

Stress distribution of Class V composite resin restorations: A three-dimensional finite element study

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ABSTRACT

This study was to investigate the influence of composite resins with different elastic modulus, cavity modification and occlusal loading condition on the stress distribution of restored notch-shaped noncarious cervical lesion using 3-dimensional (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 and a modified cavity with a rounded apex were modeled. Unmodified and modified cavities were filled with hybrid or flowable resin. 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.

The results were as follows:

1. In the unrestored cavity, the stresses were highly concentrated at mesial CEJ and lesion apex and the peak stress was observed at the mesial point angle under both loading conditions.
2. After restoration of the cavity, stresses were significantly reduced at the lesion apex, however cervical cavosurface margin, stresses were more increased than before restoration under both loading conditions.
3. 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.
4. Cavity modification the rounding apex did not reduce compressive stress, but tensile stress was reduced. [J Kor Acad Cons Dent 33(1):28-38, 2008]

Key words : Cervical lesion, class V lesion, composite resin, finite element analysis, stress distribution

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I . INTRODUCTION

Noncarious cervical lesions (NCCLs) are characterized as structural defects found on the tooth surface of the cemento-enamel junction (CEJ)¹⁾. Loss of tooth structure through noncarious mech-

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anisms may vary in etiology and clinical presentation for each individual and may be associated with physiological or pathological processes²⁾.

Clinically, these lesions have sharp, angular, wedge-shaped defects principally found on the buccal and labial aspects of the teeth. According to Telles et al.³⁾, the most commonly affected teeth are the maxillary premolars. The most important cause of formation of wedge-shaped lesion is the stress applied in the cervical area of the tooth under oral physiological and pathological loads⁴⁾. Lee and Eakle⁵⁾ have proposed a mechanical theory of cervical lesion formation and Grippo⁶⁾ defined pathological loss of hard tissues at the CEJ caused by flexure and ultimate fatigue of enamel at a location away from the point of loading as abfraction.

These lesions may affect either a single tooth or many ones depending on the occlusal forces concentrated. The extent of stress of a cervical lesion, as shown by one study⁷⁾, is directly related to the area of the periodontal ligament and the amount of tooth mobility under loading. Another study also showed that the lesions were increased as the loads on the tooth moved further away from the long axis⁸⁾.

Loss of tooth structure in the cervical area of a NCCL may cause esthetic problems and discomfort due to dentinal hypersensitivity^{3,6)}. NCCLs occur in a variety of forms depending on the type and severity of the etiological factor, but not all lesions require restorations⁹⁾. 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^{9,10)}. Treatment materials have included the restoration with resin-based composites, glass ionomers¹¹⁾.

In the restoration of NCCLs, restorative materials with esthetic and bonding characteristics are required. Composite restorations are appreciated for their esthetic qualities, relative wear resistance, and smooth surface texture. Recently, flowable resin was introduced. Due to the flexibil-

ity of this material, it can be used to restore NCCLs.

A number of studies of modification of cavity design have been conducted. Modified designs of cavity preparation have been proposed as a way of reducing residual shrinkage stresses and margin opening^{12,13)}. Osborne-Smith et al.¹⁰⁾ and Lee et al.¹⁴⁾ proposed that preparation design may need to be changed, depending on whether adhesive retention is adequate or if mechanical retention is necessary. Leinfelder¹⁵⁾ suggested reshaping the axial wall to reduce the stress distribution of the notch-shaped lesion. In recent years, there has been increasing interest in understanding the effect of minimal cavity preparation by retaining the V-shape and alternative approaches of preparing the cavity to U-shape for improved retention¹⁶⁾.

In the oral cavity, teeth and restorations are exposed to various overloads as a result of biting forces that cause variable patterns of stress in dental tissues. The durability of the restored teeth largely depends on various factors such as tooth flexure, occlusal stress, the sclerosis of the dentinal surface and elastic modulus of the restorative materials.

