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Influence of Surface Area and Geometry of Specimens on Bond Strength in a Microtensile Test: An Analysis by the Three-Dimensional Finite Element Method

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Abstract

Purpose: This study employed three-dimensional (3D) finite element analysis to investigate the stress distribution patterns in a microtensile test with the goal of evaluating the effects of the bond surface area and geometry on bond strength.
Materials and Methods: Finite element models of six specimens were generated: three stick models and three hourglass models. All models simulated the bond strength between dentin and ceramic. The mechanical properties of the materials—the modulus of elasticity and Poisson's coefficient—were defined according to a literature review. The base of each specimen was considered inserted (constrained area) and possessed nodes with displacements restricted in all directions. A traction load, which was calculated to generate a uniformly distributed stress of 20 N/mm^2 at the bond interface, was applied to the top of the specimen. The distribution pattern of the generated stress was qualitatively and quantitatively measured based on color scales ranging from blue to red, according to the von Mises equivalent stress.
Results: Specimens with similar shapes demonstrated similar stress distributions. Ceramic specimens had a higher stress value (30.35 MPa) compared to specimens consisting of resinous cement (23.59 MPa) and dentin (19.77 MPa). At the bond interface, the specimens with square sections demonstrated stress values ranging from 22.00 to 24.20 MPa. For the circular section, the stress values ranged from 23.40 to 27.00 MPa.
Conclusion: The maximum stress values determined for the circular and square sections were similar among specimens with the same interface area. At the bond interface, the highest stress values were observed in hourglass-shaped specimens.

Adhesive procedures have caused marked changes in dental practices and alterations in clinical restorative procedures. The rapid development of adhesives together with esthetic restorative materials has improved the quality of restorative dentistry. In addition, the development of adhesives has created a need to measure the adhesive bond strength of restorative materials to mineralized tissues. An understanding of the physical phenomena that occur in a tooth cavity during material placement, setting, and functional processes is crucial for determining the appropriate restorative techniques and selecting the best material.[1,2] In recent years, several methods have been developed to evaluate the adhesive bond strength of materials to dental substrates, including mechanical tensile tests, shear tests, and the microtensile test.[1-11]

Sano et al[12] proposed the use of the microtensile test in dental studies. This test uses specimens of very small dimensions, typically hourglass or stick (parallelograms) shaped, which require a great deal of care at the time of the specimen preparation.[5,12] Some of the advantages of the microtensile test are the possibility of measuring the bond strength in a small area of the interface, the ability to map the bond strength in different regions of the tooth,[4,12,13] the requirement for a smaller number of teeth (material savings),[2] and a smaller number of cohesive failures.[14] Although the microtensile bond strength testing method is considered a more reliable adhesion test, it is labor intensive, time consuming, and technically demanding.[5] Other limitations include the following: very low bond strengths (<5 MPa) are difficult to measure, specimens are

Table 1 Characteristics of the analyzed specimens

Identification of specimens	Type of bond interface	Dimensions of base mm × mm	Area of the bond interface mm^2	Maximum dimensions of the elements Volume I mm	Volume II mm	Volume III mm
P1	Square	0.80 × 0.80	0.64	0.05	0.20	0.40
P2	Square	1.00 × 1.00	1.00	0.05	0.20	0.40
P3	Square	1.20 × 1.20	1.44	0.05	0.20	0.40
A1	Circular	0.98 × 0.98	0.64	0.05	0.20	0.40
A2	Circular	1.22 × 1.22	1.00	0.05	0.20	0.40
A3	Circular	1.47 × 1.47	1.44	0.05	0.20	0.40

susceptible to dehydration, specimens are easily damaged, specimens with a consistent geometry are difficult to fabricate, and there is a lack of consensus regarding the protocol used for the test and the reporting of pre-test failures and fractures beyond the designated test area.[2]

The finite element method constitutes one of the most complete tools for the study of stress distribution.[2] This method has been used in the aeronautical industry for several decades. In addition, the finite element method has been used successfully in studies in the biomechanical area because it provides information about the state of stresses in complex structures, such as teeth, via a numerical analysis. This method has been shown to be precise because it accounts for the intrinsic characteristics of various structures that comprise the teeth. Thus, the finite element method provides a more adequate response to multivectorial loads. In addition, this method allows the simulation of stresses in two-dimensional (2D) and three-dimensional (3D) mathematical models, which can reproduce complex structures with irregular geometries.[15,16] Many variables affecting the mechanical behavior of restorations can be studied via simulation in a numerical modeling approach,[7,11] and a systematic understanding of the stress patterns involved in bond failure is an important factor in evaluating the usefulness of a specific bond strength testing method.[7]

