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RESEARCH AND EDUCATION

When to restore: Critical crack-size thresholds in human first premolars

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ABSTRACT

Statement of problem. Although cracked teeth have been a prevalent clinical concern, a consensus on appropriate treatment strategies—particularly for early-stage cracks without clinical symptoms—remains lacking. Current guidelines do not specify the critical crack dimensions, in terms of depth and width, at which tooth structural integrity becomes significantly compromised, leading to uncertainty in clinical decision-making between monitoring and restorative intervention.

Purpose. The purpose of this study was to investigate the effects of crack depth and width on the ultimate strength and stress distribution of human first premolars to guide clinical treatment decisions.

Material and methods. Forty extracted, sound human first premolars were divided into 5 groups: a control group (no crack) and 4 groups with experimental mesio–occluso–distal cracks of varying depth (D:2 to 4 mm) and width (W:0.5 to 1 mm). Compression tests were conducted to assess ultimate strength, fracture origin, and propagation direction. Statistical analyses were performed using 1-way ANOVA and multiple linear regression (α=.05). Finite element analysis (FEA) was used to simulate stress distribution based on both principal stress and energy-based failure theories. The computational results were validated with experimental findings. Smaller cracks (D:1 to 3 mm; W:0.1 to 0.5 mm) were modeled via FEA to identify subclinical critical thresholds.

Results. Crack depth dominated tooth ultimate strength reduction (β=−.803, P<.001), while width became insignificant at a depth of 4 mm (β=−.059, P=.480). Fractures in cracked teeth originated at crack tips (91% of cases), whereas fractures in sound teeth occurred at the palatal cusp. The von Mises stress criterion accurately predicted the behavior of cracked teeth, unlike the principal stress theory. Critical crack size thresholds were identified: a 15% strength reduction in the D1W0.5 and D2W0.1 cases and a 67% strength reduction (relative to sound teeth) when cracks extended to the pulp chamber in the D3W1 case.

Conclusions. Increasing crack size significantly weakens tooth strength, with depth being the dominant factor. The von Mises stress theory is recommended for analyzing cracked teeth. The identified critical crack sizes provide actionable thresholds for restorative intervention. (J Prosthet Dent 2026;136:196-206)

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The authors declare that they have no competing interests.

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Clinical Implications

In addition to assessing clinical symptoms and pulp condition, clinicians may consider early treatment when a crack reaches the 15% strength reduction threshold (D1W0.5 and D2W0.1) to prevent progression into the pulp and potential tooth fracture.

Cracked teeth have become one of the most prevalent dental problems in contemporary dental practice.[1] The European Society of Endodontology (ESE) defined a cracked tooth as "a crack extending into the dentin, of unknown depth or size, which may extend subcrestally into the root. There may be pulpal involvement."[1] Cracked teeth have been most commonly found in posterior teeth, with mandibular molars exhibiting the highest prevalence (51.5% to 64.4%), followed by maxillary molars (26.6% to 41.4%) and maxillary premolars (5.7% to 8%).[2–4] Microscopic examination of asymptomatic posterior teeth revealed that 84% had at least one crack,[5] while the National Dental Practice-Based Research Network reported 50% of cracked teeth were asymptomatic,[6] suggesting that this condition may be more common than recognized.

The treatment of cracked teeth depends on the crack extent and pulp status, ranging from monitoring and resin composite restoration to cusp coverage or endodontic treatment.[1] Early detection enhances preservation success.[7] However, a universally accepted treatment protocol is currently lacking, particularly for teeth with a normal pulp or reversible pulpitis.

For cracks associated with a normal pulp or reversible pulpitis, monitoring has been recommended.[8] A 3-year follow-up study of such situations showed minimal crack progression.[9,10] However, a crack represents an incomplete fracture that can extend into the pulp or periodontal ligament if left untreated. Consequently, some suggest removing the crack and restoring the tooth with resin composite[11,12] or placing a crown[13–15] to prevent crack propagation. However, tooth preparation may weaken the remaining structure and risk pulp exposure.[8] Studies on crowned cracked teeth with reversible pulpitis reported that 20% to 29% required endodontic treatment later,[12–14] questioning whether early-stage cracks without pulpal involvement should be monitored or treated.[16] At present, evidence remains insufficient to reach a definitive conclusion.

Studying cracks on extracted teeth presents challenges, as teeth may have varying degrees of prior structural loss, and the extraction process can create or exacerbate existing cracks,[17] potentially affecting results. Thus, using sound extracted teeth with experimentally created cracks, tested alongside finite element analysis (FEA), could alternatively offer some important insights. Maxillary first premolars, although not the most commonly cracked teeth, are sometimes extracted for orthodontic purposes, making them a suitable choice for this study.

In general, the ultimate strength of a material declines markedly when cracks are present, depending on the width and depth of the crack.[18–20] In human teeth, cracks alter internal stress distribution and reduce strength. Beyond certain width or depth thresholds, strength may decrease sharply, leading to rapid crack propagation and fracture. Since critical crack dimensions remain undefined, the aim of this study was to investigate the effects of crack size—width and depth—on the ultimate strength and stress distribution in human first premolars using experiments and FEA to identify the critical crack size that may guide treatment strategies for early-stage cracked teeth without pulpal involvement. The research hypothesis was that crack depth would have a stronger effect than crack width on the ultimate strength of human first premolars.

MATERIAL AND METHODS

Both experimental and FEA approaches were used (Fig. 1). The experimental phase evaluated the ultimate strength and fracture characteristics of first premolars with controlled crack dimensions, while the FEA simulation—validated by experimental results—extended analysis to smaller crack sizes not feasible to reproduce experimentally.

