DENTAL MATERIALS 27 (2011) 934–941

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

An acoustic emission study on interfacial debonding in composite restorations

Xiaozhou Liu[a], *Haiyan Li*[b], *Jianying Li*[b], *Peijun Lu*[c,*], *Alex Siu-Lun Fok*[b]

[a] *Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, PR China*
[b] *Minnesota Dental Research Center for Biomaterials and Biomechanics, School of Dentistry, University of Minnesota, MN, USA*
[c] *Research Center of Engineering and Technology for Computerized Dentistry, Ministry of Health, Peking University School and Hospital of Stomatology, Beijing, PR China*

ARTICLE INFO

Article history:
Received 6 January 2011
Received in revised form
22 April 2011
Accepted 18 May 2011

Keywords:
Interfacial debonding
Composite restoration
Acoustic emission
Finite element method
Shrinkage stress

ABSTRACT

Objective. This paper studied in vitro the effect of the C-factor on interfacial debonding during curing of composite restorations using the acoustic emission (AE) technique. Finite element (FE) analyzes were also carried out to evaluate the interfacial stresses caused by shrinkage of the composite resin in restorations with different C-factors.

Materials and methods. Twenty extracted third molars were divided into 4 groups of 5. They were cut to form Class-I (Groups 1 and 2) and Class-II (Groups 3 and 4) cavities with different C-factors. The average C-factors of the four groups were 3.37, 2.88, 2.00, and 1.79, respectively. The cavities were then applied with an adhesive and restored with a composite, which was cured by a halogen light for 40 s. A 2-channel AE system was used to monitor the interfacial debonding, caused by shrinkage stress, between the tooth and restoration through an AE sensor attached to the surface of the specimen. Recording of the AE started at the same time as curing of the composite and lasted 10 min. Simplified FE models were used to evaluate the interfacial stresses in restorations with different C-factors, with a thermal load (temperature decrease) being applied to the composite resin to simulate its shrinkage.

Results. The mean and standard deviation of the total number of AE events for the four groups were 29.6 ± 15.7, 10.0 ± 5.8, 2.6 ± 1.5, and 2.2 ± 1.3, i.e. the number of AE events increased with an increase in the C-factor. The FE results also showed that, the higher the C-factor of the restoration, the higher the interfacial tensile stress between the tooth and restoration.

Significance. From the results of the AE tests and FE simulations, it can be concluded that, the higher the C-factor, the higher the shrinkage stress and the more likely is interfacial debonding.

1. Introduction

The polymerization shrinkage of composite resins presents one of the biggest challenges in their application to dental restoration. It is ascribed to the shortening of distance between molecules in the cross-linked polymer networks following polymerization [1]. During curing of the composite, because of restriction due to bonding to the tooth cavity walls, shrinkage stresses are built up within the tooth structure and restoration which may cause tooth deflection and post-operative sensitivity. When the shrinkage stresses along the

* *Corresponding author*. Tel.: +86 10 62188981.
E-mail address: kqlpj@bjmu.edu.cn (P. Lu).
0109-5641/$ – see front matter
doi:10.1016/j.dental.2011.05.008

interface exceed the bond strength, debonding will take place. The latter, as demonstrated by both in vivo and in vitro experiments, may lead to microleakage, marginal staining and even secondary caries [2–5].

The magnitude of the shrinkage stress is affected by several factors, for example, material properties, the restorative technique and configuration of the cavity [6]. The latter is often characterized by the so-called C-factor (C) of the restoration, which is defined as the ratio of the bonded areas to the unbonded areas [7–10]. Feilzer et al. [8] investigated the effect of the C-factor on the shrinkage stress using a simulated cavity where the composite resin was bonded to two opposing rigid parallel discs. They found that, after curing of the composite, all specimens with $C > 2$ had fractured cohesively, while only some of the specimens with $1 < C < 2$ had failed. Further, all specimens with $C \leq 1$ had remained intact. Although the tests were carried out in laboratory conditions, the results indicated that increasing the C-factor would increase the incidence of interfacial failure, probably as a result of an increased shrinkage stress. Similarly, Nikolaenko et al. [9] investigated the influence of the C-factor on the bond strength of resin-dentin specimens prepared from composite-restored teeth. The results showed that the higher the C-factor, the lower the bond strength. Again, the reduced bond strength of the specimens was attributed to the higher shrinkage stress in restorations with a high C-factor that had caused more interfacial debonding. Some studies indicated that volume of the restoration also influenced the relationships between the C-factor, the shrinkage stress and the amount of interfacial debonding [7,10].

