The influence of combining composite resins with different elastic modulus on the stress distribution of class V restoration: A three-dimensional finite element study

Jeong-Kil Park[1], Bock Hur[1], Sung-Kyo Kim[2]*

[1]Department of Conservative Dentistry, School of Dentistry, Pusan National University, Busan, Korea
[2]Department of Conservative Dentistry, School of Dentistry, Kyungpook National University, Daegu, Korea

ABSTRACT

This study was to investigate the influence of combining composite resins with different elastic modulus, and occlusal loading condition on the stress distribution of restored notch-shaped non-carious cervical lesion using 3D finite element (FE) analysis.

The extracted maxillary second premolar was scanned serially with Micro-CT. The 3D images were processed by 3D-DOCTOR. ANSYS was used to mesh and analyze 3D FE model. A notch-shaped cavity was modeled and filled with hybrid, flowable resin or a combination of both. After restoration, a static load of 500N was applied in a point-load condition at buccal cusp and palatal cusp. The stress data were analyzed using analysis of principal stress.

Results showed that combining method such that apex was restored by material with high elastic modulus and the occlusal and cervical cavosurface margin by small amount of material with low elastic modulus was the most profitable method in the view of tensile stress that was considered as the dominant factor jeopardizing the restoration durability and promoting the lesion progression. [J Kor Acad Cons Dent 33(3):184-197, 2008]

Key words : Non-carious cervical lesion, Stress distribution, Composite resin, Elastic modulus, Finite element analysis

Ⅰ. INTRODUCTION

Non-carious cervical lesions (NCCLs) are characterized by the loss of dental hard tissue at the cemento-enamel junction (CEJ)[1]. The etiology and diagnosis of NCCLs remain controversial. Previously, clinicians believed this to be caused solely by toothbrush abrasion, but presently many clinicians now classify this as tooth failure due to occlusal loading[2-4]. It has been suggested that occlusal loads cause the tooth to flex, particularly during lateral excursion. As the tooth flexes, tensile and shear stresses are generated in the cervical region of the tooth that cause disruption of the

* Corresponding Author: **Sung-Kyo Kim**

Department of Conservative Dentistry
School of Dentistry, Kyoungpook National University,
188-1, Samduk 2ga, Jung-gu, Daegu, 700-412, Korea
Tel: 82-53-420-5935
E-mail: skykim@knu.ac.kr

bonds between the hydroxyapatite crystals, leading to crack formation and eventual loss of enamel and the underlying dentine[5].

Grippo[6] proposed a new classification of tooth structure loss called abfraction (from the Latin words *ab* – away, and *fraction* – breaking). He defined this as the pathologic loss of tooth substance primarily caused by biomechanical loading forces resulting in flexure and failure of enamel and dentin at a location away from loading.

Clinically, abfraction lesions are wedge-shaped defects that are principally found on the buccal and labial aspects of the teeth. Once the lesion has been formed, the highest stress concentration was observed around the apex of the wedge-shaped lesion[7].

NCCLs occur in a variety of forms depending on the type and severity of the etiological factor, but not all lesions require restorations[8]. The decision to restore NCCLs is based on the desire to strengthen the tooth and decrease the theoretical stress concentration and flexure, mitigate lesion progression, prevent hypersensitivity and pulp involvement, improve oral hygiene and enhance esthetics[8,9]. Treatment materials have included the restoration with resin-based composites, glass ionomers or a combination of these materials[10,11].

Owing to the lack of inherent macromechanical retention in restorations of NCCLs, adhesion is the most important factor in retention of such restorations. However, the retention is affected by various factors such as tooth flexure, occlusal stress, the character of the dentinal surface and elastic modulus of the restorative materials. A clinical study with earlier generation adhesive systems showed that retention of restorations in NCCLs was influenced by the elastic modulus of the composite resin[12].

Clinically, composite restorations are appreciated for their esthetic qualities, relative wear resistance, and smooth surface texture. Recently, flowable resin was introduced. Due to the flexibility of this material, it can be used to restore NCCLs. The combination of flowable and microfilled or microhybrid composites combines the advantages of both materials[13] and materials

combinations may be possible.

According to Park's study[14], when restoring the notch-shaped lesion, material with high elastic modulus worked well at the lesion apex and material with low elastic modulus worked well at the cervical cavosurface margin.

The finite element (FE) method has been widely used in biomechanics for evaluating interfacial relationships inside biomaterials or between restoration and tooth surface.

The purpose of this study was to investigate the influence of combining composite resins with different elastic modulus, occlusal loading condition on the stress distribution of the restored notch-shaped NCCL using 3D FE analysis.

Ⅱ. MATERIALS AND METHODS

1. FE model

To develop a 3D FE model, an intact normal extracted human maxillary second premolar was used. The extracted premolar was scanned serially with Micro-CT (SkyScan1072; SkyScan, Aartselaar, Belgium) to expose the tooth sections perpendicular to the long axis of the tooth (58 ㎛ in thickness) and parallel to the occlusal plane. Image processing software, 3D-DOCTOR (Able Software Co., Lexington, MA, USA), was employed to make the boundaries of enamel, dentin and pulp and to construct a surface model of tooth from the sectioned two dimensional images. ANSYS (Swanson Analysis Systems, Inc., Houston, USA) was used to mesh and analyze 3D FE model.

