Effect of porcelain and enamel thickness on porcelain veneer failure loads in vitro

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Statement of problem. Bonded porcelain veneers are widely used esthetic restorations. Although high success and survival rates have been reported, failures occur. Fracture is the most common failure mode. Fractures range from incomplete cracks to the catastrophic. Minimally invasive or thin partial veneers have gained popularity.

Purpose. The aim of this study was to measure the influences of porcelain veneer thickness and enamel substrate thickness on the loads needed to cause the initial fracture and catastrophic failure of porcelain veneers.

Material and methods. Model discoid porcelain veneer specimens of varying thickness were bonded to the flattened facial surfaces of incisors, artificially aged, and loaded to failure with a small sphere. Individual fracture events were identified and analyzed statistically and fractographically.

Results. Fracture events included initial Hertzian cracks, intermediate radial cracks, and catastrophic gross failure. Increased porcelain, enamel, and their combined thickness had like effects in substantially raising resistance to catastrophic failure but also slightly decreased resistance to initial Hertzian cracking. Fractographic and numerical data demonstrated that porcelain and tooth enamel behaved in a remarkably similar manner. As porcelain thickness, enamel thickness, and their combined thickness increased, the loads needed to produce initial fracture and catastrophic failure rose substantially. Porcelain veneers withstood considerable damage before catastrophic failure.

Conclusions. Increased enamel thickness, increased porcelain thickness, and increased combined enamel and porcelain thickness all profoundly raised the failure loads necessary to cause catastrophic failure. Enamel and feldspathic porcelain behaved in a like manner. Surface contact damage occurred initially. Final catastrophic failure followed flexural radial cracking. Bonded porcelain veneers were highly damage tolerant. (J Prosthet Dent 2014;111:380-387)

Clinical Implications

Increased enamel and porcelain thickness both substantially raised the loads needed to cause the catastrophic failure of model porcelain veneers. Porcelain and enamel thickness should be maximized, with enamel preservation being prioritized. Porcelain veneers are highly damage-tolerant restorations. Wherever possible, occlusal contact should be avoided on porcelain veneers.

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Bonded porcelain veneers have been widely used to address esthetic dental problems for more than 3 decades.[1,2] Porcelain veneers have many advantages, including pleasing esthetics, abrasion resistance, and stability. Tooth preparation for veneers preserves much precious tooth structure, especially enamel and the important dentinoenamel junction.[3-5] The success of porcelain veneers has been attributed to a durable bond between 2 materials of similar elastic moduli, porcelain and enamel.[6-9]

Initial reports on porcelain veneers described a nonpreparation technique.[2,6,10] However, bulky gingival contours can limit cleansing and provide unnatural gingival profiles, and gingival recession is a common problem.[11] Subsequently, techniques with tooth preparation became widely accepted. Conservative tooth preparation facilitates optimizing the emergence profile and overall contour and provides a definite finishing line. As well as facial reduction, preparation designs often include incisal, proximal, and even lingual reduction.[8,12-18]

Recently, minimally invasive veneer preparation designs have become popular. These involve less tooth reduction, partial coverage, and minimal porcelain thickness.[19-23] Minimally invasive veneers have also been described as being mini, minimal, minimal thickness, ultraconservative, ultrathin, partial, or sectional veneers.[19-25] Thicknesses of 0.3 mm have been reported for minimally invasive veneers,[19-22] whereas conventional porcelain veneers generally range from 0.3 to 1.0 mm in thickness.[14,16,17,26-29] Clinical outcome data for minimally invasive veneers have yet to be published.

Excellent clinical outcomes, good satisfaction ratings, and high survival rates have often been reported for conventional porcelain veneers.[10,12,14-16,28-37] However, more rigorous studies with a wider variety of outcome metrics, Kaplan-Meier or lifetime survival curves, and entailing more demanding analyses have generally reported lower long-term success and survival rates.[7,11,17,18,38-45] Although leakage, marginal discrepancies, debonding, esthetic problems, caries, periodontal problems, and pulpal disease may all occur, fracture is the most common failure mode.[10,11,14-18,39,42,45]

