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Effect of Different Mechanical Properties of Core Build-up Materials on the Root Furcation of A Severely damaged Primary Molar: A Finite Element Analysis

Nuttha Suwannasri* Kunyawan Thaungwilai Pairod Singhatanadgid** Nichamon Chaianant* Weerachai Singhatanadgit* Piyaporn Pultanasarn***

Abstract

Objectives: To assess the von Mises stress and stress distribution pattern on the root furcation of a severely damaged primary molar restored with different core build-up materials and stainless-steel crown (SSC).

Materials and Methods: The finite element analysis was used to investigate stresses induced in the tooth structures included a sound primary molar and severely damaged primary molars restored with four different core-build up materials, including flowable composite core build-up, bulk-fill resin composite, RMGIC and nano-RMGIC. The maximum von Mises stress was used to represent the internal load induced in the model.

Results: Overall maximum von Mises stresses was the highest in the sound tooth. However, when focusing on apico-cervical aspect, all restored primary molars showed higher maximum von Mises stress than the sound tooth. The stress distribution pattern of each group was similar, except for the nano-RMGIC group that showed high stress concentrated at the tooth furcation and the buccal aspect of the root furcation. From the ratio of its tensile strength and the maximum von Mises stress, the nano-RMGIC possessed the highest fracture resistance, followed by bulk-fill composite, RMGIC and flowable composite core group, respectively.

Discussion: Although nano-RMGIC possessed the highest fracture resistance, it showed an unfavorable stress distribution pattern, which caused high stress at the root furcation. The bulk-fill composite possessed not only high fracture resistance but also favorable stress distribution.

Conclusion: The present study introduces crucial information that could lead to an alternative treatment for severely damaged primary molar. Our findings recommend bulk-fill composite as a potential core build-up material.

Keywords: Crown, Finite Element Analysis, Tooth, Deciduous, Molar

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**Faculty of Dentistry, Thammasat University, 99 Moo18 Phahonyothin Road, Klong Luang, Pathumthani, 12120, Thailand.*

***Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Phayathai Road, Pathumwan, Bangkok, 10330, Thailand.*

Introduction

Early childhood caries (ECC) is still one of the important public health problems among the Thai children population. According to the eighth Thailand National Oral Health Survey in 2017 revealed the prevalence of dental caries, 52.9% of children aged three years old and 75.6% of children aged five years old (1). The result showed that the prevalence of dental caries in primary dentition is still high. ECC has several negative impacts on a child's dental and general health (2). The common treatment option for severely damaged primary teeth (complete loss of clinical crown) is extraction, which results in premature loss of primary teeth. Early loss of primary teeth might develop morphological, functional and psychological problems (3). Although the space maintainer appliance can be utilized to prevent premature space loss, several deliberations, such as close monitoring, well cooperation between patient and parent and good oral hygiene, are required (4). To prevent tooth extraction and the adverse consequence, pulp treatment and a core build-up in severely damaged primary teeth with stainless steel crown (SSC) could be an alternative treatment option.

An extensive carious lesion in the primary molar is challenging for management. The gold standard treatment option for severely damaged primary molars is stainless-steel crowns (SSCs). Several studies reported clinical success of using SSCs in a pediatric patient (5). It is a cost-effective treatment, decreases the risk of secondary caries, and eases handling (6), especially for treatment under sedation and general anesthesia (7,8). However, SSCs failures could usually be attributed to either crown perforation or crown loss as a result of cement wash out (9,10). Our previous *in vitro* study has shown that restoring severely damaged primary posterior teeth (complete loss of the clinical crown) with a flowable composite core build-up (MultiCore®, Ivoclar Vivadent, Liechtenstein) is possible and help increase fracture resistance. The fracture load is ten times higher than the physiologic chewing force (11). However, the failure mode of prepared teeth appeared to be a non-restorable fracture at the root furcation. The failure at root furcation was shown by finite element analysis (FEA) to be associated with a high-stress concentration at the floor of pulp chamber and the root furcation (11,12). These may be due to the biomechanical nature of the tooth restored using the high modulus MultiCore® as the core-build up material.

