TRANSLATING DENTAL PERFORMANCE INTO ENGINEERING SCIENCE WITHIN A SENIOR CAPSTONE DESIGN PROJECT

by

Dr. GLENN E. VALLEE, Ph.D., P.E.

ASSOCIATE PROFESSOR

MECHANICAL ENGINEERING

WESTERN NEW ENGLAND COLLEGE

SPRINGFIELD MASSACHUSSETS

and

Dr. RICHARD P. BENIOT, DMD

DIRECTOR OF DENTAL SERVICES

UNIVERSITY OF CONNECTICUT HEALTH CENTER

FARMINGTON, CONNECTICUT

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ABSTRACT

A capstone senior design project in mechanical engineering at Western New England College was developed to provide a student the opportunity to work with dental professionals to determine the causes of porcelain crown failures, and to recommend improvements in crown design and installation [1]. The project afforded the student a unique opportunity to understand how component performance as viewed by the engineer can differ greatly from that of the medical professional. From a dental perspective, performance was viewed as the durability of the crown when bonded using a dental adhesive. From an engineering perspective, this performance was quantified using measurements of material properties in both the bonded and unbonded conditions in both quasistatic and dynamic loading conditions, the later derived by relating approximate human bite forces and loading rates to dynamic modulus and energy absorption up to fracture. Charpy Impact tests were used to characterize energy absorption at moderate loading rates, and the Split Hopkinson Pressure Bar technique was used to determine both the energy absorbed and dynamic modulus at very high loading rates. The problem was complicated by difficulties in the determination of dynamic strength due to the brittle nature of the porcelain. The strength and fracture resistance of the porcelain material was greatly enhanced by the bonding adhesive, as supported by the locations of actual crown failures in patients which occurred away from the bonding region. The study resulted in a number of recommendations for improving performance through variations in crown geometry and bonding. A number of challenges were overcome regarding the management of a dental-mechanical engineering project as a balance between the expectations of the dentist and the requirements of the senior capstone design course needed to be achieved.

I. INTRODUCTION

The installation of porcelain crowns has become a common solution to the problem of severely eroded or cracked teeth. Advanced manufacturing techniques are now used to fabricate crowns which usually restore the tooth to its previous size and shape while improving its durability. The chemical and thermal resistance of porcelain make it ideal for use in the human mouth, and its hardness is usually equivalent to or greater than that of the original tooth enamel. The porcelain displays a very high tensile strength and elastic modulus and is attached to the underlying tooth using a high strength adhesive. After creating a three dimensional model of the original tooth, the damaged portions of the actual tooth are removed and an optical scan is made of the resulting cavity. CNC machining techniques are then used to fabricate a porcelain crown which, after final shaping and polishing, very closely resembles the original tooth in both color and geometry.

While these crowns have proven to be durable over many years in vivo, failures do occur. Although the cause is often unknown, crown failures typically result in removal of the damaged crown and adhesive; a process which often reduces the strength of the underlying, original tooth. This can result in an increase in the overall size of the crown and a weakening of the crown-tooth interface. It would therefore be beneficial to determine the mechanisms behind such failures which are dynamic in nature, as most result when the tooth is subjected to impact loads during biting onto hard substances such as popcorn seeds, hard candies and even eating utensils. An understanding of the underlying causes of failure is critical in determining modifications to the crown design and installation which can reduce the occurrence of failures.

The senior capstone design course at Western New England College was uses as the vehicle to address the problem of crown failures. This 3 credit course requires that the student work to solve a real world problem through analysis, design and testing. The student was assigned the task of working with a local Dentist to determine, from a medical and patient prospective, the performance requirements of the crown in an attempt to translate these into engineering parameters which can be used to quantify the problem and determine potential solutions. To the dental professional, failure is defined as a fracture which prevents the crown from performing as the original tooth. The cause of the failure is viewed as either a severe overloading caused by the patient, degradation of the underlying tooth substrate, or inadequate bonding, including gaps, between the crown and underlying tooth. The results of this failure are patient discomfort and the added expense involved in repairing the crown or, in the most severe cases, extraction of the underlying tooth and replacement with a denture or implant. From an engineering perspective, failure is defined as material fracture or degradation which again, prevents the crown from performing as intended. The cause of the failure is an overstressing of the crown material caused either by overloading or inadequate material cross section, or a poor bond with the tooth enamel, resulting in inadequate bond strength. As premature failures are of the most concern in this study, high cycle fatigue failures were not considered.

