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RESEARCH AND EDUCATION

Crown fracture: Failure load, stress distribution, and fractographic analysis

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ABSTRACT

Statement of problem. The outcomes from load-to-failure tests may not be applicable to clinical situations.

Purpose. The purpose of this study was to critically evaluate the efficacy of load-to-failure tests in the investigation of the fracture load and pattern of metal-free crowns.

Material and methods. Four groups were formed from 128 bovine roots restored with metal posts, resin cores, and feldspathic, leucite, or lithium disilicate ceramic systems or polymer crowns. Each group was divided into 4 (n=8) according to the cement: zinc phosphate, self-adhesive resin, autopolymerizing resin, and glass ionomer. Mean fracture loads from compressive tests were submitted to ANOVA and Tukey HSD test. Finite element and fractographic analyses were performed and associated with the fracture load and pattern.

Results. Significantly higher fracture load values were obtained for the lithium disilicate ceramic, but finite element and fractographic analyses showed that the cement effect could not be determined. The finite element analysis showed the cement likely affected the fracture pattern, confirmed that stresses in the cements were little affected by the crown materials, and found that the stressed conditions were lowest in the lithium disilicate compared with other crowns for all cement combinations. The stressed conditions in the crowns depended more on the adhesive properties than on the elastic modulus of the cement materials. The level of the stressed condition in the crowns at the occlusal surface was about the same or higher than along their cement interface, consistent with the fractography, which indicated fractures starting at the load point. Higher stress levels in the crowns corresponded with a lower number of catastrophic fractures, and higher stresses in the cements seemed to reduce the number of catastrophic fracture patterns. The highest stressed conditions occurred along the occlusal surface for crown materials with a low elastic modulus or in combination with adhesive cements.

Conclusions. The method used was not appropriate either for investigating the crowns' fracture load and pattern or for stating the role of the cements within the crown-cement-tooth interaction. (J Prosthet Dent 2015;114:447-455)

Teeth restored with metal-free crowns have been submitted to load-to-failure tests to determine and compare the fracture load of different restorative systems.[1-3] The first criterion for determining the use of a given restorative material is that the mechanical properties must be adequate to support the masticatory forces and protect the remaining tooth structure.[4] Studies have reported that the improved esthetic appearance of metal-free restorations are accompanied by an increase in fracture failures compared with metal ceramic crowns.[1-3,5] However, a recent literature review presented evidence suggesting that ceramic restorations have an acceptable clinical longevity in addition to their esthetic advantages over metal ceramics.[6] In order to reduce the fracture risk, ceramic materials have been reinforced with leucite,[7] lithium disilicate, and alumina, increasing the restoration fracture strength to levels compatible with occlusal forces.[8,9] The fracture mechanism of a crown restoration is complex and

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Clinical Implications

Clinicians should not make choices about restorative technique or material or the cement and cementation technique on the basis of results from protocols similar to the current study because they appear to be inconsistent with clinical situations.

determined by the combined effect of the tooth structure, crown restoration, and the luting agent.[10-14] Several studies have reported that the fracture strength of metal-free restorations is directly related to the cement used,[13,15-19] but others have found no significant influence of the cement on the fracture load of posterior ceramic crowns.[14,20] A clinical evaluation showed that acid-etched Dicor restorations luted with composite resin exhibited more favorable survivor functions than non-etched Dicor restorations luted with glass ionomer (GI) or zinc phosphate.[5] Resin cement may fill voids and microcracks,[21,22] while polymerization shrinkage might strengthen ceramic restorations,[23] thus resulting in higher fracture strength. The overall strength of restorative materials has been determined in laboratory tests[13,15-18,24-27] by following questionable protocols[28-30] in which the fracture mechanism was not investigated or was different from clinical conditions.[31-38] If a laboratory test is performed following a protocol inconsistent with the clinical situation, the results may lead clinicians to make wrong choices related to the restorative technique and material and the cement and cementation technique. Appropriate laboratory studies should comprise mechanical testing under well-controlled conditions attempting to reproduce the clinical situation; stress analysis to investigate how the restoration, cement, and dental structure interact[39,40]; and fractography to examine the fracture surfaces to understand failure events[40] and provide information about crack origin and propagation.[33-37]

Although difficult, the fracture behavior of metal-free ceramic crowns would be best obtained under clinical conditions.[3,6,41] Attempting to make load-to-failure laboratory tests more clinically relevant, studies have discussed and proposed protocols that provide results that are clinically applicable.[28,30,42,43] The purpose of this study was to critically evaluate the efficacy of the load-to-failure test in the investigation of the fracture load and pattern of metal-free crowns cemented with different materials. The failure mechanism was investigated by using finite element and fractographic analysis. The null hypothesis was that the traditional protocol used in load-to-failure tests is appropriate for providing clinically applicable results.