Core build-up materials have long been shown to be beneficial for restoring severely destructed permanent teeth and, to a lesser extent for primary teeth (11,13,14). These can be divided into three main categories: 1) metal-based materials such as amalgam and casting alloy, 2) resin composite materials such as MultiCore®, and 3) resin-modified glass ionomers (RMGI) (15-17). For restoring severely damaged teeth, the mechanical properties of the core build-up materials is one of the key factors in the success of the restored tooth (18). To minimize stress concentration at the root furcation of a severely damaged primary tooth, a core material used should have an elastic modulus close to that of dentin (19). So, the occlusal stress is evenly distributed on the remaining tooth structure, particularly the furcation dentine. It has also been suggested that the mechanical properties of core material are not the only factor that influences the fracture resistance of the restored teeth. Core build-up material should also be bonded with the root dentine to obtain stabilized restoration that helps decrease the risk of dislodging and prevent root furcation fracture (20). In conclusion, various properties of the core build-up material above mentioned participating in tooth resistance to the fracture.

Consequently, four core build-up materials that have different biomechanical properties, including elastic modulus and tensile strength, were used in this study. Besides different biomechanical properties, working with pediatrics patients has unique characteristics which may need a material that is easy to manipulate, utilize less clinical chair time and decrease moisture sensitivity (21,22). Therefore, apart from flowable composite core build-up (MultiCore®, Ivoclar Vivadent, Liechtenstein), another three different types of material, commonly used in a pediatric clinic, including bulk-fill resin composite (Filtek^{TM} Bulk Fill, 3M ESPE, USA), RMGIC (Fuji II LC®, GC, Japan) and nano-RMGIC (KetacTM Nano, 3M ESPE, USA) were chosen in this study.

Finite element analysis, which is a well-established numerical method used in engineering applications, was adopted in this study. In the finite element procedures for stress analysis, a solid model of the tooth structures of interest is discretized into a small domain called "element", which is connected to other elements at the nodes. Boundary conditions which include boundary constraints and load conditions, are pre-assigned to the simulated model. Displacement, strain and stress on the elements can be determined from the set of algebraic equations and applied boundary conditions.

To determine the effect of different mechanical properties of various core build-up materials on the root furcation fracture of a severely damaged primary molar, this study assessed the von Mises stress and stress distribution pattern of the materials frequently used in pediatric dentistry. Finite element analysis of the SSC-restored primary molar, using four dental materials with different elastic modulus and tensile strength as core build-up materials, was performed.

Materials and Methods

In this investigation, stresses induced in the tooth structures were determined and compared between each case of the study. The tooth used in this study included a sound primary molar and a severely damaged primary molar (complete loss of clinical crown) with SSC restorations (11). For the cases of a restored molar, core-build up materials used in the model were flowable composite core build-up (MultiCore®, Ivoclar Vivadent, Liechtenstein), bulk-fill resin composite (FiltekTM Bulk Fill, 3M ESPE, USA), RMGIC (Fuji II LC®, GC, Japan) and nano-RMGIC (KetacTM Nano, 3M ESPE, USA). These core build-up materials possessed different elastic modulus (ranging between 4000-16,000 MPa) and tensile strength (ranging between 40-75 MPa) (11,23-26).

The finite element model was obtained from the CT-scanned images of a sound primary molar from previous study (11). The scanned images were processed and cleaned using Catia V5 (Dassault Systèmes, Vélizy-Villacoublay, France) and an open-source program Blender (https://www.blender.org/), which are computer-aided design software, to delete and reconstruct the defective parts of the image. The software was also used to generate the restored primary molar model by substituting the upper part of the tooth with the re-constructed SSC and core-build up materials. The outer boundaries of the sound primary molar and the restored primary molar are identical so that the stress analysis from the finite element program can be compared.

