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Class I and Class II restorations of resin composite: An FE analysis of the influence of modulus of elasticity on stresses generated by occlusal loading

Erik Asmussen, Anne Peutzfeldt*

Department of Dental Materials, School of Dentistry, University of Copenhagen, 20 Nørre Alle, 2200 Copenhagen N, Denmark

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ABSTRACT

Objectives. It was the aim of the study to analyze by the FE method stresses generated in tooth and restoration by occlusal loading of Class I and Class II restorations of resin composite. On the basis of available information on the influence of the modulus of elasticity, the research hypothesis was that the marginal stresses would decrease with increasing modulus of elasticity of the restoration.

Methods. A cylindrical tooth was modelled in enamel and dentin and fitted with a Class I or a Class II restoration of resin composite. In one scenario the restoration was bonded to the tooth, in another the restoration was left nonbonded. The resin composite was modelled with a modulus of elasticity of 5, 10, 15 or 20 GPa and loaded occlusally with 100 N. By means of the soft-ware program ABAQUS the von Mises stresses in enamel and dentin were calculated.

Results. In the bonded scenario, the maximum stresses in the enamel were located at the occlusal margins (range 7–11 MPa), and in the dentin centrally at the pulpal floor (range 3.4–5.5 MPa). The stresses decreased with increasing modulus of elasticity of the resin composite. In the nonbonded scenario, the stresses were higher in the dentin and lower in the enamel than in the bonded cases, and the influence of the modulus of elasticity was less pronounced. The marginal stresses in the restoration were below 6 MPa in the bonded scenario and below 3 MPa in the nonbonded scenario.

Significance. Occlusal restorations of resin composite should have a high modulus of elasticity in order to reduce the risk of marginal deterioration.

1. Introduction

The modulus of elasticity of resin composites has been the subject of numerous investigations [1–6]. The investigations have shown that the modulus varies widely among resin composites. The main determining factor for the magnitude of the modulus is the filler content [2,6], but also the monomer composition plays a role [7]. For a given monomer composition and filler content, the modulus increases with the degree of conversion of the monomer [3,8,9]. Also the curing mode of light curing composites has been found to have an effect on the modulus [9,10].

The question now arises whether a high or a low modulus of elasticity is preferable. In situations where the configuration of the composite restoration has a high C-factor [11], there is a risk of gap formation due to polymerization contraction

* *Corresponding author*. Tel.: +45 3532 6580; fax: +45 3532 6505.
E-mail address: ea@odont.ku.dk (E. Asmussen).

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of the material. Theoretical considerations and experimental evidence support the notion that the modulus in this case should be low to reduce the risk of gap formation [4]. A low modulus reduces marginal stresses and increases the probability that the bond between composite and the walls of the cavity remains intact [11].

However, once the restoration has polymerized, stresses in the marginal areas may be generated by a different source. Depending on the state of bonding of the restoration (bonded versus nonbonded), occlusal loading by contact with an opposing cusp will induce stresses at the interface between restoration and tooth. As a consequence, the marginal integrity may be at risk and debonding a liability. In this situation, arguments have been advanced that the modulus should be so high as to withstand deformations induced by the masticatory forces [1,3,6,12], but only few investigations exist on which to base this argument. Lambrechts et al. [12] found that certain high-modulus resin composites perform well clinically and suggest that the reason for this may be the magnitude of the modulus of elasticity. Microfilled resin composites are low-modulus materials and have been found to exhibit a relatively high degree of marginal crevicing or ditching at occlusal margins compared to macrofilled composites [13,14]. Finally, in an in vitro study it was found that two high-modulus composites were better able to maintain marginal integrity under simulated occlusal loading than were two low-modulus composites [15]. Thus, a study dealing with the question of the preferred size of the modulus of elasticity of resin composite in occlusal restorations seems warranted.

A study based on laboratory experiments may give the answer to this question, but in view of the variability of the mechanical properties and shape of teeth, an FE analysis may be more appropriate. It was the aim of this study to analyze by the FE method stresses generated in tooth and restoration by occlusal loading of Class I and Class II restorations of resin composite. On the basis of the rather scarce available information on the influence of the modulus, the research hypothesis was that the marginal stresses would decrease with increasing modulus of the restoration. It was further hypothesized that bonded restorations would give rise to higher stresses in the marginal area than nonbonded restorations.

