A COMPARISON BETWEEN THE CAPACITY OF 2D AND 3D FINITE ELEMENT MODELS IN ANALYZING THE STRESS DISTRIBUTION IN SHEAR AND MICROSHEAR BOND STRENGTH TESTS

ABSTRACT

Numerical computational analyses by means of finite element method (FEM) have been allowing the understanding of how the test set-up configurations influence on stress distribution in the tested specimen. During such analysis, the models are simplified but, at the same time, they must allow obtaining enough data and, thus, enough knowledge for changing and standardizing the tests set-ups. This study aimed at comparing the capacity of 2D plane strain simplified finite element models, simulated in a previous study, in analyzing the shear and microshear bond strength tests set-ups, compared to 3D more refined models. Booth 2D and 3D models represented a resin-composite cylinder (with two different stiffness) adhered to a dentin flattened surface by means of an adhesive layer. The shear and microshear specimens had dimensions in a 5:1 ratio, except for the adhesive layer thickness, which remained constant in booth-sized models. It was simulated a load applied by an orthodontic wire-loop in all the cases, varying the distance from the load to the adhesive interface. The 2D models showed to be enough for analyzing the stress distribution patterns along the dentin-adhesive interface. They also allowed verifying the influence of variables such as the relative thickness of the adhesive layer and the distance between the loading and the adhesive interface on the stress distribution. However, the 2D plane strain models showed an opposite effect of the elastic modulus of the resin-composite cylinder on the stress concentration. Furthermore, they lead to a different prediction with respect to the real test set-up configurations. As the 3D models were built with more realistic geometrical refinements compared to the simplified 2D models, they should be considered as more reliable than the 2D models for analyzing the shear and microshear bond strength test set-ups.

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KEYWORDS

Composite shear strength. Composite resins. Adhesive. Dental stress analysis. Mechanical stress. Computer-assisted numerical analysis. Finite element analysis. Dental materials.

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| **Received** 27 Dec 2012 **Received in revised form** 21 Jan 2013 **Accepted** 17 Mar 2013

INTRODUCTION

It is assumed that, in a bond strength laboratorial test, the major the bond strength between a restorative material and dental structures registered, the major the capacity of the interface support efforts and, thus, the major is the clinical longevity of the adhesive restoration.

The bond strength value provided by mechanical laboratorial tests usually is a stress (MPa), calculated by dividing the load at the fracture (Newton –N) by the adhesive interface cross sectional area (mm^2), which is known as nominal strength[1-3].

In Dentistry, it is very difficult to elaborate an experimental test set-up able to generate a uniform stress distribution in the region of interest. If it is generated a non-uniform stress distribution, the fracture may initiate at the local of the major stress concentration and, from this point, propagate to the rest of the adhesive interface area. It means that, the experimental nominal stress, when calculated based on the false idea of uniformity of stress distribution, represents a smaller value than that maximum stress that the interface truly supported at fracture moment[4, 5]. It happens because, the major the stress concentration in a specific region, the lower the load necessary to lead the specimen to failure and thus, the lower the calculated laboratorial nominal bond strength (N/mm^2 = MPa). Therefore, a major stress concentration during the laboratorial mechanical test can lead to a false interpretation, considering the adhesive interface as weaker, when it can have supported a high stress value before the fracture.

Besides this fact, the stress state generated in the specimen, as a result of external stimuli (load), is usually complex, i.e., there are more than one kind of developed stress, although the applicated load was pure (only tensile, compression, or shear, for instance). The material can failure under a specific kind of all the stresses generated, depending on its fracture criteria (if brittle, the material tends to failure under tensile stress; if ductile, it tends to failure under shear stress). Thus, the specimen can failure under a kind of stress, although the applied load was only one other pure kind of effort.

Each kind of laboratorial test set-up has configuration that can provoke different stress distribution in a same specimen. Some examples of such configurations are the mode of specimen fixation, specimen geometry[3, 6, 7]; the mode as the load is applied (tensile, bending, compression, torsion, shear[8]); the region of load application[3], loading speed[9], and the discrepancy between the elastic modulus of the materials.

According to these literature findings, it can be assumed that the bond strength results obtained in a same laboratorial test and, mainly, by different laboratories, cannot be compared if not all the test set-ups configuration were standardized. Among different tests, a same material can present different failure modes and values of nominal strength, although its truly strength was always the same. A study found that even the bond strength ranking of different materials can vary in function of the type of mechanical bond strength test employed (it were evaluated tension, shear and push-out tests, the last one performed by two different operators)[10].