Clinical fracture modes for conventional bonded porcelain veneers include longitudinal or radial cracking; chipping or fracturing in incisal areas, areas of occlusal contact, and areas close to the veneer margins, and in marginal areas, semicircular half-moon fractures,[10,14,15,17,18,28-30,39,42,46] reminiscent of those found in porcelain jacket crowns.[47] Fractures have been ascribed to the application of flexural tensile stresses to porcelain veneers by functional loading,[15,17,31,39] cement polymerization shrinkage, and thermal cycling.[46,48]

Fractographic analyses of clinically fractured ceramic crowns have indicated that failures initiate on their inner, or tensile, surfaces.[49,50] For ex vivo crown models, flexural radial cracking is dependent on ceramic thickness.[51] These ex vivo crown models underwent 2 distinct fracture events: first, Hertzian cone cracking at the surface contact area, and second, radial cracking starting from flaws in the inner ceramic surface from flexural tensile stresses. Although veneers differ from crowns in that they are thinner and more flexible, as well as durably bonded to an intact layer of supporting enamel, similar fracture events may occur.[52] A finite element analysis indicated that thinner porcelain veneers were prone to high stresses on both their internal and external surfaces after bonding with resinous cements.[48] Furthermore, an ex vivo compressive test reported that increasing the thickness of a porcelain veneer from 0.5 to 1 mm increased the fracture strength.[53]

The effects of both porcelain and enamel substrate thickness on fracture resistance warrant investigation, particularly given the increasing use of minimally invasive porcelain veneers and the limited thickness of tooth enamel.[54] The purpose of this study was to measure the influence of porcelain veneer thickness and enamel substrate thickness on the loads needed to cause initial and catastrophic porcelain veneer failure. The null hypothesis was that porcelain thickness and enamel thickness do not influence the loads needed to produce catastrophic failure.

MATERIAL AND METHODS

Teeth

Maxillary central and lateral incisors with completely intact crowns and roots and free of caries or restorations were selected, cleaned, and stored in 0.01% thymol solution at room temperature. The teeth were embedded in epoxy resin (Fast Cure Epoxy; Extec) within phenolic rings ($1^1/_4''$ Ring Molds; Extec). The labial surfaces were gently ground under water with 240, 400, and 600 grit silicon carbide (Carbimet Paper Strips; Buehler) until flat areas of enamel more than 6 mm in diameter were obtained. All experimental procedures were performed in an ambient atmosphere of 70% to 75% humidity and 20°C to 23°C.

Porcelain veneers

Model discoid porcelain veneer specimens were sectioned from cylinders made of feldspathic porcelain. Feldspathic dental porcelain powder (Vita VM13; Vita Zahnfabrik) was placed in a 6.2-mm-diameter cylindrical polyvinyl siloxane mold (Aquasil Ultra XLV Regular Set; Dentsply Intl). The powder was packed into the mold against a glass slab with an acrylic resin plunger, and sufficient water was added to wet the material. The wet powder was then compressed by using the plunger with light tapping forces from a small mallet. Excess moisture was removed with an absorbent tissue. The porcelain specimens were removed, and the remaining moisture was extracted by drying in front of a heated furnace (Vacumat 40T; Vita Zahnfabrik). Specimens were preheated to 450°C, held for 2 minutes, and fired with a heat rise of 25°C/min to 890°C under vacuum for 17.3 minutes, held for 2 minutes, let cool to 350°C with the muffle 70% open, then held under the muffle for 10 minutes. The porcelain cylinders were then trued to a diameter between 5.4 and 5.5 mm and sectioned with a slow-speed diamond saw (Isomet; Buehler) to make specimens with a thickness ranging from 0.2 to 1.4 mm. The thicknesses of the individual specimens were measured with a dial caliper (Mitutoyo) to ±0.01 mm.

