Investigation of the Effects of Adhesive Materials of Different Types and Thicknesses on Dental Tissue Stress via FEM Analysis

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The aim of this study was to investigate the types and thicknesses of adhesive materials used in restorative treatment in dentistry in class I occlusal and class II disto-occlusal cavities and to examine the effects of stress distribution on enamel, dentin, restoration material, and adhesive material using the finite element stress analysis method. A 3-dimensional geometry of the tooth was obtained by scanning the extracted 26 numbered upper molar tooth with dental tomography. The 3D geometry obtained by using the Geomagic Design X 2020.0 software was divided into surfaces, and necessary arrangements were made. With the Solidworks 2013 software, 2 different cavity modeling, class I occlusal and class II disto-occlusal, with a cavity angle of 95 degrees on the 3D model, as well as 10, 30, and 50 micrometers thick, four types of adhesive materials and the modeling of the bulk-fill composite material on it were made. With finite element stress analysis, the stress distribution was analyzed using the Abaqus software. The materials used in the study are included in the simulation as isotropic linear elastic. Periodontal ligament and jawbone were not included in the analysis. A total of 600 N pressure was applied on the models. In our study, it was observed that the amount of stress on the tooth structures changed when the thickness, elastic modulus, and Poisson ratios of the adhesive material were changed. In addition, when all models are examined, it is seen that when the thickness is increased, more stress is placed on the adhesive material compared to the restoration, while when 50-micrometer-thick adhesive material is used, more stress is placed on the restoration compared to the adhesive material.

1. Introduction

Dental caries is one of the most common chronic diseases worldwide, one to which people are susceptible throughout their lives [1, 2]. Restorations mean changing the natural tooth biomechanical balance. This is especially true for resin-based composite restorations because the hardness of the materials used may not exactly match natural teeth [3].

Resin-based composites have been a revolutionary innovation in restorative materials. These materials were mainly developed to restore the aesthetics and function of teeth and are now widely used for class I and II restorations [4–6]. In particular, following the detailed examination and analysis of the forces occurring in the mouth, the forces emerging as a result of these analyses should be distributed according to an appropriate physiological balance, and the restorations on the teeth should be in accordance with the principles of
oral rehabilitation [7]. The primary source of stress in a restored tooth is usually dimensional changes or occlusal loads at the interface of the composite, tooth, and restorative material [8].

This analysis method has been developed as a solution to certain problems that arise in experimental environments and are very difficult to solve. In this method, the object or material to be examined is modeled by dividing it into certain quantities of elements, and analyses are performed on these modeled parts. With the finite element method, some problems such as heat transfer, stress analysis, electromagnetism, and fluid mechanics can be analyzed [9–12]. Since this analysis method has many useful features, it has frequently been a preferred method for research in today’s dentistry. While it is impossible to repeat a study many times in clinical trials, the experiments performed with this method can be easily repeated [13–16]. The analysis of materials with irregular shapes, which are used in many treatments in the field of dentistry, can be easily done with the finite element stress analysis method [17, 18].

This method is one of the most important modern scientific techniques, and the use of computer programs is mandatory as billions of arithmetic operations are performed in its application [7, 19]. Compared to laboratory tests, this analysis method has many advantages; living tissues are not needed and variables can be manipulated, while maximum standardization is achieved as a result [9]. Another advantage is that it is much less time-consuming compared to many other methods [14].

A warm air blow technique, an active application technique, and a double-layer application have been reported to improve the bonding performance of adhesive materials, and some of these techniques also influence the thickness of the adhesive layer [20–25]. The aim of this study was to investigate the types and thicknesses of adhesive materials used in restorative treatment in dentistry in class I occlusal and class II disto-occlusal cavities, as well as to examine the effects of stress distribution on enamel, dentin, restoration material, and adhesive material using the finite element stress analysis method.