The most employed bond strength tests in Dentistry are tensile, microtensile, shear and microshear[11-14]. Even with the increasing employment of the microtensile test, the shear and microshear ones are still commonly used, because they do not requires cutting or trimming procedures after the adhesion for obtaining the specimens, as it occurs in the case of microtensile test. Thus, authors say that the shear and microshear tests are more suitable for testing specimens made of brittle material, as well as those with low adhesive or cohesive strength[6, 7, 15-20]. In shear and microshear tests, a cylinder of restorative material is built on the flattened dental surface after the adhesive procedure, and the load is applied parallel to the adhesive interface by means of a knife, a stainless steel wire-loop or a stainless steel ribbon[6, 7].

Numerical computational analyses by means of finite element method (FEM) have been allowing the understanding of how the test set-up configurations influence on stress distribution in the tested specimen[6, 7, 14, 21, 22]. During such analysis, the models are simplified but, at the same time, they must allow obtaining enough data and, thus, enough knowledge for changing and standardizing the test set-ups, including the specimen configurations.

Many studies have simulated the shear and microshear test by FEM using bi-dimensional (2D)[3, 6, 7, 9, 23] and three-dimensional (3D)[1] models, and found out many variables which provoke different stress distribution in a same adhesive interface.

Simulations of 2D models by FEM have the advantage of a lower time and computer memory consume for processing the results; however, they have limitations related to the representation of complex geometries, as it happens in the case of biological structures and tri-dimensional test set-ups. In their turn, the 3D models allow obtaining results closer to the real cases because they can simulate more complex problems. Nevertheless, the 3D models require a major time consuming, a major computer process capacity and, sometimes, a more sophisticated procedure for building the 3D structures.

A study made by Placido et al.[6, 7] (2006 and 2007), which simulated the shear and microshear tests by means of a 2D plane strain model with simplified geometry, found the following sources of variation of the stress distribution in the specimens:

• the relative adhesive layer thickness, which varies according to the size of the specimen: this layer has its thickness almost always constant, whereas the size of the shear specimens is bigger than the microshear ones. So, the microshear specimens have a relative thicker adhesive layer;
• the elastic modulus of the restorative material;
• the distance between the load application and the adhesive interface. When the distance is lower, it occurs an increase in the stress concentration at the adhesive interface because of the Saint-Venant effect (regarded to the generalized stress concentration in regions nearest the load application). On the other hand, with the increasing of the load distance, it is also noticed a stress concentration at the adhesive interface due to the increase of the bending moment[6, 7, 15]. The increase of the bending moment occurs because, although it is applied a shear load (external stimulus), it is developed not only shear stress in the specimen, but also tensile stress, with higher concentration at the same side of the loading, and compression stress at the opposite side[6, 7, 15]. Although the tensile stress concentration varies in function of the loading distance, it has always higher values than the shear stress in the areas of major stress concentration[6, 7, 15].

It would be interesting to verify the capacity of the 2D models in analyzing the shear and microshear bond strength tests set-ups compared to 3D models.

Therefore, this work aimed at evaluating the differences between the capacity of the 2D models simulated by Placido et al.[6, 7] (2006 and 2007) in verifying the stress distribution patterns and the influence of the test set-up configurations on the stress developing, compared with 3D models.

MATERIAL AND METHODS

The softwares used to perform the finite element analysis were MSC.Patran 2005r2® for the pre and post-processing and the MSC.Marc® for the processing step (MSC.Software Corporation, Santa Ana, CA, USA).

1. BI-DIMENSIONAL MODELS

The 2D plane strain models were built and analyzed during the already published study of Placido et al.[6, 7] (2006 and 2007). These models represented a resin-composite cylinder (with different elastic modulus), an adhesive layer with the same diameter of the resin-composite cylinder and a dentin cylinder with a major diameter (the structure dimensions can be seen in Table 1). The specimens of shear and microshear were simulated in a 5:1 scale, except for the adhesive layer thickness, which remained with a constant thickness of 50 micrometers (μm). It were simulated a perfect union in all the interfaces (equivalence of nodes) and all the materials were assumed to be isotropic, homogeneous, elastic and linear (material properties can be seen in Table 2).

The mesh was created with four-node, isoparametric, quadrilateral elements.