Concerning the study of adhesion, numerical techniques that employ finite element analysis (FEA) can be used to determine the state of stress and strain, energy release rates, or stress-intensity factors within a bonded joint.[8] In 1989, Betamar et al[17] conducted a study in which an FEA was used to examine common methods for measuring bond strength and to propose a standardization of the procedures. The results revealed that the properties of the materials and the variations in geometry and loading conditions had a significant influence on adhesive bond strength values. Interestingly, the stress distributions determined using the finite element method reproduced the fracture pattern observed in specimens submitted to microtensile tests.[13]

Researchers have employed several tests to measure adhesive bond strength, such as tensile, shear, microtensile, and microshear tests.[4] Unfortunately, the data obtained using the

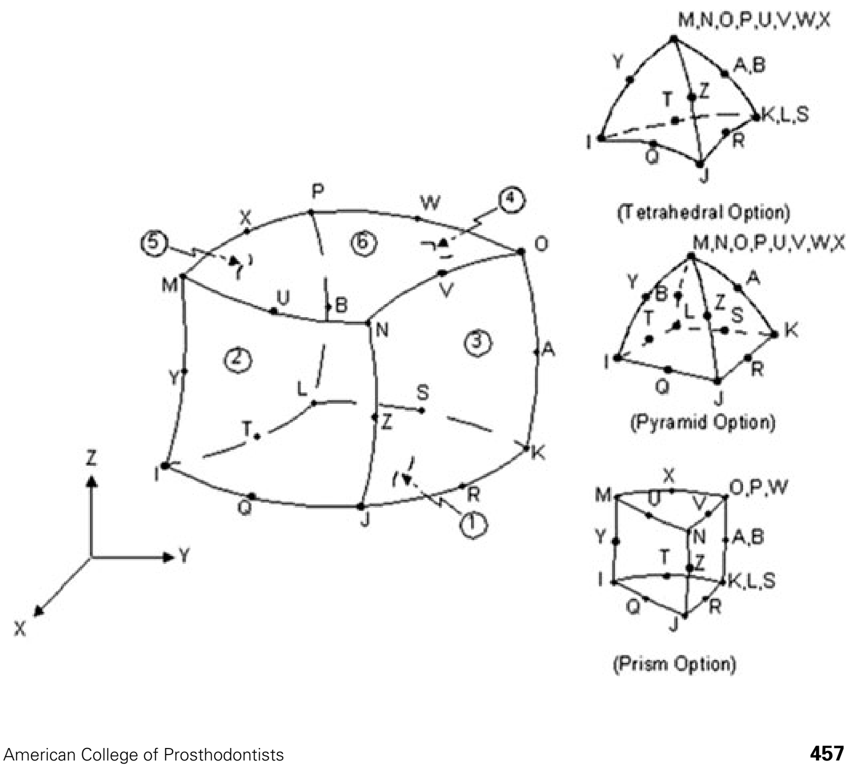

Figure 1 Geometry of the SOLID95 element from the library of the program ANSYS 8.0 showing the shape options of the elements from the coincidence of the knots.

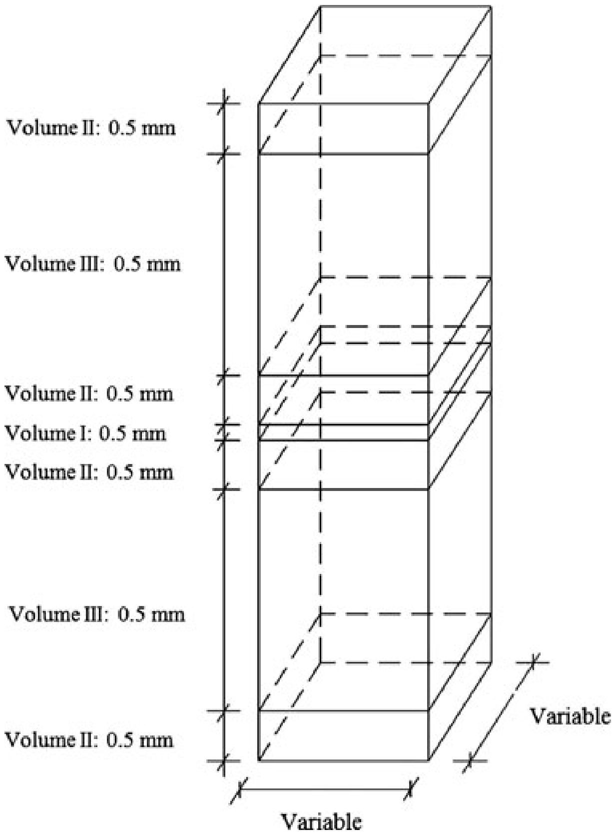

Figure 2 Typical division of the specimens into volumes for discretization.

