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FRACTOGRAPHIC ANALYSIS OF BROKEN CERAMIC DENTAL RESTORATIONS

G. D. Quinn
Volpe Research Center
American Dental Association Foundation
Stop 854-6, NIST
Gaithersburg, MD 20899

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ABSTRACT

This presentation shows fractographic analyses of seven fractured ceramic bridges and one crown made with modern dental restorative materials. The overall breakage patterns were evaluated and stereoptical and scanning electron microscopy used to find the causes of fracture. There were multiple causes of fracture, but faulty restoration design or fabrication laboratory faults accounted for most fractures. Fracture stresses were relatively low.

INTRODUCTION ^{1,2,3,4,5,6,7,8,9}

All-ceramic restorations are now being used in increasing numbers in prosthetic dentistry. Crowns are restorations to a single tooth. Bridges are restorations involving multiple teeth and are termed fixed partial dentures (FPDs). Sometimes restorations break and it is important to identify the causes of fracture so that manufacturers, clinicians, and laboratory technicians can minimize the incidence of breakage. Identification of the mechanisms of fracture can help researchers can develop clinically relevant testing procedures. Analysis of ceramic restorations can be difficult. Rarely are there fracture mirrors centered on an origin. Fractographic analysis is a cumulative learning experience and we have been analyzing as many fractured restorations as we can to increase our experience base and to identify the causes of fracture. This is the latest in a series of papers to present case studies on this topic.¹⁻⁹ Six of the cases have not been published previously.

EXPERIMENTAL PROCEDURE

Several fracture cases occurred *in vivo*, that is, in the patient's mouth after installation. Several occurred during fabrication in the dental laboratory. All the matching pieces were available in some cases, but in others, only one or two critical pieces were retrieved. Conventional fractographic analysis techniques with stereoptical and scanning electron microscopy were performed in accordance with the Guide to Fractography.¹⁰ In some cases the fractures were easy to interpret, but in others a systematic approach to analyze a fracture was necessary.⁵ The local directions of crack propagation across the fracture surfaces were interpreted utilizing markings such as wake hackle from pore/bubbles in the veneer and twist hackle in the framework or veneer ceramics. Detailed maps of the entire fracture surface were made in some instances. It was possible to back track to an origin site for each case. Although a fracture analysis may require a dozen or even a hundred photographs, only the primary results and a few illustrative figures are shown in this manuscript due to space limitations.

RESULTS

The eight case studies, including seven bridges and one crown, are summarized in Table 1 and analyzed in order below. Six fractures occurred *in vivo* and two were in the laboratory.

Table 1. Cases analyzed

Case	Teeth	Clinical	Material ^a	Cause of fracture
B1	Posterior bridge +	Broke <i>in vivo</i> 2003	Dentsply-Ceramco Cercon CAM zirconia	Break in bending at the connector from grinding cracks.
B2	Training course bridge with one incisor +	Broke in the lab 2003	Dentsply-Ceramco Cercon CAM zirconia	Broke in the lab during preparation. The origin was bubbles and damage in the veneer.
B3	Training course 4 unit posterior bridge +	Broke in the lab 2003	Dentsply-Ceramco Cercon CAM zirconia	Broke in the lab during preparation. The origin was bubbles and damage in the veneer.
B4	3 unit bridge, anterior #8 - #10*	Broke <i>in vivo</i> at 4 years, 2009	alumina-glass composite, Vita Inceram alumina?	Margin initiated crack near connector, propagated by hoop stresses Ref. 9
B5	3 unit bridge, units European #25 - #27 **	Broke <i>in vivo</i> at 4 years 2011	alumina-zirconia with glass, Vita Inceram AZ?	Faulty preparation. The connector was too thin but also was cracked during fabrication. The crack was sealed by glass.
B6	3 unit posterior bridge ***	Broke <i>in vivo</i> at 7 weeks 2011	Ivoclar/Vivadent e.max Press lithium disilicate	Connector fracture from normal loading. Origin was a tiny contact damage site in the veneer. The connector was too small.
B7	5 unit telescoping bridge	Broke 2 days <i>in vivo</i> after installation 2010	Zirconzahn zirconia	Faulty preparation. A two stage fracture. Thermal crack during fabrication started at an adjustment and other damage in the core surface. Final fracture from cantilevered loading in the patient's mouth. Ref. 9
C1	Incisor crown, European #13 ****	Broke in 14 months <i>in vivo</i> 2011	Zenotec Zirox zirconia	Residual stresses from firing caused a crack in the veneer. The crack grew and caused the entire veneer to detach.

+ Courtesy Dr. V. Sundar, Ceramco, York, PA, USA.

* Courtesy Dr. E. Brzozowski, Florida, USA.

** Courtesy Prof. T. Kosmac, Joseph Stephan Institute, Slovenia.

*** Courtesy Dr. S. Gritz, North Potomac, MD, USA

**** Courtesy Dr. G. Arnetzyl, Vienna, Austria.

? Probable material type, see text.

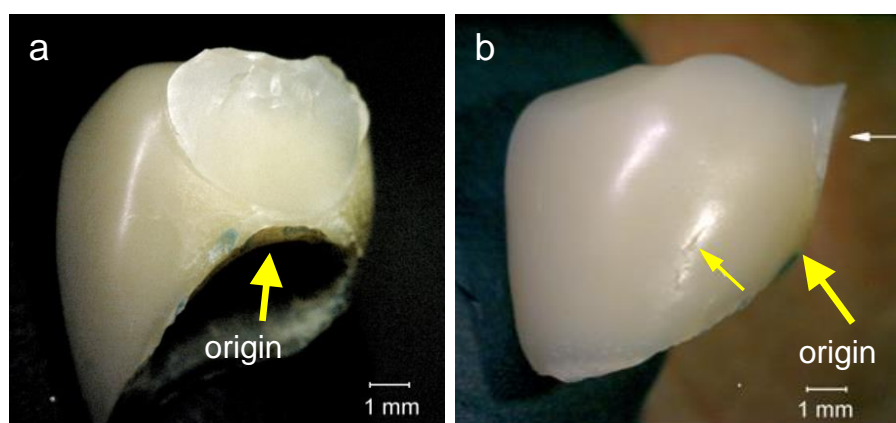


Figure 1 Case B1. Views of the fractured zirconia bridge. The origin was on the underside of the connector. A small medium-sized arrow in (b) shows a large sintering crack.

^a Commercial products and equipment are identified only to specify adequately experimental procedures and does not imply endorsement by the authors, institutions or organizations supporting this work, nor does it imply that they are necessarily the best for the purpose.