Sound first premolars extracted for orthodontic reasons (age 20 to 40 years old) were collected with ethical approval (HREC-DCU 2022–036 and 2025–094) and with the informed consent of all participants. The specimens were selected to match the standard Asian maxillary first premolar profile[21] (tooth length and buccolingual and mesiodistal widths). This standardization minimized geometric variability in the remaining buccal and palatal walls after the centralized crack creation. Sample size was calculated using a software program (G*Power 3.1.9.7; Heinrich-Heine-Universität Düsseldorf) (α=.05, power=80%, f=0.7), yielding 8 specimens per group (N=40). The roots were coated with a 0.2- to 0.3-mm layer of polyvinyl siloxane (Silagum; DMG) to simulate the periodontal ligament (Fig. 2A) and embedded in resin-polyvinyl chloride (PVC) cylinders (Fig. 2B). The absence of pre-existing cracks was confirmed via blue light transillumination (Elipar DeepCure-S; 3M).[22,23]

Forty sound specimens were divided into 5 groups (n=8): sound control and 4 with mesio-occluso-distal cracks (depth: 2 or 4 mm; width: 0.5 or 1 mm). To precisely control crack dimensions,[24,25] experimental cracks were created along the central groove with the distal

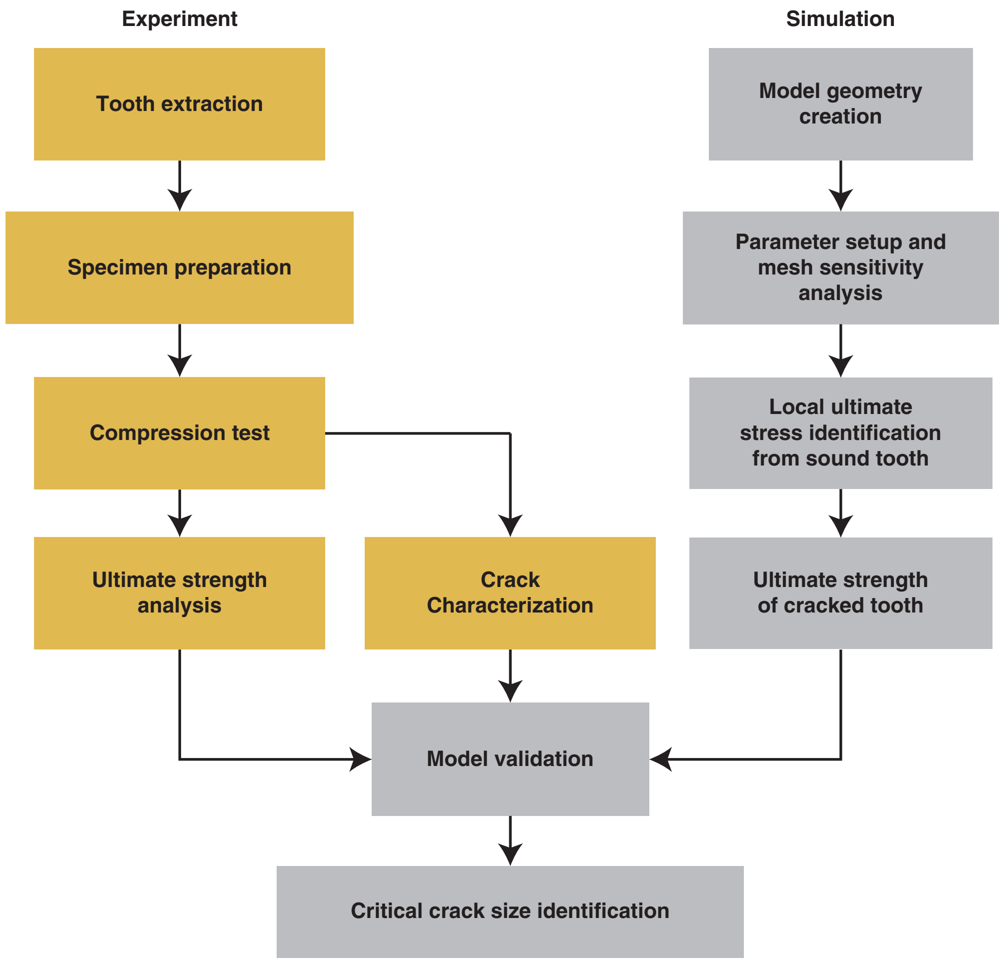

Figure 1. Research workflow of this study.

marginal ridge as a fixed anatomic reference (Fig. 2C, D) using a microcomputer numerical control (micro-CNC) milling machine (RXP 300; Röders TEC). Crack dimensions were confirmed by micro-CT (μCT 35; SCANCO Medical). Specimens containing unintended cracks were excluded from the experiments. Two blinded investigators (S.N.L., P.D.) independently verified preparation and dimensional accuracy.

Compression testing was performed using a universal testing machine (TM-G10k; INTRO Technology) with a 6-mm-steel ball indenter at 0.5 mm/minute. To calculate ultimate strength (MPa), the contact area was determined by applying a 100-N preload onto inlay wax covering the occlusal surface[26] and measuring the resulting indentation with a stereomicroscope (SZ61, Olympus). Ultimate strength (MPa) was calculated as fracture force divided by contact area. The fracture direction was quantified as the degree of deviation from the vertical axis using an imaging software program (cellSens version 1.16; EVIDENT).

The data were analyzed with a statistical software package (IBM SPSS Statistics, v29.0; IBM Corp). Normality and homoscedasticity were confirmed via Shapiro–Wilk and Levene tests (P>.05). Differences in ultimate strength were analyzed using 1-way ANOVA and multiple regression (α=.05). Additionally, a 2-way ANOVA was performed on the cracked subgroup to verify the independence of factors and assess interaction effects. The post hoc power analysis exceeded 90% for all significant results.