Table 1. Composition of and manufacturer's information on materials used

Material	Composition	Manufacturer
Noritake (FELD)	Feldspathic ceramic	Noritake Kizai Co Ltda
Cergogold (LEUC)	Leucite reinforced ceramic	Degussa
IPS Empress II (DISIL)	Lithium disilicate reinforced ceramic	Ivoclar Vivadent
Adoro (POLYM)	Laboratory-processed composite resin	Ivoclar Vivadent
Zinc phosphate cement (ZP)	Zinc cement	Vigodente
Ketac Cem (GI)	Glass ionomer cement	3M ESPE
Cement-post (AP)	Autopolymerizing resin cement	Angelus
Rely X Unicem (SAd)	Self-adhesive dual polymerizing resin cement	3M ESPE

AP, autopolymerizing resin; FELD, feldspathic; DISIL, lithium disilicate reinforced ceramic; GI, glass ionomer; LEUC, lithium disilicate reinforced; POLYM, laboratory-processed polymer; SAd, self-adhesive resin, ZP, zinc phosphate cement.

Table 2. Treatment protocol for tooth and restoration bonding surfaces before cementation

Cement	Tooth Surface Treatment	Restoration Bonding Surface Treatment: FELD LEUC DISIL POLYM
ZP	Cleaning with pumice paste + washed + dried	Cleaning with 70% alcohol + washed + air dried
GI		
AP	30% phosphoric acid for 20 seconds + washed/dried + adhesive	10% hydrofluoric acid (FELD for 2 min, LEUC and POLYM for 60 s, DISIL for 20 s) + washed/dried + ceramic primer for 60 s + adhesive system + photopolymerization
SAd	Cleaning with pumice paste and water + washed/dried	

AP, autopolymerizing resin; FELD, feldspathic; DISIL, lithium disilicate reinforced ceramic; GI, glass ionomer; LEUC, lithium disilicate reinforced; POLYM, laboratory-processed polymer; SAd, self-adhesive resin, ZP, zinc phosphate cement.

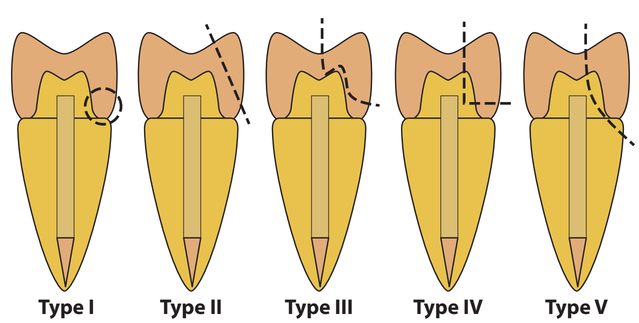

Figure 1. Schematic illustration of fracture pattern from tested specimens.

MATERIAL AND METHODS

Comparisons were made among 4 restorative groups (n=32 for each group): feldspathic (FELD), leucite reinforced (LEUC), and lithium disilicate reinforced (LEUC) ceramic systems and a laboratory-processed polymer (POLYM). Each group was divided into 4 (n=8) according to the cement used: zinc phosphate (ZP), self-adhesive

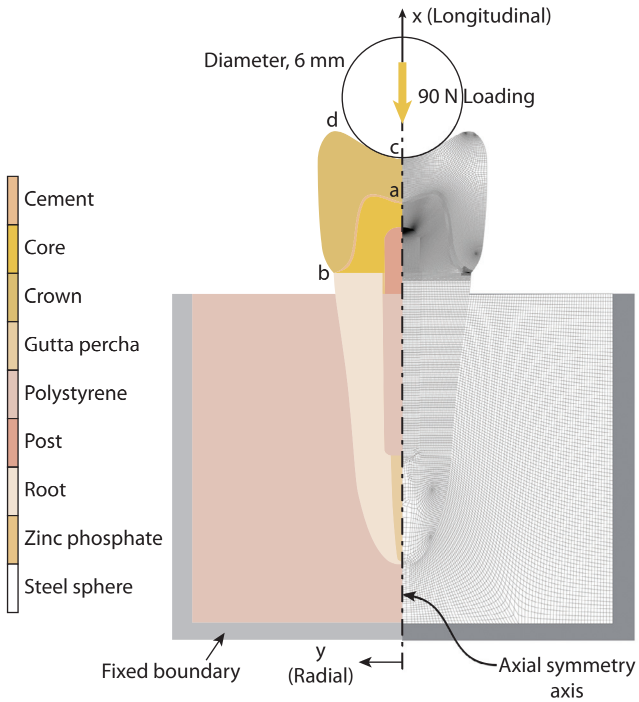

Figure 2. Geometric model showing different materials, mesh distribution, coordinate system (x is longitudinal direction, y is radial direction), boundary conditions (fixation around polystyrene embedding and occlusal loading on steel sphere), beginning and end path locations where stresses were collected (a) midocclusal abutment to (b) cervical; (c) central groove to (d) cusp tip.

resin (SAd), autopolymerizing resin (AP), and GI. On the basis of the sample size of other studies,[3,17] 8 specimens per group were 2-way analyzed (material×cement), which resulted in 128 specimens with 112 degrees of freedom for the residual (error degrees of freedom); this sample was higher than necessary given the variability observed from the data. Thus, as the data were collected, the power test was calculated with software (Power and Sample Size v3.1; SAS Institute Inc) at the 5% significance level, which showed the test power to be over .90 for the main effects (material×cement) and their interaction. Information on the materials is shown in Table 1, and specimen preparation followed the protocol used in a previous study.[36] The manufacturers' instructions were followed for all materials, and all restorations had the shape of a premolar, with an axial thickness of approximately 1 mm in the cervical third and 1.5 mm on the occlusal surface as evaluated with a digital caliper (Mitutoyo).