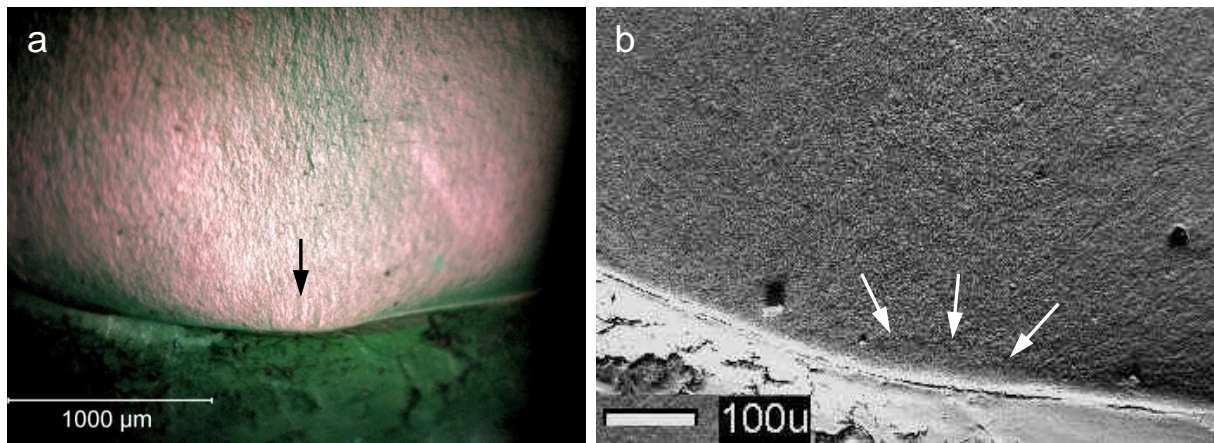


Figure 2. Case B1. Views of the origin site. (a) The low magnification optical image shows hackle leading back to the origin site as well as localized machining crack hackle at the origin itself. (black arrow). (b) Dr. J. Quinn used montages of many SEM photos to painstakingly create a map leading back to this site. She marked the origin grinding flaw with the arrows shown. The small steps and shadows in (a) are washed out by the SEM.

CASE B1: A zirconia bridge

This Cercon CAM (computer assisted machining) prepared zirconia bridge fractured *in vivo* 2003. No documentation was furnished and only one piece was retrieved. Figure 1 shows that the fracture occurred at the connector to an end molar unit. The connector had a good cross section size. Figure 1b appeared in the Guide to Fractography as illustration (Figure 4.7a) of how a large sintering crack could be present in a ceramic, but not necessarily act as a fracture origin. Figure 2 shows the fracture surface and radiating hackle lines led back to the origin site. The origin was on the underside of the connector was grinding cracking that generated “machining crack hackle” once fracture occurred. These are described in detail in Refs. 11,12,13. They are much easier to see with a low power optical microscope (Figure 2a) than with the scanning electron microscope (SEM) (Figure 2b).

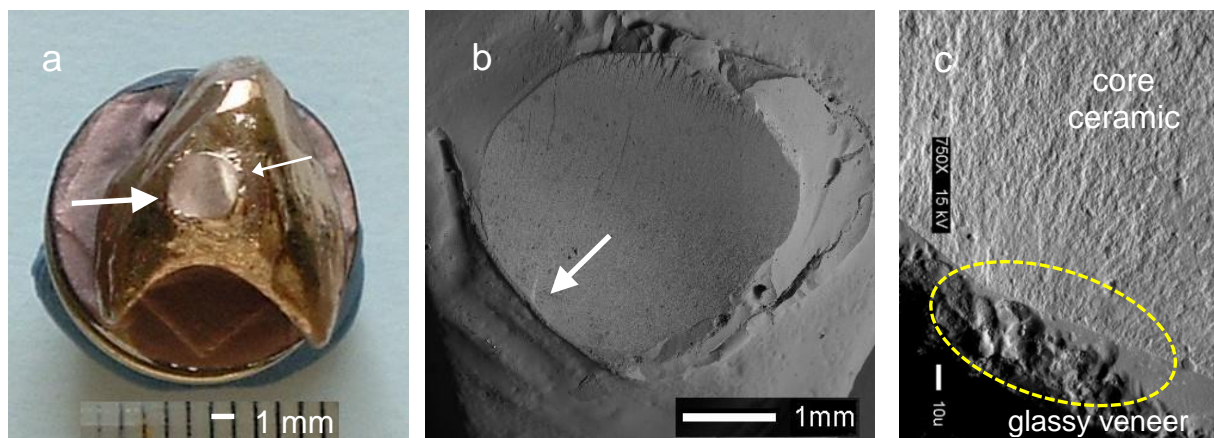


Figure 3. Case B2. A laboratory fractured zirconia bridge. (a) shows the gold-coated incisor end unit. The connector size is too small. The small arrow in (a) shows a compression curl. The large arrow shows the origin site. (b) shows the fracture surface and (c) shows the origin which is damage in the veneer (circled) that propagated a crack into the ceramic core.

CASE B2: A training course zirconia bridge

This Cercon CAD zirconia bridge fractured in the lab in 2003 during fabrication training. Only an incisor end unit (Fig. 3) was available. The connector size (≈ 2 mm) was too small. The low magnification image (Figure 3a) shows a compression curl which is indicative of a bending fracture. The origin is located opposite to it. This bridge broke primarily from a sideways force probably from mishandling or possibly during the grinding. SEM images (Figures 3b,c) show the fracture surface is very smooth and almost featureless, indicative of a low energy, low strength fracture. The origin was microcracking and bubbles in the veneer. They combined to make a crack that propagated into the core. Additional SEM images (not shown) show the core crack progressed in stages with multiple concentric semielliptical arrest lines.

CASE B3: A training course four-unit posterior zirconia bridge

This also was a training course restoration. Figure 4a shows that this bridge was designed to be supported by three abutments. Fracture occurred at one connector to the pontic. This connector was too small. The location of the compression curl indicated that this bridge also broke from sideways flexure. It also was a low energy, low strength fracture. Optical photos in Figure 5 confirmed that the origin comprised irregularities in the veneer as well as “zipper machining cracks” in the core ceramic from machining.