Complete solid model of sound and restored primary molars were then converted to finite element model using meshing function of the ANSYS v.18 (ANSYS Inc., Canonsburg, PA, USA) finite element program. Convergence studies were conducted to ensure that the models were meshed independently and the obtained stresses were converged. In this study, a tetrahedron element was chosen with an element size of 1 mm in the bone, 0.1 mm in PDL, and 0.3 mm in other parts of the model. A smaller element was required in the PDL so that stresses in the PDL region were accurately achieved. Since models were comprised of various components, types of contact between each component must be identified to acquire a more accurate solution. In this study, all interfaces were set to be bonded as described in previous study (11).

All components of the tooth models were supposed to be isotropic and homogeneous. Materials properties required in the FEA, including Young's modulus and Poisson's ratio, were shown in Table 1 (11,23-26).

With the applied 100N static occlusal loads perpendicular to occlusal surface, and prescribed boundary conditions described in previous study (11), mechanical responses in terms of displacement, stress and strain were determined. In this study, stress components in the model were of interest. They were used to calculate von Mises stress, which is defined as;

$$\sigma_v = \sqrt{\frac{1}{2}\left[\left(\sigma_{xx}-\sigma_{yy}\right)^2+\left(\sigma_{yy}-\sigma_{zz}\right)^2+\left(\sigma_{zz}-\sigma_{xx}\right)^2\right]+3\left(\tau_{12}^2+\tau_{23}^2+\tau_{31}^2\right)}$$

σ_v is von Mises stress

σ_x, σ_y and σ_z are the direct stress components at the point of interest

τ is the shear stress component

Based on the maximum distortion energy theory, von Mises stress can be used to represent the internal load induced in the model. A model with a higher von Mises stress is likely to fail before that with a lower value of von Mises stress. So, in this study, von Mises stress in the models with different core materials were compared.

Table 1. Properties of tooth structures and dental restorative materials used in FEA.

Materials	Elastic Modulus (MPa)	Poisson's ratio	Tensile strength (MPa)
Enamel	84,100	0.20	-
Dentine	18,600	0.31	-
Pulp	2	0.45	-
PDL	68.90	0.45	-
Cortical bone	13,700	0.30	-
Spongy bone	1,370	0.30	-
Zinc oxide eugenol	2,140	0.28	-
SSC	200,000	0.33	-
Cement	10,860	0.30	-
Flowable composite core (MultiCore®)	16,000	0.26	50.60
Bulk-fill composite core (Filtek™ Bulk Fill)	13,460	0.18	41.10
RMGIC core (Fuji II LC®)	10,860	0.30	45.00
Nano RMGIC Core (KetacTM Nano)	4,000	0.44	55.00

Results

In the sound tooth, the overall maximum von Mises stress was approximately 230 MPa, and it possessed an evenly distributed stress pattern (Fig. 1A). However, higher overall maximum von Mises stresses between 282 and 285 MPa were observed in severely damaged primary molars restored with different core-build up materials and SSC placement (Fig. 1B-1E). Similar stress distribution in these restored tooth models was noticed but their distribution patterns appeared to be less even compared with that of the sound tooth.