2. Materials and Methods

The 3D geometry of tooth number 26, which was taken with a dental tomography [DA1] device, was scanned. Cone beam computerized tomography (CBCT) was taken using Morita 3D Accuitomo 170 (J Morita Mfg. Corp., Kyoto, Japan). The size of the imaging volume was a cylinder with diameter 40 × height 40 mm at the X-ray rotational center. Images were taken under the exposure condition of 90 kVp (X-ray tube voltage) and 5 mA (value of the electric current) which were the standard parameters and can be changed for different subjects. Images were taken using 160 qm and 17.5-second exposure time parameters. The 3D geometry created using the Geomagic Design X 2020.0 software was divided into surfaces, and necessary arrangements were made. Periodontal ligament (PDL) was not designed, so fixed and pinned boundary conditioning was used to simulate roots as fixed in the bone. The tooth model was placed in the coordinate system so that the x-axis defines the buccolingual direction, the y-axis defines the mesiodistal direction, and the z-axis is oriented upwards (Figure 1).

With the Solidworks 2013 software (Solidworks Corp., USA), two different cavities were modeled, class I occlusal and class II disto-occlusal, with a cavity angle of 95 degrees on the 3D model. A class I cavity with an occlusal depth of 4 mm and an occlusal-gingival depth (Figure 2). A class II cavity with an occlusal depth of 4 mm and an occlusal-gingival depth of 6 mm was fixed with the occlusal margin in the enamel and the gingival margin in dentin (Figure 3).

Since the elastic modulus and Poisson ratio of adhesive materials affect the stress values on dental tissues, restoration, and adhesive material, we chose adhesive materials with different elastic modulus and Poisson ratios in this study. Four types of adhesive material, of 10-, 30-, and 50-micrometer thicknesses (Table 1), were applied to the cavities. Afterwards, bulk-fill composite material was applied on the adhesive material.

With the finite element stress analysis method, the stress distribution was examined with the help of the Abaqus software (2020 Dassault Systems Simulation Corp., Johnston, RI, USA). The restorative materials used in our study were included in the simulation as isotropic linear elastic. Periodontal ligament and jawbone were not included in the analysis, and a total pressure of 600 N was applied on the models (Figure 1).

The total number of nodes of cavity models with different adhesive thicknesses is shown in Table 2.
3. Results

As a result of the change in the adhesive material thickness in all cavity models, the enamel and dentin thicknesses are constant, while the restoration thicknesses change. The thickness of the restoration decreases when the thickness of the adhesive material increases, and the thickness of the restoration increases when the thickness of the adhesive material decreases, but the enamel and dentin thicknesses remain constant in all models.

When all models are examined individually, while the thickness increases, more stress is placed on the adhesive material compared to the restoration, while when 50-micrometer-thick adhesive material is used, more stress is placed on the restoration compared to the adhesive material. In addition, when all models are considered, the stress values on the enamel and dentin were higher than the stress values on the restoration and adhesive material.

3.1. Results Obtained in Class I Cavity as a Result of Stress Analysis

When adhesive materials with either an elastic modulus of 3.6 GPa and a Poisson ratio of 0.28 or an elastic modulus of 1.9 GPa and a Poisson ratio of 0.28 (adhesive system 1 and adhesive system 2, respectively) and when
the thickness of the class I occlusal cavity increases, the stress on the enamel and dentin increases, while the amount of stress on the restoration and adhesive material decreases. However, the highest stress value (Pmax) for enamel and dentin was found when 30-micrometer-thick adhesive material was used (Figures 4 and 5).

When an adhesive material with an elastic modulus of 1 GPa and a Poisson ratio of 0.3 (adhesive system 3) is used and when the thickness of the class I occlusal cavity increases, the stress on the enamel, dentin, and adhesive material decreases, while the amount of stress on the restoration increases. The highest stress value for enamel and
Dentin was found when 10-micrometer-thick adhesive material was used. Minimal changes were observed in the stresses on the dentin when 30-micrometer- and 50-micrometer-thick adhesive materials were used (Figure 6).