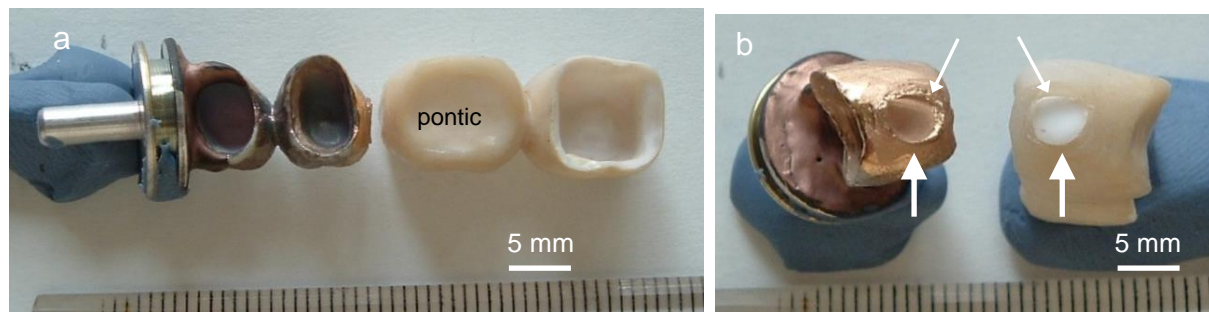


Figure 4. Case B3: A four-unit posterior zirconia bridge in (a). The piece on the left is gold coated. (b) shows the fracture surfaces with the piece's occlusal surfaces mounted back-to-back. Compression curls are marked with small arrows. The origin is marked by the large arrows.

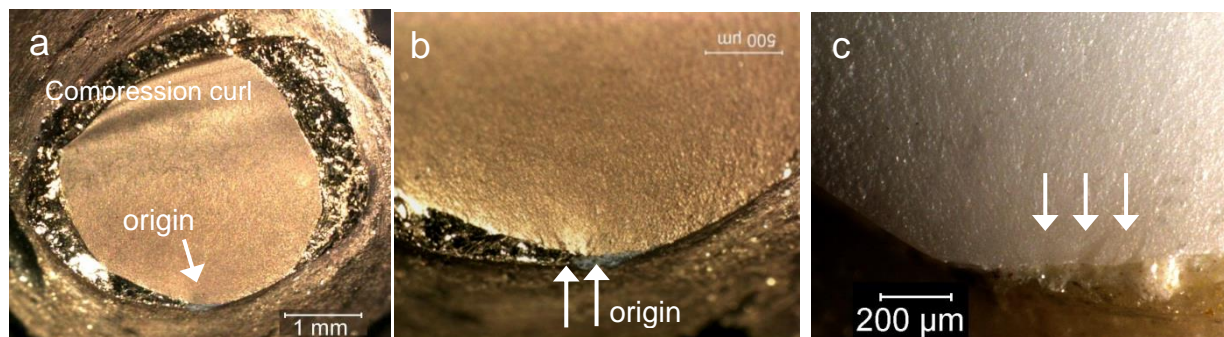


Figure 5. Case B3. Optical views of the fracture surface. (a) and (b) are gold coated. The origin is a series of small grinding cracks in the core that were covered by the veneer. Gold coating and vicinal shadow illumination make the “zipper machining crack” hackle lines easy to see with optical examination. They were not evident with high magnification SEM examination. (c) is a simple optical image of the uncoated fracture surface taken by Dr. J. Quinn in 2003 that also shows the grinding crack hackle and veneer irregularities.

CASE B4: A three-unit alumina bridge

This was a three-unit anterior maxillary bridge, shown in Figure 6, which fractured at the connector to the right central incisor in mid-2009 after approximately four years in the patient's mouth. This case was presented in some detail in Ref. 9 and this case included here for comparison to the other bridge cases. The bridge was cemented to abutments on the end two units #8 and #10. The clinician who donated the broken FPD detected a crack in the incisor (#8) during a routine checkup and monitored its progress with time. When fracture occurred, he was able to retrieve units #8 and #9 on either side of the fracture plane. The clinician believed that the restoration was a zirconia, but our analysis showed that it was actually glass-infused alumina.

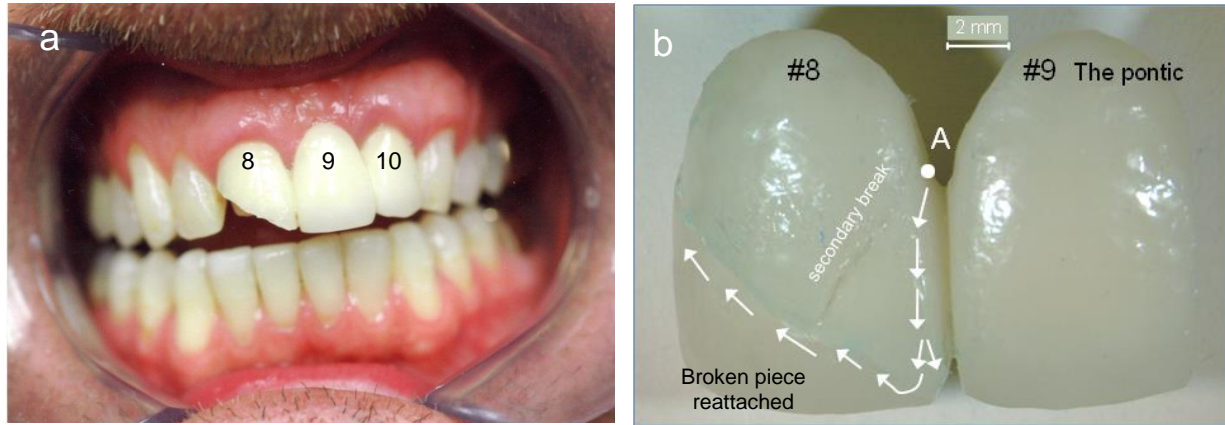


Figure 6. Case B4. The three-unit anterior maxillary bridge which broke through the side of the incisor unit #8 as shown in (a). Crack propagation occurred as shown by the arrows in (b). The triangular broken fragment was reattached for this photo.

Figure 6b shows a close-up with arrows marking the direction of crack propagation (dcp) away from the origin site A, which was on the margin. Figure 7 shows the fracture surface. The crack went down the side wall of #8 to the incisal edge. It then went around the restoration and caused a large triangular piece to break off. The origin region is shown in Figures 7a and 8. There were no severe material irregularities or gross flaws at the margin. The lack of a fracture mirror indicated the fracture stress was low. The margin was well-prepared and had a smooth rounded edge. Nevertheless, there is a small crack at the bottom, and combined with hoop stresses acting on the rim of the unit (presumably created by occlusal biting forces), the crack propagated up the thin wall of the tooth and split it. This is a failure mode that has been observed before in a number of single crowns, especially if they are very thin or if the margin is damaged during manufacture or installation. As a consequence, it is strongly advised to not use “knife-edge” or “feather” margins, which some clinicians like to use for aesthetic reasons. Such restoration margins are simply too vulnerable even if a strong ceramic is used.

