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Assessment of the Stress Distribution in Internal Resorption Cavities Filled with MTA and Biodentine in Mature Teeth: A Finite Element Analysis Study

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ABSTRACT

Introduction: Internal Root Resorption (IRR) is the gradual deterioration of dentine due to clastic activity, typically appearing as a radiolucent area in the radicular dentine in communication with the root canal. Bioceramic materials such as Mineral Trioxide Aggregate (MTA) and Biodentine are available to restore the resorption cavity, offering biocompatibility and better sealing to the dentine. The present study employs the Finite Element Analysis (FEA) method to simulate stress behaviour, providing valuable insights into the effectiveness of these materials in reducing stress concentrations and reinforcing structurally compromised teeth. The findings aim to support clinical decision-making for achieving long-term restoration success.

Aim: To evaluate and compare the stress distribution patterns in tooth models with IRR restored with MTA and Biodentine at the apical, middle and coronal thirds, employing FEA.

Materials and Methods: This FEA study was conducted in the Conservative Dentistry and Endodontics department at Sibar Institute of Dental Sciences in Guntur, Andhra Pradesh, India, from June 2024 to August 2024. Seven three-dimensional (3D) FEA models of mandibular first premolars were designed: M1 (IRR at apical third restored with MTA), M2 (IRR at middle third restored with MTA), M3 (IRR at cervical third restored with MTA), M4 (IRR at apical third restored with Biodentine), M5 (IRR at middle third restored with Biodentine), M6 (IRR at cervical third restored with Biodentine) and M7 (control model). A force of 300 N was applied to the buccal side at a 30° inclined angle to the occlusal plane. Linear analysis was conducted to assess the Von Mises stress values along the central XY plane of the tooth model. The maximum and minimum Von Mises stresses were recorded and directly compared for each virtual tooth model.

Results: Stress analysis showed maximum stress concentrations near the edges of the resorption cavities for both materials. In MTA-filled models, peak stress values were 73.35 MPa (apical), 104.35 MPa (middle) and 102.79 MPa (coronal), while Biodentine-filled models showed slightly lower peaks at 72.33 MPa (apical), 103.65 MPa (middle) and 101.86 MPa (coronal). Minimum stress values ranged from 0.0002 MPa to 0.0022 MPa across models, primarily in regions distant from the cavities.

Conclusion: Biodentine exhibited slightly better stress redistribution than MTA, with lower peak stress values across all resorption levels; however, both materials left the cavity edges as critical stress concentration zones. These findings emphasise the need for additional restorative measures to address structural vulnerabilities.

Keywords: Bioceramics, Linear analysis, Mineral trioxide aggregate, Occlusal forces, Virtual tooth model

INTRODUCTION

The IRR involves the loss of hard dental tissue due to an inflammatory process mediated by odontoclastic cells [1]. IRR is commonly linked to trauma, autotransplantation, or orthodontic treatment. The process destroys the predentin matrix and dentinal tubules, replacing hard dentin with granulation tissue, cementoid, or bone-like tissue [2]. If untreated, IRR can extend into the periodontal tissue, creating communication between the root canal and surrounding structures [3].

Restoring teeth affected by IRR is challenging due to irregular resorptive defects, leading to uneven stress distribution and an increased risk of fractures under functional loads. Understanding the biomechanical behaviour of restorative materials in these cases is essential for informed clinical decision-making.

Finite Element Analysis (FEA) is a valuable tool for simulating and evaluating stress distribution in restored teeth under various loading conditions. This method involves creating a computerised mesh of nodes and elements that represent the structure's physical properties, such as elastic modulus and Poisson's ratio. Stress distribution is assessed through equations and resultant displacements at the nodes, providing insights into material performance under specific conditions. Originally developed by A. Hrennikoff and Richard Courant for structural analysis in aeronautical engineering [4], FEA has become a reliable, cost-effective method for analysing stress distribution in dental structures [5-7].

Biodentine, a calcium silicate-based cement introduced in 2010 by Gilles and Oliver (Septodont, France), is specifically designed as a dentin substitute. Its compressive strength increases progressively, reaching 100 MPa within the first hour, 200 MPa after 24 hours and 300 MPa after one month, closely matching that of natural dentin (297 MPa) [8]. A lower powder-to-liquid ratio further enhances its compressive strength [9]. MTA, another bioceramic material, also provides excellent sealing properties and biocompatibility, but its compressive strength is 40 MPa after 24 hours and increases to 67 MPa after 21 days [10]. These differences in mechanical properties make material selection crucial, particularly for larger resorptive defects or teeth exposed to high occlusal forces.