In this study, the final model consisted of 16,668 elements with 18,245 nodes. A notch-shaped lesion with a 4.28 ㎜ vertical height and a 5.31 ㎜ mesiodistal width was modeled. The modified notch model was the same shaped lesion except for the rounded lesion apex (Figure 1).

The physical properties of the tooth and supporting structures used in this study are given in Table 1. All materials were assumed to be linearly elastic, homogeneous and isotropic.

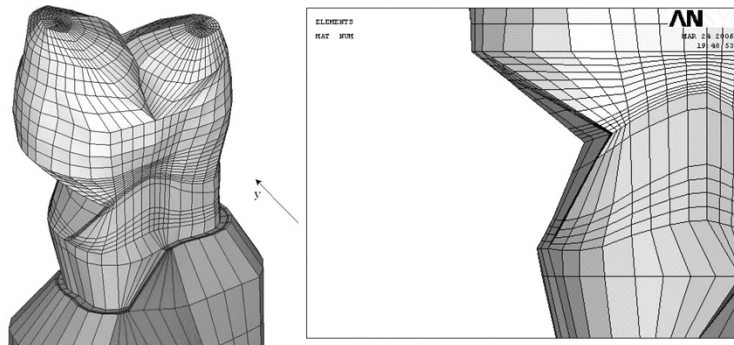The periodontal ligament was assumed to be 0.3

Figure 1. 3 dimensional finite element model of notch shaped cavity.

Table 1. Mechanical properties of the tooth and supporting structures used in the study

Materials	Mechanical properties	
	Young's modulus (㎫)	Poisson's ratio (ν)
Enamel	84000[a]	0.33[a]
Dentin	18000[a]	0.31[a]
PDL	0.667[b]	0.49[b]
Cancellous bone	13700[b]	0.38[b]
Cortical bone	34000[b]	0.26[b]

[a]: Katona *et al.*[18]   [b]: Geramy *et al.*[19]

㎜ wide, and the dimensions of the surrounding compact and cancellous bone were derived from standard texts. Alveolar bone was also generated by growing the outer surface of the tooth model from 2 ㎜ below the CEJ and the cervical cavosurface margin of the cavity[15,16]. The pulp was modeled as a void since previous researchers[17] found that omission of the pulp has no influence on stress profiles. In these models, the outer surface and the base of the alveolar bone model was fixed in order to prevent rigid body motion for FE analysis. The model was also fixed on mesiodistal direction.

2. Restorations

Notch cavities were filled with hybrid, flowable resin and combination of both (Figure 2). The data of material properties such as elastic modu-lus, Poisson's ratio and polymerization shrinkage were used by literature review[18,20,21] (Table 2). The Tetric Flow (Vivadent Ets., FL-9494-Schaan, Liechtenstein) and Z100 (3M Dental Products, St. Paul, MN, USA) were used as representatives of flowable and hybrid resin. The dentin bonding system used in this study was Scotchbond MP (3M Dental Products, St. Paul, MN, USA) and the adhesive layer thickness was 40 ㎛. The physical properties of the tooth, supporting structures and materials used in this study are given in Table 1. The adhesive layer was made by mathematical shell element modeling and the conjunctions between materials were set as complete coupling.