There are many methods to assess the level of interfacial debonding between the tooth and composite resin. The most common method is dye penetration, which needs the sample to be immersed into a dye solution, sectioned into slices and inspected under a profilometer or microscope [7,11]. Although this method is widely used, its procedure is destructive and laborious, while the information provided by the 2D sectional view is limited. Therefore, 3D non-destructive methods, such as X-ray microcomputed tomography (μCT), have been used to evaluate the interfacial condition of composite restorations [12,13]. However, because of its lower resolution, μCT cannot detect debonding at a submicron level. Further, none of the techniques mentioned above can be used to monitor debonding as it happens; they can only be used to examine the restoration at the end of the polymerization process.

Recently, another non-destructive method, based on measurement of acoustic emission (AE), was used to detect and monitor in situ the interfacial debonding of composite restorations during polymerization of the composite resin [14]. The AE technique uses transducers or sensors to detect the high-frequency sound waves produced as a result of the strain energy released within a material following fracture. It is a real-time, in situ, non-destructive and highly sensitive method for structural integrity monitoring. It has been widely used in research and industry to monitor the development of crack growth and fracture behavior in different structures. In dentistry, AE has been used since the 1990s to monitor the fracture of restorations made of composite, ceramic or fiber reinforced composite [15–18]. The experiments conducted by Li et al. [14] demonstrated the effectiveness of the AE technique for detecting interfacial debonding of restorations during polymerization of the composite resin. Their results showed clearly a relationship between the number of AE events and interfacial debonding of the tooth restoration: the more interfacial debonding there is, the higher the number of AE events.

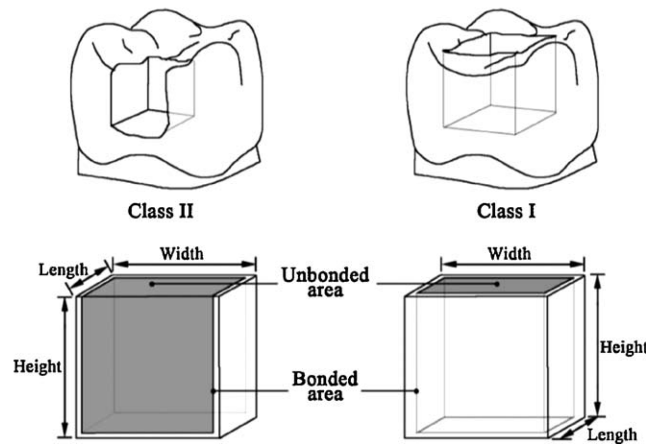

Fig. 1 – Schematic diagrams of the prepared tooth cavities with dimensions of interest. The shaded areas are the free, unbonded surface areas.

In the current study, AE would be used to evaluate the interfacial debonding in composite restorations with different C-factors during curing of the composite resin. Simple finite element analyzes (FEA) would also be carried out to estimate the shrinkage stresses due to polymerization so as to better understand the effect of the C-factor on interfacial debonding in such restorations. The hypothesis to be tested was that the higher the C-factor of the restoration, the greater the shrinkage stress and the more interfacial debonding there would be between tooth tissue and composite resin.

2. Materials and methods

2.1. *Specimen preparation*

Twenty sound human third molars, which had been extracted and stored in saturated thymol solution at 4 °C for one month, were used to prepare the specimens. The teeth were washed in running tap water and then kept in de-ionized water at room temperature for 24 h. Then they were randomly divided into four groups ($n = 5$): Group 1 with large Class-I cavities, Group 2 with small Class-I, Group 3 with small Class-II and Group 4 with large Class-II. All cavities were prepared by the same operator following standard clinical procedures with a high-speed handpiece and conically shaped carbide burs. Fig. 1 shows schematically the Class-I and Class-II cavities prepared and the dimensions of interest. The dimensions of each specimen were measured with a micrometer (Mitutoyo, Japan) whereby the C-factor was calculated. At least 3 measurements were made for each aspect of the cavity and the average value used for calculation. The average C-factors of the four groups were 3.37, 2.90, 2.00 and 1.79, respectively, as shown in Table 1.

Table 1 – Dimensions and geometrical factors of the specimens used in the experimental study.