Based on a cone beam computed tomography (CBCT) scan (3D Accuitomo 170; Morita) of a standard maxillary first premolar,[21] a 3D multicomponent model was reconstructed using a solid modeling CAD software program (Ansys SpaceClaim 2023R2; Ansys, Inc).[21,27] The model included enamel, dentin, cementum, silicone, resin, and PVC structures (Fig. 2E-G). Material properties were adopted from the literature (Table 1), with enamel and dentin modeled as orthotropic and other components as isotropic materials.

Boundary conditions replicated the experimental setup: loads were applied to buccal and palatal cusp contact areas (total 0.8 mm^2),[34] with the outer PVC surface fixed (Fig. 2H). Mesh sensitivity analysis ensured result convergence (Supplemental Fig. 1, available online). Using the experimental fracture load of the sound group (653.7 N), local

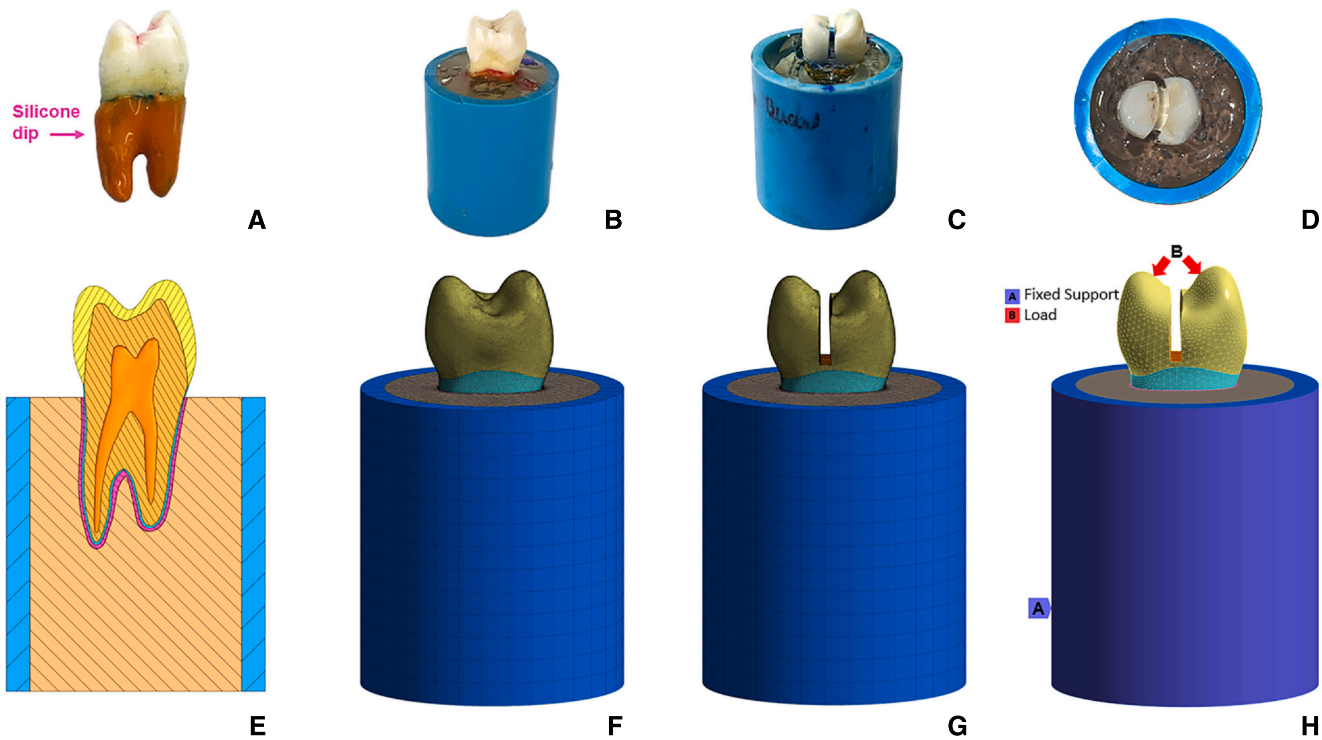

Figure 2. Tooth specimens for experiments: A, Silicone-coated root. B, Resin embedded specimen. C, With experimental cracks. D, With experimental cracks (top view). Tooth models for FEA: E, Sectional view. F, Isometric view. G, Isometric view with cracks. H, Boundary conditions. All cracks shown represent D4W1 case.

Table 1. Mechanical properties of tooth and specimen structures

Orthotropic structure	Young's Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)	Reference
Enamel				28
Coronal (X axis/XY plane)	63.27	0.23	20.89	
Longitudinal (Y axis/YZ plane)	73.72	0.23	20.89	
Sagittal (Z axis/XZ plane)	63.27	0.45	24.07	
Dentin				28
Coronal (X axis/XY plane)	5.61	0.30	1.70	
Longitudinal (Y axis/YZ plane)	17.07	0.30	1.70	
Sagittal (Z axis/XZ plane)	5.61	0.33	6.00	
Isotropic structure	**Young's Modulus (GPa)**		**Poisson's Ratio**	**Reference**
Cementum	15.5		0.31	29,30
Silicone	0.001		0.3	31
Resin	3.45		0.35	32
PVC pipe	2.746		0.35	33

ultimate stress thresholds were determined based on maximum principal and von Mises criteria.[35,36] Because the tooth contains both brittle and ductile tissues with limited known strengths, it was necessary to consider both failure theories until model validation confirmed which best represented cracked-tooth behavior under testing conditions. Each cracked model was loaded until it reached the local ultimate stress, and its simulated ultimate strength was computed by dividing the ultimate load by the contact area.