Bonding procedure

Thirty veneers of different thickness were assigned to teeth. The porcelain veneers were etched with 9.5% buffered hydrofluoric acid gel (Porcelain Etchant; Bisco) for 90 seconds, rinsed with water, and thoroughly air dried. Two coats of a 2-part silane coupling agent (BIS-SILANE; Bisco) were applied and dried 30 seconds later. The teeth were cleaned with a slurry of pumice, rinsed, and dried. The enamel was etched with 32% phosphoric acid with benzalkonium chloride (UNI-Etch; Bisco) for 15 seconds, rinsed thoroughly, and dried lightly, leaving the enamel visibly moist. Two coats of a 2-part dual-polymerized bonding agent (ALL-BOND3; Bisco) were applied, air dried for 12 seconds to evaporate solvents, and light polymerized for 10 seconds. Thin layers of a porcelain bonding resin (Hema-free unfilled resin; Bisco) were applied to the veneers, which were lined with a light-polymerized veneer cement (Veneer cement, Choice 2; Bisco). The veneers were gently seated, and static vertical loads of 2.83 N were applied to standardize seating load and cement layer thickness.[48] The seated veneers were light polymerized (Optilux 500; Kerr) for 4 seconds to tack them in place before excess cement was removed. The veneers were then polymerized circumferentially from their peripheries for 40 seconds before being polymerized from their facial aspects for a further 40 seconds.

Artificial aging

Bonded specimens were stored in air for 10 minutes, in 100 % humidity for another 50 minutes, then stored in water for 10 days. Specimens were artificially aged by thermal cycling 1000 times between 5°C and 55°C, with dwell times of 120 seconds and a transfer time of 15 seconds. Thermal cycling is known to decrease the strength of bonded veneers.[52,55] Extended dwell times were used to ensure adequate heat transfer for the specimens and their large mounts.[56]

Testing and analysis

Specimens were radiographed digitally (XDR; Cyber Medical Imaging) to measure the enamel thickness beneath the center of each veneer. Moist specimens were placed onto the platen of a universal testing machine (5966; Instron) with the porcelain uppermost. A tungsten carbide sphere, 1.59 mm in radius, was placed on the center of each model veneer. The radius of the sphere was somewhat larger than the radius of an incisal edge but smaller than that of a large cusp. This method was known to produce elastic deformation before Hertzian cracking and plastic deformation in the outer surface contact area without initially causing bulk or catastrophic fracture.[57] Radial cracking was expected to start from the inner bonded ceramic surface after surface damage[51]; clinical cracking and chipping in the areas of occlusal and incisal contacts has been widely reported for veneers[10,14-17,30,32,33,39,42,44,45] and for glass-ceramic onlays.[58] The specimens were loaded at a crosshead speed of 0.01 mm/min, and load-time data were recorded until catastrophic failure occurred. Individual fracture events were identified by post hoc analysis of the universal testing machine load-time data files with a spreadsheet (Excel; Microsoft). During pilot testing on additional specimens, individual fracture events were studied and sequenced by stopping the test after individual events had been identified on the load-time display and on performing qualitative fractographic examination. Fractographic analysis was performed with a variety of light microscopic techniques, brightfield, darkfield, Nomarski, and polarization to identify and study fracture initiation sites and modes. Fracture load was plotted against enamel thickness, porcelain thickness, and combined enamel and porcelain thickness. Regression analysis was used to identify the simple linear equations relating fracture load to thickness, and correlation coefficients, R^2, were calculated.