Cavity type	Group	Length (mm)	Width (mm)	Depth (mm)	C-factor	Bond area (mm^2)	Volume (mm^3)
Class I	1	3.94	2.99	2.08	3.45	40.62	24.50
		3.76	3.68	1.88	3.02	41.81	26.01
		4.13	4.06	2.48	3.42	57.39	41.58
		4.00	3.79	2.02	3.08	46.63	30.62
		3.99	3.61	2.72	3.87	55.75	39.18
Mean (STD)		3.96(0.13)	3.63(0.39)	2.24(0.35)	3.37(0.34)	48.44(7.78)	30.68(7.72)
Class I	2	2.66	2.77	1.40	3.06	22.57	10.32
		3.29	3.04	1.80	3.28	32.79	18.00
		2.86	2.87	1.05	2.47	20.24	8.62
		3.59	2.70	1.10	2.43	23.53	10.66
		2.73	2.70	1.45	3.14	23.12	10.69
Mean (STD)		3.03(0.40)	2.82(0.14)	1.36(0.30)	2.88(0.40)	24.45(4.83)	11.66(3.65)
Class II	3	2.09	1.85	1.68	2.01	14.00	6.50
		2.35	1.92	1.42	1.92	13.91	6.41
		2.30	1.91	1.73	2.03	15.66	7.60
		2.39	1.94	2.02	2.13	18.21	9.37
		2.11	2.10	1.70	1.90	15.18	7.53
Mean (STD)		2.25(0.14)	1.94(0.09)	1.71(0.21)	2.00(0.09)	15.39(1.75)	7.48(1.19)
Class II	4	3.75	3.34	2.47	1.89	39.30	30.94
		4.18	3.39	2.72	1.97	46.13	38.54
		4.49	3.36	2.19	1.88	42.11	33.04
		3.63	3.51	1.58	1.63	29.76	20.13
		4.57	4.50	1.80	1.57	45.12	37.02
Mean (STD)		4.12(0.42)	3.62(0.50)	2.15(0.47)	1.79(0.18)	40.48(6.57)	31.93(7.26)

2.2. *Restorative procedure*

After preparing the cavity, the new surfaces were cleaned using ethanol pads, washed under running tap water thoroughly and then dried with compressed air. With the total-etch adhesive Adper™ Single Bond Plus (3 M ESPE, St Paul, USA) used as the bonding agent, the cavity was restored with the composite Z100 (3 M ESPE, St Paul, USA) which was bulk cured using a blue curing light (ESPE Elipar® Trilight) for 40 s. The intensity of the halogen light curing unit was measured at 550 mW/cm^2 by the built-in radiometer prior to testing. For ease of dimensional measurement, the top surface of the composite restoration was flattened prior to curing.

2.3. *AE test*

A two-channel AE system (PCI-2, Physical Acoustic Corporation, USA) was used to monitor the interfacial debonding between the tooth structure and composite resin during curing. The AE operational settings were: 40 dB pre-amplification, 100 kHz–2 MHz band pass and 32 dB threshold. Before curing the composite resin, an AE sensor (S9225, Physical Acoustic Corporation, USA) was adhered to the outer surface of the tooth with cyanoacrylate adhesive (Super Bond, Staples Inc, USA). The recording of AE started simultaneously with the curing and lasted for 10 min. During the test, the outer surface of the tooth was wrapped with a piece of wet paper to keep it moist so that it would not crack from drying and generate spurious AE signals.

2.4. *FE analysis*

Six FE models were built to study the effect of the *C*-factor on the interfacial shrinkage stress. Four Class-I and two Class-II restorations were analyzed with axisymmetric and plane-strain models, respectively. The commercial software Abaqus (version 6.9, Dassault Systèmes Simulia Corp., USA) was used for this FE study. All the models were constructed with the same basic 2D rectangular mesh, which was 6 mm in width, 10 mm in height and included three materials (enamel, dentin and composite restoration), as shown in Fig. 2(a). Depending on the type of elements selected, the model could represent an axisymmetric cylinder (Class-I) or a plane-strain rectangular (Class-II) block; see Fig. 2(c and d), respectively. Thus, CAX4 elements were used for the axisymmetric analysis and CPE4 elements were used for the plane-strain analysis. Thickness of the plane-strain models was set at 9 mm. By changing the dimensions of the restoration, different *C*-factors were achieved, i.e. 7, 5, 3 and 2 for the Class-I models and 1.04 and 0.46 for the Class-II models.

The interfacial bond between the tooth structure and the composite resin was modeled by a contact pair which tied the two surfaces together. This allowed stresses normal and tangential to the interface to be evaluated. For the axisymmetric models, the bottom of the tooth structure was fixed by constraining both the horizontal and vertical displacements. For the plane-strain models, besides fixing the bottom surface, the horizontal movement along the axis of symmetry was also constrained.

Being simple but effective, the Maxwell model was used to simulate the viscoelastic behavior of the composite during polymerization, i.e.

$$\dot{\varepsilon} = \frac{\sigma}{\mu} + \frac{\dot{\sigma}}{E} \quad (1)$$

where σ is stress, μ is viscosity, E is Young's modulus, and $\dot{\varepsilon}$ and $\dot{\sigma}$ denote the strain and stress rates, respectively. The temporal variations of volumetric shrinkage, Young's modulus, and viscosity of the composite, as shown in Fig. 2(b), were taken