By comparing bioactive materials like MTA and Biodentine, researchers can identify strategies to minimise stress concentration around resorptive lesions, thereby reducing the risk of fracture and improving long-term outcomes. These materials are recognised for their sealing ability, biocompatibility and capacity to stimulate reparative dentin [11]. However, differences in mechanical properties, such as compressive strength and elastic modulus, influence their performance.

The present study, using FEA, aimed to determine the stress distribution in internal resorption cavities restored with MTA and Biodentine. The findings will aid clinicians in selecting restorative materials that effectively support and protect structurally compromised teeth affected by IRR.

MATERIALS AND METHODS

The present FEA study was conducted in the Department of Conservative Dentistry and Endodontics at Sibar Institute of Dental Sciences in Guntur, Andhra Pradesh, India, from June 2024 to August 2024. Ethical approval was obtained (Protocol no. 456/IEC/SIBAR/2024) on June 19, 2024.

Study Procedure

Model development: Average anatomical measurements of mandibular first premolar tooth models were replicated with IRR cavities in the root canals and supporting tissues using the Ansys software programme (Version 16.2, Pentium IV system). Mandibular first premolar tooth models were selected for the present study due to their anatomical location and lingual orientation within the dental arch, allowing for the assessment of stress distribution in teeth affected by internal resorption. Seven distinct models of filled teeth were designed, consisting of enamel, dentin, composite restoration, spongy bone, cortical bone, PDL, MTA and Biodentine.

The measured diameters of the resorption cavities were 3.8 mm, 2.8 mm and 1.8 mm at the coronal, middle and apical regions, respectively. The distances from the centre of the resorption to the apices were 13 mm, 8 mm and 3 mm in the coronal, middle and apical areas, respectively. All the resorption cavities in the models were surrounded by 1 mm of dentin.

Tooth models were created in the following manner [Table/Fig-1]:

Model 1 (M1): IRR was simulated in the apical region of the root and MTA was used to obturate the root canal and resorption cavity.

Model 2 (M2): IRR was simulated in the middle region of the root and MTA was used to obturate the root canal and resorption cavity.

Model 3 (M3): IRR was simulated in the coronal region of the root and MTA was used to obturate the root canal and resorption cavity.

Model 4 (M4): IRR was simulated in the apical region of the root and Biodentine was used to obturate the root canal and resorption cavity.

Model 5 (M5): IRR was simulated in the middle region of the root and Biodentine was used to obturate the root canal and resorption cavity.

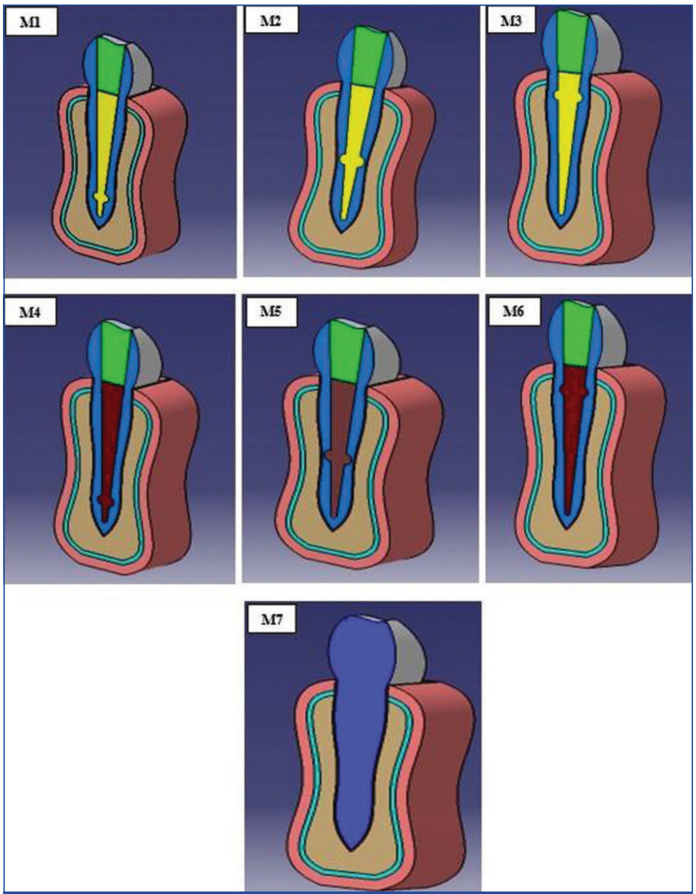
Model 6 (M6): IRR was simulated in the coronal region of the root and Biodentine was used to obturate the root canal and resorption cavity.