2. Materials and methods

The FE analysis was performed with the soft-ware program ABAQUS 6.6-1 (ABAQUS, Rising Sun Mills, Providence, RI, USA). Three materials were modeled in the calculations: enamel, dentin and resin composite. The materials were assumed to be isotropic with the elastic constants shown in Table 1 [16]. The

Table 1 – Elastic constants of materials used in the FE analysis [16]

Material	Modulus of elasticity (GPa)	Poisson's ratio
Dentin	18.6	0.31
Enamel	84.1	0.30
Resin composite	5; 10; 15; 20	0.30

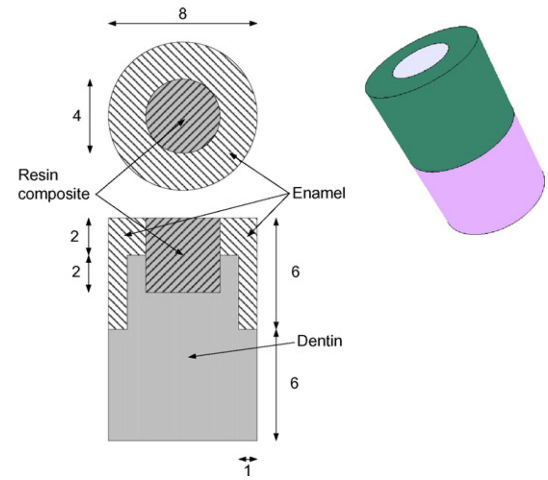

Fig. 1 – Three-dimensional finite element model of tooth restored with Class I resin composite. Dimensions are in mm.

FE analysis was based on the 3D models shown in Figs. 1 and 2. The Class I model shown in Fig. 1 was axisymmetrical. The Class II model shown in Fig. 2 was similar to the model in Fig. 1 except that the restoration was extended to include proximal boxes. The diameter of the tooth was 8 mm. Occlusally the enamel was 2 mm thick and peripherally 1 mm thick. Circumferentially, the enamel had a height of 6 mm. The Class I restoration had a diameter of 4 mm. The Class II restoration had the Class I restoration as shape of departure and was given two occlusal beams with a width of 3 mm. One approximal box finished 1 mm above the enamel margin, the other extended 1 mm below the enamel margin. The model was constrained in the apical plane. In one scenario the restorations were bonded to enamel and dentin. In another scenario, corresponding axial surfaces were free to slide with respect to one another, simulating a nonbonded situation. The restorations were loaded centrally with a force of 100 N in the axial

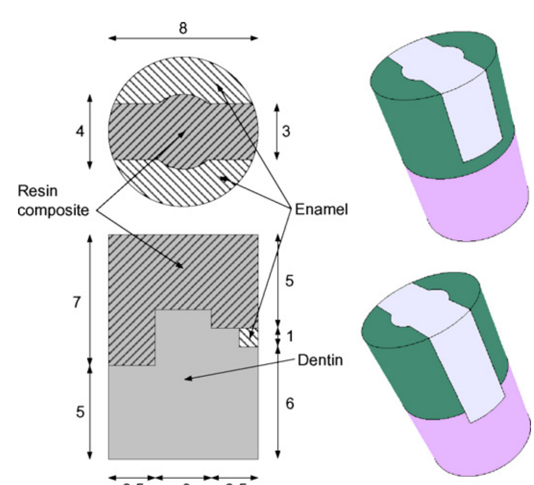

Fig. 2 – Three-dimensional finite element model of tooth restored with Class II resin composite. Dimensions are in mm.

direction. The Class I model was meshed by 29,814 hexahedral elements, the Class II model was meshed by 36,360 hexahedral elements. The resin composite was given a modulus of elasticity of 5, 10, 15 and 20 GPa, respectively, and von Mises stresses were calculated for each modulus.

3. Results

In the bonded Class I situation (Fig. 3), the maximum stresses in the enamel were located at the occlusal margin and at the enamel–dentin junction. In the dentin they were placed centrally at the pulpal floor. In the unbonded Class I situation (Fig. 4), the maximum stresses in the enamel were located at the enamel–dentin junction. In the dentin they were located at the internal line angle of the pulpal floor and the lateral walls. In the bonded Class II situation (Fig. 5), the maximum stresses in the enamel were located at the occlusal margin and at the enamel–dentin junction. In the dentin they were placed centrally at the pulpal floor. In the unbonded Class II situation (Fig. 6), the maximum stresses in the enamel were located at the gingival wall of the proximal box. In the dentin the maximum stresses were located in the facial and lingual corners of the pulpal and axial walls.