When an adhesive material with an elastic modulus of 1 GPa and a Poisson ratio of 0.24 (adhesive system 4) is used and when the thickness of the class I occlusal cavity increases, the stress on the enamel, dentin, and adhesive material decreases, while the amount of stress on the restoration material increases. However, when 50-micrometer-thick adhesive material was used, the amount of stress on the dentin increased slightly compared to the use of 30-micrometer-thick adhesive material. The highest stress value for enamel and dentin was found when 10-micrometer-thick adhesive material was used (Figure 7).

In class I occlusal cavity, when the elastic modulus is reduced from 3.6 GPa to 1.9 GPa while the Poisson ratio is constant and when 10-micrometer-thick adhesive material was used, the amount of stress on the dentin increased slightly compared to the use of 30-micrometer-thick adhesive material. The highest stress value for enamel and dentin was found when 10-micrometer-thick adhesive material was used (Figure 7).
was used, no change was observed in the stresses on the enamel. When 30-micrometer-thick adhesive material is used, the stress on the enamel increases, while when 50-micrometer-thick adhesive material is used, the stress on the enamel decreases. On the other hand, when 10-, 30-, and 50-micrometer-thick adhesive materials are used on dentin, the stress values on the dentin increase. The stresses on the restoration increased when 10- and 30-micrometer-thick adhesive materials were used, while the stresses on the restoration decreased when 50-micrometer-thick adhesive material was used. The stresses on the adhesive material decreased when 10-, 30-, and 50-micrometer-thick adhesive materials were used (Figure 8).

In class I occlusal cavity, when the elastic modulus is constant and the Poisson ratio is reduced from 0.3 to 0.24 and while the amount of stress on enamel decreased when 10-micrometer-thick adhesive material was used, the stress on enamel increased when 30- and 50-micrometer-thick adhesive materials were used.
adhesive material was used. On the other hand, the amount of stress on dentin did not change when 10-micrometer-thick adhesive material was used, while the stress on dentin increased when 30- and 50-micrometer-thick adhesive materials were used. Stress on restoration decreased when 30-micrometer-thick adhesive material was used but increased when 10- and 50-micrometer-thick adhesive materials were used. The stresses on the adhesive material decreased when 10-, 30-, and 50-micrometer-thick adhesive materials were used (Figure 9).

3.2. Results Obtained in Class II Cavity as a Result of Stress Analysis.

When an adhesive material with an elastic modulus of 3.6 GPa and a Poisson ratio of 0.28 (adhesive system 1) is used, the highest stress value in the enamel in the class II disto-occlusal cavity occurs when an adhesive material with a thickness of 50 micrometers is used, while the lowest amount of stress occurs when an adhesive material with a thickness of 30 micrometers is used. In dentin, on the other hand, the highest stress value occurs when an adhesive material with a thickness of 30 micrometers is used, while the lowest amount of stress occurs when an adhesive material with a thickness of 10 micrometers is used. The amount of stress on the restoration and adhesive material decreases as the thickness increases (Figure 10).

When an adhesive material with an elastic modulus of 1.9 GPa and a Poisson ratio of 0.28 (adhesive system 2) is used, the highest stress value in the enamel in the class II disto-occlusal cavity occurs when 50-micrometer-thick adhesive material is used, while the lowest amount of stress occurs when an adhesive material with a thickness of 30 micrometers is used. In dentin, on the other hand, the highest stress value occurs when an adhesive material with a thickness of 30 micrometers is used, while the lowest amount of stress occurs when an adhesive material with a thickness of 10 micrometers is used. The amount of stress on the restoration and adhesive material decreases as the thickness increases (Figure 11).

When an adhesive material with an elastic modulus of 1 GPa and a Poisson ratio of 0.3 (adhesive system 3) is used, the highest stress value in the enamel in the class II disto-occlusal cavity occurs when an adhesive material with a thickness of 50 micrometers is used, while the lowest amount of stress occurs when an adhesive material with a thickness of 30 micrometers is used. In dentin, on the other hand, the highest stress value occurs when an adhesive material with a thickness of 30 micrometers is used, while the lowest amount of stress occurs when an adhesive material with a thickness of 10 micrometers is used. The amount of stress on the restoration and adhesive material decreases as the thickness increases (Figure 12).