same materials and tests have been variable due to differences in the adopted methodologies. Indeed, the lack of methodological standardization among different studies employing the microtensile test (i.e., different parameters and variability in the specimen design) might lead to a misinterpretation of the results.[6,10] Although a consensus or standard approach is currently lacking in dentistry, bond strength testing remains useful and necessary to screen new products and to study experimental variables.[2]

Therefore, in the present study, the influence of the bond surface area and the geometry of the specimens on adhesive bond strength were evaluated via an analysis of the results using the finite element method.

Materials and methods

Six specimens were modeled in the present study: three stick models (parallelograms) and three hourglass models. Three bond interface areas were tested for each model: 0.64 mm^2, 1.0 mm^2, and 1.44 mm^2. The bond interface was square for the stick specimens and circular for the hourglass specimens. The dimensions of each specimen are presented in Table 1.

The numerical test for the method involved two stages: pre-processing and post-processing. In the pre-processing stage, we used the tri-dimensional element SOLID95, which was obtained from the ANSYS 8.0 program library (Ansys Inc., Canonsburg, PA), to discretize and obtain the mesh (Fig 1). This element demonstrated a tetrahedron geometry with 20 nodes and three degrees of freedom (directions x, y, and z). Both the stick and the hourglass specimens were divided into volumes, and each volume was discretized with the maximum dimensions of the element (Fig 2). The dentin and the ceramic each had a length of 6.0 mm, and the bond interface had a thickness of 50 μm.

Figure 3 shows the discretization of the stick and hourglass specimens in the complete specimen and in the bond interface region. The elements in the mesh demonstrated more condensation near the bond interface, providing greater detail.

For the dentin, resinous cement, and ceramic materials, the modulus of elasticity and Poisson's coefficient values were adopted as described previously (Table 2). All structures were considered homogenous, linear, and isotropic. Perfect adhesion between the ceramic and resinous cement and between the resinous cement and dentin was assumed.

The bases of the specimens were considered inserted (constrained area), and they displayed nodes with displacements restricted in all directions. A tensile load was applied to the top of the specimen. The applied load was calculated such that it would generate a uniformly distributed stress of 20 N/mm^2 at the bond interface. This uniform application would allow us to evaluate the influence of the specimen shape on the stress distribution.[18] The nodes located at the top of the models, where the load was applied, were restricted such that they would undergo the same displacement. This restriction simulated conditions in which the top and bottom parts of these models were fixed in rigid elements, as observed in the microtensile test.

The next stage consisted of processing (i.e., calculating the matrix of rigidity and of the nodal displacement and tensions). The distribution patterns of the stresses generated in the specimens were determined according to a color scale that ranged from blue to red.

Results

The results obtained for stress distributions are presented in Table 3. The figures that demonstrated stresses in the longitudinal direction (direction z) revealed that the distribution of surface stresses was similar for specimens with the same shape. The highest stresses occurred in ceramic (30.35 MPa), while in resinous cement (23.59 MPa) and in dentin (19.77 MPa) low stress concentrations occurred (Figs 4 and 5). Therefore, the bond interface area did not influence stress concentration.

Because the bond interface area did not influence stress concentration, specimens with an area of 1.0 mm^2 were used for further analysis. The analysis was performed in an elastic regime for loads that provided a stress of 20 N/mm^2 at the bond interface. Thus, the measured stresses were evaluated and analyzed with reference to this value.

In ceramic (0.25 mm from the bond interface), the stresses measured in the model with the square bond interface were concentrated in the transversal direction and demonstrated values of 28.20 to 30.04 MPa (Fig 6). In the circular section of the hourglass model, the stress was concentrated around the entire outline of the cross section, and the values ranged from 27.00 to 30.04 MPa (Fig 7). In the center of this circular section, a