The maximum von Mises stresses in enamel and dentin are presented in Table 2. In the bonded cases the stresses in the enamel (range 7–11 MPa) and in the dentin (range 3.4–5.5 MPa) decreased with increasing modulus of the resin composite. In the nonbonded Class I case, the stresses in the enamel (range 4.4–4.5 MPa) and in the dentin (range 8.7–8.9 MPa) were only slightly affected by changes in the modulus. In the nonbonded Class II situation, the enamel stresses (range 7.2–7.5 MPa) did not vary much, in contrast to the maximum dentin stresses (range 11.1–19.4 MPa), which decreased significantly with increasing modulus of the resin composite.

Regarding the maximum stresses in the resin composite restoration, directly below the point of loading the maximum stresses were very high, but – because of the concentrated load – cannot be considered a physical reality. In the marginal areas of the occlusal surface of the restoration the von Mises stresses were below 6 MPa in the bonded cases and below 3 MPa in the nonbonded cases. In the bonded cases the marginal von Mises stresses of the restoration decreased with increasing modulus of elasticity of the resin composite. In the unbonded cases these stresses varied only slightly with the modulus of elasticity of the resin composite.

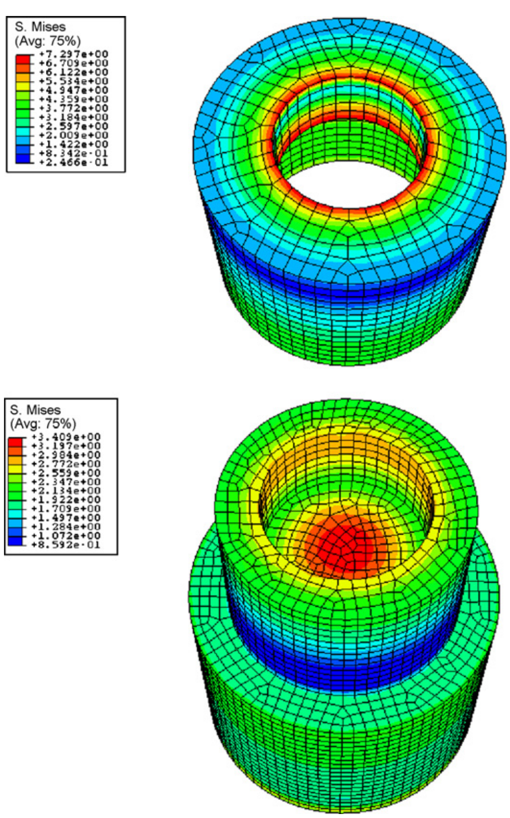

Fig. 3 – Distribution of von Mises stresses (MPa) in the enamel (top) and in the dentin (bottom) of tooth restored with a bonded Class I resin composite. The restoration was loaded centrally with a force of 100 N.

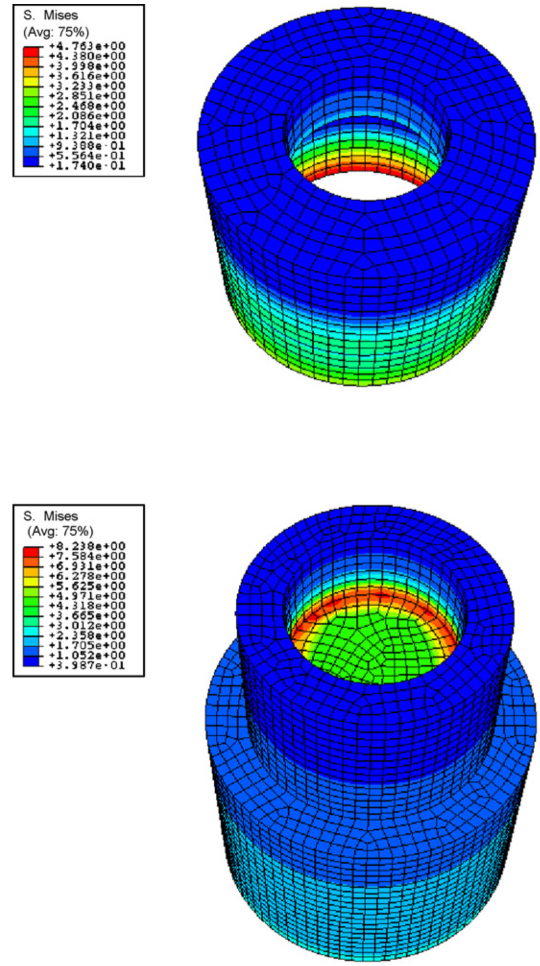

Fig. 4 – Distribution of von Mises stresses (MPa) in the enamel (top) and in the dentin (bottom) of tooth restored with a nonbonded Class I resin composite. The restoration was loaded centrally with a force of 100 N.