The treatment protocols for both the tooth and the crown bonding surface were based on a previously reported procedure[44] and are summarized in Table 2. When indicated, 30% phosphoric acid, an adhesive system (Adper Single Bond; 3M ESPE), 10% hydrofluoric acid (Condicionador de Porcelanas; Dentsply Intl), and a ceramic primer (Prosil; FGM) were used. After manipulation following the manufacturers' instructions, the cement was applied on the internal surface, the crown was fitted on the preparation, the excess cement was removed, and a 4.9 N static load was applied for 5 minutes. When indicated, the resin cements were photopolymerized for 40 seconds on each surface with a 600 mW halogen unit (Optilight; Gnatus). Silicon abrasive, low-speed rotary instruments (KG Sorensen) were used along the margin to eliminate adhesive and/or cement residues. After cementation, all specimens were stored in saline solution at room temperature for 5 days and then submitted to compressive loads in a mechanical testing machine (2000 DL; EMIC) at a 0.5 mm/min crosshead speed with a 6 mm diameter steel sphere attached to a rod to determine the fracture load (N). Loads recorded at failure were submitted to 2-way ANOVA and Tukey HSD test. The type of fracture was evaluated by 1 examiner (R.E.C.) with a stereomicroscope at ×20 magnification according to the following classification (Fig. 1): Type I, cohesive cervical fracture/crack; Type II, cohesive fracture not involving the

Table 3. Mechanical properties of tooth structures and materials used in finite element analysis

Structure/Material	Elastic Modulus (GPa)	Poisson Ratio	Study
Dentin	18.6	0.31	Dejak, 2008[45] Holmes, 1996[55]
Gutta percha	1.4×10^{-1} [Friedman, 1975[52]]	0.45 (49)	Rekow, 2006[49] Friedman, 1975[52]
Liga Ni/Cr	200.0	0.30	Campos, 2011[36]
Polystyrene resin	13.5	0.31	Soares, 2008[54]
Composite resin	16.6	0.24	Joshi, 2001[53]
Glass ionomer cement (GI)	10.8	0.30	Ichim, 2007[51]
Zinc phosphate cement (ZP)	13.7	0.33	Rekow, 2006[49]
Resinous cement (AP and SAd)	8.0	0.30	Asmussen, 2005[50]
Empress 2 (DISIL)	96.0	0.25	Dong, 2003[48]
Feldspathic ceramic (FELD)	70.0	0.19	Coelho, 2009[47]
Laboratory processed composite resin (POLYM)	18.8	0.24	Campos, 2011[36]
Cergogold (LEUC)	65.0	0.23	Holmes, 1996[55]

AP, autopolymerizing resin; FELD, feldspathic; DISIL, lithium disilicate reinforced ceramic; GI, glass ionomer; LEUC, lithium disilicate reinforced; POLYM, laboratory-processed polymer; SAd, self-adhesive resin, ZP, zinc phosphate cement.

Table 4. Fracture load mean values (N), standard deviations, 2-way ANOVA, and Tukey test ($P<.05$) results

	Cement			
Material	**ZP**	**GI**	**AP**	**SAd**
FELD	378.9 ±116.9^{Ab}	479.1 ±115.5^{Ab}	615.1 ±198.0^{Aa}	596.0 ±127.2^{Ab}
LEUC	637.1 ±186.2^{Ab}	653.6 ±146.7^{Ab}	613.2 ±223.7^{Aa}	758.8 ±337.7^{Ab}
DISIL	1331.4 ±187.2^{Aa}	1437.9 ±241.8^{Aa}	846.6 ±237.6^{Ba}	1450.0 ±248.1^{Aa}
POLYM	695.9 ±273.0^{ABb}	693.5 ±214.5^{ABb}	553.0 ±333.1^{Ba}	947.5 ±368.0^{Ab}

AP, autopolymerizing resin; FELD, feldspathic; DISIL, lithium disilicate reinforced ceramic; GI, glass ionomer; LEUC, lithium disilicate reinforced; POLYM, laboratory-processed polymer; SAd, self-adhesive resin, ZP, zinc phosphate cement.
Means followed by different superscript letters (capital in rows and lowercase in columns) are statistically different.

Table 5. Frequency of fracture type (%) comparing results from restorative materials with different cements

Material	Cement	Type of Fracture (%)				
		I	II	III	IV	V
DISIL P=.0015	ZP	0 (0.0)	0 (0.0)	6 (75.0)	1 (12.5)	1 (12.5)
	AP	0 (0.0)	0 (0.0)	1 (12.5)	3 (37.5)	4 (50.0)
	GI	0 (0.0)	0 (0.0)	3 (37.5)	0 (0.0)	5 (62.5)
	SAd	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	8 (100.0)
LEUC P=.15	ZP	0 (0.0)	0 (0.0)	7 (87.5)	1 (12.5)	0 (0.0)
	AP	0 (0.0)	0 (0.0)	7 (87.5)	0 (0.0)	1 (12.5)
	GI	0 (0.0)	0 (0.0)	5 (62.5)	3 (37.5)	0 (0.0)
	SAd	0 (0.0)	0 (0.0)	6 (75.0)	0 (0.0)	2 (25.0)
FELD P=1.00	ZP	0 (0.0)	0 (0.0)	7 (87.5)	0 (0.0)	1 (12.5)
	AP	0 (0.0)	0 (0.0)	7 (87.5)	1 (12.5)	0 (0.0)
	GI	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
	SAd	0 (0.0)	0 (0.0)	7 (87.5)	1 (12.5)	0 (0.0)
POLYM P=NS	ZP	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
	AP	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
	GI	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
	SAd	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)

AP, autopolymerizing resin; FELD, feldspathic; DISIL, lithium disilicate reinforced ceramic; GI, glass ionomer; LEUC, lithium disilicate reinforced; POLYM, laboratory-processed polymer; SAd, self-adhesive resin, ZP, zinc phosphate cement.