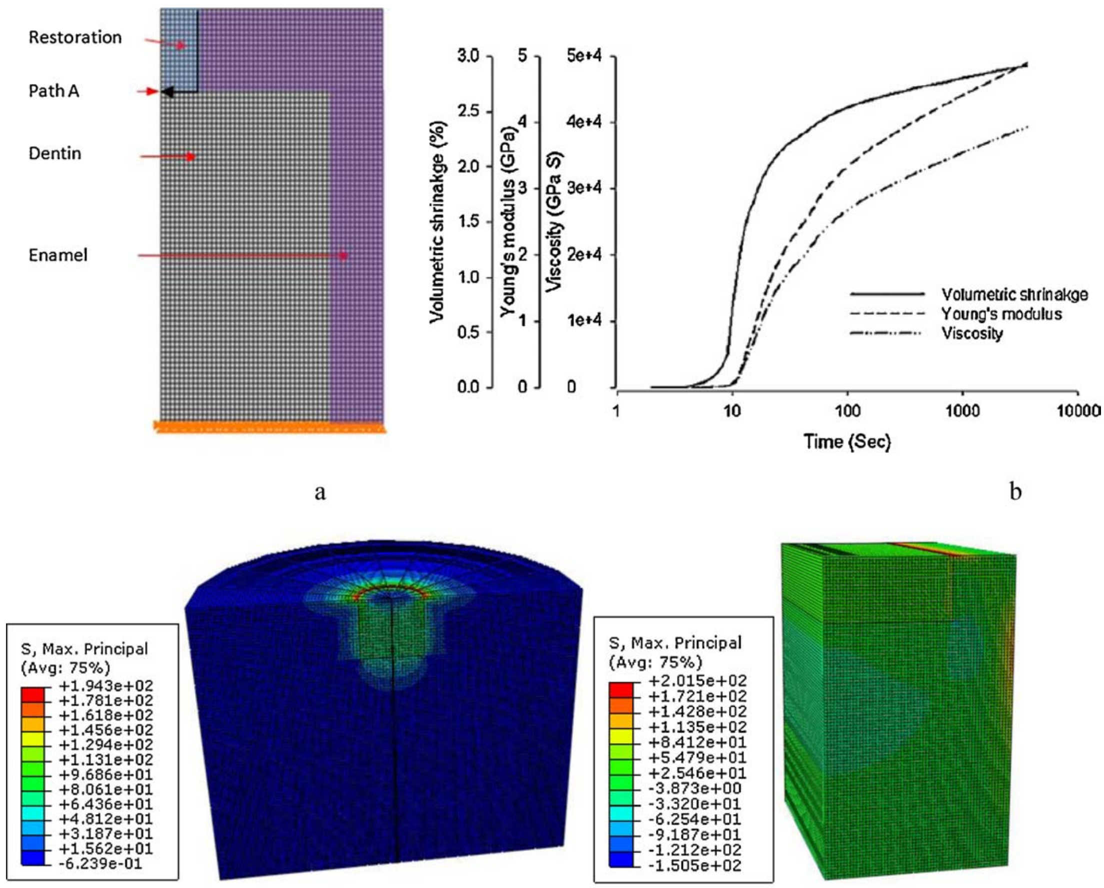

Fig. 2 – Models for FE analysis: (a) basic mesh, (b) temporal variations of volumetric shrinkage, Young's modulus and viscosity of the composite resin [19], (c) maximum principal stress distribution in an axisymmetric model representing a Class-I restoration (C = 5), and (d) maximum principal stress distribution in a plane-strain model representing a Class-II restoration (C = 1.04).

from the investigation of Li et al. [19]. The material properties of dentin and enamel used in the FE study are listed in Table 2.

3. Results

3.1. AE results

Fig. 3 shows the mean cumulative number of AE events against time for the four test groups, with the standard deviations shown as vertical bars. AE caused by interfacial debonding was first detected about 20 s into the curing of the composite and developed rapidly thereafter. Even after the curing light was switched off at 40 s, significant debonding of the composite could still be detected up till about 5 min. The mean and

Table 2 – Mechanical properties of enamel and dentin used in the FEA.

Materials	Young's modulus, E (GPa)	Poisson's ratio, ν
Enamel	84.1	0.30
Dentin	18.6	0.31

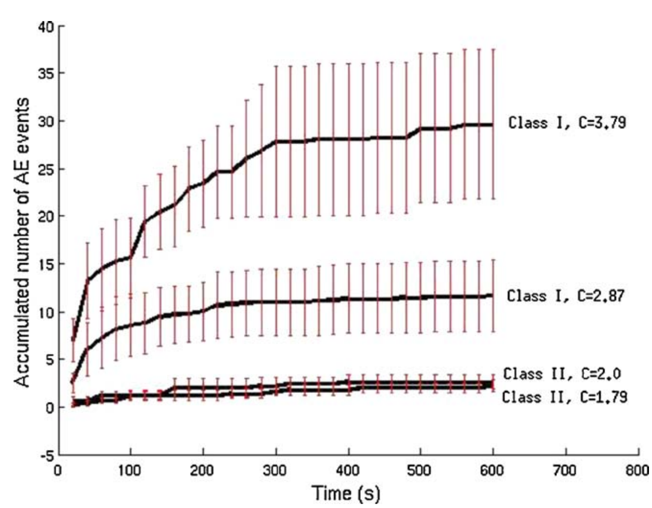

Fig. 3 – The cumulative number of AE events against time for the 4 test groups.