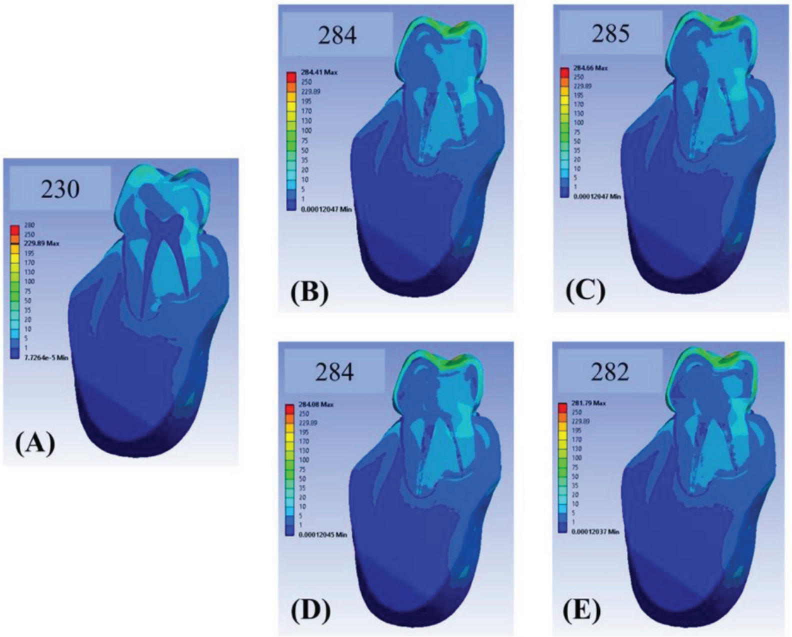


Fig.1. Finite element analysis showing overall maximum von Mises stress and stress distribution in the sagittal plan of a sound tooth (A) and SSC restorations using the following materials as core-build up materials: flowable composite core (B), bulk-fill composite (C), RMGIC (D) and nano-RMGIC (E). The numbers shown are maximum von Mises stress in MPa. Color ranged from blue to red indicated the lowest to the highest von Mises stresses.

The results further showed that in the sound tooth, the maximum von Mises stress at apico-cervical aspect was approximately 56 MPa. The stress concentration was found at its linguo-cervical area but not involving its furcation (Fig. 2A). However, much lower maximum von Mises stresses were observed in severely damaged primary molars restored with different core-build up materials and SSC placement (32-36 MPa) (Fig. 2B-2E). It is noteworthy that the stress distribution pattern of the flowable composite core (Fig. 2B), bulk-fill composite (Fig. 2C) and RMGIC (Fig. 2D) groups appeared to be similar to that of the sound tooth group, but the stress concentration in the nano-RMGIC group was observed at the linguo-cervical area and involving the tooth furcation (the red arrow in Fig. 2E).