Table 6. Frequency of fracture type (%) comparing results from cements with different restorative materials

Cement	Material	Type of Fracture (%)				
		I	II	III	IV	V
ZP P=.886	DISIL	0 (0.0)	0 (0.0)	6 (75.0)	1 (12.5)	1 (12.5)
	LEUC	0 (0.0)	0 (0.0)	7 (87.5)	1 (12.5)	0 (0.0)
	FELD	0 (0.0)	0 (0.0)	7 (87.5)	0 (0.0)	1 (12.5)
	POLYM	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
AP P<.001	DISIL	0 (0.0)	0 (0.0)	1 (12.5)	3 (37.5)	4 (50.0)
	LEUC	0 (0.0)	0 (0.0)	7 (87.5)	0 (0.0)	1 (12.5)
	FELD	0 (0.0)	0 (0.0)	7 (87.5)	1 (12.5)	0 (0.0)
	POLYM	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
GI P<.001	DISIL	0 (0.0)	0 (0.0)	3 (37.5)	0 (0.0)	5 (62.5)
	LEUC	0 (0.0)	0 (0.0)	5 (62.5)	3 (37.5)	0 (0.0)
	FELD	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
	POLYM	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)
SAd P<.001	DISIL	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	8 (100.0)
	LEUC	0 (0.0)	0 (0.0)	6 (75.0)	0 (0.0)	2 (25.0)
	FELD	0 (0.0)	0 (0.0)	7 (87.5)	1 (12.5)	0 (0.0)
	POLYM	0 (0.0)	0 (0.0)	8 (100.0)	0 (0.0)	0 (0.0)

AP, autopolymerizing resin; FELD, feldspathic; DISIL, lithium disilicate reinforced ceramic; GI, glass ionomer; LEUC, lithium disilicate reinforced; POLYM, laboratory-processed polymer; SAd, self-adhesive resin, ZP, zinc phosphate cement.

interface; Type III, cohesive fracture involving the interface (core preserved); Type IV, fracture involving the core (root preserved); and Type V, fracture involving root. Data from fracture load and pattern were submitted to statistical analysis (α=.05).

The stress distribution in the tooth-post-core-restoration complex was evaluated under a static load application using finite element analysis (FEA).[45,46] A geometric model was created from a longitudinal slice of one lithium disilicate reinforced ceramic (DISIL) specimen (Fig. 2), and the same general geometry was adapted for each group to reflect its specific characteristics. The geometric characteristics were applied using computer aided design software (Mechanical Desktop, AutoCAD v6; Autodesk) and exported to FEA software (MSC.Marc; MSC.Software). Axisymmetric models were created by subdividing (meshing) half of each structure with higher-order 8-noded quadrilateral elements (Fig. 2). The properties applied for the various materials and their sources are listed in Table 3.[36,45,47-55] The flexural strength properties were determined with 3-point bending tests according to ISO 4049 standard.[56] In the FEA, all material properties were assumed to be isotropic, linear-elastic, and homogeneously distributed. The SAd and AP resin cements were modeled as bonded to the crowns, whereas no bonding was modeled between the crowns and the ZP or GI. Because the contact friction coefficient between the nonbonded cements and all crown materials was not known, an arbitrary value of 0.25 was used. Besides the boundary conditions dictated by the axisymmetrical conditions, model movements were also restricted (fixed) in all directions at the external lateral outline and base of the simulated polystyrene resin cylinder. A 90 N load was applied on the crown to simulate the steel sphere used in the experiments. Maximum principal stresses were recorded in the central integration point (Gauss point) of all elements located along the cement-crown interface (for both crown and cement aspects) and along the occlusal surface (crown), as indicated in Figure 2.

A fractographic analysis was conducted in 3 steps as follows:[34] visual inspection to select specimens containing visible markings of fracture; examination under stereomicroscope magnification (×10 to ×40) to select areas of interest for further scanning electron microscopic (SEM) investigation; and SEM examination under high-resolution close-ups of the regions of interest. Selected fractured specimens were prepared for SEM observation (JSM 5600; JEOL Ltd) and searched for fracture markings such as arrest lines, hackles, and wake hackles[31,34,35,41] to determine the crack origin and direction of propagation.