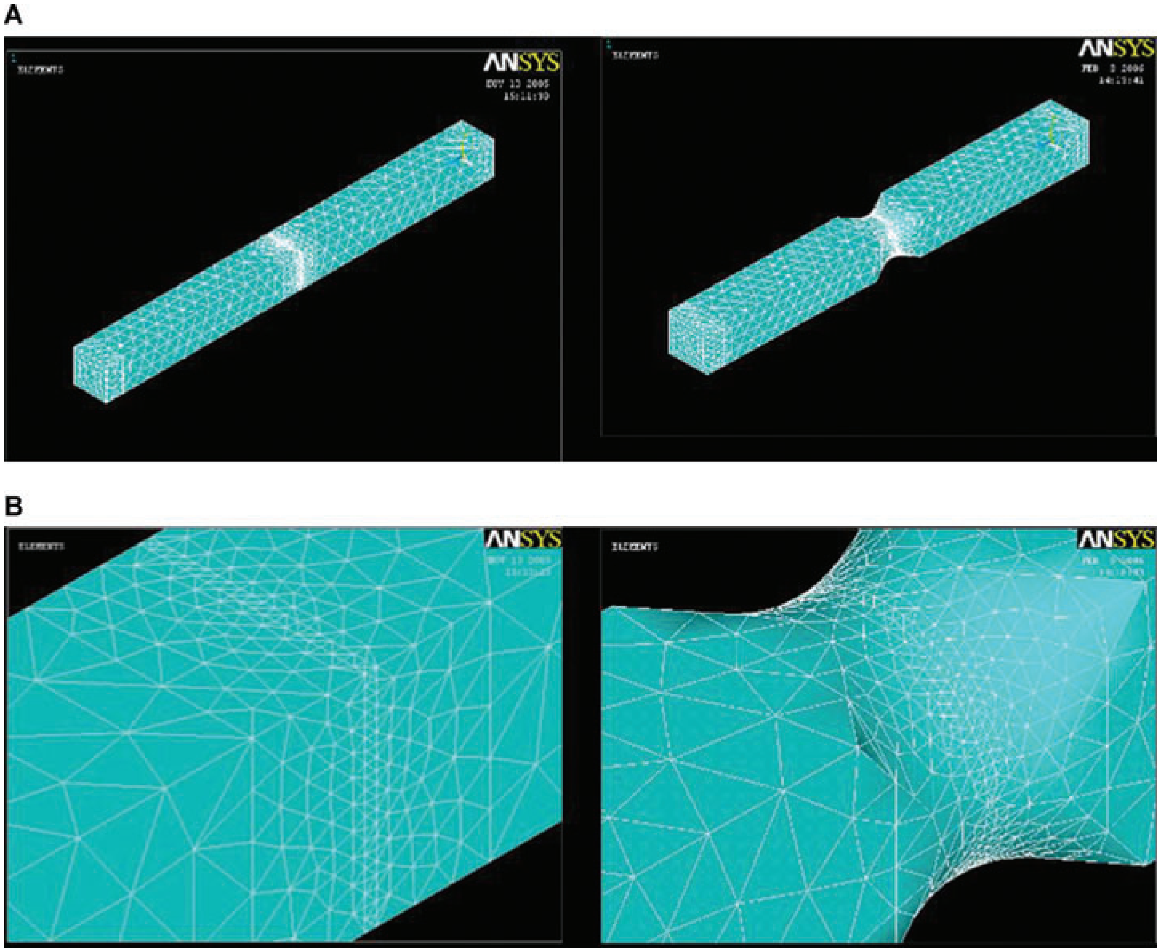

Figure 3 Typical discretization of the stick-shaped and hourglass-shaped specimens: (A) complete specimen; (B) bond interface region.

Table 2 Modulus of elasticity and Poisson's coefficient values for dentin, resinous cement, and ceramic

	Modulus of elasticity (N/mm^2)	Poisson coefficient
Dentin[16]	18.000	0.31
Resinous cement[16]	22.200	0.30
Ceramic[4]	69.000	0.28

stress of 12.6 to 16.2 MPa was detected, which was less than the stress measured in the center of the square section (18.0 to 20.0 MPa).

In the bond interface, the specimens with square sections (Fig 8) displayed stresses at the edges, reaching values of 22.00 to 24.20 MPa. In the circular section (Fig 9), the stresses along the outline ranged from 23.40 to 27.00 MPa. Interestingly, at the surface of the specimens, the maximum stress concentration was greater in circular than in square sections.

In dentin (0.25 mm from the bond adhesive), the stresses varied between a maximum (in surface) of 20.00 to 22.00 MPa and a minimum (center) of 18.00 to 20.00 MPa (Fig 10); however, the stresses varied between a maximum (in surface) of 19.80 to 23.40 MPa and a minimum (center) of 16.20 to 19.80 MPa (Fig 11). Interestingly, the stress values measured in dentin were very similar to the applied load (20 MPa), which was justified by the mechanical properties of dentin.