Model 7 (M7) (Control Group): Mature tooth model without any resorption cavity.

Material properties: Material properties, Poisson's ratio and Young's modulus were obtained from the literature [Table/Fig-2] [7,12].

Boundary conditions and loading: Solid 45 is a higher-order 3D, 8-node solid element characterised by eight nodes, each with three degrees of freedom: translations along the x, y and z axes. It is particularly suited for detailed deformations and stress distribution simulations under applied forces. This element accurately represents the 3D geometry of tooth structures, making it ideal for modelling the biomechanical behaviour of dental tissues and restorative materials under realistic functional loads. However, it has limitations, such as low order accuracy in handling curved surfaces, bending-dominant loads and large deformations.

A 300 N oblique force was applied at the top of the tooth structure. This force was directed towards the buccal side at an angle of 30° to the occlusal plane. The oblique nature of the force is designed to replicate the realistic functional loads experienced during chewing, which often involve complex directional forces rather than simple vertical loading [13]. The Periodontal Ligament (PDL) and alveolar bone were simulated around the tooth to represent the boundary conditions. The PDL was modelled as a thin, elastic material layer with viscoelastic properties, allowing slight movement and effective load dissipation. Constraints were applied to the alveolar bone, ensuring realistic load transfer through the PDL to the surrounding bone structure.



[Table/Fig-1]: Virtual tooth models filled with MTA (M1,M2,M3), Biodentine (M4, M5, M6) and Control model (M7).

Material	Youngs modulus (E) (MPa)	Poisson's ratio
Enamel	41,000	0.31
Dentin	18,600	0.31
Biodentine	22,000	0.33
MTA	15,700	0.23
Resin composite	24,494	0.30
Cortical bone	13,700	0.30
Spongy bone	1370	0.30
Periodontal Ligament (PDL)	68.9	0.45

[Table/Fig-2]: Material properties used in the finite element models [7,12].

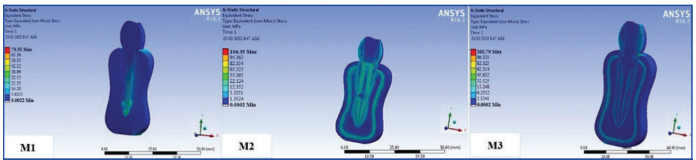
Finite Element Analysis (FEA): In the present study, structural static analysis determines the displacements, stresses, strains and forces in structures or components subjected to loads, assuming minimal inertia and damping effects. The loads and the structure's response are assumed to change gradually under steady loading and response conditions. Mesh sensitivity analysis may not be needed for stress distribution after restoring internal resorption cavities with MTA and Biodentine, as their low elasticity and high damping capacity reduce localised stress variations. Instead, material properties and boundary conditions play a more crucial role than mesh refinement.

Under specified loading conditions, a linear analysis was conducted to assess the von Mises stress values along the central XY planes of the entire roots.

Post-processing and data analysis: Numerical data were converted into colour images to enhance the visualisation of stress distributions in the FEA models. The maximum and minimum von Mises stresses were recorded and compared for each virtual tooth model. A direct comparison was performed.

RESULTS

MTA-filled model with internal resorption present at apical third (M1): The maximum stress of 73.35 MPa occurs near the apical resorption cavity, which acts as a stress concentrator due to the reduced thickness of the surrounding dentin (M1) [Table/Fig-3].



[Table/Fig-3]: MTA filling models with IRR at apical third (M1), middle third (M2) and coronal third (M3), show maximum stress (red colour) and minimum stress (blue colour) along XY plane.

The minimum stress of 0.0022 MPa is distributed across areas farther from the cavity, particularly in the crown and middle sections, where the structure remains largely intact (M1) [Table/Fig-3].