Model validation was established by statistically comparing simulated and experimental ultimate strengths and further supported by the mechanical consistency of observed fracture locations. Fracture propagation direction from experiments was also evaluated, as a previous study[37] showed that brittle materials fracture with slight deviation from the vertical axis, whereas ductile materials exhibit greater deviation. Once validated, 6 additional FEA models with smaller cracks (width<0.5 mm) were analyzed to identify the critical crack size, defined as the largest crack that did not notably reduce tooth strength compared with the sound model.

RESULTS

Compression testing with a Ø6-mm-steel ball indenter (Fig. 3A) showed tooth strength decreased significantly

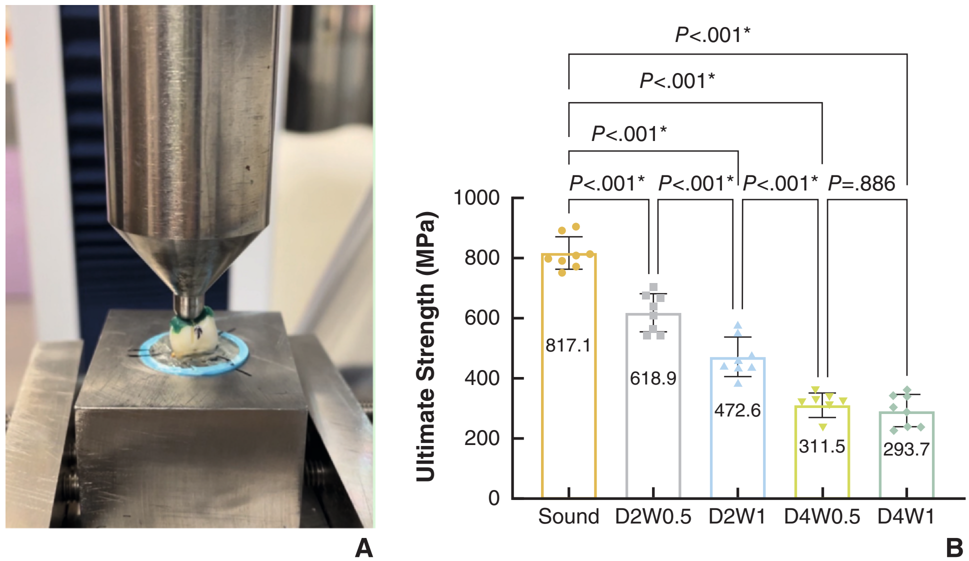

Figure 3. A, Compression test design. B, Tooth ultimate strength of sound and cracked tooth specimens. Data expressed as mean ±standard deviation.

with increasing crack size ($P<.001$). The mean strength ranged from 817.1 MPa (sound) to 293.7 MPa (D4/W1) (Fig. 3B). Regression analysis identified crack depth as a stronger influence than width (β=–.803, $P<.001$). At a 4-mm depth, width became insignificant (β=–.059, $P=.480$). To confirm the robustness of the regression findings, a 2-way ANOVA was conducted on the cracked specimens (n=32). The analysis confirmed crack depth was the dominant factor (F=148.574, $P<.001$) followed by crack width (F=16.928, $P<.001$). A significant interaction between depth and width was observed ($P=.003$), confirming that the influence of crack width on ultimate strength significantly diminished as crack depth increased. Fracture patterns were categorized and are presented in Figure 4. All sound teeth fractured from the palatal cusp (SPC). In cracked teeth, 91% of fractures initiated at the palatal crack tip (PCT, n=22) or buccal crack tip (BCT, n=7). Only 9% (n=3) originated from cusp contact areas (CPC/CBC).

The fracture propagation angle (Fig. 5) increased with crack size, from 15.5 degrees in sound teeth to 49.4 degrees in the D4 W1 group ($P<.001$), driven significantly by depth ($P<.001$) rather than width. These angles aligned with the analytical model for predicting failure angle derived from the energy-based universal failure theory,[37] in which the failure angle approaches 0 degrees for ideally brittle materials and asymptotically approaches 54.7 degrees for ideally ductile materials under uniaxial compression. The observed progressive increase in failure angle with crack depth therefore indicated a transition in the dominant failure mechanism, from brittle enamel-controlled behavior to increasingly ductile behavior governed by dentin and pulp.

Stress analysis indicated that cracked teeth followed the von Mises rather than the principal-stress failure criterion.[35] Normal stress components (σ_{11}, σ_{22}, σ_{33}) at cusps of the sound and cracked tooth models showed a complex state, with normal stresses of similar magnitudes across all 3 directions (Supplemental Data 2, available online). Under these conditions, the tooth behaved extrinsically in a more ductile manner, with stress states resembling hydrostatic pressure.[35] According to the energy-based universal failure theory, this stress state can be relatively large before failure occurs.[35] Stress distributions at 4 crack corners (BCT-mesial, BCT-distal, PCT-mesial, PCT-distal) were asymmetric, aligning with experimental fracture sites (Fig. 4C). Larger cracks reduced cusp stress because of load redistribution and greater cusp flexibility.

Simulated and experimental results were compared using the Pearson correlation and root mean square error (RMSE) analysis (n=40). The principal stress-based simulation showed a correlation of r=0.861 ($P<.001$) and a coefficient of determination (R^2) of 0.741, but with a high prediction error (RMSE=350.46 MPa), particularly in cracked specimens (Fig. 6A). In contrast, the von Mises stress-based simulation demonstrated a stronger correlation (r=0.912, $P<.001$; R^2=0.832) and significantly higher accuracy (RMSE=133.75 MPa). Consequently, the von Mises criterion provided a more accurate and precise prediction of ultimate strength across all groups (Fig. 6B), despite increasing discrepancies at the 4-mm depth. Stress distribution analysis revealed that, in the sound model, peak von Mises stress occurred at the palatal cusp (Fig. 7A), while, in crack models, stress concentrated at both mesial-side BCT and PCT (Fig. 7B). This aligned with the experimentally observed fracture origins (Fig. 4C). The consistency of fracture origin and strength validated the von Mises stress-based model influenced by crack size.