Discussion

FEA is capable of quantifying the effect of each tested parameter on bond strength. Previous studies have shown that FEA predictions are consistent with the experimental results with respect to relative bond strengths in three different geometries.[8,10] Two specimen types were used in the present study, and the finite element model showed that the stresses were not uniformly distributed in either type. This finding is consistent with the results of previous studies.[5,10,17,19,20] Because we used a 3D model, we were also able to examine cross sections of the specimens, permitting a more accurate determination of the stress distribution. As expected, the highest concentration of stresses occurred in the ceramic component because it was the most rigid part of the model.[21]

Table 3 Stress distribution (N/mm^2) in specimens according to the shape of bond interface and location of tension

	Ceramic		Bond interface		Dentin	
	Square	Circular	Square	Circular	Square	Circular
Surface	28.2 to 30.4	27.0 to 30.4	22.0 to 24.2	23.0 to 27.0	20.0 to 22.0	19.8 to 23.4
Center	18.0 to 20.0	12.6 to 16.2	18.0 to 20.0	12.6 to 16.2	18.0 to 20.0	16.2 to 19.8

In the present study, the pattern of stress concentration was independent of the area of the bond interface. These results were justified because an elastic analysis was used, and a standard tension of 20 N/mm^2 was simulated at the bond interface. In addition, there were no flaws or defects in specimens. Soares et al [11] found that an increase in defects in the area of the interface results in an elevated stress concentration, especially around the simulated faults. We fabricated hourglass specimens to obtain higher strength values. Indeed, we hypothesized that hourglass specimens would provide a better stress distribution because they demonstrated a decreased cross-sectional area at the bond interface and lacked the angles present in the stick specimens. Indeed, the finite element model showed that the hourglass specimens distributed the stresses along the bond interface better than did the stick specimens because the tensions were distributed along the periphery of the bond interface rather than being concentrated at the edges. This result suggested that the adhesive bond strengths of the specimens with square sections should be significantly lower compared to those of the circular specimens. Indeed, a similar result was obtained by Phrukkanon et al,[13] who used cylindrical and rectangular specimens. Nevertheless, when these same authors compared the stresses generated by the finite element method with the bond strength values obtained in the microtensile tests, they found that the bond strength obtained for specimens with rectangular sections did not differ significantly from the values obtained for specimens with cylindrical sections. According to Betamar et al,[7] even in a single bond interface, the bond strength may be influenced by the adhesive system. They also showed that the semicircular hourglass design could act as a point of high stress concentration due to a change in geometry at the adhesive interface. Interestingly, the stick shape exhibits a regular structure lacking any changes in geometry.

In the present study, the highest stress concentrations were found in the hourglass specimens. This result was also verified by Betamar et al,[7] who demonstrated a strain of 95 MPa for stick specimens and a tension of 115 MPa for hourglass-shaped specimens. Ghassemieh[10] suggested that hourglass specimens failed at lower stress values compared to stick specimens because of the large stress concentration induced in the adhesive. The large number of designs employed for hourglass specimens must also be considered because variations in the curvature of different hourglass specimens would directly influence the stress concentration. In addition, the presence of sharp notches or grooves in the specimens could results in a nonuniform, triaxial stress state. In this state, even a simple load such as an axial pull could lead to a nonuniform axial, nonzero radial, and/or circumferential normal stress component.[9] One advantage of stick specimens is that no additional trimming is necessary after the specimen has been sectioned, and therefore, the risk of introducing microcracks or defects in the free-edge area is reduced.[9]

The lowest stress values were observed in the center of the specimens, and the maximum stress values were detected on the surface for the stick specimens (square sections) and along the entire periphery of the bond interface for the hourglass specimens (circular sections). These findings can be explained by the observation that the tension in the adhesive layer was concentrated at the angles and increased with a decreasing distance from the surface.[5] According to the fracture mechanism, these results suggested that the failures should occur in the peripheral region of the bond surface and should be directed toward its center.[13]

Although the results suggested that the hourglass model provided the best stress distribution at the bond interface, in practice, we must also consider the process of obtaining the specimens. Indeed, the trimming technique used for hourglass specimens may result in a weakening of the bond interface due to the additional stress caused by the action of the diamond tip.[22,23] Interestingly, Mannocci et al[24] used 1.5-mm-thick hourglass specimens because 0.7- to 1.0-mm-thick specimens resulted in a high fracture rate.