3. Loading conditions
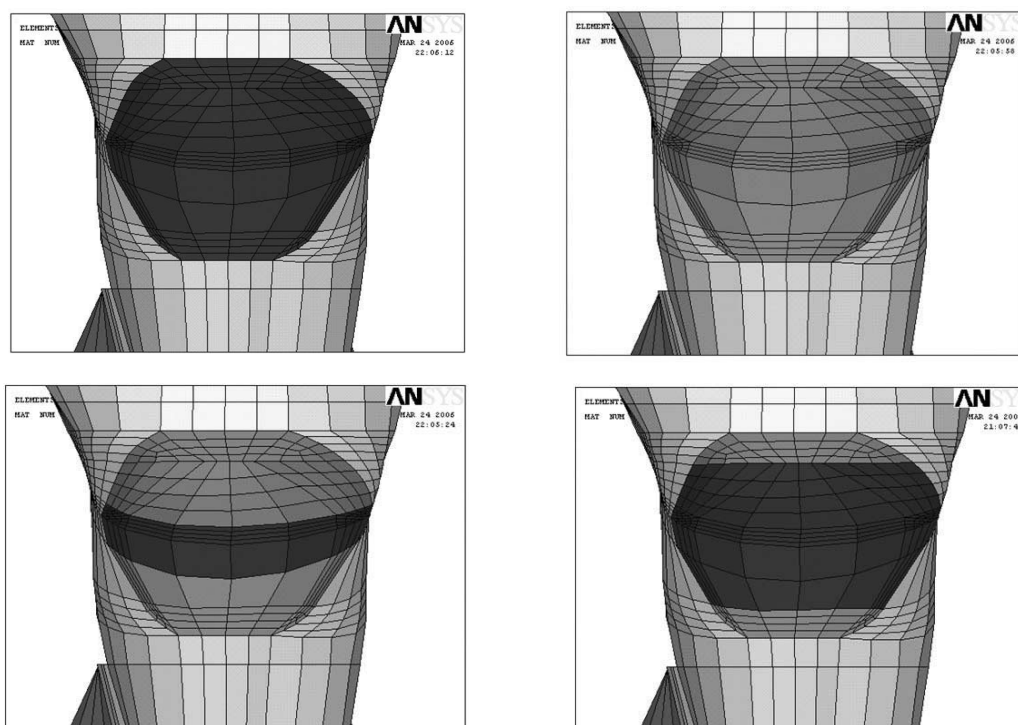
The model was loaded with two vertical loads of

Figure 2. Simulated restorations of notch-shaped NCCL (Upper left; Z100-dark brown, Upper right; Tetric Flow-light brown, Lower left; Combination 1, Lower right; Combination 2).

Table 2. Mechanical properties of the materials used in the study

Materials	Mechanical properties		
	Young's modulus (MPa)	Poisson's ratio (v)	Contraction stress (MPa)
Tetric Flow (T)	5300[a]	0.28[a]	23.5[c]
Z 100 (Z)	15200[a]	0.28[a]	7.6[c]
Scotchbond MP	1640[b]	0.28[b]	–

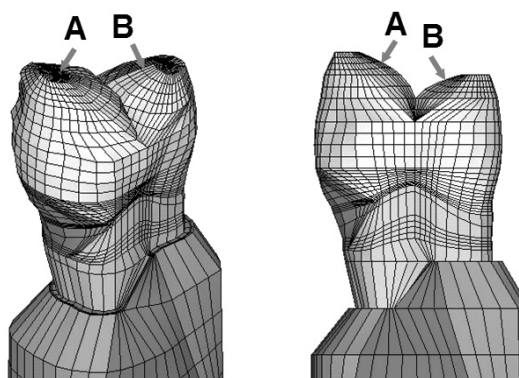[a]: Katona *et al.*[18], [b]: Le *et al.*[20], [c]: Kleverlaan *et al.*[21]

Figure 3. Schematic diagram of loading points (A; Perpendicular load on the upper third of the palatal slope of the buccal cusp, B; perpendicular load on the upper third of the buccal slope of the palatal cusp).

500 N each, shown in Figure 3. Perpendicular load on the upper third of the palatal slope of the buccal cusp (Load A) and perpendicular load on the upper third of the buccal slope of the palatal cusp (Load B) were used.

4. Experimental groups

The variables were restoration methods (Tetric Flow; T, Z100; Z, Combination 1; C1, Combination 2; C2), and loading conditions (Load A; A or Load B; B).

Combination 1(C1) method was that apex was restored by small amount of Z100 and the occlusal and cervical cavosurface margin by large amount of Tetric Flow. Combination 2 (C2) method was that apex was restored by large amount of Z100 and the occlusal and cervical cavosurface margin by small amount of Tetric

Flow (Figure 2).

The tested groups were classified as 8 situations (Table 3).

5. Stress analysis

To explore the stress condition of the element, the principal stresses presented in the buccal cervical area were used. Under Load A, minimum principal stress was analyzed and under load B maximum principal stress was analyzed. The principal stresses are in fact normal stresses, acting on principal planes on which the shearing stresses are zero, and are found by using the existing six normal and shearing stress components rx, ry, rz, sxy, sxz and syz. If the absolute value of one principal stress of an element was larger than the other and positive, the element was determined to be in the tensile condition, if it

Table 3. Simulated groups according to cavity designs, restoration methods and loading conditions

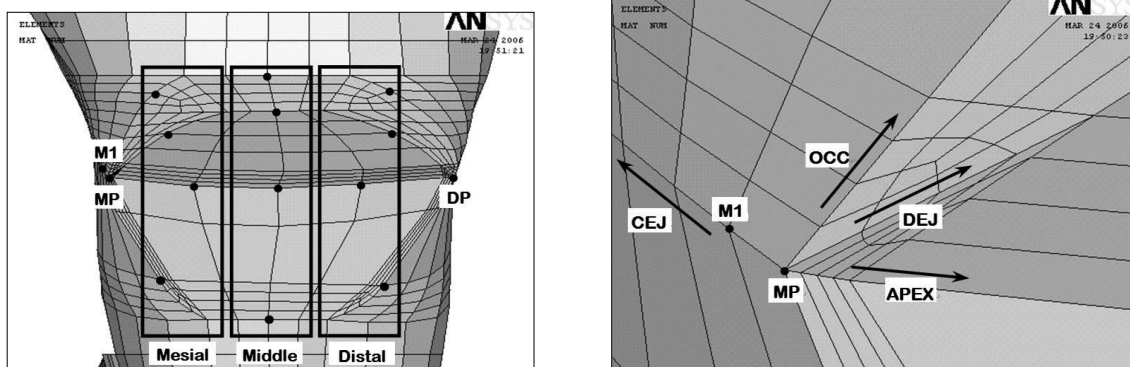| Materials	Load A (A)	Load B (B)
Z100 (Z)	ZA	ZB
Tertric Flow (T)	TA	TB
Combination 1 (C1)	C1A	C1B
Combination 2 (C2)	C2A	C2B

Figure 4. Node selection (left) and magnified aspects (right) of mesial corner of notch-shaped lesion. Along the cavity 4 lines, each 4 nodes were selected at the 3 areas (MP: Mesial point angle, DP: Distal point angle, M1: Nodes near mesial point angle, CEJ: Cemento-enamel junction, Occ: Occlusal cavosurface margin, DEJ: Dentino-enamel junction, Apex: Lesion apex).