Table 2 – Maximum von Mises stresses (MPa) in enamel and dentin in relation to modulus of elasticity of the resin composite

Modulus (GPa)	Material	Class I bonded	Class I nonbonded	Class II bonded	Class II nonbonded
5	Enamel	9.5	4.4	10.7	7.5
	Dentin	3.9	8.8	5.5	19.4
10	Enamel	8.4	4.4	8.7	7.2
	Dentin	3.7	8.7	4.3	13.9
15	Enamel	7.6	4.5	7.6	7.2
	Dentin	3.5	8.7	3.9	11.7
20	Enamel	7.0	4.5	6.9	7.3
	Dentin	3.4	8.9	3.6	11.1

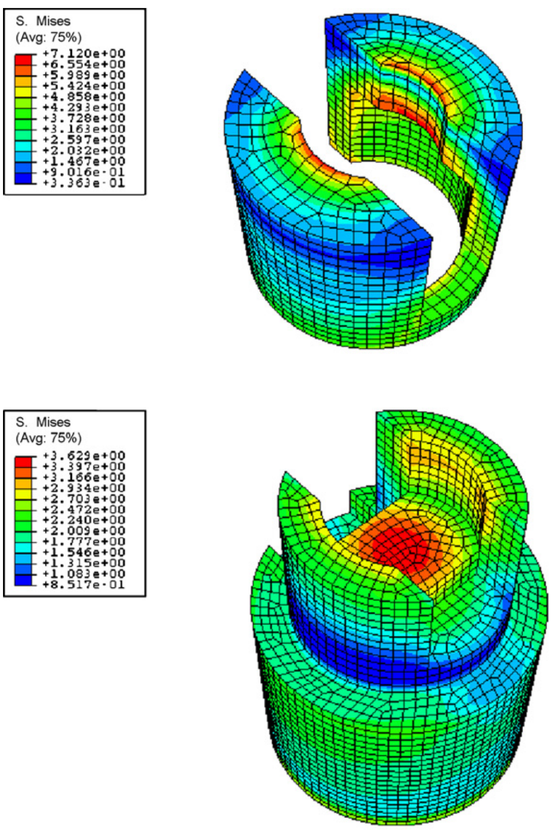

Fig. 5 – Distribution of von Mises stresses (MPa) in the enamel (top) and in the dentin (bottom) of tooth restored with a bonded Class II resin composite. The restoration was loaded centrally with a force of 100 N.

4. Discussion

The FE analysis has shown that the modulus of elasticity of the resin composite influences the stresses generated in enamel, dentin and restoration when Class I and Class II restorations are loaded occlusally. Depending on the state of bonding of the restoration, the stresses were either unaffected or decreased when the modulus of elasticity of the resin composite increased. Further, marginal stresses were generally higher in bonded restorations than in nonbonded restorations. Thus, the hypotheses expressed in the introduction were validated, but only in part.

The maximum stresses ranged between 3 and 19 MPa when the restoration was loaded with 100 N. In a clinical situation, considerably higher occlusal loads may occur, leading to a proportional increase in the calculated stresses.

Regarding the enamel, in the bonded restorations the maximum stresses were found to be located at the enamel margins. The range of the stresses was 7–11 MPa. Assuming a tensile strength of enamel of 10 MPa [17] and considering the fact that higher occlusal loads than the one used in the present FE analysis may occur, it becomes evident that breakdown of