Since 1991, researchers have described the need for a standardization of bond tests, but different methodologies have made it difficult to compare laboratory results.[25] Therefore, the data obtained in the present study must be analyzed in conjunction with the results of studies that have evaluated the bond strength of specimens submitted to microtensile tests. Concerning square sections, researchers must determine whether the cutting process damages the experimental model, which may alter the measured bond strength values. A standardized specimen preparation is important to improve interpretations of bond strength data between studies. Indeed, a standardized specimen preparation is necessary to determine various parameters, such as the shape and size of the specimen, the shape, size, and thickness of the bond area, the configuration of loading, the shape fixation of the specimens, and the properties of the materials.

Although the hourglass specimens demonstrated a higher stress concentration at the outer surface of the adhesive interface, these specimens are associated with greater difficulty in standardization and acquisition.[5,7] Thus, the use of stick specimens would likely permit greater comparability between studies.

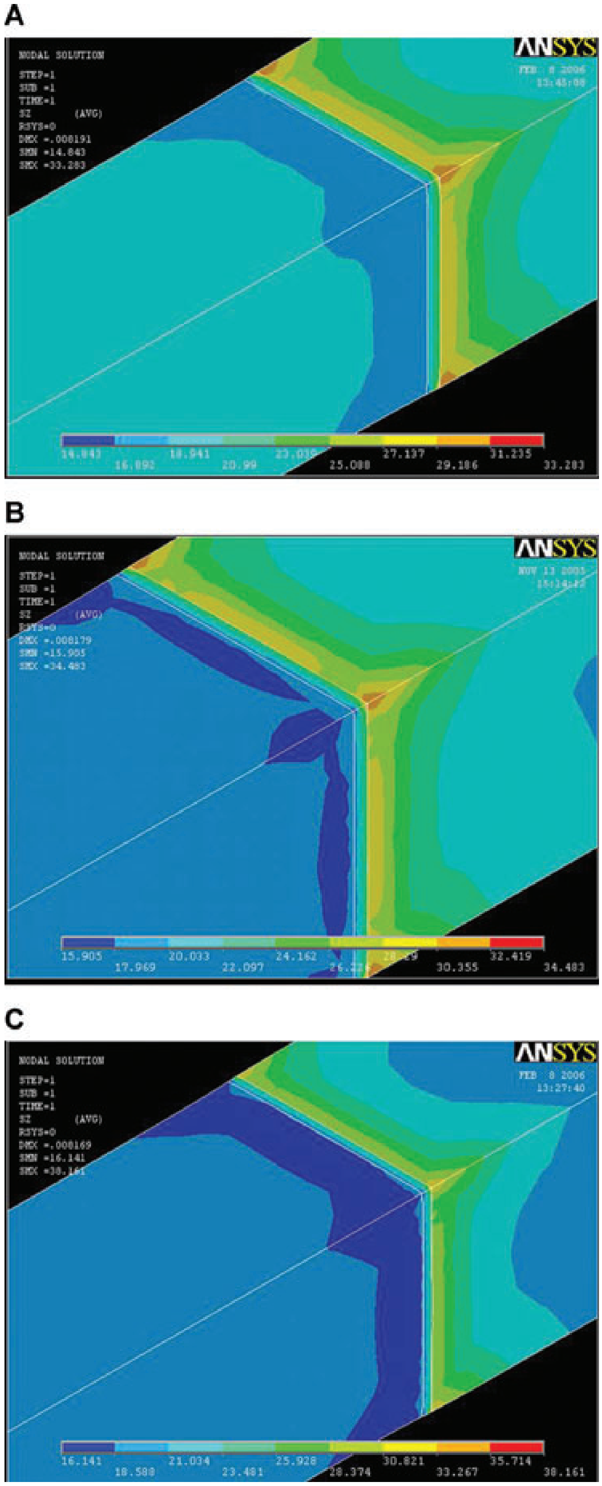

Figure 4 Stresses in the longitudinal direction on the surface of stick-shaped specimens with different bond interface areas: (A) specimen P1 (0.64 mm^2); (B) specimen P2 (1.0 mm^2); (C) specimen P3 (1.44 mm^2).