The goal of this study was to gain an understanding of how the mechanical properties of the crown and the crown as bonded to the underlying tooth affect crown performance. Both the quasistatic and dynamic properties were considered in bonded and unbonded conditions. The effects of geometry, along with mechanical strength considerations, lead to recommendations for improving crown durability.

II. PORCELAIN CROWNS

A dental crown or cap as they are commonly called is used when there is no longer sufficient tooth structure remaining to hold a filling or the remaining natural tooth is so heavily filled or broken down that the only way to restore it is by covering what is left with a suitable material. The process of crowning a tooth is the covering of the entire tooth with a material of adequate strength. Crowns were originally fabricated by casting gold using the lost wax technique where a wax reproduction of the tooth was invested in plaster, melted out and molten gold cast in through a sprue. When the technology and techniques improved gold crowns were generally replaced with porcelain fused to metal crowns. This process used the lost wax technique, but then incorporated the step of adding porcelain to the metal and glazing in an oven fusing the porcelain to the metal.

While these techniques are all still in use today the trend is toward all porcelain crowns which provide superior esthetics and biocompatibility. Until the use of all porcelain began, crowns were cemented with a variety of luting agents. The precise fit of the cast base and parallel walls of the tooth prepared by the dentist only required an agent that would harden locking the crown in place. The cements were developed to resist washing out. With the newer all porcelain crowns such as the CEREC CAD/CAM produced restorations the cementations rely more on bond strength than a passive locking action of previous cements. The new resin based cements fuse the porcelain to the tooth. The inner portion of the crown is acid etched creating micro pores for retentions. The tooth is similarly treated allowing the resin cement to obtain a mechanical bond to both crown and tooth. When light cured the contraction of the cement on hardening fuses the porcelain to the tooth with greater bond strength than natural enamel to dentin. This cementation technique adds to the passive locking mechanism with a physical bond between materials. It also allows for preservation of tooth structure by minimizing preparation requirements.

Other than recurrent caries (decay), long term crown failure is typically do to repetitive fatigue fracture or the breakdown of the bond between the crown material and tooth. When this happens a new crown needs to be fabricated. The most common reason for the breakdown of the bond is the differing thermal expansion coefficient of the tooth, cement, and crown material. Differing rates of expansion and contraction, in conjunction with occlusal load cause the bond to degrade over time and allow micro leakage of bacteria. It is the differing thermal expansion coefficients of all filling materials with respect to that of the tooth that leads to much of the thermal sensitivity people observe and the inevitable failure of any dental restoration. Short term crown failure is predominantly due to fracture resulting from a single bit impact which fractures the crown, the underlying tooth or both simultaneously. It was decided that a solution to the problem of short term fracture would be the focus of this work.

III. MECHANICAL PROPERTIES VS. PERFORMANCE

As a dental professional, the important properties of a crown are viewed as compressive strength, esthetics, and biocompatibility. The thermal coefficient of expansion of Zirconium-Oxide is almost identical to that of enamel. Since this material expands and contracts with the tooth the bond between them is less prone to breakdown due to differing rates of expansion. This means that there is typically less sensitivity and that they last longer than their cast counterparts.