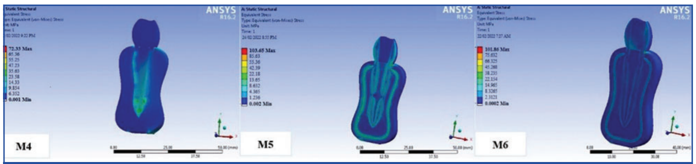
The apical region (near the resorption cavity) shows a gradient of stress, with some localised high-stress zones. These stress peaks are expected in areas with structural discontinuities, such as resorption cavities, where load transmission is less uniform. Stress levels are lower in the crown and middle root regions, as indicated by the blue regions, reflecting minimal deformation or stress under the applied load. These areas are not directly influenced by the structural defect in the apical part, likely due to load dissipation along the canal filled with MTA (M1) [Table/Fig-3].

MTA-filled model with internal resorption present at middle third (M2): The red and orange zones, particularly near the resorption cavity, indicate areas of high von Mises stress. These regions are at or near the stress maximum of 104.35 MPa. Such high-stress regions often suggest potential structural vulnerability and are critical for assessing fracture risks. The green, blue and cyan zones represent lower stress magnitudes. The lowest stress observed is 0.0002 MPa, as indicated in the dark blue areas, likely far from the load application points. The stress distribution indicates that the cavity amplifies stress concentration in the mid-root region. This is a common phenomenon, as cavities disrupt the continuity of the material, leading to a redistribution of stress and often amplifying it near the defect edges. Since the root canal is filled with MTA, its material properties (elastic modulus, Poisson's ratio) play a significant role in mitigating or exacerbating stress transfer. MTA's relatively high stiffness likely provides some degree of reinforcement to the weakened structure but may still leave the resorption cavity as a weak point (M2) [Table/Fig-3].

MTA-filled model with internal resorption present at coronal third (M3): The red and orange zones indicate high-stress regions, with the peak von Mises stress recorded at 102.79 MPa. These stress concentrations are localised around the edges of the coronal resorption cavity, where the structural discontinuity causes stress amplification.

High stresses in these regions suggest a potential risk of fracture or failure under functional loading. The stress distribution transitions smoothly from high (red) to low (blue) as you move away from the cavity, particularly towards the apical portion of the root. The lowest stress magnitude is 0.0002 MPa, observed in regions far from the cavity and load application points. Placing the cavity in the coronal portion significantly alters stress distribution compared to a mid-root cavity. The coronal position experiences higher forces due to proximity to loading points (e.g., masticatory forces), leading to more pronounced stress amplification. The presence of MTA in the root canal reduces stress concentration to some extent by redistributing loads; however, the compromised coronal structure remains a critical zone of vulnerability (M2) [Table/Fig-3].

Biodentine-filled model with internal resorption present at apical third (M4): The maximum von Mises stress is 72.33 MPa, observed near the apical resorption cavity, particularly at the cavity edges. This stress concentration is a direct result of the structural discontinuity caused by the resorption cavity. High stress at this location is critical, as the apical portion is mechanically less robust compared to the coronal part. The stress gradually reduces as it moves away from the apical cavity, transitioning to lower values in the middle and coronal parts of the root. The lowest recorded stress is 0.001 MPa, seen in regions distant from the load application and the cavity. Biodentine, a material known for its dentin-like properties and good compressive strength, contributes to stress redistribution. However, the presence of the resorption cavity still causes localised stress amplification. An apical cavity tends to experience lower stress compared to coronal or mid-root cavities under typical vertical loading. However, its proximity to the root apex and smaller cross-sectional area make it more susceptible to fracture (M4) [Table/Fig-4].



[Table/Fig-4]: Biodentine filling models with IRR at apical third (M4), middle third (M5) and coronal third (M6) show maximum stress (red colour) and minimum stress (blue colour) along the XY plane.