Table 4. Mechanical failure range of teeth[22]   (MPa)

Compressive strength of enamel	277 – 384
Compressive strength of dentin	249 – 347
Tensile strength of enamel	10 – 24
Tensile strength of dentin	32 – 103
Tensile strength of dentino-enamel junction	52

was smaller than the others and negative, the element was determined to be in the compressive condition.

The principal stresses in the occlusal cavosurface margin and dentino-enamel junction (DEJ) of occlusal wall, lesion apex, and cavosurface margin of cervical wall were analyzed using ANSYS.

6. Node selection for stress analysis

Nodes were selected according to cavity 4 line (occlusal cavosurface margin line, DEJ line, lesion apex line and cervical cavosurface margin line) with 3 areas (mesial, middle, distal) to compare stresses before and after restorations. At the initial pilot study, the highest stress in the unrestored cavity was observed at the mesial point angle (MP). After the cavity was restored with composite resin, the peak stress was moved to more proximal node than MP. Thus, an additional M1 node was selected (Figure 4).

7. Comparison with mechanical properties of teeth

The obtained data were compared with the reported mechanical failure range of teeth[22] (Table 4).

III. RESULTS

1. Before restoration

General principal stress distributions before restoration were shown in Figure 5.

The peak compressive stress of 588.0 MPa was concentrated at MP under Load A and the peak tensile stress of 193.3 MPa was concentrated at MP under Load B and these peak stresses were over the stress limit of teeth.

The lesion apex line stresses showed the largest stress value, followed by DEJ line, cervical cavosurface margin line and occlusal cavosurface margin line. Larger apex stresses were observed in the mesial area than in the distal area.

Principal stress distributions of 4 cavity line were shown in Figure 6.

2. After restoration

General compressive and tensile stress distributions were shown in Figure 7. After restoration, significant stress relief was shown in the all cavity areas, especially at the lesion apex. However, stress concentration at the mesial corner was still observed as unrestored cavity.

Under Load A, stress relief was smaller than other restoration methods when the entire cavity was restored by Tetric Flow (TA) at the lesion apex.

Under Load B, In C2B, stress relief was the largest at the lesion apex and mesial root dentin. Peak stresses were shown in Table 5.

(1) Occlusal cavosurface margin

On occlusal cavosurface margin, generally similar compressive stress was seen independently of restorations under Load A (Figure 8). The highest compressive stress of 152.5 MPa was concentrated at MP in C1A under Load A. In ZA, the lowest compressive stress of 142.7 MPa was concentrated at MP. These two stresses were within the limit stress of tooth.

In case of tensile stress, there were a lot of dif-
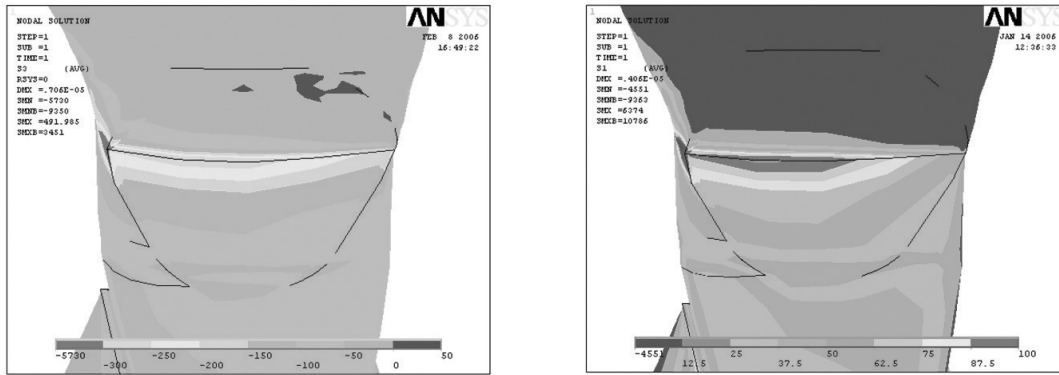
Buccal view