From an engineering perspective, fracture is typically associated with exceeding some critical material property parameter in service. Assuming that chemical degradation is not a contributing factor, several possible mechanical causes of failure are possible. First, repeated loading could cause a fatigue failure, as successive stress cycles below the tensile strength of the material slowly and progressively damage the material to the point where the final stress cycle fractures the material. Second, a single impact event could result in either an energy or stress which then exceeds the material strength. If regions of the crown are installed such that areas of the porcelain are inadequately supported, tensile stresses could develop which initiate a crack. Finally, a failure of the tooth substrate, either due to decay or overloading, could subsequently result in a crown failure. Energy, stress and the effect of bonding on these quantities were therefore studied.

A. QUASISTATIC MATERIAL PROPERTIES

The dental porcelain used in this study was taken from blocks of 3M™ Paradigm™ MZ100 restorative material used in the CEREC® restorative system. Paradigm MZ100 block material contains 85 wt% ultrafine zirconia-silica ceramic particles that reinforce a highly cross linked polymeric matrix. The adhesive used to bond the crown to the tooth is 3M™ RelyX™ Adhesive Resin Cement (ARC). The quasistatic mechanical properties of the porcelain and the RelyX adhesive used in this study were taken from [2] and are given in Table 1. Although a number of non-mechanical properties, such as chemical resistance, are readily available, only a relatively small number of mechanical properties are listed. No data regarding the dynamic mechanical properties of the material could be found in the literature.

Table 1: Quasistatic properties of 3M™ Paradigm™ MZ100 Blocks and Rely X Unicem dental cement bonded to Human Dentin

Compressive Strength	520 MPa	Fracture Toughness	1.4 MPa
Flexural Strength	125 MPa	Elastic Modulus	6 GPa
Biaxial Fracture Strength	112 MPa	Flexural Modulus	10 GPa
Rely X Shear strength	15 MPa		

The lack of dynamic property information, particularly impact properties, required that they be determined experimentally in this work.

B. DYNAMIC TESTING

The dynamic properties which were considered to have the greatest effect on the durability of crowns were impact strength in both the bonded and unbounded condition, and the dynamic stress vs. strain response in compression. The experimental procedures for each and experimental results are discussed in detail below.

1. Drop testing

Drop tests were performed to determine the strain rates and strain magnitudes developed during a porcelain to porcelain collision (i.e., a hard bite). It is known that the average human bite pressure is typically between 19 and 29 MPa in the molar region of the mouth [3], so the technique used here involved varying the drop height and drop weight of an impactor until a compressive strain amplitude which corresponded to this pressure was achieved in the porcelain drop test specimen. The resulting impact velocities were small and on the same order as a human bite velocity. The drop test fixture is shown in Figure 1. A base with three linear bearing columns was used to hold a porcelain test specimen block approximately 1.47 cm in length, 1.31 cm in width, and 1.86 cm high. A strain gage was applied vertically to the side of the porcelain specimen to monitor strain pulse during impact. A second porcelain specimen of similar size was affixed to an impact head which was mounted on the linear bearings to reduce the friction.

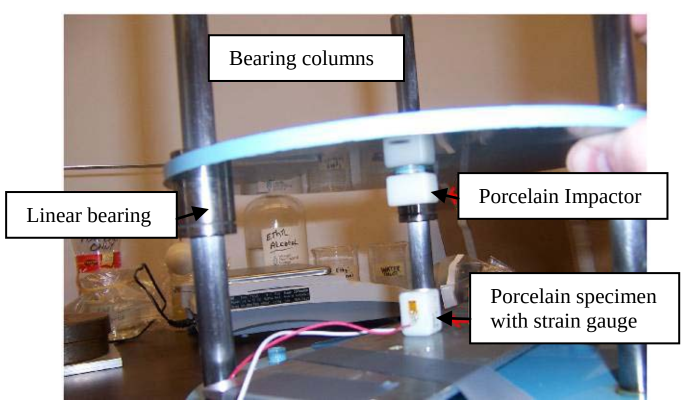

Figure 1: Drop Test Fixture

A compressive strain which correlates to a compressive stress of approximately 29 MPa can be calculated using Hooke's law [4] in Equation 1, where ε = strain, E = elasticity modulus and σ = Stress.

$$\sigma = E\varepsilon \tag{1}$$

This resulted in a strain of approximately 4833με. The height and magnitude of the drop weight were then varied so the strain developed in the sample approximately matched this value. A typical strain vs. time profile developed in the drop test is shown in Figure 2.