RESULTS

Fracture load mean values and standard deviations are shown in Table 4. After square-root transformation of fracture load values using PROC LAB procedures from the SAS statistical program (2003, release 9.1; SAS Institute Inc), data were submitted to 2-way ANOVA and Tukey HSD test. Within the DISIL group, results for AP cement were significantly lower, and within the POLYM

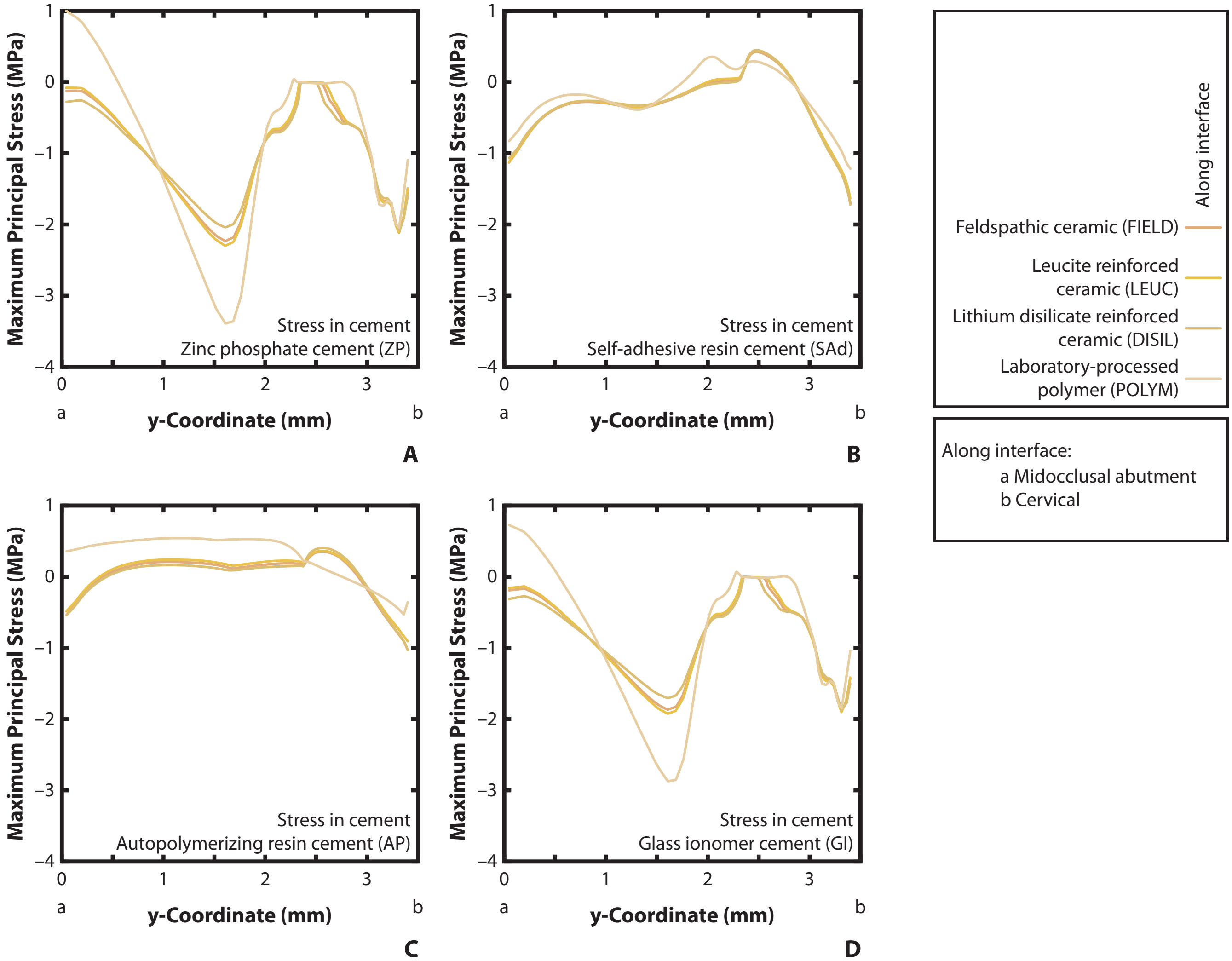

Figure 3. Maximum principal stresses (MPa) in cement layer ('a' to 'b'; Fig. 2) close to interface with crown. (A) Zinc phosphate cement (ZP); (B) self-adhesive resin cement (SAd); autopolymerizing resin cement (AP); and (D) glass ionomer cement (GI). Positive stress values are tensile stresses, negative values are compressive stresses. y-Coordinate is distance in radial (lateral) direction, where y=0 corresponds with 'a' and y=3.4 corresponds with 'b' (Fig. 2).

group, significantly higher values were observed for the SAd cement than for the AP. When the restorative material effect was considered, the results from DISIL were significantly higher, irrespective of the cement used, except for the AP group. The fracture patterns were analyzed by means of frequency distribution tables (absolute and relative) and the Fisher exact test. Significant differences for the DISIL were found when comparing results from the restorative material with different cements (Table 5). When comparing results from the cement with different restorative materials, significant differences in the fracture patterns were observed for AP, SAd, and GI (Table 6). Type III fracture pattern occurred in 95% of the specimens from FELD and POLYM groups and in 82% of specimens from the LEUC group. In the DISIL group, the Type V fracture pattern was present in 56% of the specimens, Type IV in 12%, and Type III in 32%. Overall, a predominance of Type III fracture patterns was found in 75% of the specimens.