Figure 5. Principal stress distribution of notch-shaped cavity before restoration (Left; Minimum principal stress-Compressive stress, Right; Maximum principal stress-Tensile stress. Upper and lower view's scales were different each other).
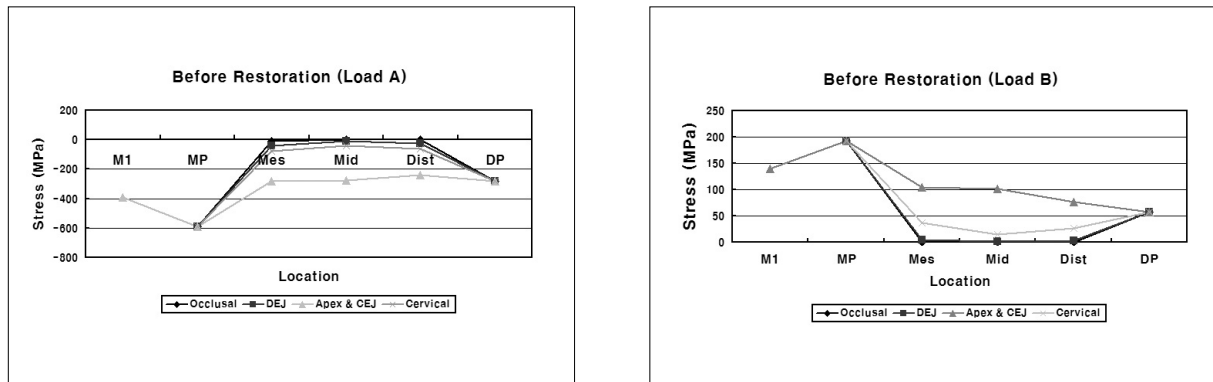

Figure 6. The compressive and tensile stress distribution on occlusal cavosurface margin (Occlusal), DEJ, lesion apex and CEJ (Apex & CEJ), cervical cavosurface margin (Cervical) under Load B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).

ferences of stress value according to restorations at MP. The highest tensile stress of 47.5 ㎫ was concentrated at MP in TB under Load B. In C2B, the lowest tensile stress of 31.3 ㎫ was concentrated at MP. As there were a lot of quantities of Tetric Flow (TB, C1B), stresses were developed at MP.

(2) DEJ

On occlusal DEJ, like the occlusal cavosurface margin, similar compressive stress was seen independently of restorations under Load A (Figure 9). The highest and lowest compressive stress value and site under Load A were the same as in

the occlusal cavosurface margin.

Under Load B, the peak stress value and site were the same as in the occlusal cavosurface margin. However, the stress pattern was different. Two stress reduction patterns were shown. As there was a lot of Tetric Flow (TB, C1B), the peak stress was increased at MP, but stresses were steeply decreased in the middle and distal area.

(3) Lesion apex and CEJ

On the lesion apex and CEJ, similar compressive stresses except peak stress value were observed in all restorations under Load A. The
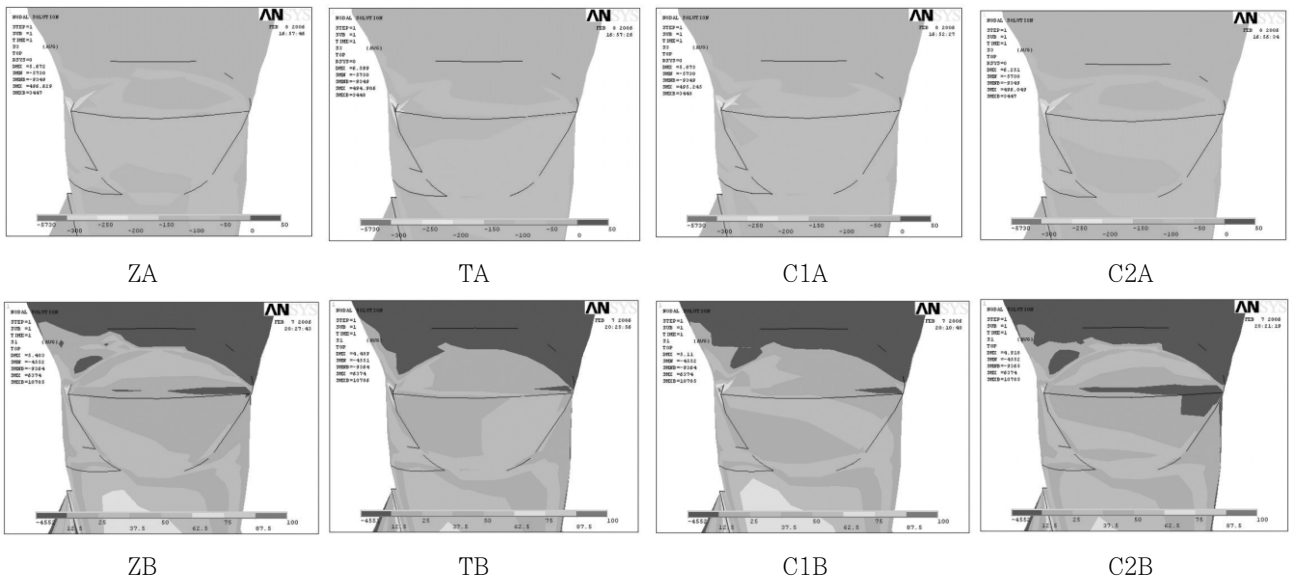
Figure 7. The Principal stress distribution under Load A and B.