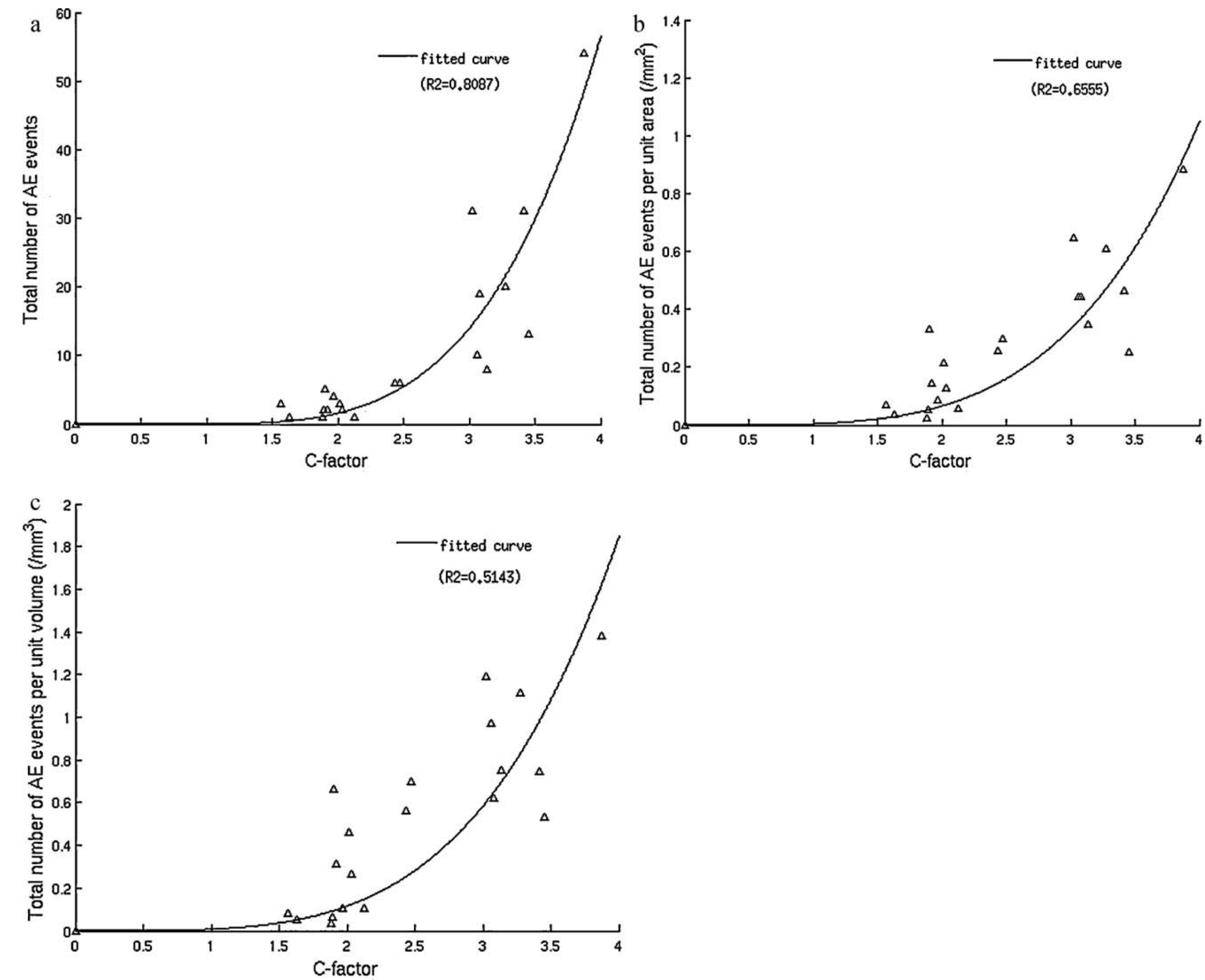

Fig. 4 – The total number of AE events as a function of the C-factor: (a) total number, (b) total number per unit bond area (/mm^2), and (c) total number per unit composite volume (/mm^3).

standard deviation of the total number of AE events for the four groups were 29.6 ± 15.7, 10.0 ± 5.8, 2.6 ± 1.5, and 2.2 ± 1.3 (Table 3), which showed an increase with an increasing C-factor. Table 4 shows the statistical significance (*p*-value) of the difference in total number of AE events between the different groups. It can be seen that the differences were significant, except that between Groups 3 and 4 which had very similar C-factors.