In all the 2D cases, the load was applied for obtaining an arbitrary nominal stress value of 4 MPa. The load was applied concentrated in a single node simulating an orthodontic wire-loop loading. In some shear and microshear models, it was simulated loading application distances proportional to the diameter of the resin-composite cylinder, in order to isolate the influence of the adhesive thickness variable on the stress distribution. In other models, the distances between the load and the dentin-adhesive interface were simulated for analyzing the real experimental set-ups with orthodontic wire-loop with different diameters found in the literature by Placido et al.[6, 7] (2006 and 2007). These real cases were: microshear specimens with flowable and with high elastic modulus resin-composite cylinder and a distance of load application equal to 0.1 mm; and shear specimens with a high elastic modulus resin-composite cylinder and a distance of load application equal to 0.25 mm.

All the distances between the load application and dentin-adhesive interface simulated for the 2D models are presented in Table 3.

The nodes at the lateral and bottom edges of the dentin cylinder were constrained in all directions.

The image of the 2D models, including the geometry, mesh and boundary conditions can be seen in the already published studies[6, 7].

2. THREE-DIMENSIONAL MODELS

The diameters of the resin-composite cylinders were the same simulated for the 2D models[6, 7], but in order to simulate a more realistic experimental geometry of the specimens, some modifications were added:

- the adhesive layer was simulated with a higher diameter than the resin-composite cylinder diameter (see, in Figure 1, the 3D models geometry, and Table 4 with the 3D structure dimensions), in order to represent the technique of applying the adhesive on a region beyond the limits of the resin-composite cylinder. This detail avoided the stress concentration artifact provoked by a sharp angle between the dentin and adhesive layer just under the load application on the resin-composite cylinder;
- it was simulated a resin-composite rounded fillet (an excess of resin-composite) at the confluence between the adhesive layer and the

resin-composite cylinder (Figure 1), in order to eliminate the sharp angle between the two structures. The profile shape of the fillet was different in shear and microshear 3D models, because it were measured in five real specimens of each size by means of a profile projector. It lead to the simulation of adhesive layer diameters in shear and microshear models without a 5:1 scale, because the diameter depended on the measure of the resin-composite fillet, and booth diameters were not equal to the 2D models adhesive diameter (see Table 4, with structure dimensions for the 3D models and Table 1, which presents the 2D models structure dimensions);

- the diameter of the dentin cylinder was established, through initial tests, as the minimal capable of avoiding stress concentration in the adhesive interface because of the total fixation of the nodes on the lateral and bottom surfaces of the cylinder. It resulted in a major dentin diameter and thickness than in 2D models (it is possible to compare, again, the 3D with the 2D models structure dimensions through Table 4 and Table 1, respectively).

The material properties were the same as those assumed for the 2D models[6, 7] (Table 2).

The 3D mesh was built with four-node tetrahedral elements, more refined at the periphery of the adhesive interface and neighborhood (Figure 1), where it was observed, in initial tests, the major stress concentration. The final number of elements were 178,731 and 196,902 for shear and microshear 3D models, respectively.

As in 2D models, it was simulated perfect unions in the interfaces of the 3D models (equivalence of nodes).

The orthodontic wire-loop loading for the 3D models was simulated by the application of a force distributed throughout a line at half perimeter of the resin-composite cylinder[8]. The value of such loading (*N*) was deduced by the formula:

$$2T = \int_0^{\pi} r\, N \sin\alpha \; dx \;\therefore\; N = T/r$$

The correspondent schematic representation of the formula is showed in Figure 2, and the respective values (of *N*) for shear and microshear models were 12.57 N/m and 2.51 N/m. This way of simulating the loading resulted in the same arbitrary nominal stress at the interface, as done for 2D models, and seems to be the most realistic way for simulating a wire-loop loading, because it considers the capacity of the metallic wire to deform and to compress the resin-composite cylinder. The distances between the load application and dentin-adhesive interface were the same as those simulated for the 2D models (Table 3), except for the 0.05 mm, which was not simulated.

Table 1. Structure dimensions simulated for 2D models[6, 7].