When an adhesive material with an elastic modulus of 1 GPa and a Poisson ratio of 0.24 (adhesive system 4) is used, the highest stress value in the enamel in the class II disto-occlusal cavity occurs when 50-micrometer-thick adhesive material is used, while the lowest amount of stress occurs
when 30- and 10-micrometer-thick adhesive materials are used. In addition, when 10- and 30-micrometer-thick adhesive materials were used, no change was observed in the stresses on the enamel. In dentin, on the other hand, the highest stress value occurs when using adhesive material with a thickness of 30 micrometers, while the lowest amount of stress occurs when using adhesive material with a thickness of 10 micrometers. The amount of stress on the restoration and adhesive material decreases as the thickness increases (Figure 13).

When the elastic modulus is reduced from 3.6 GPa to 1.9 GPa while the Poisson ratio is constant in the class II
In class II disto-occlusal cavity, when the elastic modulus is constant and the Poisson ratio is reduced from 0.3 to 0.24, the amount of stress on enamel and dentin increased when 10-, 30-, and 50-micrometer-thick adhesive materials were used. The stress values on restoration and adhesive material decreased when 10-, 30-, and 50-micrometer-thick adhesive materials were used (Figure 15).

In class II disto-occlusal cavity, the amount of stress on enamel and dentin increased when 10-, 30-, and 50-micrometer-thick adhesive materials were used. The amount of stress on the restoration increased when 10- and 50-micrometer-thick adhesive materials were used but decreased when 30-micrometer-thick adhesive material was used. The stresses on the adhesive material decreased when 10-, 30-, and 50-micrometer-thick adhesive materials were used, and the greatest rate of reduction in stress occurred when adhesive material with a thickness of 10 micrometers was used (Figure 14).
4. Discussion

Knowing the intraoral biomechanics, the stresses caused by the forces on the teeth and their destructive effects on the dental tissues ensure that the restorations are more successful and long lasting.

Meijer et al. in their study proved that the two-dimensional analysis does not reflect reality sufficiently.
In other studies, it has been shown that the three-dimensional finite element stress analysis method gives more realistic results [33–35]. In addition, Kamposiora et al. stated that the method would be simpler by reducing the three-dimensional material data to two dimensions, so that high-capacity computers would not be needed and the cost would be reduced [36].

Directly applied posterior resin composites, machinable block composites, and ceramic materials can be used successfully to restore decayed teeth [37]. These materials are able to resist the occlusal forces of class I and II restorations. Direct or indirect restorative materials and technologies are widely used; however, there is no consensus on the best choice for restoration [38]. We used bulk-fill composite as restorative material in our study. Bulk-fill composites can be adequately polymerized at a thickness of 4 mm [39–41]. Some studies showed a possible depth of cure up to 5.5 mm [42]. Further, bulk-fill composites result in having less shrinkage and lower values of contraction stress in comparison to the conventional types of composite resins [43]. It has been suggested that it may be beneficial to use a thin layer of restorative materials such as glass ionomer cements, flowable composites, or nanofilled adhesives into the cavity before resin filling materials are applied to reduce stress [44]. The stiffness or elastic modulus of dental restorative materials and adhesive materials is extremely important at the adhesive-tooth-restoration interface. Ausiello et al. showed that in class II adhesive restorations, tubercle displacement is greater for more rigid composites due to stress from polymerization shrinkage, but lower tubercle movements are seen when more flexible composites are used [45].

In the literature, there are studies using different adhesive thicknesses such as 2, 5, 10, and 30 micrometers. In the study by Ausiello et al. in 2011, a thin (10 micrometers) adhesive layer was used [46]. The thicker the adhesive layer, the higher the magnitude of the peel stresses and strains and thus the larger the bending deformation [47]. Takamizawa et al. in their study changed the adhesive thickness clinically by applying strong or light air to the adhesive material, increasing or decreasing the air application time, and applying the adhesive material in layers [48].