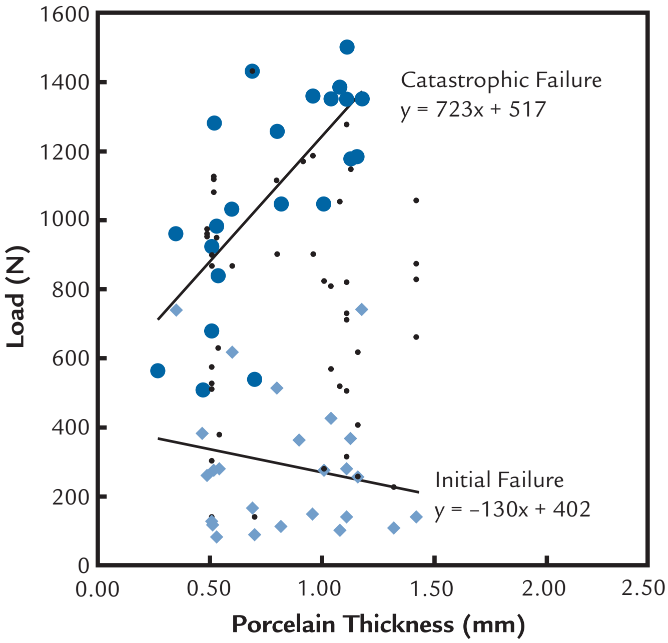
RESULTS

Influence of porcelain veneer thickness on porcelain veneer fracture events

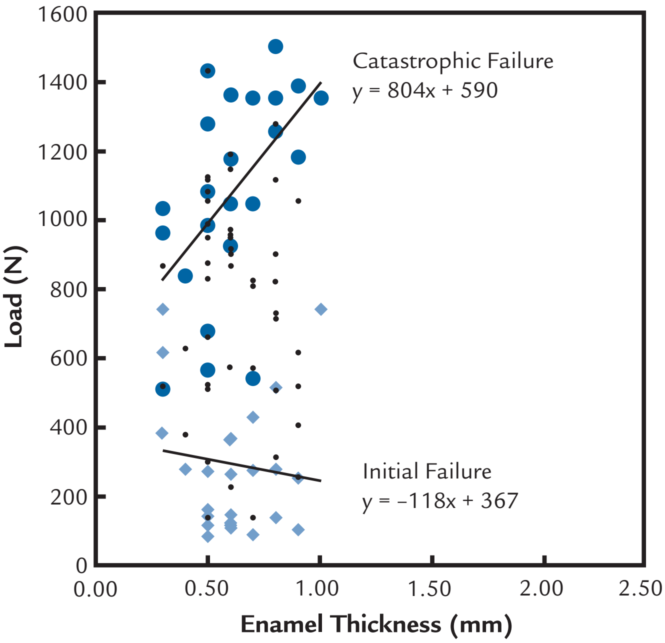
Increasing porcelain thickness tended to slightly decrease the load needed to form initial cone cracks (Fig. 1); the linear equation produced by regression analysis for the influence of porcelain veneer thickness on the initial cone crack fracture event was $y=-130x+402$ ($R^2=0.04$). Increasing porcelain thickness markedly increased the load needed to produce terminal catastrophic fracture (Fig. 1); the linear equation produced by regression analysis for the influence of porcelain veneer thickness on the terminal catastrophic fracture event was $y=723x+517$ ($R^2=0.5$).

Influence of enamel thickness on porcelain veneer fracture events

The influence of enamel thickness on porcelain veneer fracture events was remarkably similar to that of porcelain thickness (Figs. 1, 2). Increasing enamel thickness tended to slightly decrease the loads needed to form initial cone cracks (Fig. 2); the linear equation produced by regression analysis for the influence of enamel thickness on the initial cone crack was $y=-118x+367$ ($R^2=0.01$). Increasing enamel thickness markedly increased the load needed to produce terminal catastrophic fracture (Fig. 2); the linear equation produced by regression analysis for the influence of enamel thickness on the terminal catastrophic fracture event was $y=804x+590$ ($R^2=0.3$).



1 Plot of fracture load against porcelain veneer thickness. Initial Hertzian surface cracks are plotted as light blue diamonds; intermediate radial cracks as small black dots; and final catastrophic failures as large blue circles. Regression lines for initial Hertzian surface cracks and final catastrophic failures are plotted.



2 Plot of fracture load against supporting enamel thickness. Initial Hertzian surface cracks are plotted as light blue diamonds; intermediate radial cracks as small black dots; and final catastrophic failures as large blue circles. Regression lines for initial Hertzian surface cracks and final catastrophic failures are plotted.

Influence of combined porcelain veneer and enamel thickness on porcelain veneer fracture events

The influence of combined porcelain veneer and enamel thickness on porcelain veneer fracture events was consistent with those of separately plotted porcelain veneer and enamel thicknesses (Figs. 1-3). Increasing porcelain thickness tended to slightly decrease the load needed to form initial cone cracks (Fig. 3); the linear equation produced by regression analysis for the influence of porcelain veneer thickness on initial cone crack fracture events was $y=-83x+413$ ($R^2=0.04$). Increasing porcelain thickness markedly increased the load needed to produce the terminal catastrophic fracture (Fig. 3); the linear equation produced by regression analysis for the influence of porcelain veneer thickness on the terminal catastrophic fracture event was $y=405x+506$ ($R^2=0.4$).

Intermediate radial crack loads were not subjected to regression analysis because, for individual specimens, multiple intermediate events often occurred at different loads (Figs. 1-3).