The FEA calculated the stresses for the different combinations of crown and cement materials. Maximum principal stresses in the cement are shown in Figure 3. The stresses in each cement were similar regardless of crown material for the ceramic systems (FELD, LEUC, and DISIL). Only in combination with the polymer crown did nonresin cements (ZP, GI) experience higher stress values. Maximum stresses in the adhesive resin cements (SAd and AP) were hardly affected by the choice of crown material, even for the polymer crown (POLYM).

Comparing stress values between materials with different strengths is not meaningful because strength determines their significance. To make a more relevant comparison of the stress conditions among crowns made

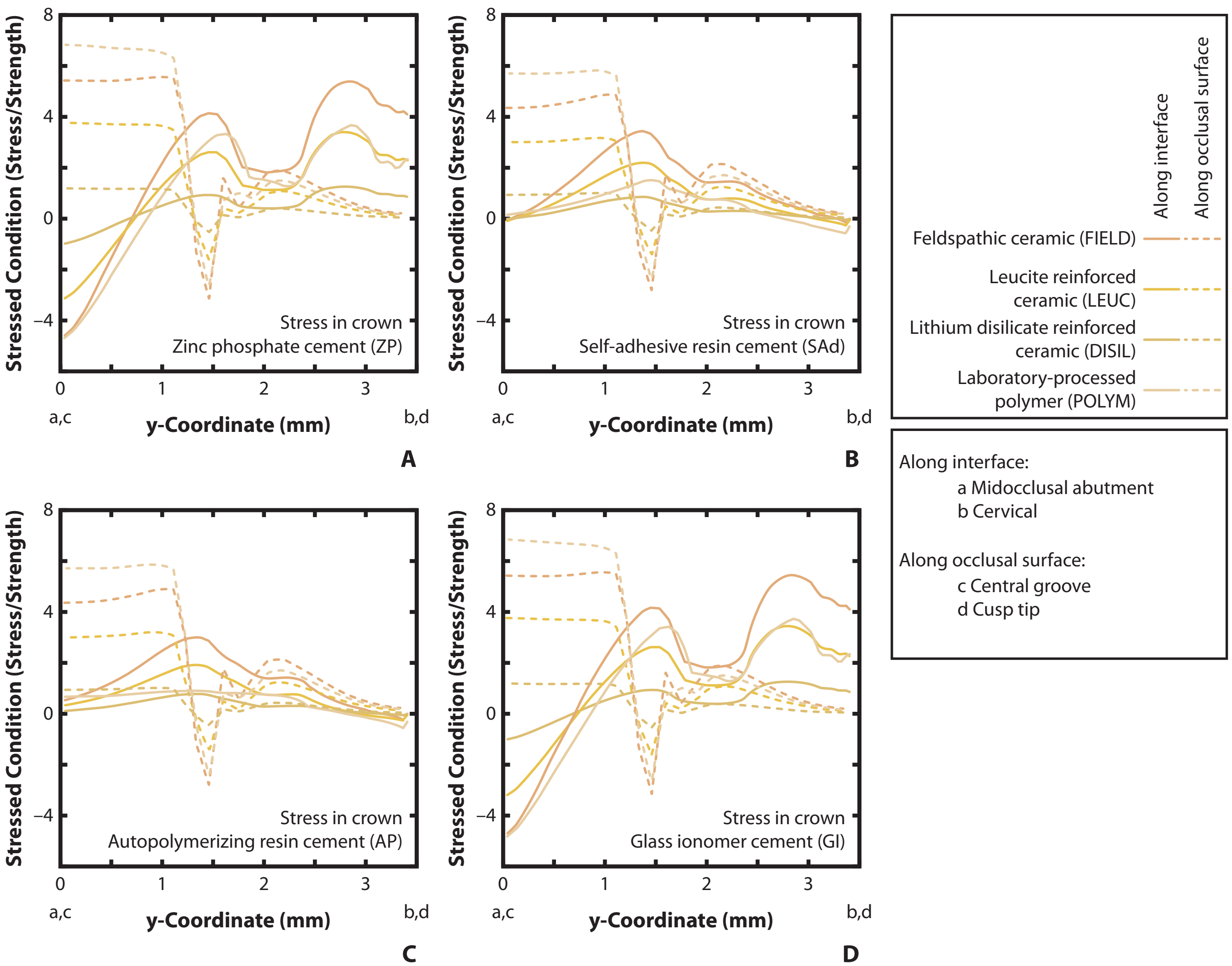

Figure 4. (A) Zinc phosphate cement (ZP); (B) self-adhesive resin cement (SAd); autopolymerizing resin cement (AP); and (D) glass ionomer cement (GI). Stressed conditions (defined as ratio maximum principal stress/flexural strength) in crown along interface with cement ('a' to 'b'; Fig. 2; solid lines) and along occlusal surface ('c' to 'd'; Fig. 2; dashed lines). Positive values indicate tensile stresses, negative values indicate compressive stresses. y-Coordinate is distance in radial (lateral) direction, where y=0 corresponds with 'a' or 'c,' and y=3.4 corresponds with 'b' or 'd' (Fig. 2).