Table 3 – Results from the AE tests: mean (standard deviation).

Group	Total number of AE events	Total number of AE events per area (/mm^2)	Total number of AE events per volume (/mm^3)
1	29.6(15.7)	0.54(0.24)	0.89(0.37)
2	10.0(5.8)	0.39(0.14)	0.81(0.22)
3	2.6(1.5)	0.17(0.10)	0.36(0.21)
4	2.2(1.3)	0.05(0.02)	0.07(0.03)

Table 4 – Statistical significance (*p*-value) of the difference in total number of AE events between different groups.

Group	2	3	4
1	0.031	0.005	0.005
2		0.025	0.019
3			0.667

In Fig. 4(a), the total number of AE events for all the specimens were plotted against the C-factor. To account for the differences in bond area or volume of restorations with similar C-factors, the total number of AE events per unit bond area and that per unit composite volume are plotted in Fig. 4(b and c), respectively, for comparison. The mean and standard deviation of these normalized numbers for the 4 groups are also listed in Table 3. Despite the large variations in the number of AE events detected among specimens with similar C-factors, it can be seen that the amount of debonding increased with an increase in the C-factor. The trend remained the same even

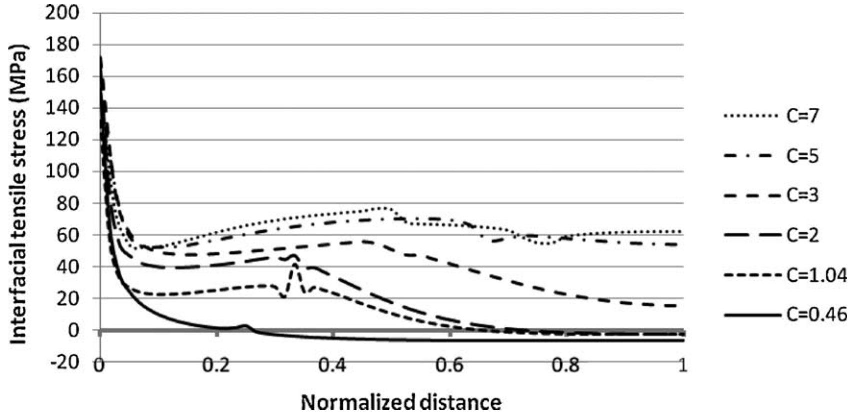

Fig. 5 – Distribution of interfacial normal stress along Path A, shown in Fig. 2(a), predicted by FEA for restorations with different C-factors.

when possible influence from the bond area and restoration volume was taken into account.

3.2. FEA results

Fig. 2(c and d) shows the distributions of the steady-state maximum principal stress in a model Class-I and Class-II restoration, respectively. High stresses can be seen along the tooth-restoration interfaces, especially at the occlusal surface and at the bottom corner of the restorations caused by material and geometric mismatches. The stresses normal to the interface for models with different C-factors are plotted in Fig. 5 against the normalized distance along Path A as defined in Fig. 2(a). It can be seen that there is a very high tensile stress concentration near the occlusal surface (normalized distance < 0.1) for all the models. However, the interfacial stresses reduce rapidly as the depth increases. It can also be seen that, along most of the interface, the normal tensile stress increases with an increase in the C-factor. An average stress over the length of the interface was calculated for all the C-factors (0.46–7) considered in the FE study (Fig. 5) and, through linear interpolation, representative stress values were determined from the results for the 4 experimental groups according to their C-factors (1.79–3.37). These were then plotted against the total number of AE events recorded to illustrate their relationship, as shown in Fig. 6. It can be seen that the number of AE events detected increased dramatically when the shrinkage stress was greater than 40 MPa.

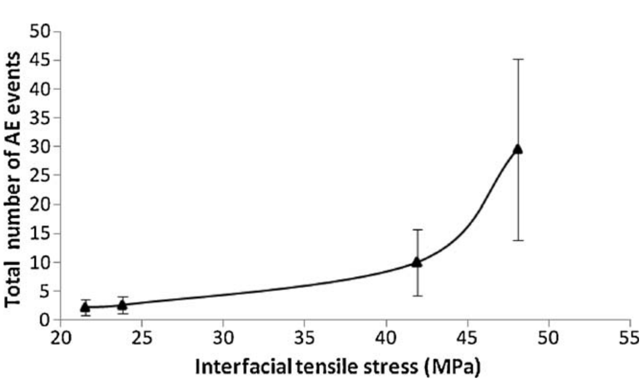

Fig. 6 – The total number of AE events plotted against the average interfacial tensile stress, as interpolated from the FEA results, for the 4 test groups.

