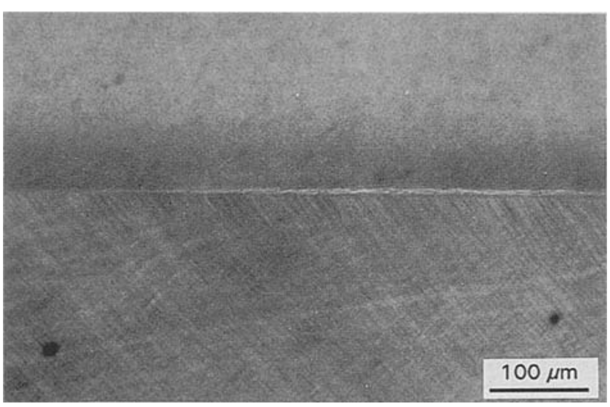

Figure 1 Example optical micrograph of the resin composite/dentine interface (Light Bond; Tokuyama Co, Yamaguchi, Japan). The bonding area is observed as the interface.

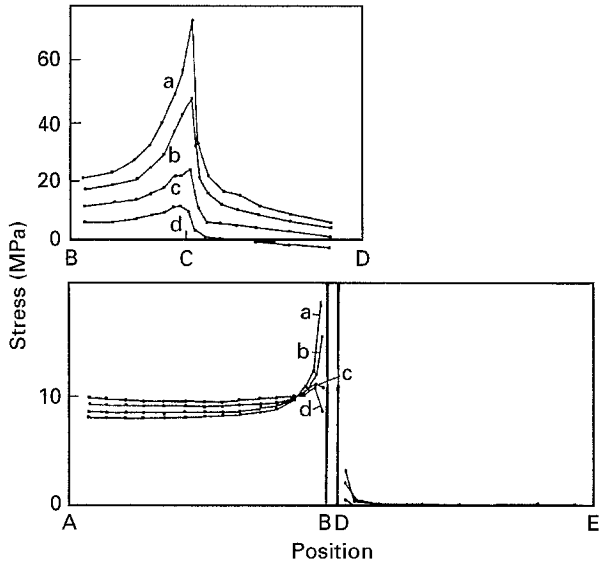

Figure 4 Interfacial stress distribution at tensile bond strength value of 10 MPa calculated at BCD interface and ABDE line. ABDE line = 6 mm. BC and CD distances = 40 and 60 μm. Symbols a, b, c, and d denote 12.0, 3.0, 0.3, and 0.03 GPa, respectively.

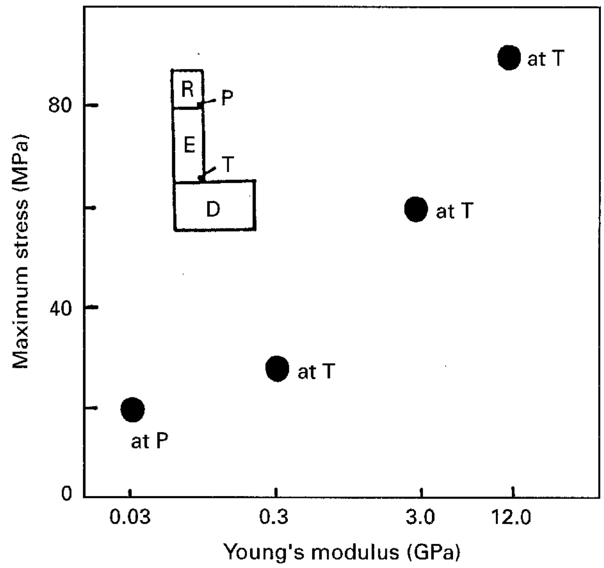

Figure 6 Change of maximum interfacial stress with elastic Young's modulus at tensile bond strength of 10 MPa during tensile loading at sites P (resin composite/bonding area interface) and T (bonding area/dentine interface).

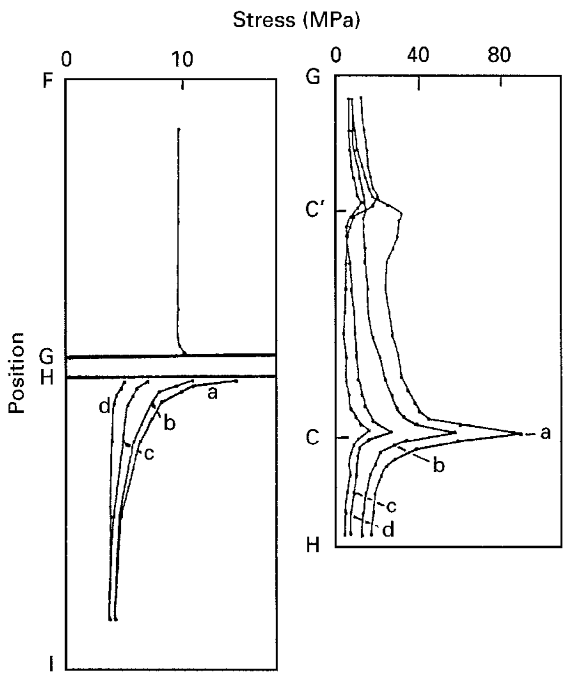

Figure 5 Stress distribution at tensile bond strength of 10 MPa along tensile direction at FGHI (6 mm) and GC′CH (GC′ = 60 μm, C′C = 100 μm, CH = 60 μm). Symbols a, b, c, d denote 12.0, 3.0, 0.3, 0.03 GPa.