from different materials, the stress values were normalized by dividing them by their flexural strength values (Table 3). The obtained ratio represents the stressed condition, where a positive value indicates that the maximum principal stress component is tensile and a negative value indicates compression. The normalized stresses in the crowns along the cement interface for the different crown-cement combinations are shown in Figure 4, which shows that the stressed condition in each crown material only differed depending on the bonding condition, not the cement. In all cases, the FELD ceramic crown had the highest stressed condition, and the DISIL crown the lowest. If the cement bonded to the crown, the stressed condition in the LEUC crown was higher than in the polymer crown. If the cement did not bond, the order reversed (stressed condition in POLYM higher than in LEUC). Stressed conditions along the crown occlusal surface, where the load was applied through the sphere, also depended on the bonding condition rather than the cement (Fig. 4). Adhesive cements resulted in slightly lower stress conditions, but the distribution was similar regardless of cement type. The stressed conditions were lowest at the occlusal surface of the DISIL crown and highest for the polymer crown (POLYM). The stressed condition of the polymer crown at the occlusal surface was in all cases substantially higher than along its cement interface, whereas for the other crown materials they were only higher with the nonadhesive cements. The fractographic analysis showed that the fracture origin was at the occlusal loading point and that the crack propagated to the cervical area as revealed by wake hackles[34-37] under different magnifications (Fig. 5).

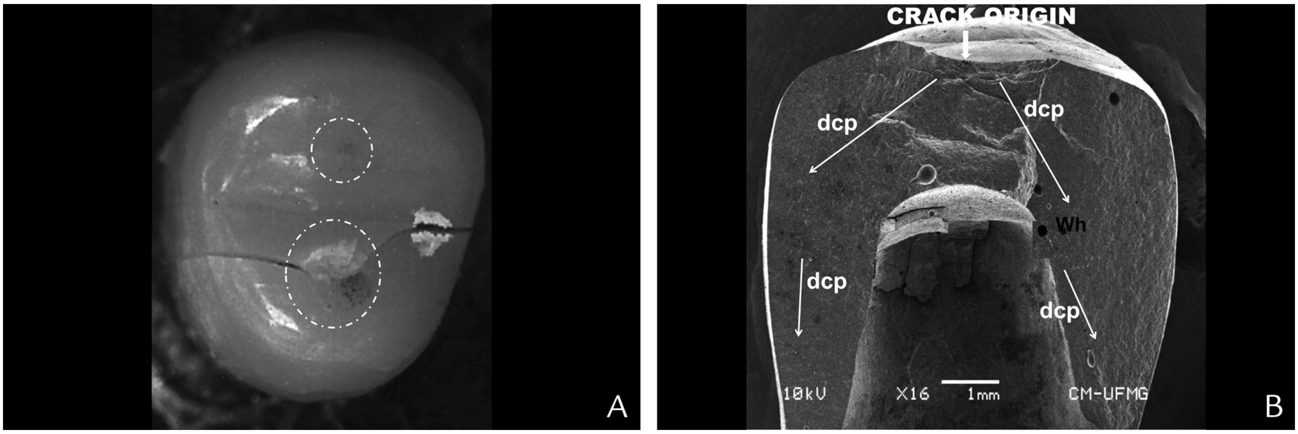

Figure 5. Representative sketch of crack origin and propagation of FELD Type IV fractured specimen. A, Markings and initial damage in load points. B, Occlusal edge chip probably corresponding to damaged occlusal load point and probable fracture origin. Several wake hackles (Wh) starting from pores within ceramic restoration indicate direction of crack propagation (dcp) from occlusal to cervical (white arrows). Wake hackles were observed in magnifications ranging from ×400 to ×3000.

DISCUSSION

The present study evaluated the efficacy of traditional load-to-failure mechanical tests in determining the mechanical behavior of metal-free ceramic crowns. Mechanical testing, FEA, and fractographic analysis were used to investigate the influence of the cement on the fracture load and pattern of metal-free ceramic crowns. The higher failures rates reported for metal-free crowns[1-3,5] have been attributed to their composition along with the effect of the cement used.[13,14,16-18,20,21] However, as the FEA and fractographic analysis from the current study showed, the methodology used was not appropriate for investigating either the crowns fracture load or the cement/cementation effect. Thus, the null hypothesis was rejected. Such results are corroborated by clinical trials in which the findings from fractured metal-free restorations[5,6,37,41] differ from the results from the current study. Thus, in vitro methods providing clinically applicable results for investigating the mechanical behavior of restorative materials were proposed.[28-30,43]

FEA was used to study how the combination of different properties represented by the crowns and cements affected the internal stress distributions. As one basic cross-sectional tooth shape was selected and subjected to an axisymmetric analysis for all the comparisons, the results of the FEA in this study should therefore be interpreted qualitatively to provide a basic insight into how cement and crown properties interact, and not to quantitatively predict the crown failure. The actual failure loads were likely to have been strongly affected by local individual properties beyond the scope of this simulation.