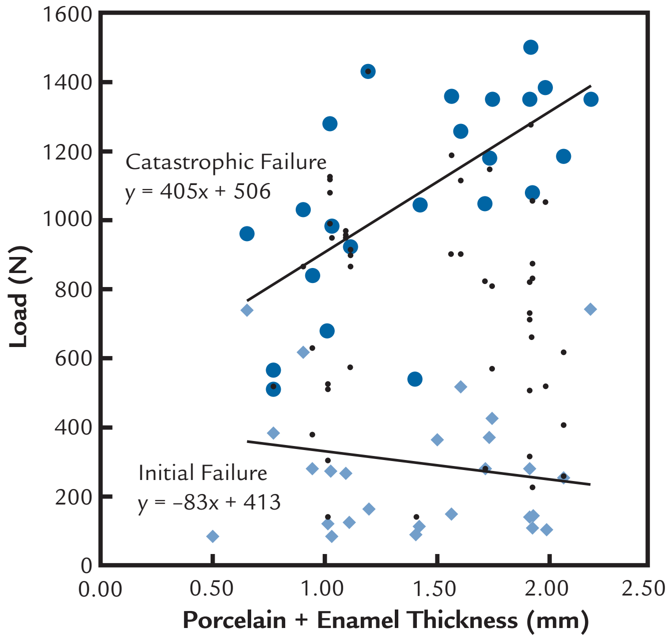
Qualitative fractography

No porcelain fractures or debonding occurred during cementation, thermal cycling, or storage. Upon loading, the initial fracture event was the formation of a Hertzian cone crack in the porcelain veneers of all thicknesses (Figs. 1-4). In half of the specimens, 15 of 30, complete cone cracks continued through the cement and extended into enamel (Fig. 5). In another 3 specimens, partial cone cracks extended into enamel. Some of the extensions into enamel were shallow; others penetrated to the dentinoenamel junction (DEJ), but none crossed the DEJ into dentin. Intermediate fracture events involved the formation of radial cracks within the veneer before final catastrophic failure (Figs. 1-4). In these bonded veneer specimens, most radial cracks appeared to originate from sites on the internal intaglio surface involved in the Hertzian cracks rather than from natural flaws directly under the blunt loading point. Some radial cracks extended from porcelain into enamel, or vice versa, but did not cross the DEJ (Fig. 5). Often, several distinct intermediate radial cracking events were identified after initial Hertzian cracking and before gross catastrophic failure (Figs. 1-3).

DISCUSSION

The null hypothesis was rejected; porcelain thickness, enamel thickness, and their combined thickness all influenced the loads needed to produce catastrophic failure.

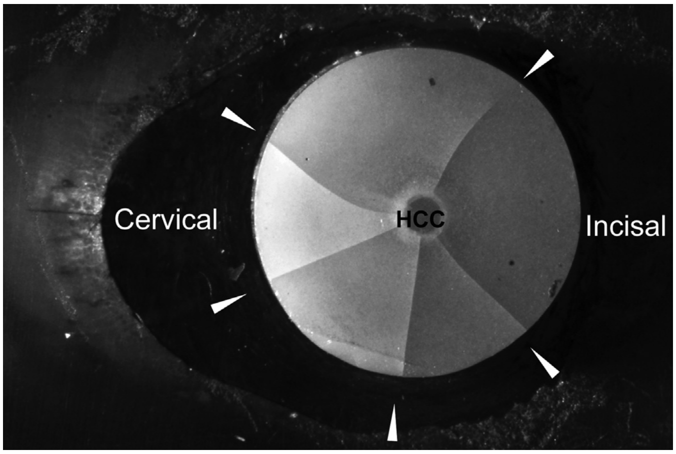
The results of this study showed that the effects of porcelain and enamel thickness were almost identical, both for the initial fracture events and for the final catastrophic events (Figs. 1, 2). Consistent with this finding, the effects of porcelain and enamel thickness were summative (Figs. 1-3). Qualitative fractographic findings also indicated that porcelain and enamel behaved in mechanically similar ways (Figs. 4, 5).