Three dimensional (3D) finite element (FE) stress analysis is a particularly useful method for examining the stress distribution in teeth because it can cope with the complex geometric shape of a tooth and the large variations in the physical properties of the materials which make up a tooth and its supporting structures⁷⁾.

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

II . MATERIALS & METHODS

FE model

To develop a 3D FE model, an intact normal extracted human maxillary second premolar was used. The extracted premolar was scanned serial-

ly with Micro-CT (SkyScan1072; SkyScan, Aartselaar, Belgium) to expose the tooth sections perpendicular to the long axis of the tooth (58 μm 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 mm vertical height and a 5.31 mm mesiodistal width was modeled. The modified notch model was the same shaped lesion except for the rounded lesion apex (Figure 1).

Restorations

Unmodified and modified notch cavities were filled with hybrid or flowable. Z100 (3M Dental Products, St. Paul, MN, USA) and The Tetric Flow (Vivadent Ets., FL-9494-Schaan, Liechtenstein) were used as representatives of hybrid and flowable 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 μm . The physical properties of the tooth, supporting structures and materials used in this study are given in Table 1.

Loading conditions

The model was loaded with two vertical loads of 500 N each, shown in Figure 2. 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.

Experimental groups

The variables were cavity designs (Unmodified cavity; U or Modified cavity; M), restoration methods (Tetric Flow; T, Z100; Z), and loading conditions (Load A; A or Load B; B). The tested groups were classified as 8 situations (Table 2).

Stress analysis

To explore the stress condition of the element, the principal stresses presented at 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 of five nodes (Mesial point

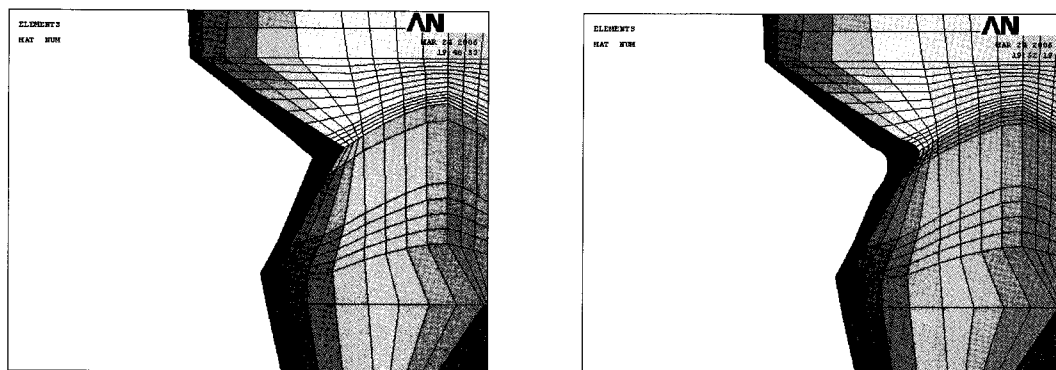
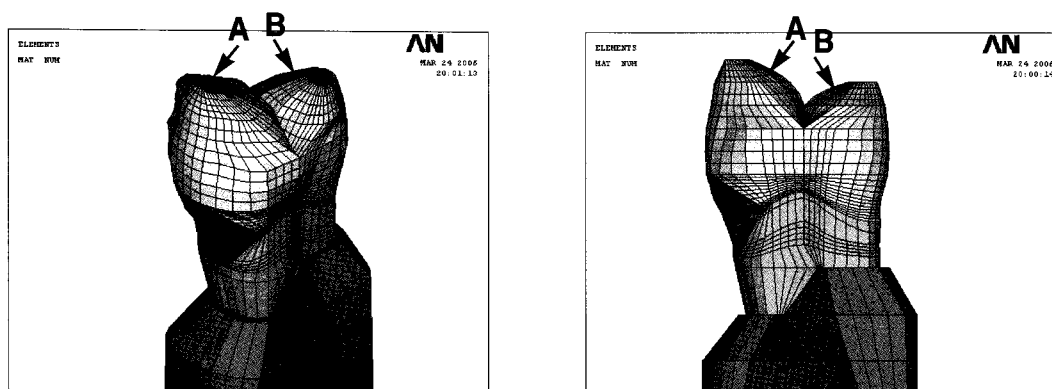


Figure 1. Schematic diagram represents unmodified and modified cavity configuration (Left: Unmodified cavity, Right: Modified cavity).