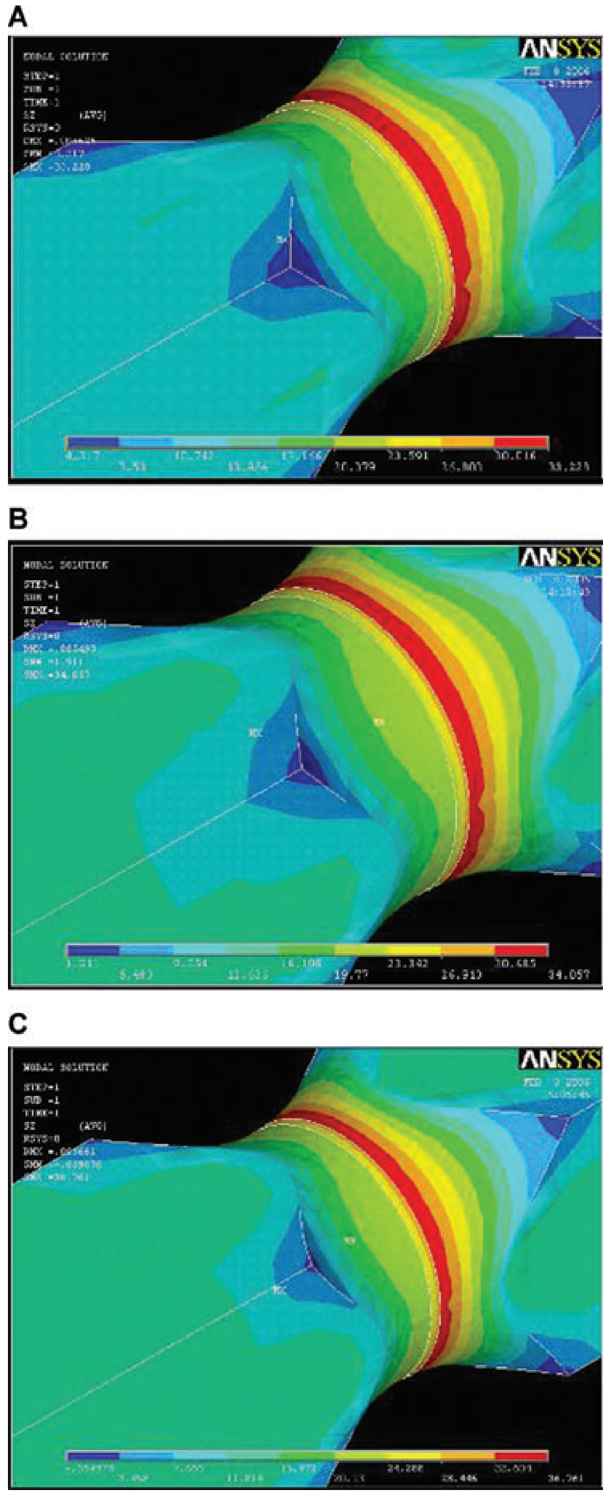

Figure 5 Stresses in the longitudinal direction on the surface of ampule-shaped specimens with different bond interface areas: (A) specimen A1 (0.64 mm^2); (B) specimen A2 (1.0 mm^2); (C) specimen A3 (1.44 mm^2).

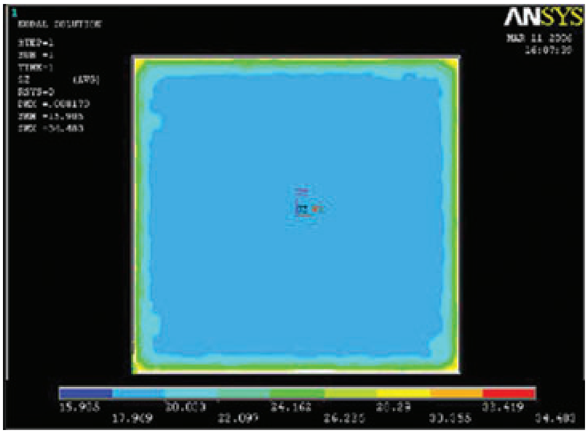

Figure 6 Stresses in ceramic, at 0.025 mm from the bond between the ceramic and the cement in the longitudinal direction of the stick-shaped specimen in cross sections in the bond interface region.

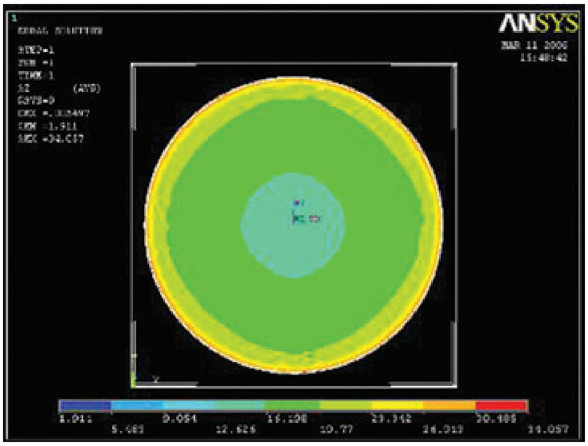

Figure 7 Stresses in ceramic, at 0.025 mm from the bond between the ceramic and the cement in the longitudinal direction of the hourglass-shaped specimen in cross sections in the bond interface region.