Alp et al. prepared three class II models using an adhesive layer with a thickness of 30 micrometers [49]. In the first model, amalgam (M1) was placed on the adhesive and in the second model glass carbomer cement (M2), and in the third model, 1 mm thick resin modified glass ionomer cement was placed on it, followed by a 30-micrometer-thick adhesive material and then resin composite (M3). While the stress values occurring in the adhesive layer as a result of the forces applied to the models were close and high in the M2 and M3 models, the lowest value was found in the M1 model. At the same time, when the stress values in all models were examined in this study, it was observed that more stress occurred in the restoration materials and adhesive material compared to enamel and dentin.
Kemp-Scholte and Davidson, in their study in 1990, reported that the thicker adhesive layer caused the formation of lower interface stresses [44]. A greater adhesive layer thickness can theoretically be beneficial in terms of providing a more flexible and stress-absorbing transition between dentin and composite [50].

In the study by Coelho et al., which uses the three-dimensional finite element stress analysis method, it was observed that the maximum stress values increased and the bond strength values decreased as the adhesive thickness increased for single bond [50]. In a study by Zheng et al., it was reported that the bond strength decreases as the adhesive layer thickness increases for single bond [51]. In our study, when the adhesive system with a Poisson ratio of 0.28 and an elastic modulus of 3.6 GPa, or a Poisson ratio of 0.28 and an elastic modulus of 1.9 GPa, is used in class I occlusal cleft, the stresses on enamel and dentin are low when 10-micrometer-thick adhesive material is used, while it increases when 30-micrometer-thick adhesive material is used. However, when the adhesive thickness was increased to 50 micrometers, the stress values on enamel and dentin decreased again. As a result, the clinical benefits of having a thin or thick adhesive layer are still a matter of debate [52, 53].

5. Conclusion

Elastic modulus, Poisson ratio, and thickness of the adhesive material are used in restorative dentistry. It significantly affects the amount of stress on the enamel, dentin, restorative material, and adhesive material. For adhesive materials and composites of different hardness, FEM analysis allows the determination of the optimum adhesive layer thickness that provides maximum stress distribution. However, there are not enough studies in the literature on the effects of the thickness of the adhesive materials on the stresses on dental tissue.

In our study, when the elastic modulus decreases while the Poisson ratio remains constant, the stress values on enamel and dentin in class I and class II cavities vary, but the thickness of the adhesive material, where the maximum stresses occur, did not change. Also, when the elastic modulus is constant and the Poisson ratio decreases, the stress values on enamel and dentin in class I and class II cavities show a slight variation, while the thickness of the adhesive material at which the maximum stresses occur does not change. When all models are examined individually, while the thickness increases, more stress is placed on the adhesive material compared to the restoration, while when 50-micrometer-thick adhesive material is used, more stress is placed on the restoration compared to the adhesive material. At the same time, it was found in our study that the stress values on the enamel and dentin in all models were higher than the stress values on the restoration and adhesive material.