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

Materials	Mechanical properties		
	Young's modulus (MPa)	Poisson's ratio (ν)	Reference
Enamel	84000	0.33	17
Dentin	18000	0.31	17
PDL	0.667	0.49	18
Cancellous bone	13700	0.38	18
Cortical bone	34000	0.26	18
Tetric Flow	5300	0.28	17
Z 100	15200	0.28	17
Scotchbond MP	1640	0.28	19

**Figure 2.** 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).**Table 2.** Simulated groups according to cavity designs, restoration materials and loading conditions

Materials	Load A (A)		Load B (B)	
	Unmodified cavity (U)	Modified cavity (M)	Unmodified cavity (U)	Modified cavity (M)
Z100 (Z)	UZA	MZA	UZB	MZB
Tetric Flow (T)	UTA	MTA	UTB	MTB

angle (MP), Mesial node (Mes), Middle node (Mid), Distal node (Dist), Distal point angle (DP)) in the lesion apex, and cavosurface margin of cervical wall were analyzed using ANSYS. At

the initial pilot study, after the cavity was restored with composite resin, the peak stress was moved to more mesial proximal node than MP. Thus, an additional M1 node was selected.

III. RESULTS

1. Before restoration

The lesion apex line stresses showed the largest stress value and larger apex stresses were observed in the mesial area than in the distal area (Figure 3).

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 teeth²⁰⁾ (Figure 4).

2. After restoration

General compressive and tensile stress distributions were shown in Figure 5. After restoration, significant stress relief was shown in the all cavity areas, especially at the lesion apex. however, cervical cavosurface margin, stresses were more increased than before restoration under both loading conditions. And stress concentration at the mesial corner was still observed as unrestored cavity.

Under Load A, similar stress relief was observed regardless of cavity design or restorations, but at

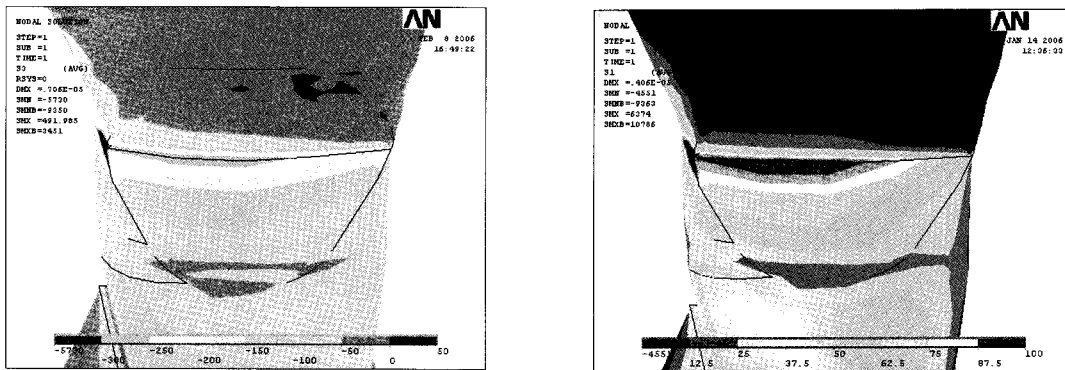


Figure 3. The principal stress distribution of notch-shaped cavity before restoration (Left: Minimum principal stress-Compressive stress, Right: Maximum principal stress-Tensile stress. Upper and lower view's scales were different each other).