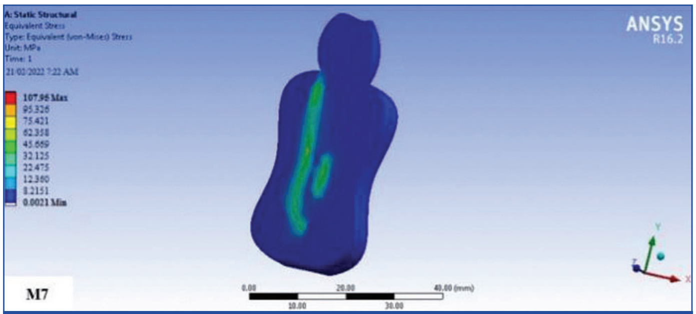
Biodentine-filled model with internal resorption present at middle third (M5): Red regions indicate the highest stress concentration (103.65 MPa), while blue represents minimal stress (0.002 MPa). The highest stress occurs in the middle region of the root, likely in the vicinity of the resorption cavity. This suggests a structural weakness due to the cavity, as the material experiences elevated stress levels under the applied load. Stresses diminish as you move away from the resorption cavity and the loaded region, with the lower regions of the root experiencing minimal stress (M5) [Table/Fig-4].

Biodentine-filled model with internal resorption present at coronal third (M6): The stress values range from 0.0002 MPa (blue) to 101.86 MPa (red). The highest stresses are concentrated in the coronal part of the root, which corresponds to the location of the resorption cavity. Stress levels decrease progressively towards the apical regions and outer root surfaces, as expected under oblique loading conditions. The highest stress concentration is observed near the edges of the coronal cavity, where structural discontinuity leads to stress amplification. The Biodentine filling helps distribute the stresses through the root structure, but the coronal cavity remains a vulnerable point due to its proximity to the force application zone (M6) [Table/Fig-4].

Control tooth model (M7): Red areas (107.95 MPa) indicate regions experiencing maximum stress, while blue areas (0.0021 MPa) represent regions with minimal stress. The highest stress concentration (red regions) is likely located along areas subject to maximum bending or loading due to the applied force, possibly near the surface where the force is applied or along structural weak points. The stress propagates along the vertical axis of the tooth, indicating how the force is distributed throughout the structure. The green and yellow areas highlight intermediate stress regions, particularly along the central axis of the tooth. Blue areas represent stress-free or minimally stressed zones, likely due to their distance from the force application point and load path (M7) [Table/Fig-5].

DISCUSSION

The stated benefits of obturating root canals with internal resorption cavities using a restorative material that possesses an elastic modulus close to that of dentin are to enhance fracture resistance through the uniform distribution of stresses [9]. Compared to the



[Table/Fig-5]: The control group (M7) shows maximum stress (red colour) and minimum stress (blue colour) values.

conventional obturating material, gutta-percha, which shows an uneven distribution of forces, the use of bioceramic materials such as MTA and Biodentine may allow stresses to be equally distributed to the surrounding dentin, thanks to their excellent sealing ability derived from their penetration into dentinal tubules [14,15].

The FEA of tooth models with internal resorption cavities under a 300 N oblique force at 30 degrees highlights critical insights into stress distribution and the mechanical behaviour of the tooth-root complex. The location of the resorption cavity (apical, middle, or coronal third) and the filling material (MTA or Biodentine) significantly influence stress concentration patterns. For MTA-filled models, maximum stresses are observed near the edges of the resorption cavities, with peak values of 73.35 MPa, 104.35 MPa and 102.79 MPa for apical (M1), middle (M2) and coronal (M3) cavities, respectively [Table/Fig-3,6]. The stress gradients reveal localised vulnerability at the cavity sites, with MTA providing some reinforcement due to its stiffness. However, MTA's inability to completely compensate for structural discontinuities underscores the need for additional restorative measures [16], particularly in cases with coronal or mid-root cavities, where stress amplification is more pronounced.

S. No.	Virtual tooth model	Maximum von mises stresses (MPa)	Minimum Von mises stresses (MPa)
1.	M1	73.35	0.0022
2.	M2	104.35	0.0002
3.	M3	102.79	0.0002
4.	M4	72.33	0.001
5.	M5	103.65	0.002
6.	M6	101.86	0.0002
7.	M7	107.95	0.002

[Table/Fig-6]: Maximum and minimum Von Mises stresses recorded in virtual tooth models.