Figure 7b shows an SEM image of a polished portion of a fragment from core ceramic portion of the specimen. It is a two-phase material with residual porosity. The primary constituents were aluminum, calcium, lanthanum and silicon. This is not a zirconia restoration, but most likely that of a glass-infused alumina and is likely Vita Inceram alumina.

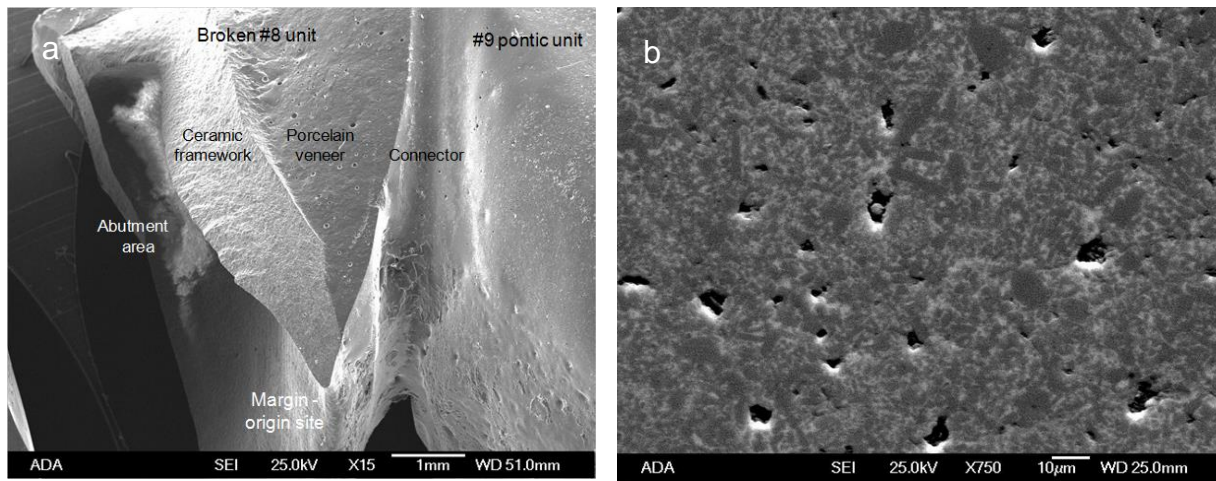


Figure 7. Case B4. (a) is a SEM image of the fracture surface on unit #8. The layered structure of a ceramic restoration is revealed. The thin tapered margin blends into the gum line and is the site of the fracture origin. This origin site is near to, but not at, the connector to the next unit, #9. (b) shows the core ceramic microstructure.

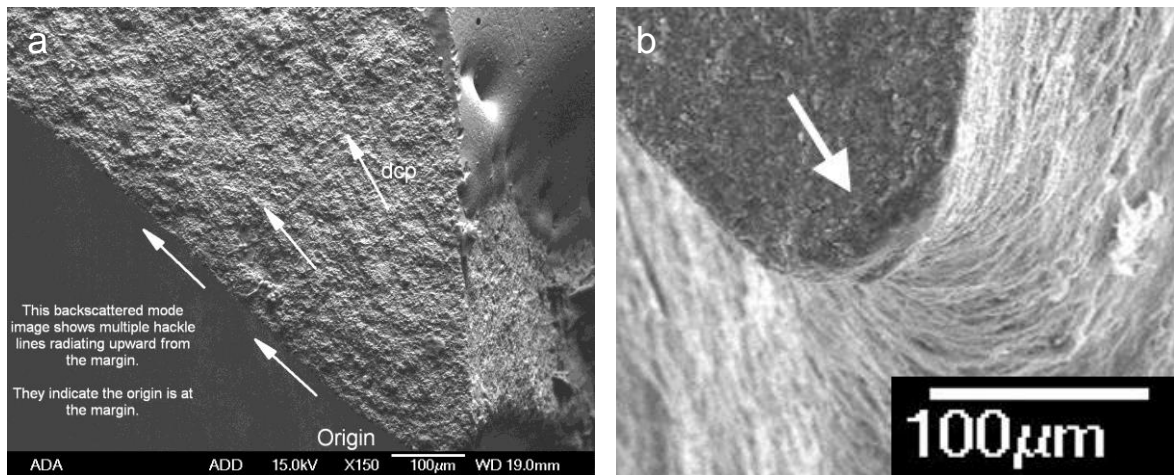


Figure 8. Case B4. SEM close-ups of the margin region showing hackle lines that indicate the dcp. Fracture started at the tip of the margin (large arrow on the right image). The margin is smooth and rounded and has no obvious faults, with the exception of a possible tiny crack.

CASE B5: Three (or more) unit zirconia bridge

This was a three (or more) unit anterior bridge, shown in Figure 9, which fractured in European unit #25 near to but not at the connector in 2011 after 4 years *in vivo*. This case has not been documented previously. Only three pieces were obtained from one end of the restoration and the documentation was incomplete. Two of the three fragments were separated during extraction. The clinical fracture face was on the left on unit #27 as seen in the figure. Units #27 and #26 were fitted to abutments, but #25 was cantilevered. The restoration was prepared during a training course and was designed by an experienced elder dental technician, but fabricated by an unknown attendee in the course. The bridge framework was made with a Sirona copy milling machine. The fracture surface (Figs. 10 and 11) and the underside of the proximal connector (Fig. 9b) had very unusual markings. The veneer was badly crazed on the connector underside, indicating an improper composition or application, or improper furnace operation.

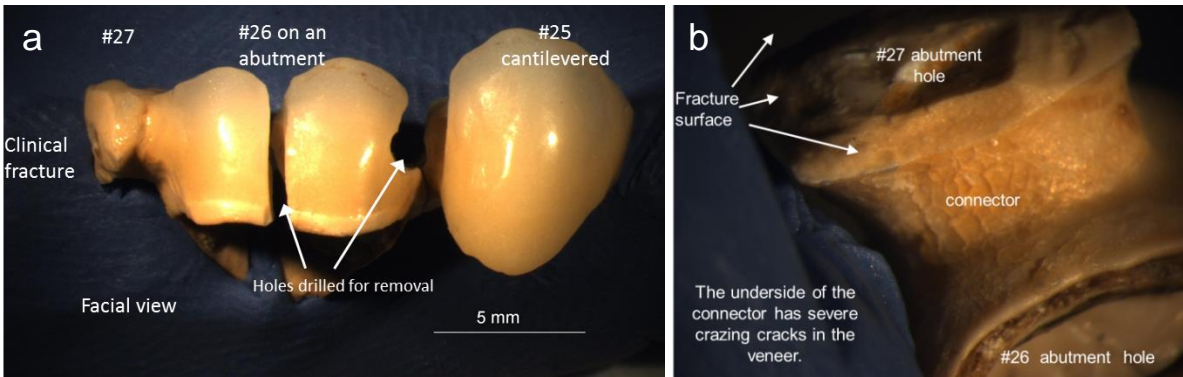


Figure 9. Case B5. Multiunit zirconia bridge. The underside of the connector and the fracture surface had very unusual features.