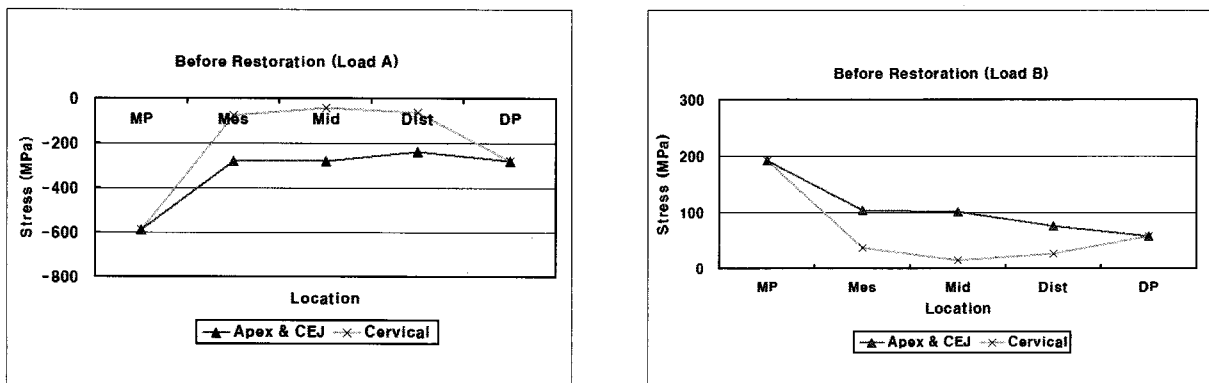


Figure 4. Before restoration, the principal stress distribution on the lesion apex and CEJ (Apex & CEJ), cervical cavosurface margin (Cervical) under Load A and B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).

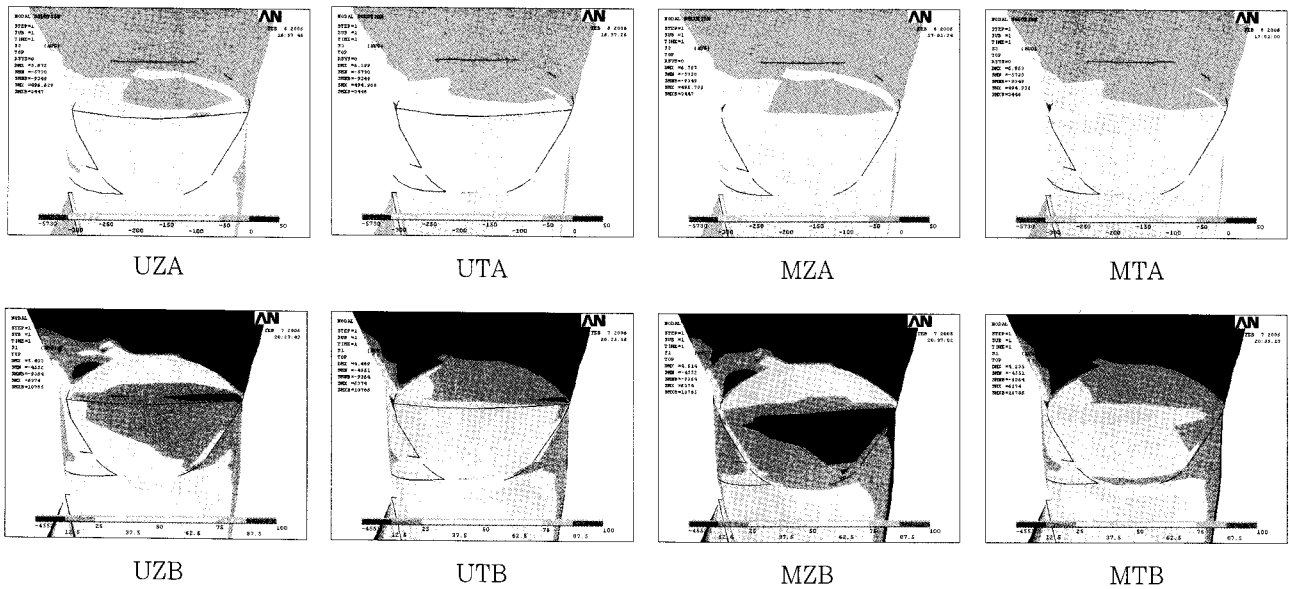


Figure 5. After restoration, the principal stress distribution in cervical cavity wall under Load A and B.