Table 5. Peak stresses of each locations under Load A and B

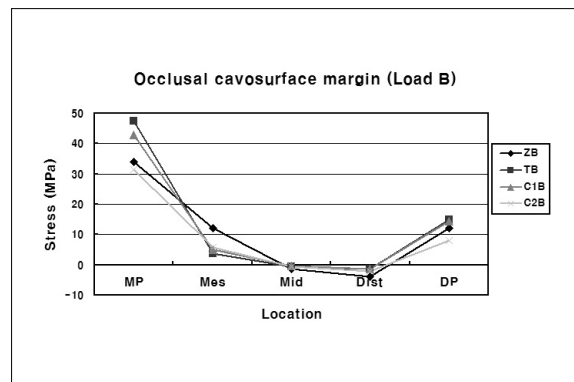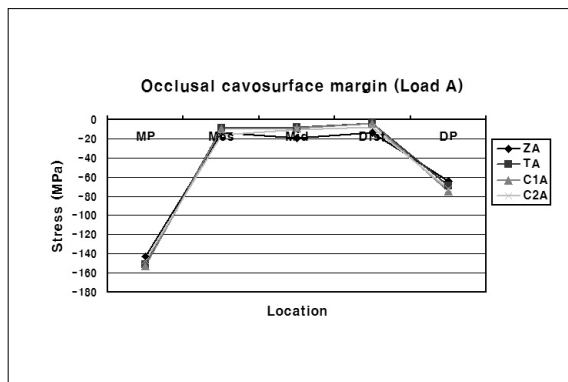| Experimental Groups	Load A (compressive stress)	Load B (tensile stress)
	MPa (node location)	MPa (node location)
Unrestored notch cavity	−588.0 (MP)	193.3 (MP)
Z100 (Z)	−232.0 (M1)	70.7 (M1)
Tetric Flow (T)	−291.4 (M1)	101.6 (M1)
Combination 1 (C1)	−238.9 (M1)	87.2 (M1)
Combination 2 (C2)	−240.7 (M1)	64.9 (M1)

Figure 8. The compressive and tensile stress distribution on occlusal cavosurface margin after restoration under Load B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).
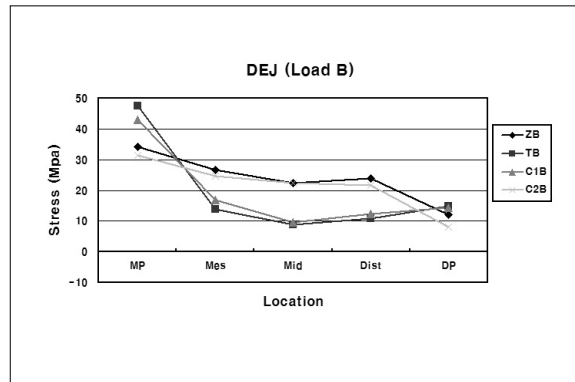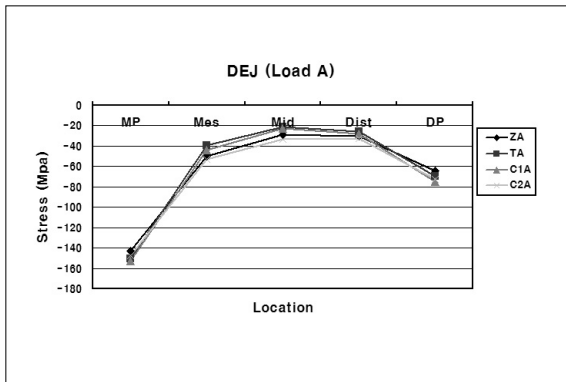
Figure 9. The compressive and tensile stress distribution on occlusal DEJ after restoration under Load B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).

Figure 10. The compressive and tensile stress distribution on lesion apex and CEJ after restoration under Load B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).

Figure 11. The compressive and tensile stress distribution on cervical cavosurface margin after restoration under Load B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).
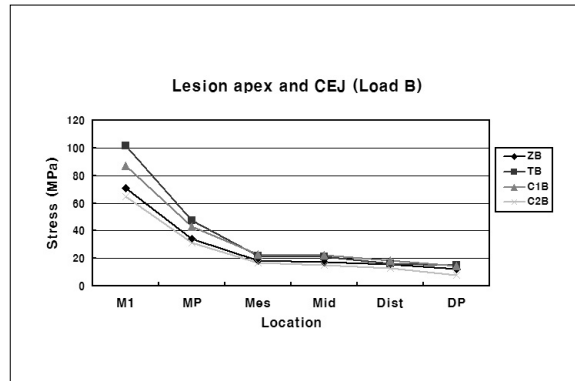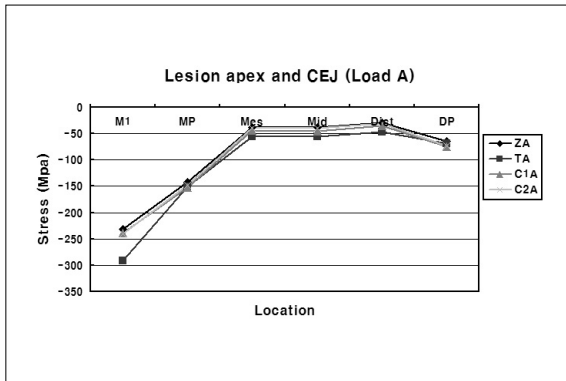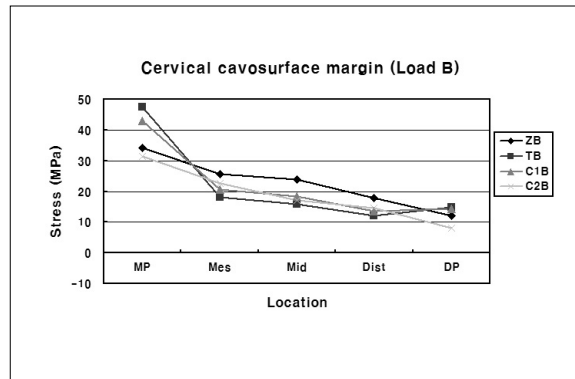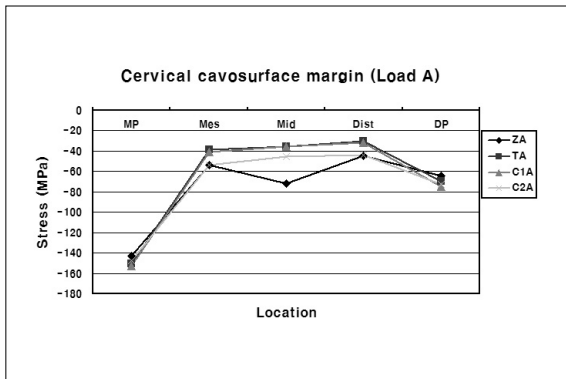
peak stress site shifted from MP to M1 (Figure 10). The highest compressive stress of 291.4 ㎫ was concentrated at M1 in TA under Load A. In ZA, the lowest compressive stress of 232 ㎫ was concentrated at M1.