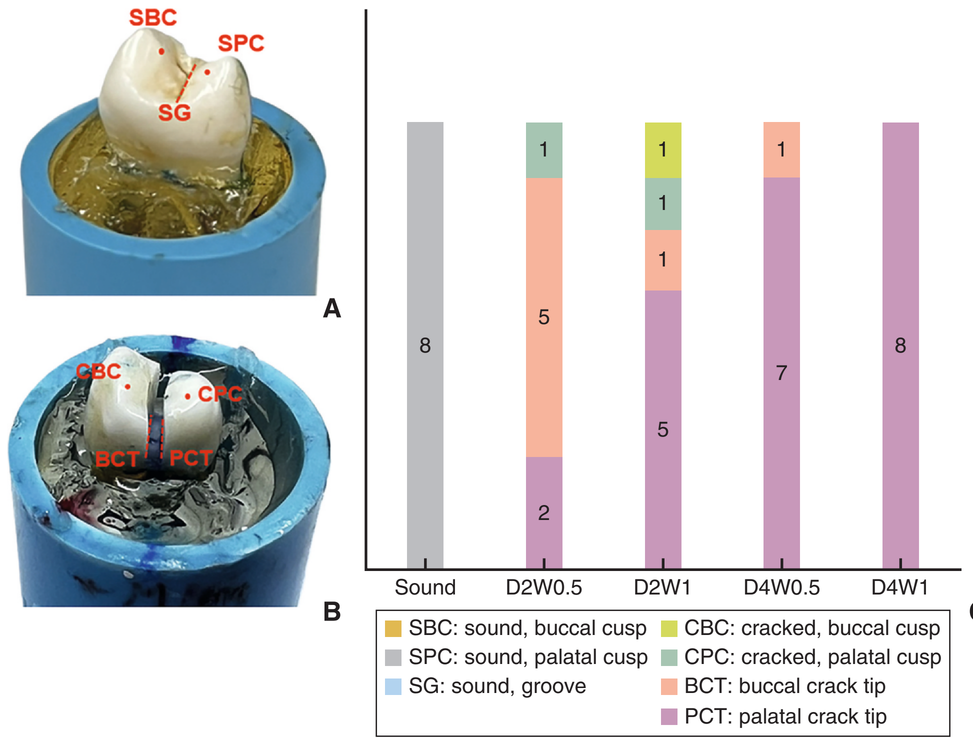

Figure 4. Illustration declaring fracture locations on A, Sound teeth. B, Cracked teeth. C, Fracture locations of each specimen group observed from compression test.

The finite element stress distributions were not used to statistically validate fracture locations. Fracture initiation sites were identified independently from experimental observations and supported by statistical analysis of strength across specimen groups. The FEA, based on deterministic continuum mechanics with

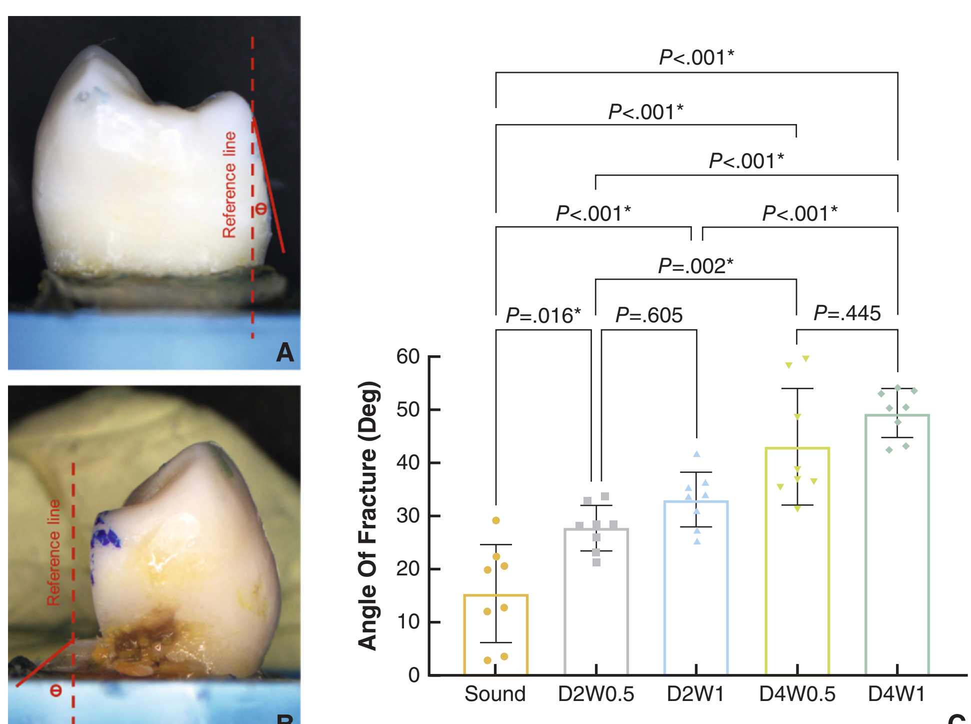

Figure 5. Example of fracture propagation direction measurement in A, Sound. B, Cracked teeth. C, Fracture propagation direction in each specimen group. Data expressed as mean ±standard deviation.