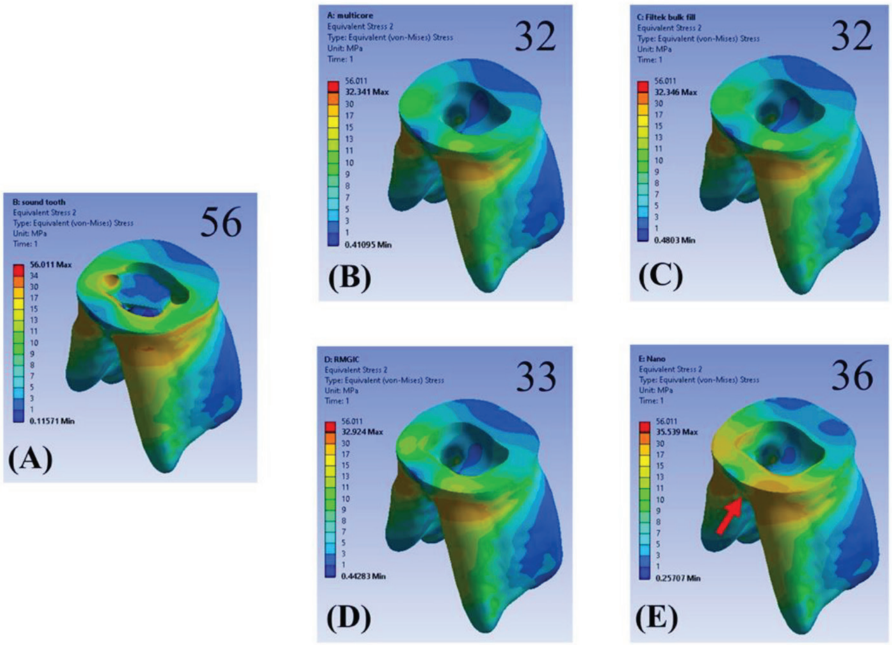


Fig.2. Finite element analysis showing maximum von Mises stress and stress distribution (apico-cervical aspect) in the tooth structure of a sound tooth having similar tooth structure to other groups (A) and in the remaining tooth structure of the severely damaged primary molar with SSC restorations using the following materials as core-build up materials: flowable composite core (B), bulk-fill composite (C), RMGIC (D) and nano-RMGIC (E). The numbers shown are maximum von Mises stress in MPa. Color ranged from blue to red indicated the lowest to the highest von Mises stresses.

Stress distribution at the pulpal floor dentine of each sample was shown in Fig. 3 revealing a clear stress concentration at the pulpal floor dentine of the nano-RMGIC group. The results also demonstrated the highest stress concentration on the pulpal floor dentine of the nano-RMGIC group (pale orange line in Fig. 3F). Again, the sound tooth group had the lowest stress at the pulpal floor dentine (blue line in Fig. 3F).