Data Availability

No data were used in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] J. L. Ferracane, "Resin composite—State of the art," Dental Materials, vol. 27, no. 1, pp. 29–38, 2011.
[2] R. H. Selwitz, A. I. Ismail, and N. B. Pitts, “Dental caries,” Lancet, vol. 369, no. 9555, pp. 51–59, 2007.
[3] P. Ausiello, A. Apicella, and C. L. Davidson, “Effect of adhesive layer properties on stress distribution in composite restorations—a 3D finite element analysis,” Dental Materials, vol. 18, no. 4, pp. 295–303, 2002.
[4] A. Yazici, I. Ustunkol, G. Ozgunaltay, and B. Dayangac, “Three-year clinical evaluation of different restorative resins in class I restorations,” Operative Dentistry, vol. 39, no. 3, pp. 248–255, 2014.
[5] E. Borgia, R. Baron, and J. L. Borgia, “Quality and survival of direct light-activated composite resin restorations in posterior teeth: a 5- to 20-year retrospective longitudinal study,” Journal of Prosthetic Dentistry, vol. 28, no. 1, pp. e195–e203, 2019.
[6] I. D. Sideridou, M. M. Karabela, and E. C. Vouvoudi, “Physical properties of current dental nanohybrid and nanofill light-cured resin composites,” Dental Materials, vol. 27, no. 6, pp. 598–607, 2011.
[7] M. Ulusoy and K. Aydin, Diş hekimliğinde hareketli bölümlü proezler, Ankara Üniversitesi Yayınları, 2010.
[8] A. Versluis, D. Tantbirjön, M. R. Pintado, R. DeLong, and W. H. Douglas, “Residual shrinkage stress distributions in molars after composite restoration,” Dental Materials, vol. 20, no. 6, pp. 554–564, 2004.
[9] A. Srirekha and K. Bashetty, “Infinite to finite: an overview of finite element analysis,” Indian Journal of Dental Research, vol. 21, no. 3, pp. 425–432, 2010.
[10] S. Moaveni, Finite Element Analysis Theory and Application with ANSYS, Prentice Hall, 3 edition, 2007.
[11] T. R. Chandrupatla, Finite Element Analysis for Engineering & Technology, Orient Blackswan, Hyderabad, 2003.
[12] T. J. R. Hughes, The Finite Element Method: Linear Static and Dynamic Finite Element Analysis, Dover Publications, 2000.
[13] J. P. Geng, K. B. Tan, and G. R. Liu, “Application of finite element analysis in implant dentistry: a review of the literature,” The Journal of Prosthetic Dentistry, vol. 85, no. 6, pp. 585–598, 2001.
[14] P. Shetty, A. M. Hegde, and K. Rai, “Finite element method—an effective research tool for dentistry,” The Journal of Clinical Pediatric Dentistry, vol. 34, no. 3, pp. 281–285, 2010.
[15] G. Jianping, Y. Weiqi, and X. Wei, Application of the Finite Element Method in Implant Dentistry, Springer, Switzerland, 2008.
[16] R. C. Van Staden, H. Guan, and Y. C. Loo, “Application of the finite element method in dental implant research,” Computer Methods in Biomechanics and Biomedical Engineering, vol. 9, no. 4, pp. 257–270, 2006.
[17] T. Baiamonje, M. F. Abbate, F. Pizzarello, J. Lozada, and R. James, “The experimental verification of the efficacy of finite element modeling to dental implant systems,” The Journal of Oral Implantology, vol. 22, no. 2, pp. 104–110, 1996.
[18] M. S. Güler, S. Sen, Y. S. Bayındır, and Ç. Güler, “İnsan diş kaplamalarında kullanılan farklı özelliklereki yapıtırıcı sımaların gerileme etkilerinin sonlu elemanlar yöntemi ile incelenmesi,” Atatürk Üniversitesi Dış Hekimliği Fakültesi Dergisi, vol. 22, pp. 31–39, 2012.

[19] Ö. Adıgüzel, “Sonlu elemanlar analizi: derleme Bölüm I: dışşekimlîğinde kullanılan alanları, temel kavramlar ve eleman tanımlarını,” Dicle Dışhemîki Dergisi, vol. 11, pp. 18–23, 2010.

[20] J. Perdigão, M. A. Muñoz, A. Sezinando et al., “Immediate adhesive properties to dentin and enamel of a universal adhesive associated with a hydrophobic resin coat,” Operative Dentistry, vol. 39, no. 5, pp. 489–499, 2014.

[21] A. Imai, T. Takamizawa, K. Sai et al., “Influence of application method on surface free-energy and bond strength of universal adhesive systems to enamel,” European Journal of Oral Sciences, vol. 125, no. 5, pp. 385–395, 2017.

[22] N. Moritake, T. Takamizawa, R. Ishii et al., “Effect of active application on bond durability of universal adhesives,” Operative Dentistry, vol. 44, no. 2, pp. 188–199, 2019.

[23] S. Fujiwara, T. Takamizawa, W. W. Barkmeier et al., “Effect of double-layer application on bond quality of adhesive systems,” Journal of the Mechanical Behavior of Biomedical Materials, vol. 77, pp. 501–509, 2018.