Structure	Dimensions (mm) (diameter x length)	
	Shear ("macro")	Microshear ("micro")
Dentin	4.8 x 0.8	0.96 x 0.16
Resin-composite cylinder	4.0 x 2.0	0.8 x 0.4
Adhesive	4.0 x 0.05	0.8 x 0.05

Table 2. Simulated material properties for 2D and 3D models[6, 7]

Material	Properties	
	Elastic Modulus (GPa)	Poisson's ratio
Dentin	15	0.23
High elastic modulus resin-composite	20	0.25
Flowable resin-composite	5	0.35
Adhesive	4	0.35

Table 3. Distance from the wire-loop load application to the dentin-adhesive interface simulated for the 2D models[6, 7].

Model size	Distance between load application and dentin-adhesive interface (mm)						
	0.05	0.1	0.2	0.25	0.4	1	2
Shear ("macro")		X	X	X	X	X	X
Microshear ("micro")	X	X	X	X	X		

Table 4. Structure dimensions simulated for the 3D models.

Structure	Dimensions (mm) (diameter x length)	
	Shear ("macro")	Microshear ("micro")
Dentin	9.0 x 2.0	1.8 x 0.4
Resin-composite cylinder	4.0 x 4.0	0.8 x 0.8
Adhesive	5.866 x 0.05	1.248 x 0.05

RESULTS

The results provided by the 2D simulation are presented in the already published studies made by Placido et al.[6, 7] (2006 and 2007). The present work presents the results provided by the 3D models, corresponding to the nodes at a median line chosen in the dentin-adhesive interface. It is worth remembering that the adhesive layer had a major diameter than that of the resin-composite cylinder and the loading distance of 0.05 mm was not simulated for 3D models.

In some cases, it was noticed that the general behavior of flowable resin-composite cylinders was the same as the higher elastic modulus ones. In these cases, it were plotted only the results provided by the flowable resin-composite, in order to respect the space limits available for this paper.

Figures 3 and 4 present, respectively, the variation of the maximum principal and maximum shear stresses along the median line at the dentin-adhesive interface. The position 0% corresponds to the node at the limit of the adhesive interface on the loading side, and the 100% position, to the node at the opposite limit. The results plotted in these figures corresponds to shear and microshear models with proportional loading distances (i.e., in a 5:1 scale). Figures 3 and 4 of the present work and the figures 2.a and 2.b of the study made by Placido et al.[7] (2007) allow noticing the non-uniformity of booth stresses along the adhesive interface and comparing their values in each position to the nominal stress of 4 MPa. Figures 5 and 6 of this work show the maximum principal and maximum shear stress peaks found for each model size according to the loading application distances. Figure 5 presents the stress peaks provided by the flowable resin-composite models, whereas the figure 6 presents those correspondent to the high elastic modulus resin-composite. These two figures and the figures 4.a and 4.b presented in the study made by Placido et al.[7] (2007) allow noticing the differences between the stress peaks and the nominal stress.

Figures 7 and 8 present the variation of the maximum principal stress/maximum shear stress ratio along the median line at the dentin-adhesive interface for shear and microshear 3D models, respectively. In the horizontal axis, the position 0% corresponds to the node at the limit of the adhesive interface on the loading side, and the 100% position, to the node at the opposite limit. The figures 7 and 8 of the present work and the figure 3 of the work made by Placido et al.[7] (2007) allow noticing ratio values between 0 and 1 (i.e., when the maximum shear stress values surpass the maximum principal stress values) only in areas of low stress concentration (in regions where the ratio value is negative, there is a predominance of compression stress).

Figure 1. Geometry and mesh in a longitudinal sectional view of a shear model. There is a mesh refinement in the periphery of the adhesive interface and neighborhood. It can be noticed a surplus of the adhesive layer in the *z*-direction, in order to simulate the application of the adhesive on the entire dentin substrate.

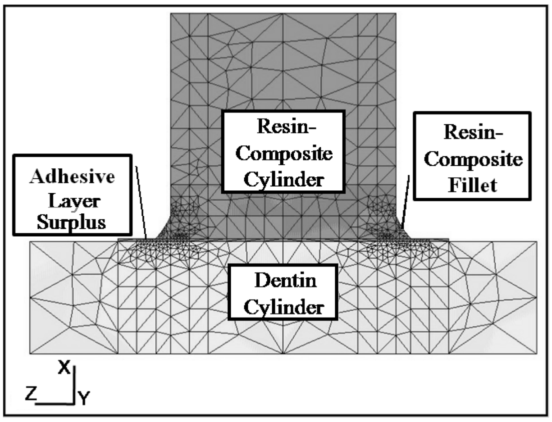


Figure 2. Schematic representation of the wire-loop loading application (T)[8] in order to deduce the value of *N* (the corresponding formula is in the above text) for obtaining a nominal stress of 4 MPa in booth sizes of 3D models.