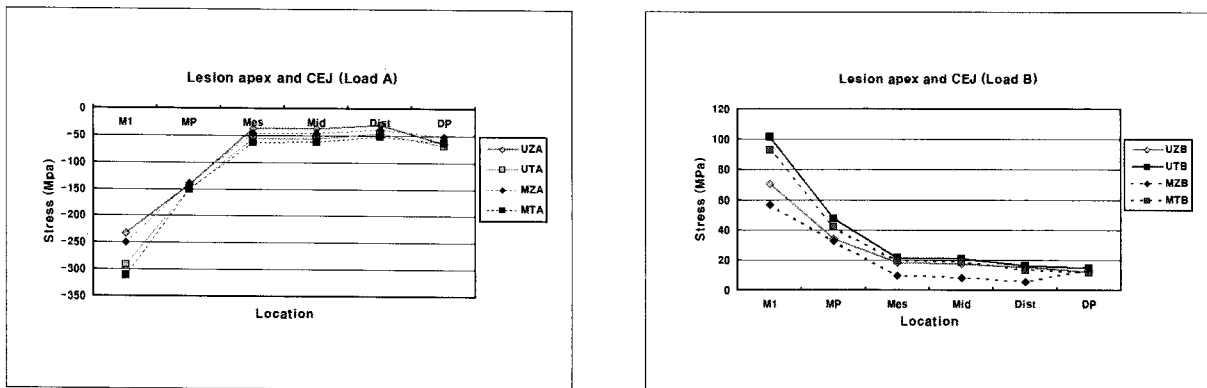


Figure 6. The principal stress distribution on lesion apex and CEJ after restoration under Load A and B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node, M1: more mesial proximal point than MP).

the lesion apex, stress relief was smaller when the cavity was restored by Tetric Flow than Z100.

Under Load B, stress values were smaller than Load A. However, larger tensile stress concentrations were observed in the mesial root dentin as well as at the lesion apex in UZB.

1) 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

peak stress site shifted from MP to M1 (Figure 6). The highest compressive stress of 310.7 MPa was concentrated at M1 in MTA under Load A. In UZA, the lowest compressive stress of 232.0 MPa was concentrated at M1.

Under Load B, the peak stress site also moved from MP to M1. The highest tensile stress of 101.6 MPa was concentrated at M1 in UTB. Tensile stresses were more reduced in the modified cavity than in the unmodified cavity.