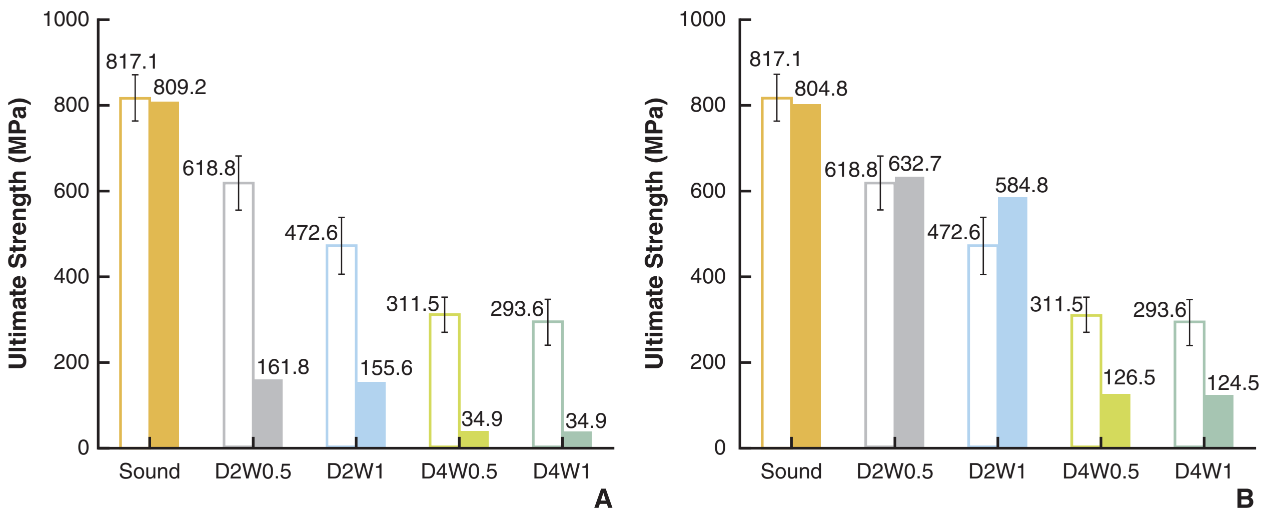

Figure 6. Comparison of tooth ultimate strength obtained from experiments (transparent) and simulation (opaque) based on A, Principal stress. B, von Mises stress.

prescribed geometry and loading, was used to evaluate whether the fracture origins coincide with regions of peak von Mises stress. Thus, the agreement reflected mechanical consistency rather than circular validation, confirming that fracture initiation was governed by the stress concentration predicted by energy-based failure mechanics.

Six additional simulated cracks too small for experimental fabrication revealed 2 mechanically significant reductions in simulated tooth ultimate strength as crack size increased (Fig. 8). The first (approximately 15% strength loss) occurred for cracks D1W0.5 and D2W0.1 (804.8 to 680.6 MPa). The second, more severe drop (approximately 67%, to 263.6 MPa), occurred when cracks reached the pulp (D3W1). The first reduction occurred at smaller crack sizes, indicating the onset of a mechanically meaningful degradation in load-bearing capacity. A second, more pronounced reduction corresponded to a substantial loss of structural integrity. These values arose from deterministic FEA simulations and should be interpreted as reference levels reflecting transitions in mechanical behavior, rather than statistically defined clinical thresholds. These results identified 2 crack-size thresholds requiring early intervention.

DISCUSSION

The data support the research hypothesis that crack depth had a stronger effect than width on the ultimate strength of first premolars. By combining experimental and numerical approaches, this study examined the impact of crack size on the fracture strength and characteristics of first premolars, providing a framework for determining critical crack sizes that require interventions.

Typical experimental cracks created via liquid nitrogen lack precision regarding direction and size.[24,25] Cracks in patient teeth often originate as a small crack on either the mesio- or disto-occlusal surfaces—or occasionally both. Over time, these cracks may propagate along the groove and merge to form a mesio-occluso-distal crack pattern. In practice, the width and depth of such cracks are typically not uniform. For model validation, however, precise and reproducible cracks were required. To achieve this, a micro-CNC machine was used to fabricate standardized 3-sided cracks, representing cracked—but not split—teeth as defined by the ESE.[1]

Experimentally, ultimate strength decreased significantly with increasing crack size, with depth dominating width. This agrees with fracture mechanics, where deeper cracks disrupt stress distribution within enamel and dentin, reducing load-bearing capacity and weakening structural integrity.[19] A significant interaction (P=.003) confirmed the impact of width is depth-dependent: significant at 2 mm but negligible at 4 mm. This suggests that once a crack penetrates deeply into the pulp cavity, load-bearing capacity depends on penetration depth rather than lateral spread, consistent with previous findings.[20] The fracture patterns in sound and cracked teeth exhibited distinct characteristics. In sound teeth, fractures originated at the palatal cusp due to localized stress concentration under compression, aligning with clinical observations of cusp fractures in intact premolars.[38] Conversely, in cracked specimens, fracture initiation shifted to crack tips, emphasizing the role of stress concentration at these locations.[39,40]

Fracture propagation direction increased with crack size, indicating a shift from brittle enamel-dominated to ductile dentin-controlled behavior. According to a previous study,[37] fracture propagation direction tends to approach 0 degrees (parallel to load) for brittle materials under compression, while brittle-to-ductile transition