Under Load B, the peak stress site also moved from MP to M1. The highest tensile stress of 101.6 ㎫ was concentrated at M1 in TB. In C2B, the lowest tensile stress of 64.9 ㎫ was concentrated at M1. In whole lesion apex and CEJ line, the greatest tensile stress relief was observed in C2B.

(4) Cervical cavosurface margin

On cervical cavosurface margin, the highest and lowest compressive stress value and site under Load A were same as at occlusal cavosurface margin. At the middle site, in ZA, compressive stresses were larger than others (Figure 11).

Under Load B, the stresses were reduced moving from the MP to DP. Stress declines were all different. The highest tensile stress value and site were same as occlusal cavosurface margin. Similarly, at the lesion apex and CEJ, the best tensile stress relief was observed in C2B.

Ⅳ. DISCUSSION

NCCLs vary in size, shape, and most importantly, the cause from which they have resulted. Some clinicians have hypothesized that wedge-shaped noncarious cervical lesions are caused primarily by tooth flexure as a consequence of malocclusion, bruxism, and parafunctional habits[2-4].

Once the lesion was formed, the highest stress concentration was observed around the apex of the wedge-shaped lesion[7]. The discontinuity of the enamel and dentin may cause increased stress and damage in the enamel[23]. The severity of geometric discontinuity of NCCL can be expected to have strong influence on the development of internal stress in teeth[24]. In our experiment, the stresses converged in the apex line with more mesial side under both loading conditions. These asymmetric patterns of mesial stress distribution were related to the anatomical asymmetry of the teeth.

When clinically assessing NCCLs, dental practitioners must consider if the cervical defect requires a restoration and if so, which restorative material will provide the best outcome. Additionally, the clinician must consider a modulus of elasticity, resistance to wear and ability to withstand acid dissolution[9,25]. A number of researchers have reported controversies regarding restoration of class V cervical lesions[8,10,11]. Recently resin composites with dentin bonding agents have become a popular for the restoration of NCCLs[26]. In the current experiment, lesions were restored by conventional hybrid resin and flowable resin.

Important factor affecting retention failure is the elastic modulus of the restorative materials. It has been demonstrated that a strong correlation exists between marginal failure and Young's modulus of the composite restoration material in the class V situation[27]. It is a general rule of engineering that stress will always follow the path of the stiffest material, that is, the path with the highest elastic modulus. In the case of an intact tooth, the stiffest material is the enamel, and an applied occlusal load is generally passed through the enamel and into the underlying dentine, with the load being dissipated through the crown and down into the root in a radial and apical direction[28].

Therefore, strictly from a mechanical point of view, it can be said that the best approach is to apply restorative materials with high Young's modulus as possible. Yaman *et al.*[29] concluded that for class V applications Z 100 gives the most promising results. According to Nakayama *et al.*[30] a Young's modulus equal to or greater than that of the dentine is required for resin composite to resist deformation by occlusal stress. In addition, resin composite Z 100 has a high Young's modulus and a high percentage of volume fraction filler, which increases resistance to deformation by occlusal force[31]. When using a hard material, the stiffest restoration-tooth interface resulted in the lowest restoration displacement.

In contrast, some researchers contend that one

of the methods used to maximize the retention rates of class V restorations is the placement of low elastic modulus materials. Heymann and colleagues[32] reported that the retention rates for restorations of a material with lower elastic modulus were significantly higher than those of a material with higher elastic modulus. The rationale behind this is that high modulus materials are unable to flex when the tooth structure is deformed under load and therefore they are displaced from the cavity. In contrast, low modulus materials can flex with the tooth and therefore can remain in situ. Thus, these resins will absorb much of the masticatory stresses rather than transferring it to the dentin-restoration interface[11]. A low elastic modulus also contributes to stress relief from polymerization shrinkage of composites, preserving the marginal integrity of restorations[33]. This property allows for good wetting along the cavity walls, which improves the adaptation of the restorative material.