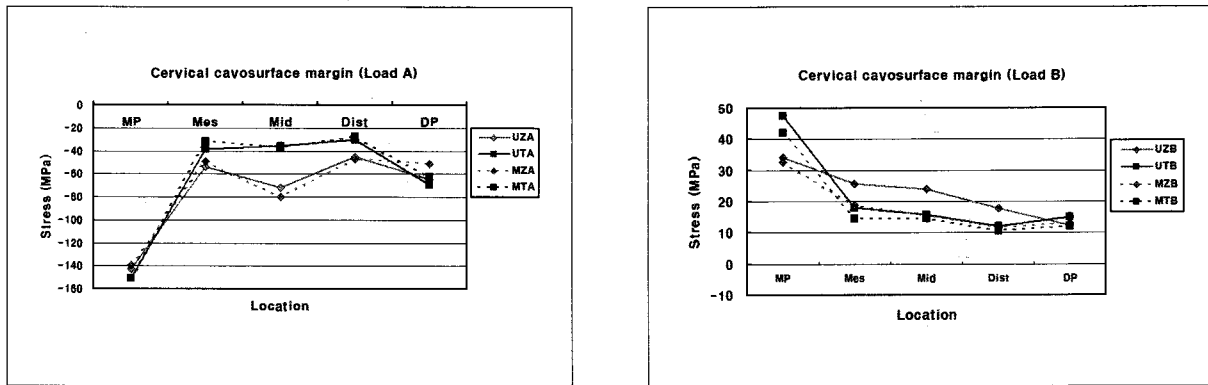


Figure 7. The principal stress distribution on cervical cavosurface margin after restoration under Load A and B (MP: Mesial point angle, DP: Distal point angle, Mes: Mesial node, Mid: Middle node, Dist: Distal node).

2) Cervical cavosurface margin

On cervical cavosurface margin, the highest compressive stress of 150.7 MPa was concentrated at MP in UTA under Load A. In MZA, the lowest compressive stress of 137.1 MPa was concentrated at MP. At the most site, in Z100 restorations, compressive stresses were larger than Tetric Flow restoration except MP and DP (Figure 7).

Under Load B, the stresses were reduced moving from the MP to DP. The highest tensile stress of 47.5 MPa was concentrated at MP in UTB under Load B. In MZB, the lowest tensile stress of 32.5 MPa was concentrated at MP. At the most site, in Z100 restorations, tensile stresses were also larger than Tetric Flow restoration except MP and DP. Similarly, at the lesion apex and CEJ, tensile stresses were more reduced in the modified cavity than in the unmodified cavity.

IV. DISCUSSION

In the current study, 500 N oblique loads were applied to the inner aspects of the buccal or lingual cusp slopes to reproduce of the lateral force that causes NCCL. The highest maximum and minimum principal stress values of between 193.3 and 588 MPa were found in the unrestored cavity. These values were all beyond the potential limit stress value of teeth²⁰⁾. These types of stress concentrations may contribute to fatigue of the tooth structure and accelerate the progression of

NCCLs.

Once the lesion was formed, the highest stress concentration was observed around the apex of the wedge-shaped lesion. The discontinuity of the enamel and dentin may cause increased stress and damage in the enamel. 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.

Restoring these lesions also will change the stress distribution within the tooth. Grippo⁶⁾ suggested that if the lesions were left unrestored, the stress concentration caused by the cervical lesion would facilitate further deterioration of the tooth structure. Kuroe et al.²¹⁾ demonstrated that resin composite restoration of these lesions leads to substantial improvement in the internal stresses within the tooth. Similarly, in the current study, the stresses were greatly reduced after restoration, especially in the lesion apex.

In the clinical assessment of this lesion type, dental practitioners must consider whether the cervical defect requires restoration and choose proper restorative material that will provide the best outcome. The choice of material to restore these lesions is crucial. Glass ionomer may be used, especially in patients with high caries rates. Recently resin composites with dentin bonding agents have become a popular alternative to glass

ionomer cement for the restoration of NCCLs. In the current experiment, lesions were restored by conventional hybrid resin and flowable resin.

After restoration of these cavities, restored teeth are also subjected to the physical forces of mastication with their attendant compressive, tensile, shear and bending forces. Concentration of compressive and tensile stresses at the cervical area induced by eccentric or heavy centric occlusal forces may progressively dislodge and eventually debond resin restorations.

Another 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 situation²²⁾. Yaman et al.²³⁾ concluded that for class V applications Z 100 gives the most promising results. According to Nakayama et al.²⁴⁾ 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 force²⁵⁾. When use 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 colleagues²⁶⁾ 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.

On the other hand, there is an investigation found no differences between a microfilled and a hybrid resin, although the two materials have widely different moduli of elasticity²⁷⁾.