[24] E. Hirokane, T. Takamizawa, Y. Kasahara et al., “Effect of double-layer application on the early enamel bond strength of universal adhesives,” Clinical Oral Investigations, vol. 25, no. 3, pp. 907–921, 2021.

[25] M. Yokoyama, T. Takamizawa, T. Tamura et al., “Influence of different application methods on the bonding effectiveness of universal adhesives to dentin in the early phase,” The Journal of Adhesive Dentistry, vol. 23, no. 5, pp. 447–459, 2021.

[26] K. Palka, J. Bieniaś, H. Dębksi, and A. Niewczas, “Finite element analysis of thermo-mechanical loaded teeth,” Computational Materials Science, vol. 64, pp. 289–294, 2012.

[27] M. D. Rodrigues, P. B. Soares, M. A. Gomes et al., “Direct resin composite restoration of endodontically-treated permanent molars in adolescents: bite force and patient-specific finite element analysis,” Journal of Applied Oral Science, vol. 28, article e20190544, 2020.

[28] W. Jiang, H. Bo, G. Yongchun, and N. LongXing, “Stress distribution in molars restored with inlays or onlays with or without endodontic treatment: a three-dimensional finite element analysis,” The Journal of Prosthetic Dentistry, vol. 103, no. 1, pp. 6–12, 2010.

[29] P. Ausiello, S. Ciaramella, A. Fabianelli et al., “Mechanical behavior of bulk direct composite versus block composite and lithium disilicate indirect class II restorations by CAD-FEM modeling,” Dental Materials, vol. 33, no. 6, pp. 690–701, 2017.

[30] H. Mustafa, M. Kandil, T. Nassef, and T. Hussien, “Fracture toughness of different adhesive/dentin interfaces analyzed by finite element stress analysis,” Egyptian Dental Journal, vol. 67, no. 2, pp. 1505–1515, 2021.

[31] J. Juloski, D. Apicella, and M. Ferrari, “The effect of ferrule height on stress distribution within a tooth restored with fibre posts and ceramic crown: a finite element analysis,” Dental Materials, vol. 30, no. 12, pp. 1304–1315, 2014.

[32] H. J. Meijer, F. J. Starmans, F. Bosman, and W. H. Steen, “A comparison of three finite element models of an edentulous mandible provided with implants,” Journal of Oral Rehabilitation, vol. 20, no. 2, pp. 147–157, 1993.

[33] U. R. Darbar, R. Huggett, and A. Harrison, “Stress analysis techniques in complete dentures,” Journal of Dentistry, vol. 22, no. 5, pp. 259–264, 1994.

[34] S. A. Romeed, S. L. Fok, and N. H. F. Wilson, “A comparison of 2D and 3D finite element analysis of a restored tooth,” Journal of Oral Rehabilitation, vol. 33, no. 3, pp. 209–215, 2006.

[35] Y. H. Ismail, L. N. Pahountis, and J. F. Fleming, “Comparison of two-dimensional and three-dimensional finite element analysis of a blade implant,” The International Journal of Oral Implantology, vol. 4, no. 2, pp. 25–31, 1987.

[36] P. Kampusgora, G. Papavasiliou, S. C. Bayne, and D. A. Felton, “Finite element analysis estimates of cement microfracture under complete veneer crowns,” The Journal of Prosthetic Dentistry, vol. 71, no. 5, pp. 435–441, 1994.

[37] R. W. K. Li, T. W. Chow, and J. P. Matinlinna, “Ceramic dental biomaterials and CAD/CAM technology: state of the art,” Journal of Prosthodontic Research, vol. 58, no. 4, pp. 208–216, 2014.

[38] J. S. Mendonça, R. G. Neto, S. L. Santiago, J. R. Lauris, M. F. Navarro, and R. M. de Carvalho, “Direct resin composite restorations versus indirect composite inlays: one-year results,” The Journal of Contemporary Dental Practice, vol. 11, no. 3, pp. 25–32, 2010.