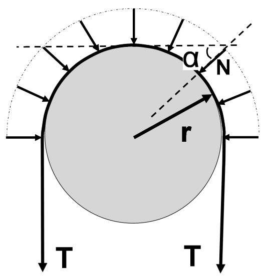


Figure 3. Maximum principal stress distribution along the dentin-adhesive interface for shear and microshear models with correspondent load application distances (i.e., 5:1 ratio). The models are identified by such distances. The nominal stress is also presented as a reference.

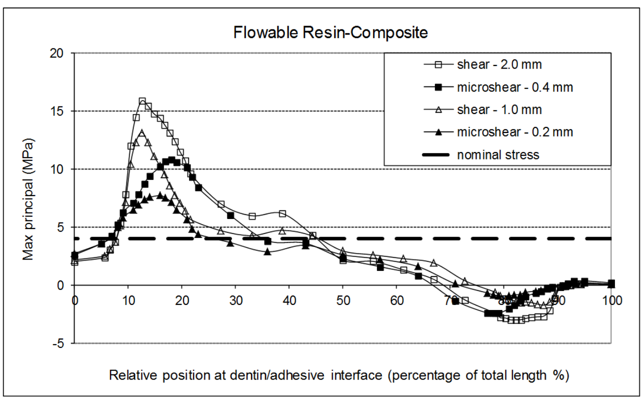


Figure 4. Maximum shear stress distribution along the dentin-adhesive interface for shear and microshear models with correspondent load application distances (i.e., 5:1 ratio). The models are identified by such distances. The nominal stress is also presented as a reference.

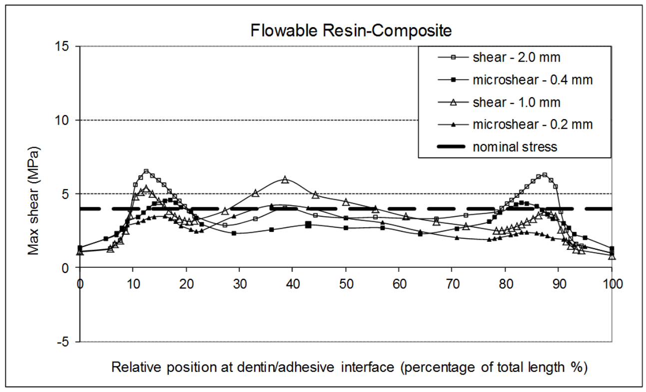
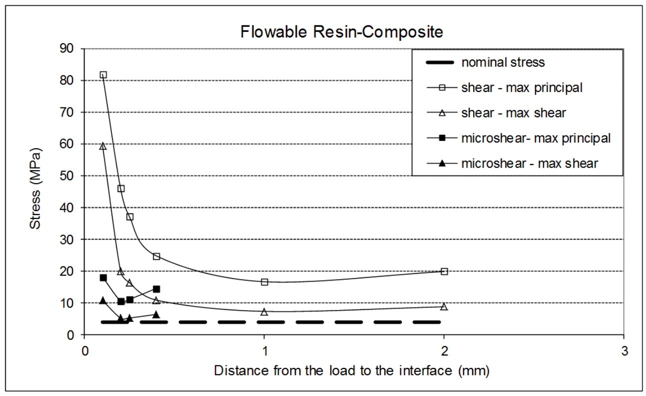


Figure 5. Peaks of maximum principal and maximum shear stresses according to the distance between the wire-loop load application and the dentin-adhesive interface in shear and microshear models with flowable resin-composite models. The nominal stress is also presented as a reference.