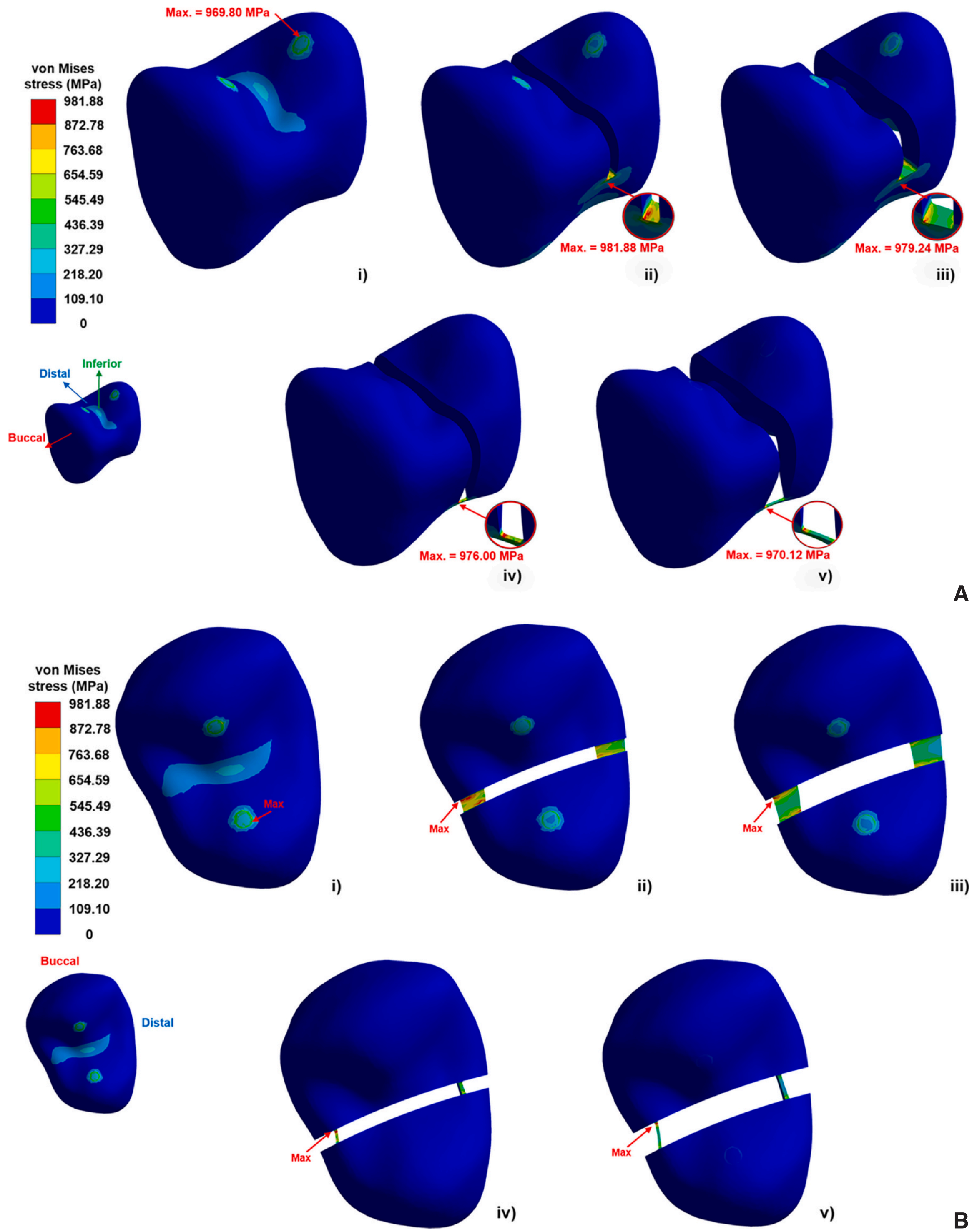

Figure 7. von Mises stress distribution on enamel layer of tooth models under their respective ultimate force; (i) sound, (ii) D2W0.5, (iii) D2W1, (iv) D4W0.5 and (v) D4W1 presented in A, Isometric. B, Top views. *Red arrows* indicate position of maximum von Mises stress in each case.

occurs at 31.72 degrees. The present results (15.5 to 49.4 degrees) reflect this transition as cracks extended into dentin.

The statistical agreement between simulated and experimental strength was R^2=0.832, RMSE=133.75 MPa. The von Mises criterion was more appropriate, as deeper cracks induced multi-axial stresses characteristic of ductile failure.[35] The discrepancy of ultimate strength at a depth of 4 mm suggests additional factors such as microstructural variations. Hyperviscoelastic material