Most of the groups investigated in the present study had fracture loads exceeding reported maximum occlusal loads.[9] Except for the FELD/ZP group, all crowns cemented with the nonadhesive technique had fracture loads compatible with maximum occlusal forces. The statistically significant higher failure values obtained for the DISIL (Table 4) can probably be attributed to the lithium disilicate reinforcement rather than the type of cement, considering its performance with ZP, GI, and SAd cements. Lower fracture loads of DISIL crowns cemented with ZP were expected as a consequence of the nonadhesive interaction among the structures, but such an effect was not evident. A recent study showed that ZP cement appears to be as effective as resin cement in protecting the ceramic when a micromechanical bond is present.[19] The FEA showed that the stressed conditions were lowest in the DISIL compared with other crowns for all cement combinations. In this model, this could also be attributed to the higher strength of the DISIL material and not its higher elastic modulus because a higher elastic modulus value would increase the stressed condition in a crown (compare FELD and POLYM) for the same strength. Within the methodology, the role of the cement in the fracture mechanism could not be defined, and the fracture loads seemed to be more related to the restorative material than to the cement. The FEA also confirmed that stresses in the cements were little affected by the crown materials and indicated that the stressed conditions in the crowns depended more on the adhesive properties of the cement material than on the elastic modulus properties of the cements.

The use of the AP cement in association with DISIL and POLYM resulted in significantly lower fracture load values than the use of SAd cement. Such a result was unexpected considering that the thickness of the restorative material may not allow effective photoactivation of the SAd cement, thus resulting in lower polymerization and a subsequently lower fracture load.[12] The FEA, which assumed complete polymerization for all cements, showed little difference in the stressed conditions in crowns with either AP or SAd cements. This difference in behavior between experiments and FEA may indicate bond failure in the DISIL/AP and POLYM/AP restorations. The FEA indicated that the level of the stressed condition in the crowns at the occlusal surface was about the same or higher than along their cement interface. This is consistent with the fractographic analysis, which indicated that the fractures started from the occlusal surface (at the load point) and propagated in a cervical direction, in compliance with a previous report.[36] Because adhesive cements lowered the stressed conditions at the cement interface, as shown in Figure 4, it can be expected that fracture in such crowns are least likely to originate from the crown-cement interface. Although the methodology used for the fracture load tests failed in evaluating the actual role of the cement in the fracture mechanism, FEA indicated that stressed conditions may be influenced by the bonding conditions. Such influences were probably reflected by the differences found in the fracture patterns.

As shown in the Tables 5 and 6, within the DISIL group, results from SAd, AP, and GI cements caused a significantly higher incidence of Type V fracture. The use of ZP for cementation of DISIL crowns, with no adhesive interaction, resulted in Type III fracture in 6 out of 8 specimens, thus considerably reducing the risk of catastrophic fracture with no significant decrease in the fracture load. For the other restorative materials, irrespective of the cement, most of the fractures were Type III, which would be clinically preferable in case of failure because only the restoration is compromised and can be replaced. Most of the failures resulted in more than 2 fragments, and in all specimens, damage at the load point was observed. The fracture findings suggested that the risk of catastrophic fracture is higher when using resin cements plus the adhesive technique. However, because such findings were obtained by methods that seemed not to provide results compatible with clinical situations, clinicians should be careful as to their interpretation.

Destructive fracture load tests are primarily used as a reference to investigate restorative materials and techniques and thus predict their behavior under clinical situations. Such load values and mechanical behavior should be carefully interpreted because loading in vitro is unlikely to be the same as under in vivo conditions. Faithful reproduction of clinical conditions in laboratory tests to investigate the fracture load of restorative material is challenging because of the diversity and complexity of factors that interact in vivo.[31] However, clinical trials are expensive and time-consuming, and they require complex designs. Laboratory tests, despite their limitations and if appropriately conducted and interpreted, are supposed to provide a collection of data that is clinically relevant. Unlike clinical studies, laboratory tests also have unique strengths because experimental factors can be accurately controlled. This improves insight into the effect of individual factors and provides important information about the tested materials.

Results from the current study showed that materials with higher elastic modulus presented higher failure loads in agreement with the FEA. However, because the fractography analysis showed a crack propagation direction opposite to that of clinical situations, the methodology used failed to determine the mechanical behavior of metal-free ceramic crowns and failed to evaluate the actual effect of the cement in the fracture mechanism. Thus, because the effect of the cement/cementation technique could not be defined, the fracture loads should be assumed as being from the restorative material itself. However, as part of the tooth-crown-cement interaction and as the actual failure loads can be expected to be affected by local individual properties, the cement effect cannot be ignored. Moreover, the FEA indicated the stress distributed along the cement thickness and the fracture pattern was different among the crowns depending on the cementation bonding conditions. The actual effect of the cement in the ceramic crown must be investigated by using a different methodology.

The outcomes from the current study matched the concerns regarding traditional failure testing emphasized by Kelly et al[30] and cannot be considered clinically applicable. These outcomes were that (1) the failure loads exceeded reported functional ranges, (2) the stress was not correctly stated, (3) the fracture origin and propagation were from the occlusal load point to the cervical direction, (4) the fracture did not involve the flaw/defects population from the crown bonding surface, (5) the fractures resulted in more than 2 fragments, (6) static load was used, and (7) the effect of moisture was not investigated. The qualitative results from both the FEA and the fractographic analysis were the main indicators invalidating the results from the present load-to-failure test. A quantitative comparison between traditional load-to-failure testing and tests to provide clinically applicable results must be performed.

CONCLUSIONS

The in vitro testing method used in this study is not appropriate either for investigating the crown fracture load and pattern or for stating the effect of the cements within the crown-cement-tooth interaction because it does not compare well with the clinical situation.

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