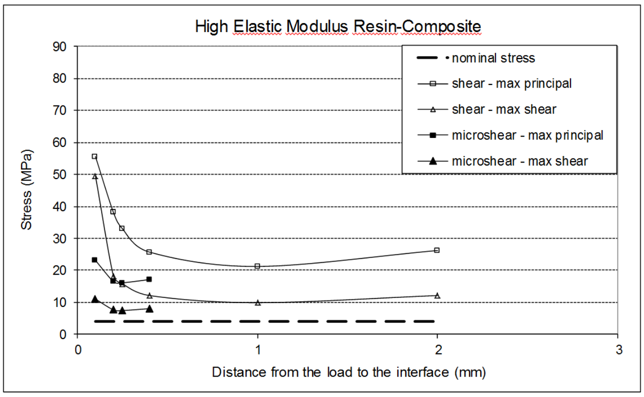
DISCUSSION

Figures 3 and 4 of the present work and the figures 2.a and 2.b of the study made by Placido et al.[7] (2007) showed a non-uniform maximum principal and maximum shear stresses distribution along the adhesive interface, with higher values near the resin-composite cylinder edges because of such geometrical discontinuity. However, the 2D models presented such stress concentration with higher values than the 3D models (in which the resin-composite cylinder edges are at about the positions 10% and 90%, since the adhesive diameter was major). It can be due to some differences in the local of major stress concentration in 2D and 3D models adhesive interface. In the 3D models, the maximum stress concentration not always occurred exactly at the chosen median line for plotting the results. Furthermore, in the 2D models, it was observed an undulated disturbance in the curves of maximum shear stress for models with lower loading distances in regions near the load application. It was interpreted as an additional effect caused by the proximity between the load application point and the adhesive interface. As this disturbance was not seen in the 3D results, it can be considered an artifact caused in 2D models.

Figures 3 and 4 of this present work and the figures 2.a and 2.b of the study made by Placido et al.[7] (2007) also allowed noticing that the relative thickness of the adhesive layer slightly influenced on the stress distribution pattern along the interface. On the other hand, the figures 5 and 6 of the present work and the figures 4.a and 4.b of the 2D study[7] showed an important influence of this variable on the stress peaks, with lower values when the adhesive layer is thicker (microshear models).

Regarding to the elastic modulus of the resin-composite cylinder, the figures 4.a and 4.b of the 2D study[7] show that the flowable composite provoked major stress peaks in all the cases. In the 3D present study, the flowable resin-composite provoked major stress peaks than the high elastic modulus composite only in the shear models with loading distances lower than 0.4mm (Figures 5 and 6). That means that, in 3D simulation, the high elastic modulus resin-composite provoked major stress peaks in almost all the cases.

Figure 6. Peaks of maximum principal and maximum shear stresses according to the distance between the load application and the dentin-adhesive interface in shear and microshear models with high elastic modulus resin-composite models. The nominal stress is also presented as a reference.



Figures 5 and 6 of this work and 4.a and 4.b of the 2D study[7] show a slightly influence of the increase of the bending moment (with the increase of the loading distance) on the maximum principal stress peaks. In booth 2D and 3D simulations, it was noticed a stress concentration in the adhesive interface caused by the Saint-Venant effect. The Saint-Venant effect is related to the stress concentration in regions near the load application, and the cited figures show major stress peaks in the adhesive interface with lower loading distances cases, even with the decrease of the bending moment.

Figure 7. Maximum principal/maximum shear stresses ratio along the dentin-adhesive interface for shear models with flowable resin-composite. 0% represents the node at the limit of the adhesive interface at the loading side, whereas the 100% position represents the node at the opposite side. The models are identified by the distances from load application to the adhesive interface.

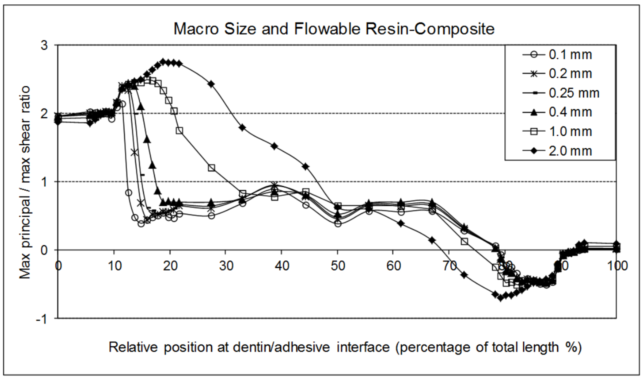
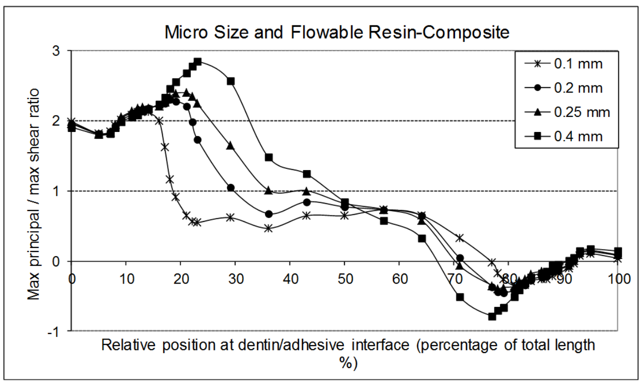