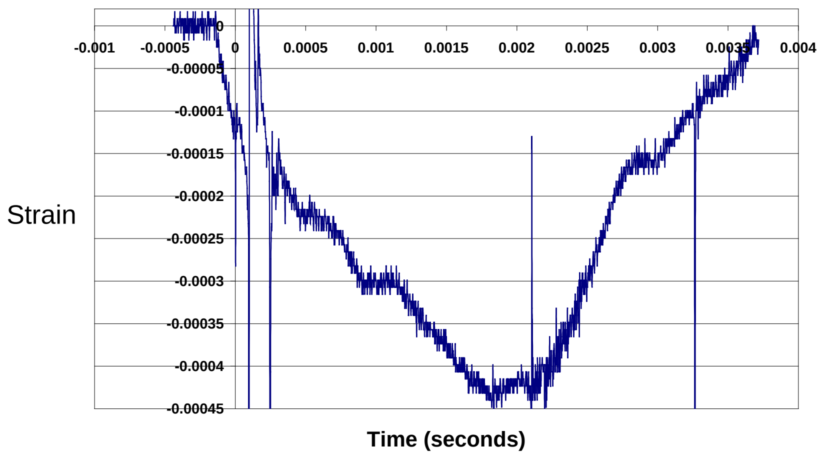

Figure 2: Typical strain vs. time profile resulting from the drop test

The average loading duration of several such drop tests was 3.5 to 4 milliseconds and appeared to be independent of the magnitude of the load. The strain rate calculated from the strain vs. time profile was on the order of 1/s.

2. Charpy Impact Testing

Charpy Impact Testing [5] is a common test procedure for measuring the energy which can be absorbed by a test specimen under impact loading conditions. Energy is imparted to a test specimen using an impact pendulum having known potential energy. As the pendulum swings from an initial height and fractures the test specimen, the specimen absorbs some energy, resulting in a reduced return swing height and therefore reduced potential energy. A V-notch is machined into a prismatic test specimen on the face opposite the side receiving the pendulum impact. This test provides impact data at relatively low strain rates when compared to the SHPB apparatus discussed later.

Blocks of the porcelain material having the same geometry used in the drop tests were cut with a diamond blade to make a 1.6 mm cut, 3.2 mm deep, as the hardness and brittle nature of the material made it extremely difficult to machine a precise ASTM V-notch into the specimens. However, this was considered to be adequate for comparing the relative impact strengths of bonded and unbonded test specimens. The relatively small size of the porcelain blocks required that the pendulum impactor geometry be reduced in size as well. An impactor having a width of 6.4 mm was used. The porcelain Charpy impact specimen is shown before and after impact in

Figure 3. The material was found to be extremely brittle, as the average energy absorbed by the porcelain was only about 10% of the input energy of 11.3 N-m.

In order to test the impact strength of bonded porcelain, two pieces of porcelain were chemically etched and bonded together using the RelyX dental cement. A notch having the same depth used in the prior tests was then machined along the porcelain-adhesive interface. The bonded impact specimen is shown before and after impact in Figure 4.

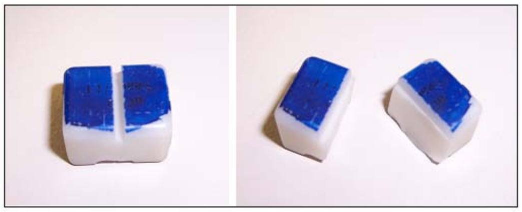

Figure 3: Porcelain Charpy sample testing

Figure 4: Bonded Charpy specimen before and after testing

The energy absorbed by the bonded specimen increased to from 10% to18% of the input energy, indicating that the bonding process results in increased dynamic toughness.