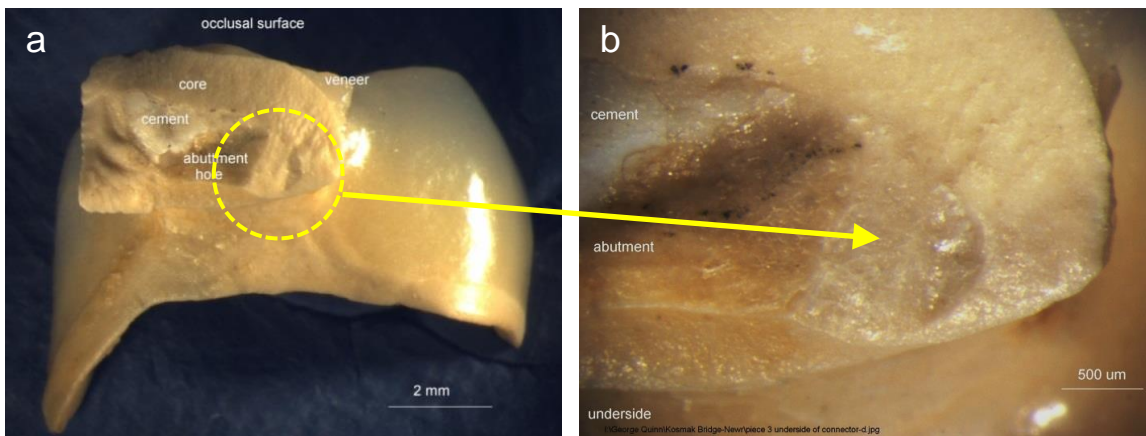


Figure 10. Case B5. Views of the fracture surface. Half of the fracture surface on either side on the bottom (circled) was extremely rough and the microstructure did not match that of the core material on the upper half of the fracture surface. Notice the glassy appearance of the material as shown on the right in the vicinity of the arrow tip.

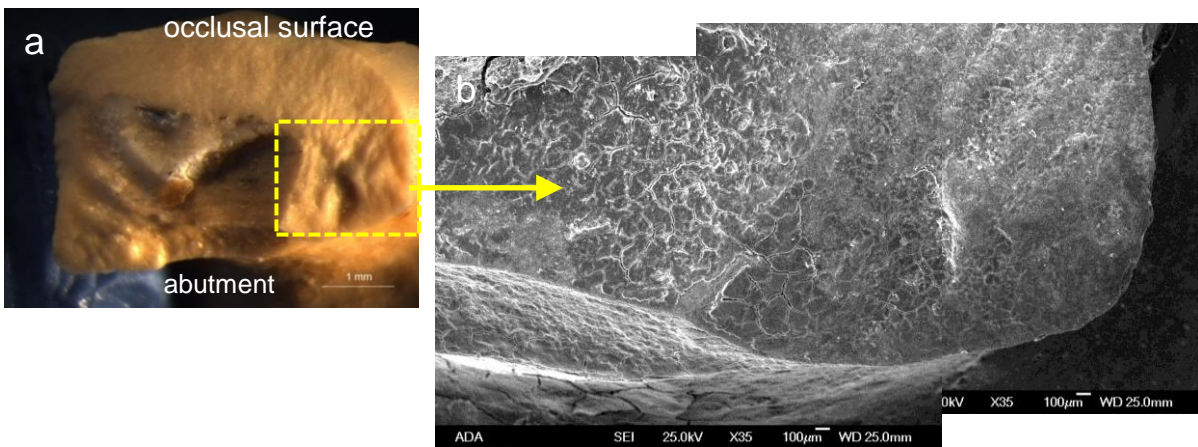


Figure 11. Case B5. Views of the fracture surface. (a) shows another view of how irregular the fracture surface was. (b) is a composite SEM image that shows the extraordinary crazing and cracking on the rough zone.

Energy dispersive spectroscopy revealed that (on a side of the bridge well away from the fracture location) the veneer contained elements typical of a feldspathic veneer: Si, K, Ca plus traces of Ti, Cr, Fe, Cu, Zn in addition to some signals of Zr, Y and Al from the core, but no La. The veneer glass composition on the connector underside where the crazing occurred was identified as Si, K, Ca, Cu or Zn, and some La as well as the Zr and Al from the core. The abnormal material on the rough part of the fracture surface was composed of strong Zr, Y, Al, Si, La, K, Ca, Zn, and possible Ti. The Zr, Y, Al, Si, and La are characteristic of Inceram AZ material, but the material in the rough zone appeared very glassy and was transparent, unlike the core material exposed at the top of the fracture surface.

No distinct fracture origin was detected, but on the basis of the extremely unusual fracture surface morphology and glassy structure of the framework material in the fracture site, it is believed that this bridge was cracked during a step in the fabrication process. Glassy material from the core and veneer “healed” the crack and the restoration survived *in vivo* for 4 years. One wonders whether the veneer crazing on the underside of the connector should have warned the technician or the clinician that something was amiss. The connector also was too small: measuring only 2 mm to 2.5 mm in height.