Figure 8. Maximum principal/maximum shear stresses ratio along the dentin-adhesive interface for microshear models with flowable resin-composite. 0% represents the node at the limit of the adhesive interface at the loading side, whereas the 100% position represents the node at the opposite side. The models are identified by the distances from load application to the adhesive interface.



With respect to the real set-up cases (microshear specimens with flowable and with high elastic modulus resin-composite cylinder and a distance of load application equal to 0.1 mm; and shear specimens with a high elastic modulus resin-composite cylinder and a distance of load application equal to 0.25 mm), the 3D and 2D[7] simulations showed different results. For the 2D simulation, the major stress concentration was presented by the microshear specimens with flowable resin-composite (figures 4.a and 4.b of the 2D study[7]), whereas in the 3D simulation, the major stress concentration was presented by the shear real set-up case (Figures 5 and 6 of this work). It is a difficult question to understand. In booth 2D and 3D simulations, the lower values of stress concentration were presented with a thicker adhesive layer (microshear models). This lead to predict that shear specimens tends to present lower experimental load at the fracture, because a lower load can already provoke a high stress value. It is in accordance with experimental studies[24, 25] which reported lower nominal experimental strength for shear compared to microshear specimens. If the findings provided by the 3D simulation made by the present work are correct, the lower experimental values found for the shear specimens can be explained not only by the Griffith's theory but also by the geometrical change, related to the lower relative adhesive thickness in shear than in microshear specimens. The Griffith's theory says that, the bigger the cross-sectional area to be tested, the major the probability of the existence of a critical defect which can concentrate the stress. If the 2D simulation results are correct, the Griffith's theory is the only explanation for the lower experimental nominal strength for shear specimens.

Figures 7 and 8 of the present work, and the figure 3 of the 2D study[7] showed a predominance of maximum principal stress in areas of major stress concentration in the dentin-adhesive interface. It means that, although the test set-up intends to verify the bond strength under shear, the specimens are subjected mainly to tensile and compression stresses in areas of major stress concentration. As the 3D models were built with refinements which resulted in geometrical differences when compared to the 2D simplified models[7], the comparison among their results are limited, because they were also influenced by the geometry. Because the 3D models simulated a more realistic geometry, their results can be considered as more precise when they presented differences compared to the 2D results.

It would be interesting to simulate, in future studies, some features not simulated here, such as the dynamic of stress distribution during the fracture propagation, as well as non-linear phenomena.

CONCLUSION

According to the results presented by this 3D FEM study and by the 2D study made by Placido et al.[7] (2007), the following can be said with respect to the capacity of the 2D models in analyzing the shear and microshear bond strength tests set-ups:

- the 2D models showed to be enough for analyzing the stress distribution patterns along the dentin-adhesive interface, presenting details such as the non-uniformity of the stress distribution and the predominance of maximum principal stress in areas of major stress concentration;
- the 2D simulation allowed verifying the influence of variables such as the relative thickness of the adhesive layer and the distance between the loading and the adhesive interface on the stress distribution. Regarding this last variable, the 2D models showed the Saint-Venant and bending moment effects on the stress concentration;
- the 2D plane strain models showed an opposite effect of the elastic modulus of the resin-composite cylinder on the stress concentration. Furthermore, they lead to a different prediction with respect to the real experimental set-up configurations.

The 3D models, which were built with geometrical refinements compared to the simplified 2D models, showed different quantitative and qualitative results when analyzing important parameters. Therefore, the 3D models should be considered as more reliable than the 2D models for analyzing the shear and microshear bond strength test set-ups.

ACKNOWLEDGEMENTS

The authors would like to thank the financial support given by CAPES. They would also like to thank Antonio Carlos Lascala and Sílvio Peixoto Soares, from the Department of Dental Materials, School of Dentistry and Raul Gonzáles Lima, from the Department of Mechanical Engineering, Polytechnic School, University of São Paulo (São Paulo/SP, Brazil) for the technical support, and Eliane Placido for the provided information about her 2D study.

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