In the current study, two different elastic modulus materials were used. The highest stress

reduction was observed at the apex in the Z100 restoration which had the higher elastic modulus. In the cervical cavosurface margin, Tetric Flow restoration showed a smaller stress value compared with Z100. 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 studies²³⁾ 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 restorations. However, under Load B, different stress values appeared. In Tetric Flow restoration, stresses were greater at the apex, but stresses were smaller at the cervical margin. 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.

Stress also depends on geometry of the cavity as well as the mechanical properties of restorative material. According to Hubsch et al.²⁸⁾, stress can be reduced by modifying the cavity design. Additionally, Leinfelder¹⁵⁾ suggested that the problem of stress concentrations can be reduced dramatically by modifying the axial wall from V-shaped configuration to one that is somewhat more concave in design and the proper shaping can be accomplished with a No 4 or in some instances a No 6 round bur.

In the present study, stresses were compared with a modified cavity form. Because the notch-shaped lesion had the highest stress concentration corresponded with sharpest geometric discontinuity at the apex of lesion, so the apex was remodeled by rounding. Contrary our expectations, in the modified cavity, the stresses of lesion apex did not decrease under Load A as compressive force. On the other hand, under Load B as

tensile force, the stresses decreased much more than in the unmodified cavity.

So considered, it is assumed that in compressive stress, the change of geometrical shape of modified cavity is not significant, similar stress concentration was observed. However, in tensile stress, from the point of view of fracture mechanics, stress was acted as a crack course in the unmodified cavity. On the other hand, in the modified cavity, the stress concentration was dispersed through crack retardation by a rounding effect^{29,30)}. For these stress characters, further study is necessary. Although compressive stress did not decreased, apex modification has a significant meaning for tensile stress which damage teeth seriously was decreased.

In general, the compressive strength of enamel is greater than that of dentin, while the tensile strength of dentin is greater than that of enamel. As the tensile strengths of enamel and dentin are much lower than their respective compressive strengths^{31,32)}, tensile stress is much more destructive than compressive stress. In terms of restoration retention in dentin bonding agent trials, tensile stresses appear to be the most destructive, at least short-term. Therefore, the developments of methods and materials that may reduce tensile stress are important.

In this experiment, the cavity modification method that cavity apex was modified by rounding was the profitable method for tensile stress reduction. Thus, this method is recommended for restoration of notch-shaped lesion because it showed the favorable effect in tensile stress.

V. CONCLUSIONS

Within the limitations of this study, it is suggested that 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. Cavity modification of the rounding apex did not reduce compressive stress, but tensile stress was reduced.

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국문초록

5급 복합레진수복물의 응력분포에 관한 3차원 유한요소법적 연구

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본 연구는 3차원 유한요소분석법적 연구를 통해 췌기형 비우식성 치경부병소의 복합레진 수복물에서 다른 탄성계수를 가진 복합레진의 수복과 와동의 형태와 응력의 방향에 따른 응력분포의 영향에 대해 알아보려고 하였다.

발거된 상악 제2소구치를 Micro-CT로 스캔한 후 3D-DOCTOR로 3차원유한요소 모형을 제작하였다. 제작된 소구치 모형에 췌기형 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 바 다음과 같은 결과를 얻었다.

1. 수복 전 응력은 근심측 백악법랑경계와 와동저 선각부에 집중되었으며 최대응력은 근심협측우각부에서 나타났다.
2. 와동수복 후 와동저 선각의 응력은 현저히 감소했으나 치경부측 변연의 응력은 수복전보다 증가하였다.
3. 췌기형태의 병소의 수복 시 와동저 선각부는 탄성계수가 높은 재료가 유리하고 치경부측변연은 탄성계수가 낮은 재료가 유리하였다.
4. 와동저 선각부를 둥글게 변화시키는 것은 압축응력은 감소시키지 않으나 인장응력은 감소시켰다.

주요어: 응력분포, 5급병소, 치경부병소, 복합레진, 유한요소분석