[39] S. Bucuta and N. Ilie, “Light transmittance and micro-mechanical properties of bulk fill vs. conventional resin based composites,” Clinical Oral Investigations, vol. 18, no. 8, pp. 1991–2000, 2014.

[40] S. Savadi Oskoe, M. Bahari, E. Jafari Navimipour, A. A. Ajami, N. Ghiasvand, and O. A. Savadi, “Factors affecting marginal integrity of class II bulk-fill composite resin restorations,” Journal of Dental Research Dental Clinics Dental Prospects, vol. 11, no. 2, pp. 101–109, 2017.

[41] F. Farahat, A. R. Daneshkazemi, and Z. Hajiahmadji, “The effect of bulk depth and irradiation time on the surface hardness and degree of cure of bulk-fill composites,” Journal of Dental Biomaterials, vol. 3, pp. 284–291, 2016.

[42] O. Polydorou, A. Manolakis, E. Hellwig, and P. Hahn, “Evaluation of the curing depth of two translucent composite materials using a halogen and two LED curing units,” Clinical Oral Investigations, vol. 12, no. 1, pp. 45–51, 2008.

[43] A. Van Ende, J. De Munck, K. L. Van Landuyt, A. Poitevin, M. Peumans, and B. Van Meerbeek, “Bulk-filling of high C-factor posterior cavities: effect on adhesion to cavity-bottom dentin,” Dental Materials, vol. 29, no. 3, pp. 269–277, 2013.

[44] C. M. Kemp-Scholte and C. L. Davidson, “Complete marginal seal of class V resin composite restorations effected by increased flexibility,” Journal of Dental Research, vol. 69, no. 6, pp. 1240–1243, 1990.

[45] P. Ausiello, A. Apicella, C. L. Davidson, and S. Rengo, “3D–finite element analyses of cusp movements in a human upper premolar, restored with adhesive resin-based composites,” Journal of Biomechanics, vol. 34, no. 10, pp. 1269–1277, 2001.

[46] P. Ausiello, P. Franciosa, M. Martorelli, and D. C. Watts, “Numerical fatigue 3D-FE modeling of indirect composite–restored posterior teeth,” Dental Materials, vol. 27, no. 5, pp. 423–430, 2011.

[47] G. Li, P. Lee-Sullivan, and R. W. Thring, “Nonlinear finite element analysis of stress and strain distributions across the adhesive thickness in composite single–lap joints,” Composite Structures, vol. 46, no. 4, pp. 395–403, 1999.
[48] T. Takamizawa, M. Yokoyama, K. Sai et al., ”Effect of adhesive application method on the enamel bond durability of a two-step adhesive system utilizing a universal adhesive-derived primer,” NATO Advanced Science Institutes Series E: Applied Sciences, vol. 11, no. 16, p. 7675, 2021.

[49] Ş. Alp, L. Gulec Alagoz, and N. Ulusoy, ”Effect of direct and indirect materials on stress distribution in class II MOD restorations: a 3D-finite element analysis study,” BioMed Research International, vol. 2020, Article ID 7435054, 12 pages, 2020.

[50] P. G. Coelho, C. Calamia, M. Harsono, V. P. Thompson, and N. R. F. A. Silva, ”Laboratory and FEA evaluation of dentin-to-composite bonding as a function adhesive layer thickness,” Dental Materials, vol. 24, no. 10, pp. 1297–1303, 2008.

[51] L. Zheng, P. N. Pereira, M. Nakajima, H. Sano, and J. Tagami, ”Relationship between adhesive thickness and microtensile bond strength,” Operative Dentistry, vol. 26, no. 1, pp. 97–104, 2001.

[52] K. K. Choi, J. R. Condon, and J. L. Ferracane, ”The effects of adhesive thickness on polymerization contraction stress of composite,” Journal of Dental Research, vol. 79, no. 3, pp. 812–817, 2000.

[53] B. Van Meerbeek, J. Perdigão, P. Lambrechts, and G. Vanherle, ”The clinical performance of adhesives,” Journal of Dentistry, vol. 26, no. 1, pp. 1–20, 1998.