In the current study, two different elastic modulus materials were used. The stress values after restoration were different at the 4 lines depending on the elastic modulus of the materials. The highest stress reduction was observed at the apex in the Z100 restoration which had the higher elastic modulus. In the other 3 lines, especially at the cervical cavosurface margin, Tetric Flow restoration showed a smaller stress value compared with Z100. Therefore, the combination of flowable and conventional hybrid composites may offer a synergistic effect of both materials. It was hypothesized that Z100 composites used as a strut would improve the reduction rates of stress in the apex. This hypothesis was based on earlier studies[29] showing that restoration using Z100 worked as a strut to prevent stress concentration of the lesion.

Under Load A, similar compressive stress was observed independently of kind of combination restorations. However, under Load B, different stress values appeared. As there was a lot of Tetric Flow, stresses were greater at the apex, but stresses were smaller at the other 3 lines. Z100 was reversed. These results show that high elastic modulus materials work well at the lesion apex. This is also involved with special feature of notch-shaped cavity. Due to its sharpest geometrical discontinuity, stress was focused on the lesion apex in the notch-shaped cavity. When biting force is applied, a high elastic modulus material like as a strut can sustain the stress at the apex. This is especially true under Load B when tensile stress occurs.

In this experiment, C2 method was the best method for tensile stress reduction. The cavity apex was restored by a combination method such that apex was restored by Z100 and the occlusal and cervical cavosurface margin by small amount of Tetric Flow. Thus, this method is recommended for restoration of notch-shaped lesion because it showed the best effect in tensile stress.

Experimental in vitro dental stress studies of abfraction generally have employed two methods: photoelastic stress models and FE analysis. In the present study, a 3D FE method has been used to calculate the stress field in directly paced class V composite restorations. A direct, quantitative comparison between the stresses generated by these techniques has been made. Two-dimensional axisymmetric finite element modeling has been used in most previous research[22,23,28]. Although numerical results can be easily obtained in two dimensional modeling, it has some significant shortcomings. Because the shape of a human tooth is highly irregular, it can not be represented in a two-dimensional space and the actual loading can not be simulated without taking three dimensions into consideration. Therefore, three-dimensional modeling with the actual dimension is preferred for a reliable analysis.

The result of this study must be interpreted with a certain amount of caution. First, it was hard to include all factors that occur intraorally in this computer simulation. Therefore, some simplification was used. Second, this study compared finite element models assuming one to have an isotropic enamel and dentin, but the real tooth model was an anisotropic enamel and dentin model. Third, these static load stresses may not reflect the actual conditions encountered intraorally, therefore may not adequately describe the

functional movement of occlusion.

Further research is needed to assess the mechanism through which noncarious cervical lesions are initiated and propagated, as well as the potential role of abfraction. Such investigations will include intervention studies with occlusal therapy to investigate whether eliminating occlusal loading factors prevents formation, progression of cervical lesions and loss of restorative material. Our future investigations will also include studies of other restoration methods as well as optimal materials of stress induced cervical lesions.

Ⅴ. CONCLUSIONS

Within the limitations of this study, it is concluded that when restoring notch-shaped NCCL, combining method such that apex was restored by material with high elastic modulus and the occlusal and cervical cavosurface margin by small amount of material with low elastic modulus was the most profitable method in the view of tensile stress that was considered as the dominant factor jeopardizing the restoration durability and promoting the lesion progression.

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국문초록

탄성계수가 다른 복합레진의 혼합수복이 5급 수복물의 응력분포에 미치는 영향에 관한 3차원 유한요소법적 연구

박정길[1] · 허　복[1] · 김성교[2*]

[1]부산대학교 치의학전문대학원 치과보존학교실, [2]경북대학교 치의학전문대학원 치과보존학교실

　본 연구는 3차원 유한요소분석법적 연구를 통해 쐐기형 비우식성 치경부병소의 복합레진수복에서 다른 탄성계수를 가진 복합레진의 혼합수복이 5급 수복물의 응력분포에 미치는 영향에 대해 알아보고자 하였다.

　발거된 상악 제2소구치를 Micro-CT로 스캔한 후 3D-DOCTOR로 3차원유한요소 모형을 제작하였다. 제작된 소구치 모형에 쐐기형 와동과 변형시킨 와동을 형성하고 각 와동을 탄성계수가 서로 다른 혼합형 복합레진 또는 흐름성 복합레진으로 수복하였다. 수복 전, 후 협측교두와 설측교두에 500N의 하중을 가한 후 응력분포를 ANSYS 프로그램을 이용하여 주 응력 분석법으로 평가한 결과 치아 및 수복물에 위해한 인장응력을 고려할 때 탄성계수가 높은 재료로 와동저 선각을 수복하고 교합측변연과 치경부측 변연은 탄성계수가 낮은 재료로 수복하는 혼합수복법이 쐐기형 비치경부병소의 수복에 있어 가장 유리하였다.

주요어: 비우식성 치경부병소, 응력분포, 복합레진, 탄성계수, 유한요소분석