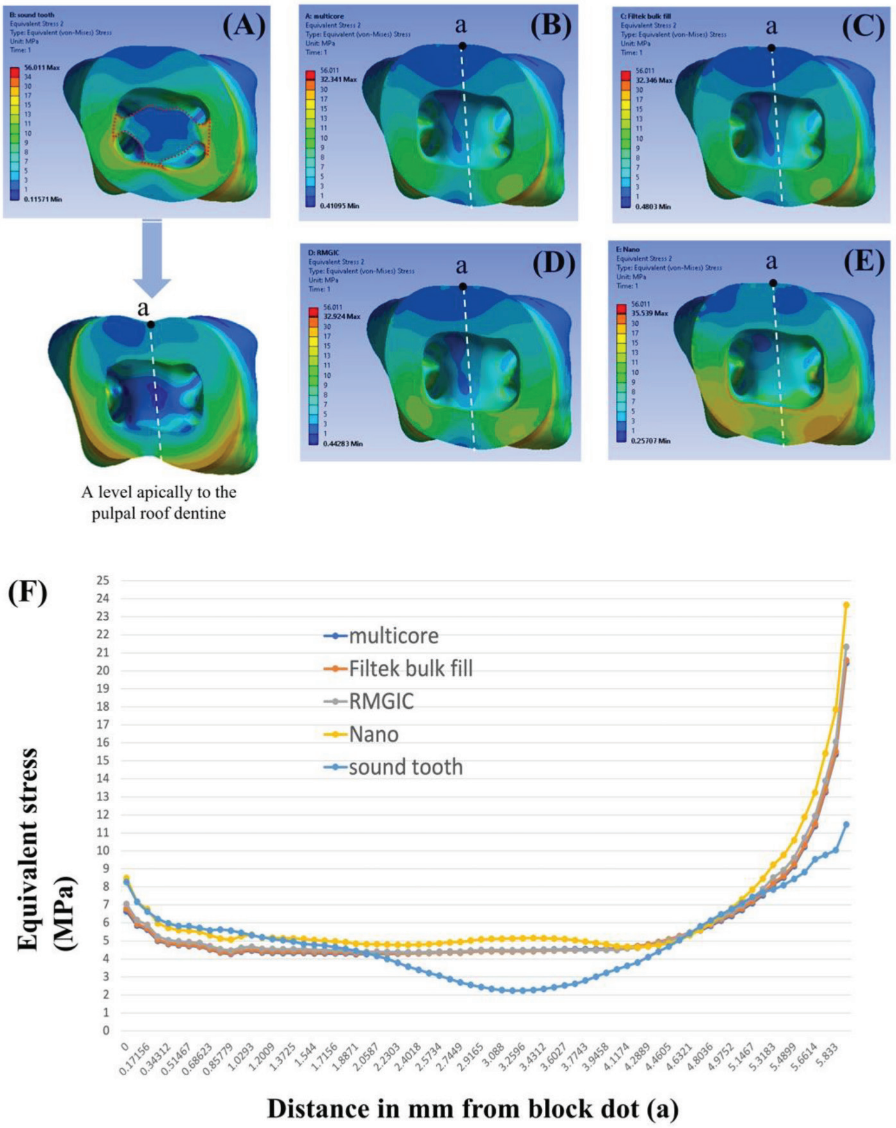


Fig.3. Finite element analysis showing stress distribution (pulpal floor aspect) in the tooth structure of a sound tooth having similar tooth structure to other groups (A) and in the remaining tooth structure of the severely damaged primary molar with SSC restorations using the following materials as core-build up materials: flowable composite core (B), bulk-fill composite (C), RMGIC (D) and nano-RMGIC (E). Red dotted line showed the area of remained pulpal roof dentine after cross-sectioning the simulated model at the same level shown in B-E. In (F), the graph showed equivalent stress along the pulpal floor (white dash lines in A-E). Color ranged from blue to red indicated the lowest to the highest von Mises stresses.

Fig. 4 Stress distribution at the root furcation of each group possessed a similar, but not identical, pattern. The only clear difference among all groups was observed at the buccal aspect of the root furcation in the nano-RMGIC group (Fig. 4E), which showed a stress concentrated line (yellow/orange) connecting (a red arrow) to the stress concentrated lines running from the buccal surface (yellow/orange).

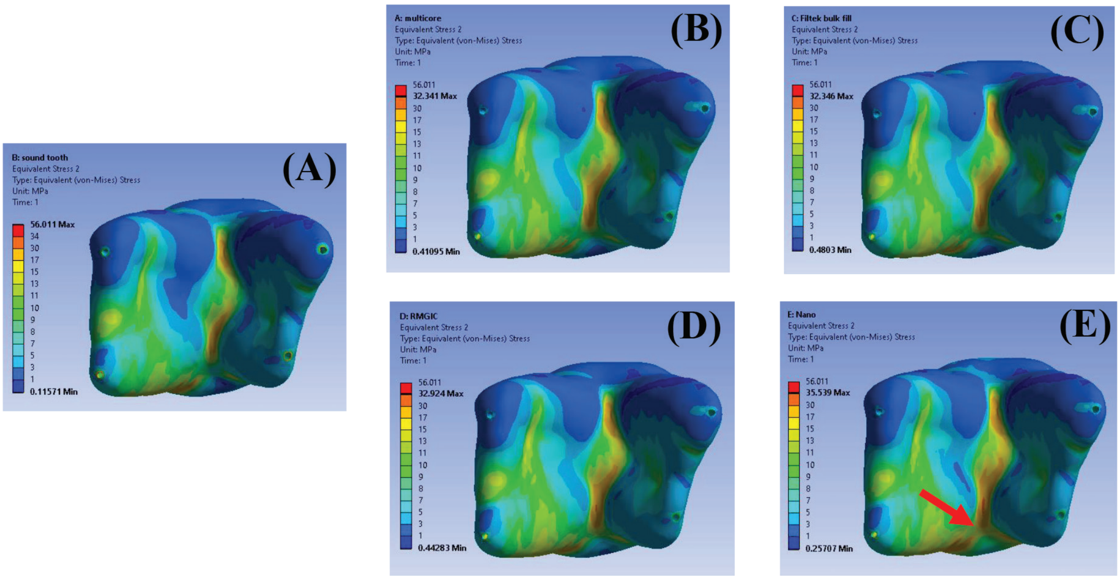
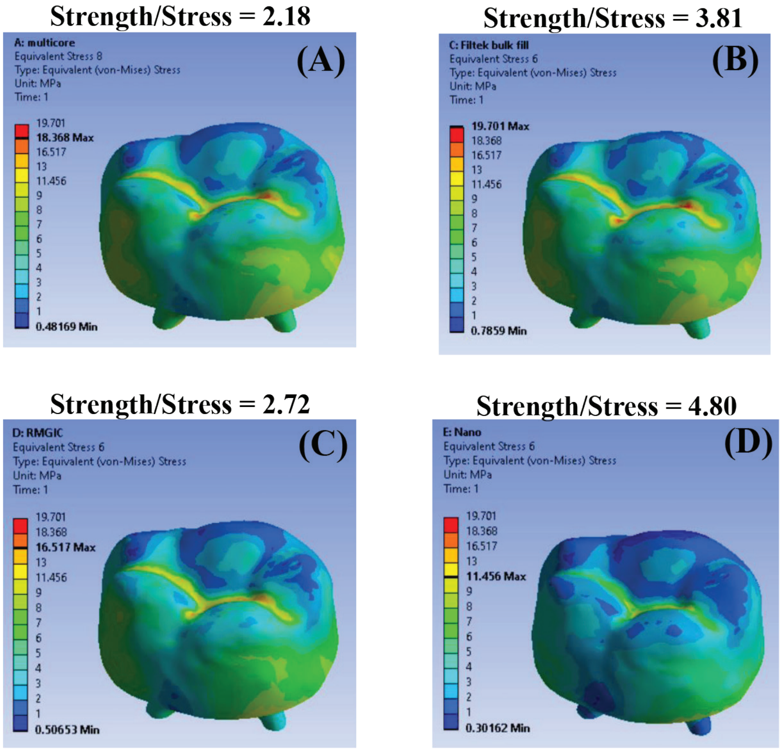