(d; 0.03 GPa), similar to the Van Noort *et al.* study in which there was no interface between resin composite and dentine [3]. Fig. 5 shows the stress distribution along the GC′CH or FGHI sites at a tensile bond strength of 10 MPa. The value at the GH site was greater at the sites C and C′. It is evident that a non-uniform stress distributes along the interfaces, in spite of the uniform mode of the tensile load. This result agrees with an earlier report by Van Noort *et al.* that non-uniform interfacial stress occurred in a resin composite/dentine model with no bonding area [3].

Fig. 6 shows the change of maximum interfacial stress values at their sites with elastic moduli of 0.03, 0.3, 3.0 and 12.0 GPa. The maximum values of interfacial stress were obtained at the most sensitive sites of the test sample. This result suggests that interfacial stress is affected by the elastic modulus of the bonding area. The interfacial stress value at the upper interface (resin composite/bonding area interface) was a maximum for the lowest value (0.03 GPa), while the interfacial stress at the lower interface (bonding area/dentine interface) had a maximum value for other values, as calculated in this study.

4. Discussion

The bonding mechanisms of various etched-dentine adhesive systems are remarkably similar, although different types of conditioners, primers and adhesive resins are used. Formation of a hybrid layer between dentine and resin composite, which was first described by Nakabayashi *et al.* [16], is thought to be the primary bonding mechanism of most dental bonding systems. A primer is applied after the conditioner is rinsed off. 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 copolymerizes with primer to form an intermingled layer of collagen and adhesive resin. The copolymerized region on the hybrid layer is the bonding area between the resin composite and the dentine, which was first described by Van Meerbeek *et al.* [15].

4.1. The nature of the bonding area

The factors which affected the magnitude of bond strength were test geometry, loading configuration and stiffness of bonding area [13, 18]. As Van Noort *et al.* [1, 3, 13] and Wakasa and Yamaki [18] demonstrated, the bonding area at the resin composite/dentine interface is important when considering bonding mechanisms. The important result was that the stress distribution along the resin composite or dentine interface site was not uniform at a tensile bond strength of 10 MPa during uniform tensile loading. The maximum stress values occurred at the edge of the resin composite site or dentine site. The bonding resins in commercial dentine bonding systems have a wide range of elastic moduli (from below 1.0 to 20.0 GPa), as estimated by nano-indentation testing [4]. The effect of the Poisson ratio of the bonding area on the magnitude of stress distribution is considered, because the value measured is 0.25 to 0.35 for unfilled resin [3, 20, 21]. Poisson's ratio for the bonding area was assumed to be 0.30 in this study. Other studies usually showed 0.30 for an adhesive resin or a unfilled base resin matrix [1, 3–5, 12,15].

4.2. Interfacial stress distribution

The stress distribution in the bonding area was not uniform in the tensile direction (Figs. 3, 4 and 5). This result agrees with the result that fracture occurred near the centre of cylindrical test samples under tensile loading, and the principal stress was a maximum for inhomogeneous stress distribution [3]. Van Noort *et al.* reported (using finite element stress analysis) that the stress distribution at both sides of the resin composite and dentine without the interface, or bonding area [13]. It is possible to consider that failure might be initiated at either the resin composite/bonding area or the bonding area/dentine interface. This consideration might correspond to such failure modes as cohesive fracture or interfacial fracture of the bonding area/dentine interface [7, 14, 16]. In our calculation model there appeared non-uniform values of interfacial stress along the interface when the elastic moduli ranged from the lowest to the highest values used (Fig. 6). This suggests that our calculation model is very important in the estimation of bond strength during fracture of the bonded area.

4.3. Effect of the elastic modulus of the bonding area on stress distribution

Dentine bonding agent systems (etching, primer and bonding agent) were estimated by shear or bonding test, and only bond strength values were discussed on the adhesive properties. Recently, elastic modulus values have been calculated by hardness measurements, and range from about 1 to 10 GPa [3, 4, 15]. The magnitude of the elastic moduli of the bonding area affected the nature of bonding agents as an adhesive resin. It is recommended that various types of adhesive resins with a range of elastic moduli should be tested to confirm our calculation results, because the maximum interfacial stress at the resin composite/bonding area or bonding area/dentine interface had different trends with different elastic moduli.

The test model including bonding area was applied to calculate the stress distribution using finite element stress analysis under an applied tensile bond test to the resin composite/dentine interface. (1) The change of principal stress was obtained with different elastic modulus of bonding area. (2) The tensile interfacial stress distribution at each site perpendicular and parallel to the tensile loading changed with increasing elastic modulus values from 0.03 to 12.0 GPa. (3) The maximum value occurred at the resin composite/bonding area interface with 0.03 GPa (elastic modulus) and at the bonding area/dentine interface with 0.3, 3.0 and 12.0 GPa.

Bond tests gave the value of the nominal strength at failure of test bonded samples [1–3, 13–16]. This study clarified that the distribution of stress was sensitive to the relative elastic moduli of the bonding area between the resin composite and the dentine. A finite element stress analysis model exhibited non-uniform stress distribution of principal stress during tensile loading at the interfaces of the resin composite/bonding area and the bonding area/dentine. In the calculation model case with bonding area, the interfacial stress along the interface was estimated, leading to the result that the magnitude of stress distributed locally at the most sensitive sites, that is, near the edge of the bonded interface.

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