CASE B6: Three-unit e.max Press lithium disilicate bridge

This three unit bridge broke in 2011 after seven weeks *in vivo* (Figure 12). When the patient was seen by the dentist, both connectors were broken, but the pontic section was still in place from mechanical interlocking. The connector shown on the right (Fig. 12c) fractured first, and continued occlusal loading and usage caused the second connector (Fig. 12a) to break from bending. Only the middle unit, the pontic was available for examination, but fortunately it had

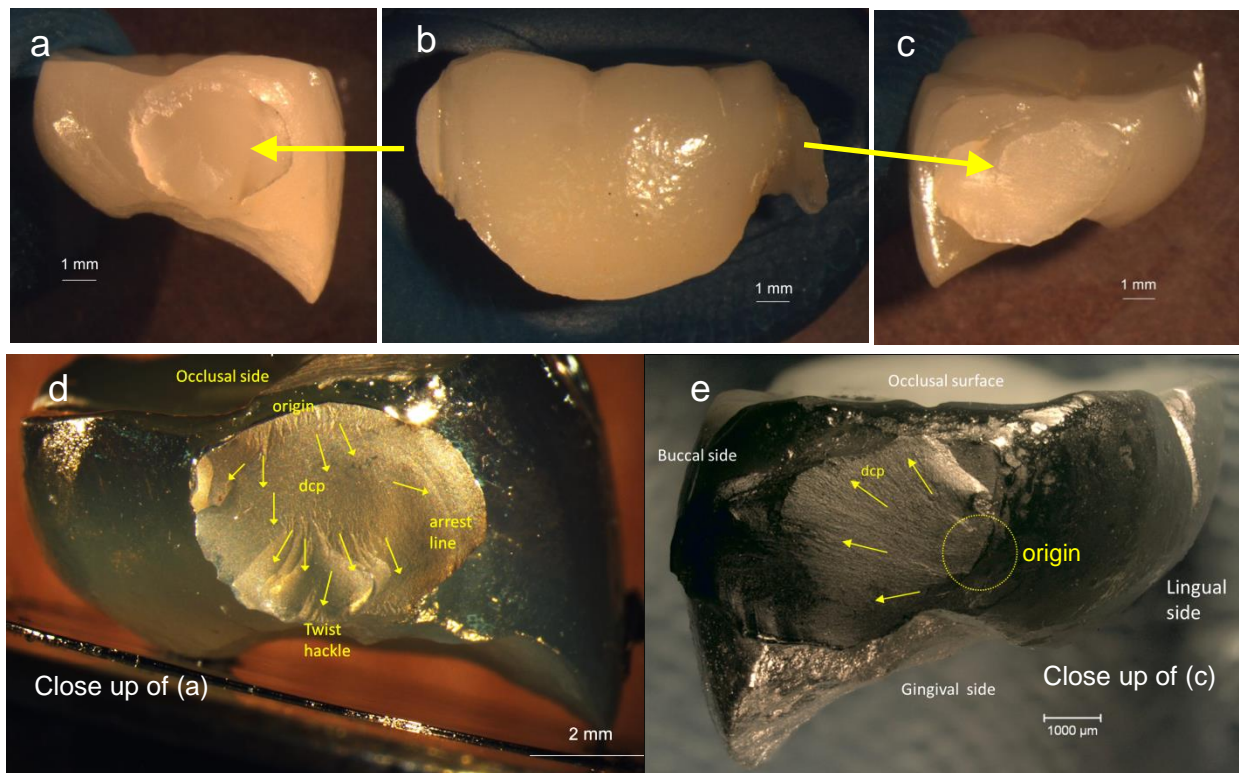


Figure 12. Case B6. Middle molar unit of a three-unit bridge. The wing photos (a) and (c) show the fractured connectors on each side. (d) and (e) are close-ups of both broken connectors after gold coating. The right connector broke first and has a flatter and straighter fracture plane.

both fracture planes. The connector cross section sizes were probably too small for this glass ceramic. The secondary fracture started with an origin at the top. There was a lot of twisting and bending of this fracture surface, and this location suggested that this fracture was the second fracture. The primary origin was on the right side from the gingival-lingual area. Close-up examination (Figure 13) revealed that the origin was a single small contact damage site on the veneer outer surface. Cracking propagated in short steps through the veneer, and then into the core, also in a few steps until final catastrophic fracture occurred. Close-up photos of the contact site (not shown here due to space limitations) reveal classical tertiary Wallner lines and localized hackle radiation right at the contact site. Since it is down on the inside of the mouth, the patient would have had difficulty inflicting damage at this site. It is more likely that a dental probe or tool in the dental lab created the initial damage. This is an excellent example of a serious issue in ceramics: one small spot or vulnerable in a surface coating can act as a weak link. The core ceramic itself can be nearly perfect, with no flaws, but once the crack initiates in the coating, it can easily propagate into the bulk.

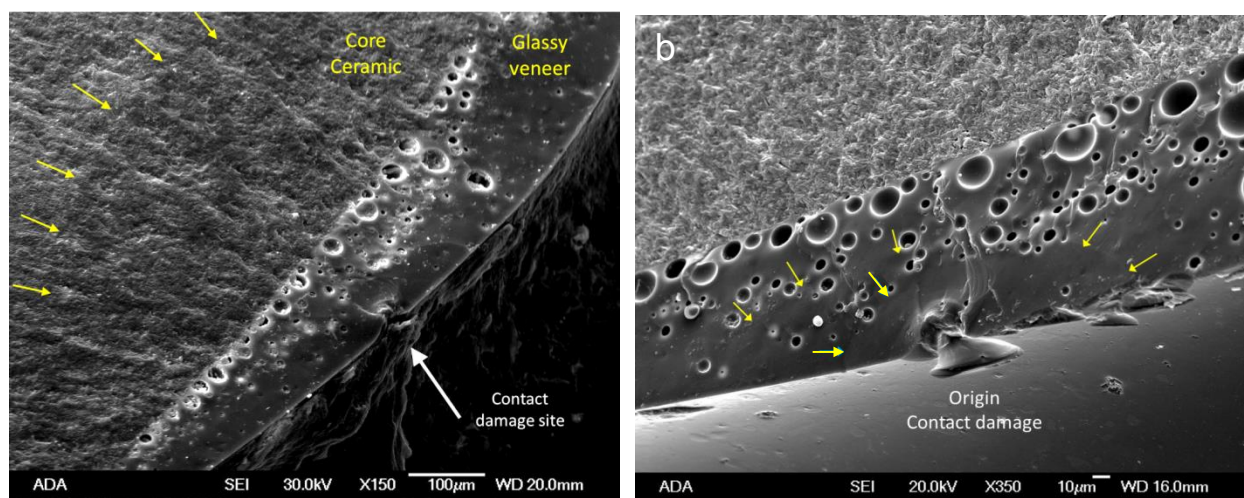


Figure 13. Case B6. SEM close ups of the origin. Radiating hackle lines converge on the origin region. The small arrows in (a) mark a subtle curved crack arrest line in the core ceramic, one of many such concentric arcs. Close-up examination of the origin in (b) reveals tiny wake hackle lines radiating behind the pores, and multiple arrest lines (marked by small arrows). Fracture initiated at the single contact damage site in the veneer outer surface, and propagated in steps through the veneer and then on into the core ceramic.