Fig. 4. Finite element analysis showing stress distribution at the root furcation of a sound tooth (A) and severely damaged primary molars with SSC restorations using the following materials as core-build up materials: flowable composite core (B), bulk-fill composite (C), RMGIC (D) and nano-RMGIC (E). Color ranged from blue to red indicated the lowest to the highest von Mises stresses. A red arrow denoted the stress distribution concentrated at the buccal root furcation area.

Maximum von Mises stress and stress distribution of the dental materials used as core build-up materials were shown in Fig. 5. Overall, lower stress was observed in the nano-RMGIC group (Fig. 5D vs Fig. 5A-5C). Resistance to fracture of a material of interest correlates with the ratio of its tensile strength and the maximum von Mises stress (27). In this study, the nano-RMGIC possessed the highest fracture resistance, followed by bulk-fill composite, RMGIC and flowable composite core group, respectively.


Strength/Stress = 2.18

Strength/Stress = 3.81

Strength/Stress = 2.72

Strength/Stress = 4.80

Fig. 5. Finite element analysis showing maximum von Mises stress and stress distribution of the following materials used as core-build up materials: flowable composite core (A), bulk-fill composite (B), RMGIC (C) and nano-RMGIC (D). Color ranged from blue to red indicated the lowest to the highest von Mises stresses. The ratios of the tensile strength and the maximum von Mises stress of each group are shown.

Discussion

Following pulp therapy, restoring the severely damaged primary molars using SSC with core build-up material is possible. This supported by the findings in the in vitro model that the restored tooth being resisted to high occlusal load (11). Finite element analysis, a reliable simulated model, has previously been shown to be correlated with in vitro experimental fracture resistance (25,28,29). The data obtained from finite element analysis could demonstrat the outcome in both qualitative, i.e. von Mises stresses and quantitative data, i.e. pattern of force distribution. In the present study, the results showed, for the first time, that although the core build-up using nano- RMGIC possessed the highest fracture resistance, it caused highest maximum von Mises stress concentrated along the root furcation, resembling the furcation fracture line previously shown (11). The bulk-fill composite appeared to be the most suitable core build-up material because the material possessed favorably high fracture resistance and caused much lower von Mises stress on tooth structures than that produced by the nano-RMGIC. Apart from short working time and less technique sensitivity, bulk-fill composite provided comparable or superior performance compared to conventional resin composite (30-32). This composite also established satisfactory outcomes for laboratory and clinical research on primary teeth (33-36). Therefore, bulk-fill composite could be recommended as core build-up material in children.