4. Discussion and conclusions

In this study, to minimize the inherent variations among the specimens, the 20 selected third molars were all of similar shapes and dimensions. Also, for consistency, all the specimens were prepared by the same operator, using the same composite resin and bonding agent. Despite these efforts, it can be seen from Fig. 3 that the AE results still exhibited very large variations within each of the 4 groups of specimens. From Table 1, it can be noticed that the dimensions and C-factors of the restorations in each group were quite different, which reflects the significant variations in cavity preparation and partly explains the data scattering within each group seen in the AE results in Fig. 3. However, Fig. 4 shows that, even for specimens with restorations of similar dimensions and C-factors, the level of debonding, as indicated by the number of AE events recorded, during curing of the composite could still be very different.

Nevertheless, the trend of increasing debonding with an increasing C-factor is clear from the results presented in Figs. 3 and 4, and the differences among groups with very different C-factors are statistically significant (see Table 4). This is in accord with other studies [20–23] which showed that the higher the C-factor, the lower the remnant bond strength and the more microleakage observed. It is worth pointing out that standalone composite samples undergoing free shrinkage, i.e. with a zero C-factor, have been shown not to create any AE events [14], which is consistent with our current findings in Figs. 3 and 4. Possible influences of the bond area and restoration volume are considered in Fig. 4(b and c), respectively. However, no obvious effect of these two factors can be discerned from the figures.

Compared with traditional approaches for studying interfacial bonding/debonding in composite restorations, e.g. dye penetration followed by microscopy examination [6,7], the main advantage of the AE technique is that it can non-destructively monitor interfacial debonding and provide real-time information during curing of the composite, even though it cannot provide visual evidence of its occurrence. The results from our previous study [14], which compares the shrinkage behaviors of different composite materials and uses micro-computed tomography for verification, have already demonstrated the viability of the AE technique for assessing interfacial debonding due to shrinkage stress. The current work shows that, in addition to considering the influence of material properties, the method is also sensitive enough for considering the geometrical effects of the restoration on the development of interfacial debonding. However, it must be emphasized that, during testing, the tooth specimen must be kept moist at all times to prevent cracking through dehydration. Otherwise, spurious results will be obtained.

Although the models used for the FE analysis were rather simplistic, they were very useful in assessing the effect of the C-factor of the composite restoration on the magnitude of the shrinkage stresses generated. It can be seen from Fig. 5 that, overall, the interfacial tensile stress increases with an increase in the C-factor, which helps to explain mechanistically the corresponding increase in the level of interfacial debonding detected using the AE technique. The interfacial stresses from our simple FE analysis were very close to the bond strength reported for the same adhesive materials (13.8–36.1 MPa) [24].

Since composite restorations with a high C-factor tend to create high shrinkage stresses with bulk curing, special techniques may be needed for placing the restoration in order to minimize the shrinkage stress and, subsequently, the level of debonding. There are several ways to reduce the stresses caused by the shrinkage of composite resin. For example, the pulse-delay method of light activation mode has been applied to effectively decrease the shrinkage stress [25,26]. The incremental layering technique is another method for reducing shrinkage stress. Even for low-shrink composites, the layering technique is recommended [27]. Restorations placed with oblique layering and the two-step curing technique were shown to have excellent durability in a 12-year clinical study [28]. On the other hand, Nikolaenko et al. [9] reported that, for deep Class-I cavities, horizontal layering resulted in significantly higher microtensile bond strength to dentin than did vertical or oblique layering.

Notwithstanding the limitation of the present study, the AE technique has confirmed that the C-factor of a composite restoration is an important factor in the development of shrinkage stress and the accompanying interfacial debonding during polymerization of the composite. Our hypothesis that the higher the C-factor, the higher the shrinkage stress and the more interfacial debonding there will be can be accepted. Future work will utilize this technique to compare the effectiveness of the different layering methods for placing composite restorations.

Acknowledgements

The authors would like to acknowledge 3M ESPE for providing the restorative materials, the Minnesota Dental Research Center for Biomaterials and Biomechanics (MDRCBB) for providing the test devices, and the Minnesota Supercomputing Institute (MSI) for their computing services in support of this study. Xiaozhou Liu would like to thank the China Scholarship Council and the MDRCBB for financially supporting her study visit to the MDRCBB.