CASE B7: A five-unit zirconia telescoping denture

Three segments were used to replace the entire upper dental arch including substantial missing hard and soft tissues as shown in the left of Figure 14. This case has been presented in detail previously.⁹ Six implant posts supported the segments. The segment that fractured after installation was the five-unit telescoping denture made of a single large piece of veneered zirconia as shown in Figure 14a. It ran from the upper left lateral incisor to the upper left first molar and was attached to two screw implants that anchored the part at the incisor and second premolar teeth. The cantilevered end unit broke off the restoration in 2010 only 2 days after cementation. The patient exerted normal biting forces. This fracture was very surprising since the last molar was connected to the rest of the restoration by a very large 10 mm x 12 mm cross section. It is hard to imagine that a patient could apply sufficient biting forces to snap off such a

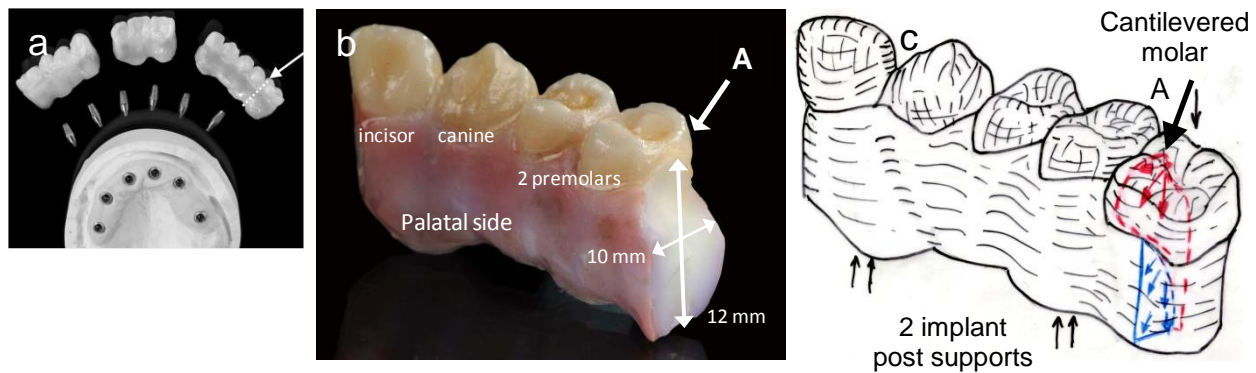


Figure 14. Case B7. Overall view of the fractured 5-unit denture. (a) is a laboratory view of the three segments comprising the maxillary arch with the location of the supporting screw implants. Fracture occurred (arrow) in the right side 5 unit segment where the last molar was cantilevered beyond the implant post. (b) and (c) show the fracture. The origin was at site A.

large, stubby zirconia cantilever.

The zirconia was CAD/CAM machined from presintered zirconia blocks and then partially reduced in size in some areas for the application of a porcelain veneer. The core ceramic was colored, sintered, and then the veneer was then applied. All processing steps were carried out in accordance with manufacturer's guidelines. The clinical aspects of this case have been documented by Karl and Bauernschmidt.¹⁴ There were two main intersecting crack systems as shown in Figure 15a. The first crack was a very smooth and almost featureless thermal crack

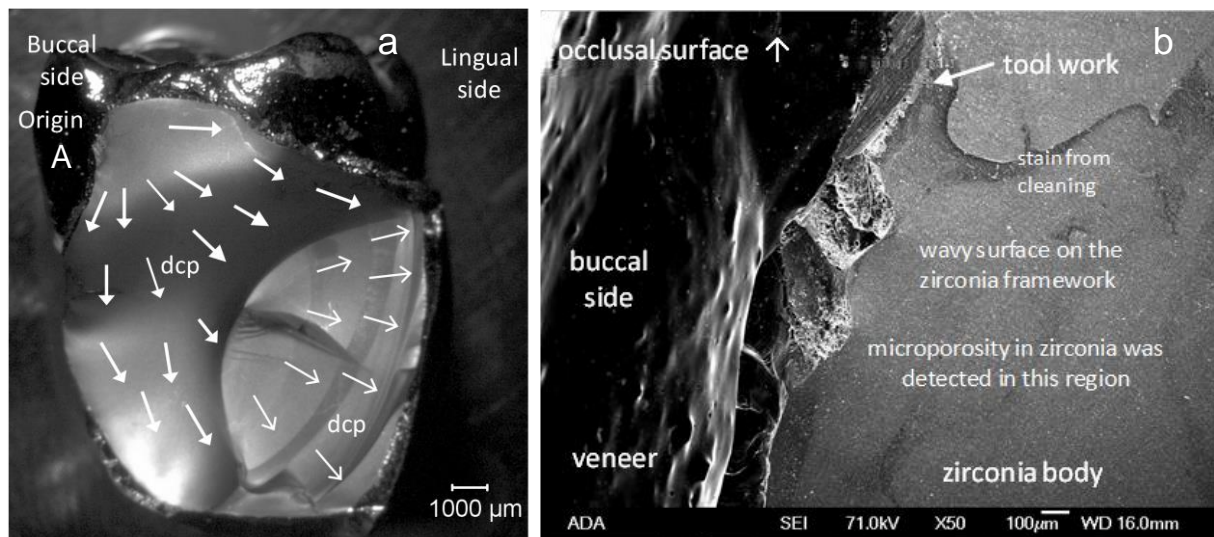


Figure 15. Case B7. Stereoptical microscope images of the gold-coated molar unit that broke off the end. The initial starting point of fracture is in the upper left in (a). A thermal crack popped in more than halfway through the piece as shown by the first set of arrows. Final fracture radiated in steps outwards towards the lingual side as shown by the second set of arrows. (b) shows a close-up of the origin site A. The core ceramic had some surface irregularities in the surface including waviness. The veneer also had grinding-adjustments that penetrated through the veneer into the core ceramic.

that popped in from origin site A during processing. The crack ran halfway through the piece and severely weakened it. The second fracture occurred when the end molar finally broke off in the patient's mouth. Close-up SEM examination of the origin shown in Figure 15b revealed irregularities in the core ceramic surface plus some grinding adjustment damage.

Very smooth, almost featureless, wavy fracture planes are commonly generated by thermal stress fractures. These can occur from: sudden temperature changes, thermal gradients set up by non-uniform heating or cooling, or internal residual stresses set up during firing. It cannot be ascertained with certainty whether the first crack formed during the cool down or after removal from the furnace. It is very likely that the veneer covered a cracked foundation piece or the crack may have popped in during the firing of the veneer.