Bio-Dentine-filled models exhibited similar stress patterns but slightly lower peak stresses of 72.33 MPa (M4), 103.65 MPa (M5) and 101.86 MPa (M6) for apical, middle and coronal cavities, respectively [Table/Fig-4,6]. Bio-Dentine's favourable mechanical properties, including high compressive strength and dentin-like behaviour, contribute to better stress distribution compared to untreated cavities [7]. However, stress concentration around the cavity edges remains a critical concern, particularly under repetitive loading conditions. The findings highlight the coronal third cavity as the most vulnerable, given its proximity to the loading zone, followed by the middle third cavity due to its central location, which disrupts load transmission paths. The apical third cavity, while less exposed to high stresses, remains at risk due to its smaller cross-sectional area and proximity to the root apex.

The control tooth model without resorption cavities demonstrated the most efficient stress distribution, with peak stresses of 107.95 MPa observed near the force application zone [Table/Fig-5]. This underscores the importance of structural integrity in mitigating stress concentrations and minimising fracture risks. The stress analysis reveals that internal resorption cavities act as stress amplifiers, leading to localised vulnerability that necessitates targeted clinical interventions. Materials like MTA and Biodentine provide structural support to varying extents, but their effectiveness is limited in completely mitigating the effects of resorption-induced discontinuities. Reinforcement techniques, such as fibre posts, crowns, or composite overlays, may be necessary to redistribute forces and improve the longevity of compromised teeth [17].

The results indicate mixed support for the concept of a monoblock, where the filling material integrates seamlessly with the root canal walls to create a unified structure capable of evenly distributing stresses [18]. Both MTA and Biodentine provide notable stress mitigation, reducing peak stresses near resorption cavities. However, stress concentrations remain near cavity edges, particularly in coronal and middle-third scenarios, suggesting structural vulnerabilities. While these materials enhance reinforcement and seal defects, they may not eliminate weak points caused by structural discontinuities. Biodentine shows slightly better performance in stress redistribution due to its dentin-like properties, but additional restorative interventions (e.g., fibre posts, crowns) are often necessary to strengthen vulnerable regions.

These findings suggest that although these materials approach the monoblock concept, they do not fully achieve it, as additional measures are required to ensure long-term durability and uniform stress distribution. These findings align with those of Elwazan GI et al., who reported that Biodentine outperforms Portland cement in restoring mid-root perforations, with lower stress concentrations observed near defect areas [12]. Similarly, Aslan T et al., reported that MTA and a combination of MTA and gutta-percha reduce stress concentrations more effectively than gutta-percha alone in immature teeth with internal resorption, using FEA [13].

Complementing these results, Ulusoy OI et al., found that Biodentine exhibits superior fracture resistance compared to injectable gutta-percha, MTA Fillapex and DiaRoot Bioaggregate in-vitro, attributed to its favourable physical properties [19]. Darak P et al., further support these findings, noting that immature teeth restored with MTA or Biodentine show higher fracture resistance than those restored with an apical plug of these materials combined with gutta-percha [20]. These studies highlight the distinct advantages of MTA and Biodentine in addressing internal resorption. MTA, with its higher stiffness, offers reinforcement but is prone to amplifying stress near cavity edges, making it more suitable for scenarios requiring rigidity. In contrast, Biodentine's dentin-like properties enable better stress redistribution, reducing localised stress concentrations and providing a more balanced load distribution. However, despite their benefits, both materials exhibit limitations in fully eliminating structural vulnerabilities at resorption sites.

Limitation(s)

The limitations of FEA must be carefully considered. FEA assumes that dentin is isotropic, linear-elastic and uniform, disregarding variations in material properties and anatomical complexities. Dentin's hardness and mechanical properties vary from the surface to the pulp, influencing stress distribution. The intricate geometry of root canals and developmental defects, which may initiate fractures, is often overlooked. Additionally, the study simulated only oblique loading scenarios, which do not fully replicate complex clinical loading conditions. Therefore, FEA results must be validated through experimental measurements to ensure accuracy.

CONCLUSION(S)

Overall, the present study emphasises the importance of cavity location and the properties of filling materials in managing teeth with internal resorption. While Biodentine outperforms MTA in stress mitigation, neither material fully compensates for structural defects. Clinical strategies should prioritise the restoration of coronal and mid-root cavities with additional reinforcement techniques to withstand functional forces and reduce fracture risks. Moreover, further research on the long-term fatigue behaviour of these restorative materials under cyclic loading is warranted to enhance clinical decision-making and treatment planning for such cases.

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