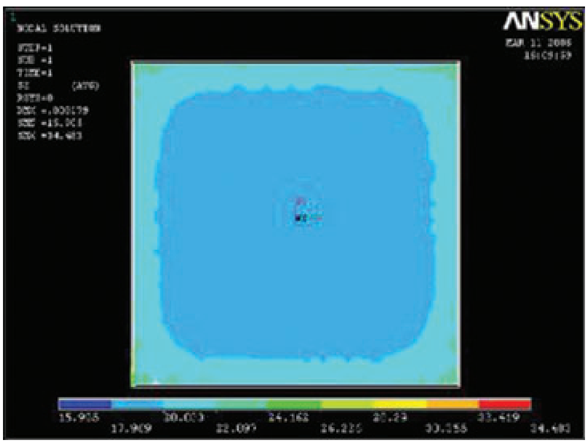

Figure 8 Stresses at the bond interface, at 0.025 mm from the bond between the cement and ceramic in the longitudinal direction of the stick-shaped specimen in cross sections in the bond interface region.

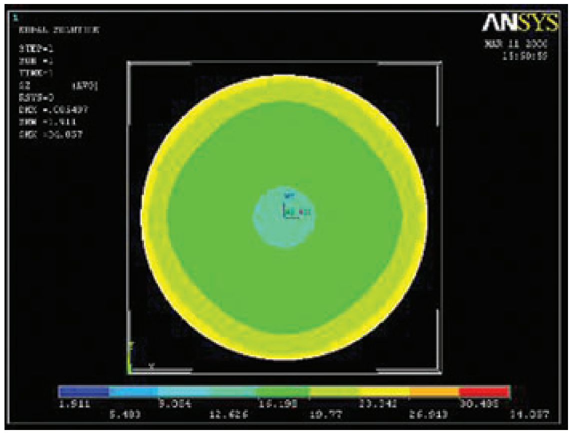

Figure 9 Stresses at the bond interface, at 0.025 mm from the bond between the cement and ceramic in the longitudinal direction of the hourglass-shaped specimen in cross sections in the bond interface region.

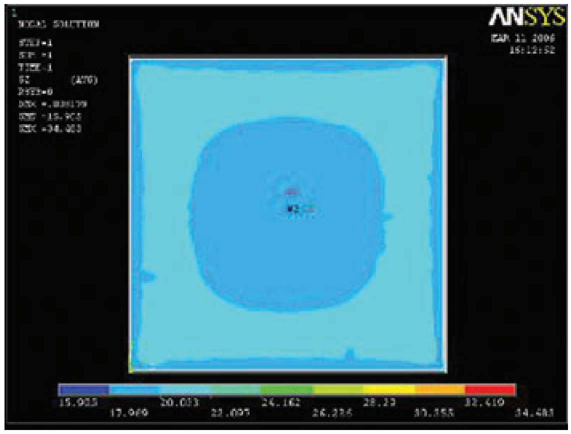

Figure 10 Stresses in dentin, at 0.025 mm from the bond between the dentin and cement in the longitudinal direction of the stick-shaped specimen in cross sections in the bond interface region.

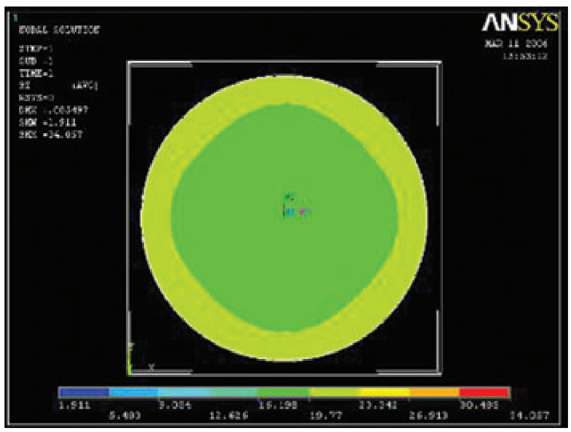

Figure 11 Stresses in dentin, at 0.025 mm from the bond between the dentin and cement in the longitudinal direction of the hourglass-shaped specimen in cross sections in the bond interface region.

Conclusions

Within the limitations of this study, we conclude the following.

1 The stress distribution for specimens with the same format was similar, regardless of the bond interface area.
2 A higher stress value occurred in ceramic compared to resinous cement and dentin.
3 The stresses were concentrated at the edges in stick specimens and distributed along the outline in hourglass specimens.
4 Stress at the outer surface is raised significantly compared to the center of the specimen.

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