REFERENCES

[1] Dewaele M, Truffier-Boutry D, Devaux J, Leloup G. Volume contraction in photocured dental resins: the shrinkage–conversion relationship revisited. Dent Mater 2006;22(4):359–65.
[2] Feilzer AJ, De Gee AJ, Davidson CL. Quantitative determination of stress reduction by flow in composite restorations. Dent Mater 1990;6(3):167–71.
[3] Opdam NJ, Feilzer AJ, Roeters JJ, Smale I. Class I occlusal composite resin restorations: in vivo post-operative sensitivity, wall adaptation, and microleakage. Am J Dent 1998;11(5):229–34.
[4] Kohler B, Rasmusson CG, Odman P. A five-year clinical evaluation of Class II composite resin restorations. J Dent 2000;28(2):111–6.
[5] Collins CJ, Bryant RW, Hodge KL. A clinical evaluation of posterior composite resin restorations: 8-year findings. J Dent 1998;26(4):311–7.
[6] Braga RR, Ballester RY, Ferracane JL. Factors involved in the development of polymerization shrinkage stress in resin-composites: a systematic review. Dent Mater 2005;21(10):962–70.
[7] Braga RR, Boaro LC, Kuroe T, Azevedo CL, Singer JM. Influence of cavity dimensions and their derivatives (volume and 'C' factor) on shrinkage stress development and microleakage of composite restorations. Dent Mater 2006;22(9):818–23.
[8] Feilzer AJ, De Gee AJ, Davidson CL. Setting stress in composite resin in relation to configuration of the restoration. J Dent Res 1987;66(11):1636–9.
[9] Nikolaenko SA, Lohbauer U, Roggendorf M, Petschelt A, Dasch W, Frankenberger R. Influence of c-factor and layering technique on microtensile bond strength to dentin. Dent Mater 2004;20(6):579–85.
[10] Watts DC, Satterthwaite JD. Axial shrinkage-stress depends upon both C-factor and composite mass. Dent Mater 2008;24(1):1–8.
[11] Opdam NJ, Roeters FJ, Feilzer AJ, Verdonschot EH. Marginal integrity and postoperative sensitivity in Class 2 resin composite restorations in vivo. J Dent 1998;26(7):555–62.
[12] Sun J, Fang R, Lin N, Eidelman N, Lin-Gibson S. Nondestructive quantification of leakage at the tooth-composite interface and its correlation with material performance parameters. Biomaterials 2009;30(27):4457–62.
[13] Sun J, Eidelman N, Lin-Gibson S. 3D mapping of polymerization shrinkage using X-ray micro-computed tomography to predict microleakage. Dent Mater 2009;25(3):314–20.
[14] Li H, Li J, Yun X, Liu X, Fok ASL. Non-destructive examination of interfacial debonding in composite restorations using acoustic emission and micro-CT. Dent Mater, submitted for publication.
[15] Walmsley AD. Applications of ultrasound in dentistry. Ultrasound Med Biol 1988;14(1):7–14.
[16] Kim KH, Okuno O. Microfracture behaviour of composite resins containing irregular-shaped fillers. J Oral Rehabil 2002;29(12):1153–9.
[17] Ozcan M, Breuklander MH, Vallittu PK. The effect of box preparation on the strength of glass fiber-reinforced composite inlay-retained fixed partial dentures. J Prosthet Dent 2005;93(4):337–45.

[18] Ereifej N, Silikas N, Watts DC. Initial versus final fracture of metal-free crowns, analyzed via acoustic emission. Dent Mater 2008;24(9):1289–95.

[19] Li J, Li H, Fok AS, Watts DC. Multiple correlations of material parameters of light-cured dental composites. Dent Mater 2009;25(7):829–36.

[20] McLeod ME, Price RB, Felix CM. Effect of configuration factor on shear bond strengths of self-etch adhesive systems to ground enamel and dentin. Oper Dent 2010;35(1):84–93.

[21] Price RB, Derand T, Andreou P, Murphy D. The effect of two configuration factors, time, and thermal cycling on resin to dentin bond strengths. Biomaterials 2003;24(6):1013–21.

[22] Yoshikawa T, Sano H, Burrow MF, Tagami J, Pashley DH. Effects of dentin depth and cavity configuration on bond strength. J Dent Res 1999;78(4):898–905.

[23] He Z, Shimada Y, Tagami J. The effects of cavity size and incremental technique on micro-tensile bond strength of resin composite in Class I cavities. Dent Mater 2007;23(5):533–8.

[24] Scherrer S, Cesar P, Swain M. Direct comparison of the bond strength results of the different test methods: a cretical literature review. Dent Mater 2010;26:e78–93.

[25] Lopes LG, Franco EB, Pereira JC, Mondelli RF. Effect of light-curing units and activation mode on polymerization shrinkage and shrinkage stress of composite resins. J Appl Oral Sci 2008;16(1):35–42.

[26] Sakaguchi RL, Wiltbank BD, Murchison CF. Contraction force rate of polymer composites is linearly correlated with irradiance. Dent Mater 2004;20(4):402–7.

[27] Van Ende A, De Munck J, Mine A, Lambrechts P, Van Meerbeek B. Does a low-shrinking composite induce less stress at the adhesive interface? Dent Mater 2010;26(3):215–22.

[28] van Dijken JW. Durability of resin composite restorations in high C-factor cavities: a 12-year follow-up. J Dent 2010;38(6):469–74.