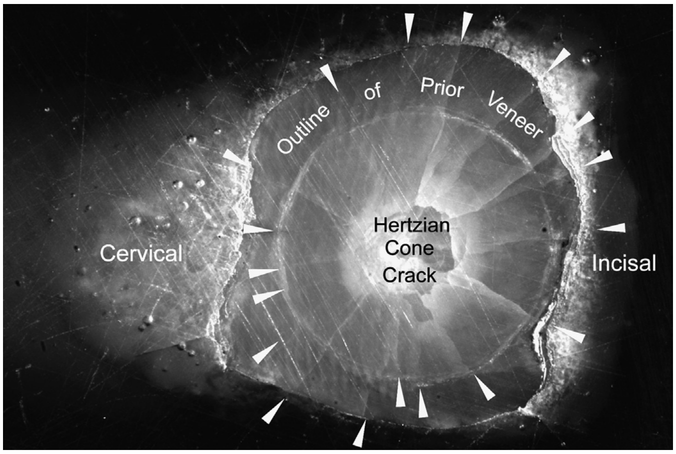
3 Plot of fracture load against combined porcelain veneer and supporting enamel thickness. Initial Hertzian surface cracks are plotted as light blue diamonds; intermediate radial cracks as small black dots; and final catastrophic failures as large blue circles. Regression lines for initial Hertzian surface cracks and final catastrophic failures are plotted.

In many instances, the Hertzian cone cracks penetrated all the way through the porcelain, through the thin cement layer, and continued into bulk enamel (Fig. 5). The Hertzian cracks did not cause the veneers to debond, nor did they directly cause catastrophic failure. A similar occurrence has been reported in vivo.[39]

Qualitative fractographic analysis revealed 3 major fracture events in this experimental model; initial Hertzian cracking extending from the outer surface downward; intermediate radial cracking extending from the inner surface outward and laterally; and finally gross catastrophic failure (Figs. 1-4). Hertzian cone cracks are formed when spherical indenters produce symmetrical tensile stress around the periphery of their contact area to cause crack propagation of conical form extending downward and outward from the surface contact area, analogous to the damage pattern produced by a bullet impacting a glass pane (Figs. 4, 5).[57,59] In contrast, the intermediate radial cracks were believed to originate from flexural tensile stresses applied to the inner intaglio surface of ceramic restorations and to travel upward to the restoration surface; they are considered to be the dominant failure mechanism of ceramic crowns (Fig. 5).[49-51] Catastrophic failure produced destruction of the specimen and disintegration into many small fragments. Clinical failures in areas of occlusal or incisal contact have been frequently reported, consistent with damage induced by direct contact.[10,14-17,30,32,33,39,42,44,45] However, this model produced "ideal" Hertzian cracks, rather than the irregular asymmetric damage typically produced by uncontrolled clinical surface contact damage. Again, it is important to stress that this in vitro model used a small hard ball, rather than the natural anatomy and material of opposing tooth structure, to load the test specimens. Radial cracking, often without gross failure, has been reported for porcelain veneers in vivo[12,15-18,30,33,35,39,42,44,46] and for enamel in vitro.[60] Clinical radial cracking probably initiates at natural flaws on the intaglio surface of the veneer in areas of stress concentration or in areas of bond failure. Gross failure of porcelain veneers has also been described.[17,31,42] Thus, the failure modes produced in this study may be considered to have clinical relevance.



4 Facial view of transilluminated porcelain veneer with initial central Hertzian cone crack (HCC) and intermediate radial cracks (white arrows) before catastrophic failure.



5 Facial view of transilluminated tooth after catastrophic failure and total loss of veneer; Hertzian cone crack and radial cracks (white arrows) extend through enamel.

The wide range in loads between initial fracture events, intermediate radial cracking events, and final catastrophic failures indicated that porcelain veneers bonded to enamel form highly damage-tolerant structures (Figs. 1-3). This success can now be explicitly attributed to a strong durable bond between substrates that are closely matched in mechanical properties, including elastic modulus, the Poisson ratio, and toughness.[61-64] Failure modes and loads could profoundly differ if veneers were made of materials differing from the feldspathic porcelain used in this study, or if the interface between the veneer and tooth was less durable.[63] Glass ceramics and ceramics tend to have higher elastic moduli than feldspathic porcelain or enamel; therefore, their failure modes and damage tolerance could differ from those of bonded feldspathic porcelain veneers.