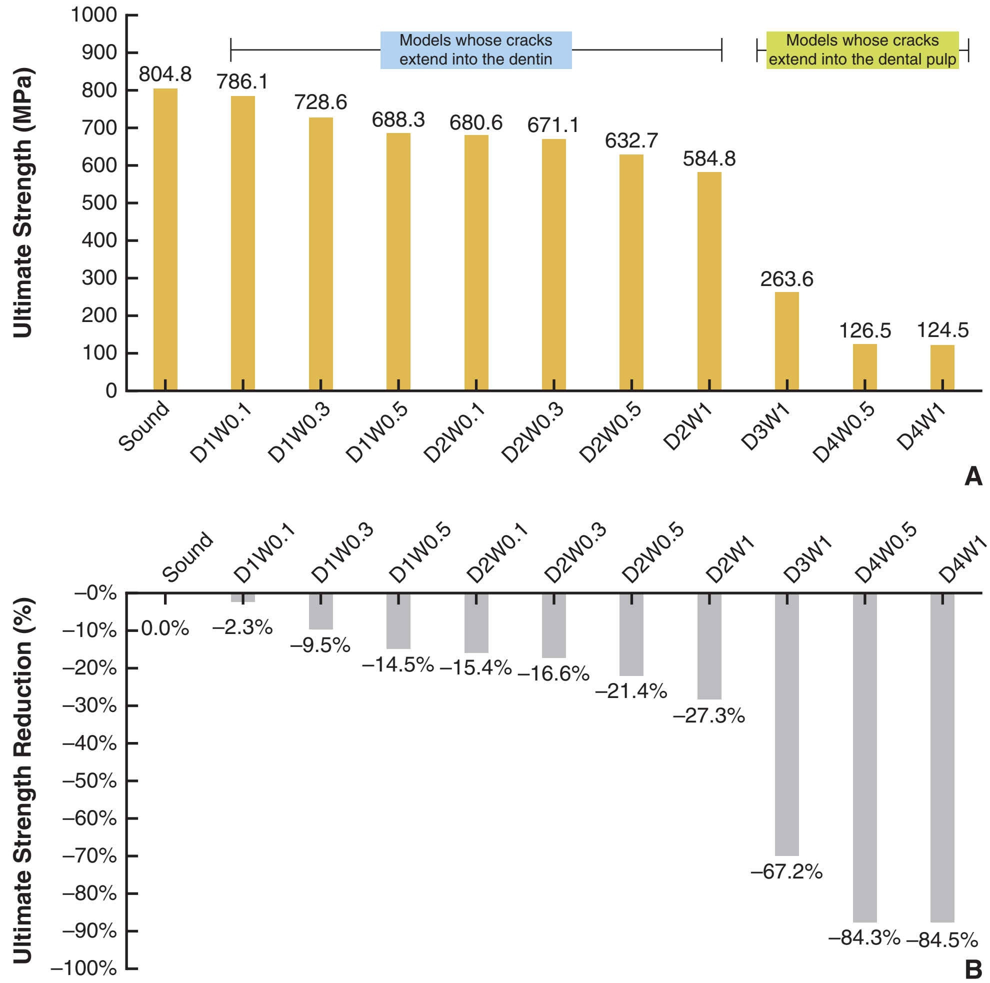

Figure 8. A, Tooth ultimate strength of various cracked tooth models estimated based on maximum von Mises stress. B, Its reduction (%) with increasing crack size compared with sound model.

behaviors may need to be considered for deeper cracks. The validated FEA allowed exploration of smaller cracks that were impractical to create experimentally, improving the understanding of crack progression and its impact on tooth strength.

Analysis of 11 models identified 2 thresholds: a 15% reduction (D1W0.5, D2W0.1) and a severe 67% drop (D3W1) when the crack reached the pulp. This sharp decline resulted from the loss of dentin support, making buccal and palatal dentin more susceptible to separation under loading. A 1-mm-wide crack would almost certainly prompt immediate restorative intervention. However, the D3W1 case results suggested that, beyond preventing pulp necrosis or infection, cracks extending into the pulp should be restored immediately to preserve tooth integrity.

The first threshold, occurring at small cracks, is particularly important clinically, as such cracks may be asymptomatic but still weaken tooth structure. Left untreated, they can progress, leading to pulp involvement and fracture.[1] Given that the human eye can typically perceive objects larger than approximately 50 to 100 µm,[41,42] the identified critical crack size thresholds suggest that small cracks invisible to the naked eye do not require immediate restorative intervention. Nevertheless, these results highlight a crucial clinical insight that even cracks with average widths around 100 µm may warrant prompt intervention if their depth reaches ≥2 mm.

Clinically, crack depth (1 to 2 mm) can be assessed using swept-source optical coherence tomography (SS-OCT)[43] or contrast-enhanced CBCT,[44] and width (0.1 to 0.5 mm) with an explorer. To translate these findings into clinical practice, we propose a protocol. Invisible cracks need no immediate treatment, as they minimally affect tooth strength. For visible cracks, a clinician can probe with a 100-µm explorer tip: if it does not engage (width <100 µm), monitoring is sufficient. If it catches (width ≥100 µm), crack depth should be assessed. Depths >2 mm warrant prompt treatment, while shallower cracks can be observed periodically.

Restorative decisions should prioritize pulp condition and symptoms, followed by mechanical stability and bacterial risk. Identifying etiology (such as bruxism) is crucial to prevent recurrence. These thresholds can serve as practical guidelines for timely intervention, addressing current gaps in early-stage cracked-tooth management.[1] While small cracks permit monitoring, those exceeding thresholds should be stabilized using minimally invasive strategies to prevent progression, weighing benefits against overtreatment risks like pulp exposure.[16]

Despite its insights, this study has limitations. Thresholds derived from first premolars may differ for molars, and predictions for cracks ≥4 mm deep require caution because of reduced accuracy. Experimentally milled cracks may differ in tip sharpness from natural cracks and do not represent all clinical patterns. The assumption of homogeneous dentin excludes potential tubule influence. Factors such as PDL dynamics,[36] cyclic loading, and viscoelastic behavior of hydrated dentin were omitted. Future studies incorporating these variables and restored models (such as with 1-piece endodontic crowns) could refine predictive accuracy and guide personalized treatment strategies.

CONCLUSIONS

Based on the findings of this in vitro and FEA study, the following conclusions were drawn:

1. Crack depth and width significantly influence tooth strength, with load-bearing capacity decreasing as cracks enlarge. Crack depth has a more pronounced effect than width; once the pulp is involved, width becomes negligible.
2. von Mises failure theory better explains failure behavior as cracks deepen into dentin.
3. Two critical thresholds were identified: pulp involvement (67.2% strength loss) and smaller cracks (D1W0.5, D2W0.1) causing ~15% loss.
4. These thresholds provide valuable guidelines for treatment strategies. They support early intervention and informed decision-making, particularly before pulp involvement.

ETHICS APPROVAL STATEMENT AND CONSENT TO PARTICIPATE

The authors confirm that all research was conducted in accordance with relevant guidelines/regulations under the protocol approved by the Human Research Ethics Committee of the Faculty of Dentistry, Chulalongkorn University (approval no. HREC-DCU 2022–036 and HREC-DCU 2025–094).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONSENT FOR PUBLICATION

Not applicable.

CONSENT TO PARTICIPATE

Informed consent was obtained from all participants.

PATIENT CONSENT

Informed patient consent has been obtained.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

(We confirm we have nothing to disclose regarding the use of generative AI in scientific writing.).

APPENDIX A. SUPPORTING INFORMATION

Supplemental data associated with this article can be found in the online version at doi:10.1016/j.prosdent.2026.03.005.

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