It is noteworthy that metal-based core build-up materials were not included in the present study because these materials may not be suitable for core build-up in children. The use of amalgam core-build up requires a long final setting time and raises a concern of mercury component while the use of metal cast post needs multiple visits. Moreover, these metal-based core build-ups cannot generally bind tightly to the dentine, resulted in dislodgement of the material, thus initiating fracture of the root furcation (37, 38). In contrast, both resin composites and RMGIC, including the nano-RMGIC, are known to be able to bind to the dentine, creating the monoblock-like property, which is expected to prevent fracture of dentine (39-43). These tooth-bonded materials also have several advantages, including proper setting time, anti-bacterial molecules, fluoride release, and inhibition of tooth demineralization (44-46).

In the present study using finite element analysis, maximum von Mises stresses in the dentine of the tooth restored with SSC and any core-material restoration were significantly lower than that of the sound tooth. This numerical result was reasonable since the stiffness of stainless steel (E = 200 GPa) is much more than that of human enamel (E = 84.1GPa). When the SSC is subjected to the applied load, its deformation occurred less than that of the enamel in a sound tooth.

So, a smaller amount of stress is transferred to the core build-up materials and to the dentin underneath. In other words, the SSC absorbs more applied load and transfers less load compared to the case of an enamel.

It is important to note that several other factors apart from those used in the present finite element analysis may play an important part in the success of the restoration of extensively damaged primary molars. For treatment of these carious teeth, the results in the present study introduced an alternative treatment (to the routine extraction) and a potential core build-up material candidate that possesses high fracture resistance of the root furcation. Tensile strength and elastic modulus play a significant part, and modification of mechanical properties of core build-up materials may be possible. To improve the mechanical properties of the complete cured GIC, nano-RMGIC was developed by incorporate nanofillers. The nano-RMGIC established comparable bond strength as effectively as conventional GIC to enamel and dentin. However, it had considerably less bonding efficiency than conventional RMGIC (47,48).

The finite element analysis is a mathematical method analyzing stress on a solid model of tooth structure. There are several strengths of using this method. As the FEA technique may also apply stress point that can be hypothetically evaluated, it is allowed to create the position, magnitude, and path of applied force. It is also not an invasive technique and does not affect the physical properties of the analyzed model. Consequently, the repetition of the test can be easily done multiple times (49,50).

On the other hand, due to it is in vitro study, based on numerical method, in which clinical conditions may not be completely replicated. In addition, FEA in this study was analyzed under the condition of static occlusal loading. Therefore, it may not mimic the clinical situation. Further studies should focus on investigating stress distributions and fracture resistance under conditions of dynamic loading force, which would be close to the actual clinical implication. In addition, further FEA method should be supplemented with clinical research

Further clinical studies to identify the most appropriate core build-up materials and success rate of this alternative treatment for extensively damaged primary molars in ECC patients will undoubtedly be beneficial to improve our patients' quality of life.

In conclusion, within the limitation of the study, the following conclusions can be drawn:

1. The nano-RMGIC core build-up material resulted in the highest fracture resistance but caused the highest maximum von Mises stress concentrated along the root furcation.
2. The bulk-fill composite appeared to be the most suitable core build-up material, providing high fracture resistance and low von Mises stress on tooth structures.

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Corresponding author:
Dr. Piyaporn Pultanasarn
Research unit in Mineralized Tissue
Reconstruction, Faculty of Dentistry, Thammasat
University (Rangsit Campus), 99 Moo18
Phahon Yothin Road, Khlong Luang,
Pathum Thani, 12120, Thailand.
Tel: (668) 1779 9698, Fax: (662) 986 9205
E-mail: maymaepiyaporn@gmail.com