CASE: C1 Incisor zirconia crown

This case has nothing in common with the previous seven, with the exception that it too was a very unusual fracture. It was provided by the clinician from Vienna, Austria who dutifully reported the material system, the dental laboratory, the duration prior to fracture and the fact that it broke during normal bite functioning. Figure 16 shows the broken piece, which as subsequent analysis showed, was all porcelain veneer! It appeared that it completely detached from the core zirconia ceramic. Fractographic images with optical (Figure 17) and scanning electron microscopy (not shown) revealed that fracture started on the inside of the crown, about 0.5 mm below the outer crown surface. The fracture was entirely within the two layer veneer, and propagated entirely around the tooth without penetrating into the zirconia at all. The zirconia part of the crown remained in the mouth attached to the abutment, but had to be extracted and replaced. The veneer porcelain was primarily composed the usual elements of a feldspathic porcelain and included Si, Al, Ca, K, Fe but also a surprising amount of Cu. The origin crack, and especially its location, is very unusual and suggestive of a thermal crack possibly created during cool down. Figure 17c shows an extraordinary array of concentric semicircular cracks radiating outward from the origin. These are arrest lines and probably correlate with fatigue stepwise growth of the crack. This fracture sequence is similar to another veneered zirconia crown analyzed by Lohbauer in 2011.¹⁵ In that case, the crack popped into the veneer from occlusal surface contact damage, and then curved around the porcelain and the interface avoiding the zirconia core. There is steadily growing literature (e.g., Tholey et al., Ref. 16) showing that cool down rates through the glass transition temperature and thermal gradients in furnaces and restorations create strong residual tensile stresses in zirconia veneers.

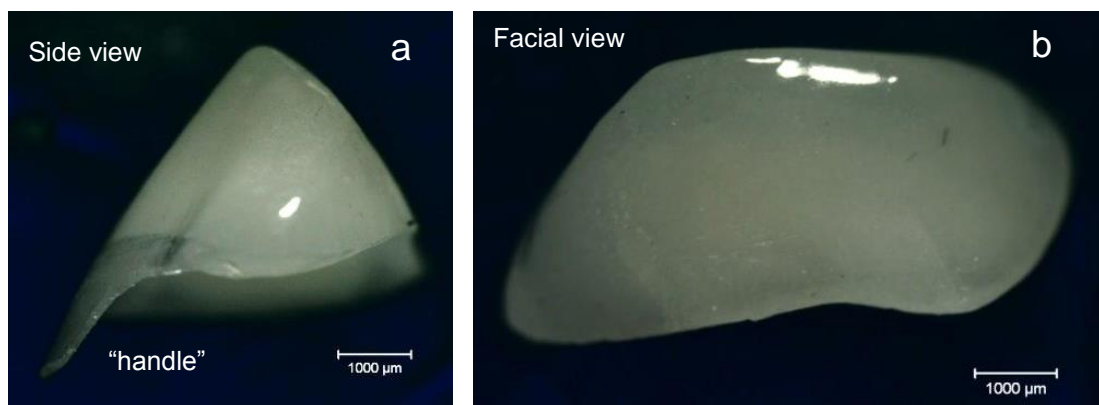


Figure 16. Case C1. Detached porcelain veneer on the incisor crown that broke in-vivo at 14 months. The side extension of the crown is termed a “handle” for orientation convenience.

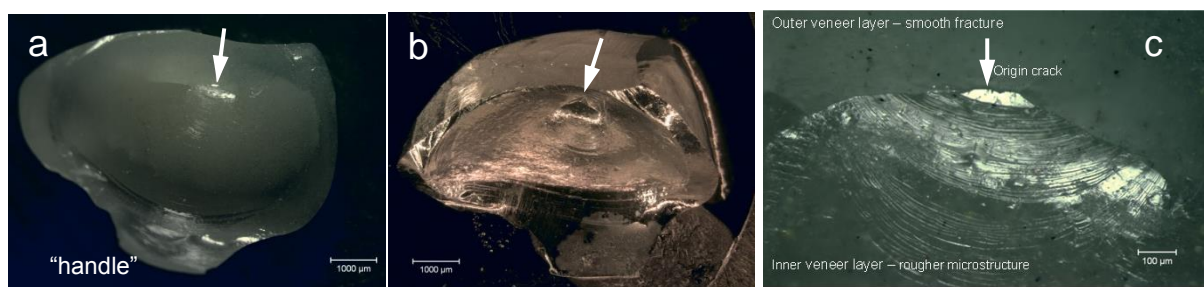


Figure 17. Case C1. Images of the interior surface. The fracture origin is an internal crack (large arrows) that started entirely in the outer veneer and then propagated into both porcelain layers in steps creating concentric arrest lines.

DISCUSSION

As noted in the introduction, it is important to identify the causes of fracture so that manufacturers, clinicians, and laboratory technicians can minimize the incidence of breakage. Identification of the mechanisms of fracture can help researchers can develop relevant testing procedures. Table 1 shows that there were multiple causes of failure including faulty design of the restoration, faulty preparation, or damage from clinician handling or adjustments. There were no fracture mirrors, so all the fractures occurred at relatively low stress levels.

These examples reinforce some lessons learned in earlier analyses. Design issues such as thin margins (Case B4) or connectors that are too small (Cases B2,B3,B5) are known contributors to fracture. Grinding cracks from CAD machining (Cases B1-B3) can create strength limiting flaws that are often easier to see optically than in the SEM. Other large (thermal) cracks may be created in the core material in the laboratory and may be sealed over by the veneer (Cases B5,B7) but severely compromise the integrity of the restoration. Chipping and delamination of veneers from zirconia crowns (Case C1) can be a problem. There also is a new growing literature of origin cracks forming in veneers, especially at concentrations of bubbles or from contact damage, and then propagating into the core. The veneers are supposed to be in residual compression, but if they are irregular with bubble clusters (Case B6),⁸ too thin, or damaged by the lab or clinician (also Case B6), they can act as fracture initiation sites. Careful application of veneers is important.

We are encouraged that fractographic analysis is increasingly being used to study clinical fractures, and that clinically relevant laboratory testing procedures are being developed as a result.^{17,18} These are far more valuable¹⁹ than “crunch the crown” type tests that were fashionable in the 1990s and 2000s.

CONCLUSIONS

Seven bridges and one crown fractures were analyzed. Several fracture modes and origin types were identified. These cases illustrate that all-ceramic restorations are susceptible to fracture from a variety of causes. Proper design and fabrication procedures must be established and followed to eliminate *in vivo* fractures.

ACKNOWLEDGEMENTS

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