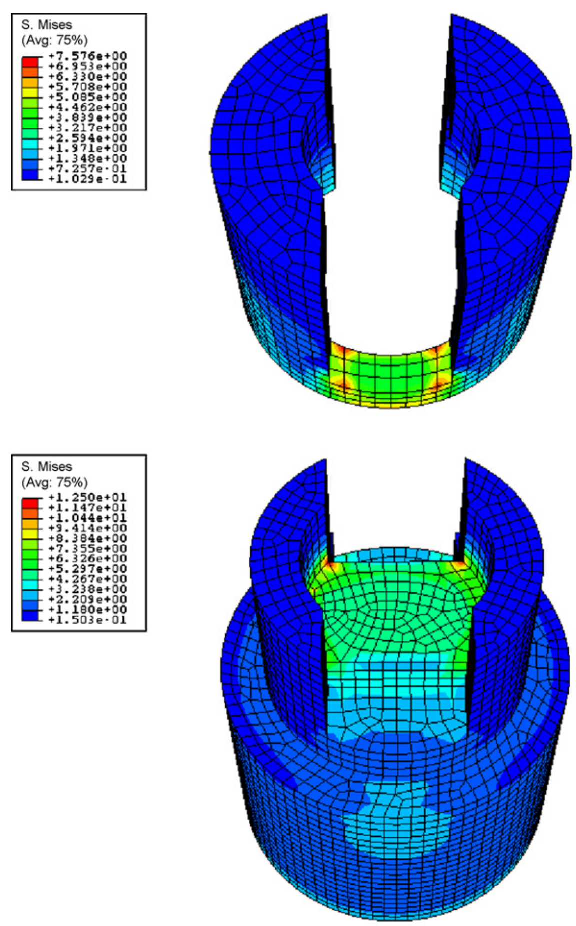

Fig. 6 – Distribution of von Mises stresses (MPa) in the enamel (top) and in the dentin (bottom) of tooth restored with a nonbonded Class II resin composite. The restoration was loaded centrally with a force of 100 N.

the enamel margins is a liability. Assuming a bond strength of resin composite to the sides of enamel prisms of 10 MPa [18], it follows that also debonding is possible. Marginal crevices, marginal defects, and the associated risk of marginal discoloration and secondary caries are indeed frequently found in relation to occlusal composite restorations [19–21] and constitute major reasons for the replacement of composite restorations. On the other hand, the von Mises stresses in the occlusal marginal areas of the resin composite restoration were less than 6 MPa; in view of a tensile strength of 50–60 MPa [7] these stresses would appear not to imply a risk of marginal fracture of the restoration.

In the bonded cases, the stresses at the occlusal enamel margins were found to increase with decreasing modulus of the resin composite. As a consequence, the prevalence of marginal deficiencies may be expected to be higher with low-modulus materials like microfilled and flowable resin composites than with high-modulus materials like macrofilled, packable and hybrid composites [1,5,6,8,11,12]. In agreement with this, it has been found that high-modulus composites behave well clinically, and it has been suggested that this may be due to the magnitude of the modulus of these materials [12]. Further, low-modulus composites have been noted to give rise to more ditching and crevicing at the occlusal margins than high-modulus composites [13,14,22]. Finally, in a laboratory study with a chewing machine it was found that the macrofilled composites maintained marginal integrity better than did the microfilled composites [15]. It should be kept in mind, however, that in the cited investigations other factors than the modulus may have influenced the findings.

In the Class I and the bonded Class II situations, high stresses in the enamel were found also at the enamel–dentin junction. This may lead to speculations about a possible stress-related disruption of enamel prisms at this location. It is conceivable that such a disruption may predispose for the invasion of cariogenic bacteria along the junction [23].

In the nonbonded cases the maximum stresses in the enamel are smaller than in the bonded cases because the restoration slides with respect to the enamel walls and transfers stresses to the dentin. The minimal influence of the modulus of elasticity of the resin composite may be explained in the same manner.

Regarding the dentin, in the bonded restorations the maximum stresses were located at the pulpal floor. The range of the stresses was 3.4–5.5 MPa. The maximum stresses in dentin were smaller than those in the enamel because bonding to a stiffer material (enamel) protects the more flexible material (dentin). Assuming a tensile strength of dentin of 50–100 MPa [24] it is evident that fracture of dentin is not likely to occur. However, the deformation associated with the stresses may cause pain when the restoration is loaded occlusally.

In the nonbonded Class II situation, the maximum stresses were found at the facial and lingual corners of the pulpal and axial walls. Apparently, these corners exhibit a stress-enhancing notch effect. The stresses at the pulpal floor were of a size of about 7 MPa, i.e. higher than the corresponding stresses in the bonded case where the stiffness of enamel offers protection.

The stresses were generally higher in the Class II situation both in the bonded and in the nonbonded cases. This reflects the fact that less tooth structure to distribute the stresses is present in connection with Class II restorations as compared to Class I restorations. It may indicate that Class II restorations may be expected to have shorter life expectancy than Class I restorations.

To conclude, within the limitations of the present work it was found that the resin composite of occlusal restorations should have a high modulus of elasticity. A high modulus will reduce marginal stresses in the enamel and the restoration when the restoration is loaded by the opposing tooth.

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