Which event, initial, intermediate, or final, matters to a patient? Although the initial event is a key step in the evolution of failure, it is unlikely to be of consequence to the patient; surface cracks and radial cracks can only be seen under certain lighting conditions, whereas catastrophic failure is obviously important. Pertinently, the loads needed to cause final catastrophic failure tended to be considerably larger than those needed to cause initial fracture, especially as enamel, porcelain, or their combined thickness increased (Figs. 1-3). Therefore, a veneer even with initial damage could survive, possibly indefinitely, until a substantially higher load was eventually applied. These data suggest that damage tolerance could be increased by retaining enamel thickness during preparation and by maximizing porcelain veneer thickness during restoration.

Initial Hertzian cone cracks occurred at relatively low loads (Figs. 1-3). These data could be interpreted to suggest that areas of occlusal contact should be maintained on intact enamel, because increased porcelain thickness does not increase the loads needed for Hertzian crack initiation. Also, accidently occluding on something hard like a piece of bone could easily initiate damage. These data may also apply to porcelain onlays. These risks of contact damage may be inevitable[58] because increased thicknesses of enamel and porcelain could also be protective of catastrophic failure.

The findings that increased porcelain thickness, enamel thickness, and combined porcelain and enamel thickness slightly decreased the load needed to cause initial cone crack fractures may at first appear counterintuitive. However, cone cracking is more likely to occur when flexure of the substrate is constrained.[59,65,66] Therefore, increasing the thicknesses of relatively stiff porcelain and enamel decreases overall specimen flexure, slightly favoring the initial surface fracture event but greatly helping to prevent final catastrophic fracture.

These results demonstrated that maximizing both remaining enamel thickness and porcelain thickness were important in preventing catastrophic failure. However, esthetics and hygiene limit practical clinical applications. Doubling the thickness of enamel, porcelain, or their combined thickness increased the loads needed to cause catastrophic failure by approximately 1.5 times (Figs. 1-3). These data suggest that nonpreparation veneers may have significant advantages in preventing catastrophic failure and avoiding dentin exposure, along with the concomitant risks of microleakage, sensitivity, and debonding. Enamel is generally thin in the gingival thirds of the facial surfaces of incisors, 0.3 to 0.5 mm, so preparation must be extremely conservative in that area.[54] By virtue of limited enamel and porcelain thickness, cervical areas will be more susceptible to catastrophic failure when loaded. Likewise, thin porcelain should be avoided in areas of high stress.

Preservation of enamel thickness should be prioritized whenever possible. Unlike porcelain, enamel is not replaceable. Furthermore, the integrity of the dentinoenamel junction zone must be preserved.[3-5] Moreover, retaining sufficient enamel is prudent in the event that the veneer needs to be replaced during the patient's lifetime.

The trends identified in this study were clear and consistent; however, considerable scatter in the data was evident (Figs. 1-3). Brittle fracture has a high inherent variance; feldspathic porcelain and enamel are both brittle. Furthermore, real incisors were used to support the porcelain veneers and had inherent differences in form and overall size; their histories before extraction were unknown.

Although this experimental model used a blunt spherical indenter to load the specimens, flexural tensile radial fracture of the veneers was produced (Figs. 1-4), as has often been reported clinically.[12,15-18,30,33,35,39,42,44,46] The results were broadly consistent with the few studies reporting on the effect of porcelain thickness on veneer fracture.[52,53,67] As in other layered systems where the elastic modulus mismatch was small, the first fracture event occurred on the top outer surface, whereas in layered systems where the mismatch was large and the underlying layer flexible, the first fracture event tended to occur at the lower internal surface.[62,65,66,68] Therefore, porcelain veneers (or other restorations) that are bonded, or bonded in part, to dentin may behave in a different manner from those bonded to enamel; additional study is needed.[11]

CONCLUSIONS

For a bonded feldspathic porcelain veneer model system:

1. Increased enamel thickness, porcelain thickness, and increased combined enamel and porcelain thickness all profoundly raised the loads to catastrophic failure.
2. Enamel and feldspathic porcelain behaved in a like manner.
3. Initial damage was from surface contact; intermediate radial cracks originating from the inner intaglio surface followed; lastly, catastrophic failure occurred.
4. Bonded porcelain veneers were highly damage tolerant.

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