3. Split Hopkinson Pressure Bar Testing

The Split Hopkinson Pressure Bar (SHPB) technique has long been used by researchers to determine the dynamic stress-strain response of a wide range of materials at extremely high strain rates on the order of 1000/s. This method was used to determine an upper bound to the dynamic stress-strain response of the porcelain, and therefore gain insights into the strain rate sensitivity of the material.

Theory

A basic schematic of the modern SHPB apparatus is given in Figure 5.

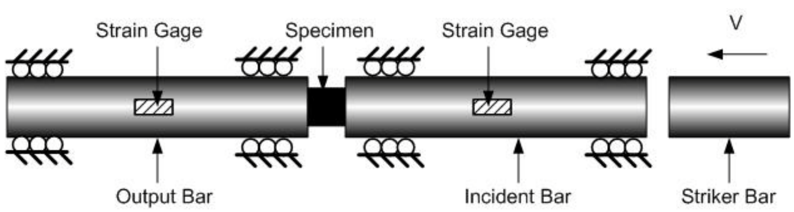

Figure 5. - Schematic of the SHPB apparatus.

The specimen of circular cross section is loaded axially between two long cylindrical rigid bars mounted on a bearing system. These bars are instrumented with strain gages to monitor the elastic wave propagation resulting from a strain pulse directed along the incident bar toward the specimen. The pulse is developed when the incident bar is impacted by a projectile (striker bar), the wavelength and amplitude of the pulse being directly proportional to the length, mass and velocity of the projectile. The pulse is partially transmitted and reflected at the incident bar/specimen interface and the transmitted portion passes through the specimen and into the transmitter (output) bar. An analysis of the incident, reflected and transmitted elastic waves occurring in the bars allows for the determination of the stresses and strains occurring in the test specimen. Using one-dimensional wave theory [6], the stress-strain response of the specimen can be determined. The true strain in the specimen, $\varepsilon_{s,}$ and the true stress, σ_s can be calculated using Equations 2 and 3.

$$\varepsilon_S = -2\frac{C_o}{L}\int_0^t \varepsilon_r dt \quad (2) \qquad\qquad \sigma_S = E\frac{A}{A_S}\varepsilon_t \quad (3)$$

where: C_o = wave speed in bar L = length of Specimen ε_r = reflected strain
ε_t = transmitted strain t = time in seconds E = bar elastic modulus
A = bar cross-sectional area A_s = specimen cross-sectional area

SHPB Apparatus
The SHPB apparatus used for the dynamic compression tests is shown in figure 6.

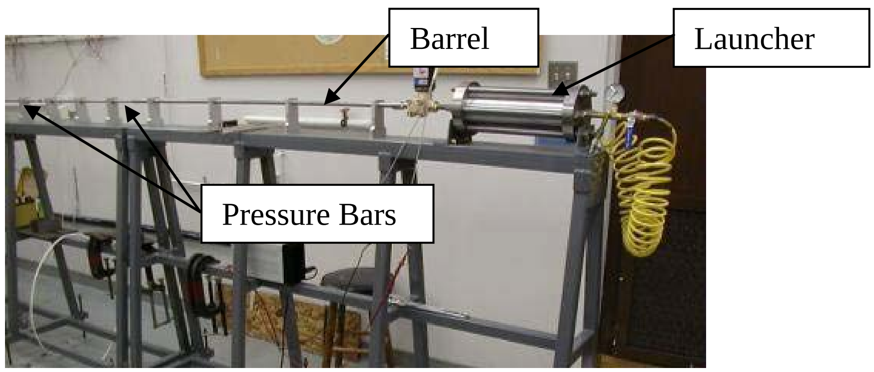

Figure 6: SHPB and Specimen Set-up

The test specimens used in the SHPB experiments were small, short cylinders 7 mm long and 10.4 mm in diameter, machined from the porcelain blocks discussed earlier using the CNC milling equipment used by the dentist to manufacture actual crowns. The test specimens were sandwiched between the two 12.7 mm diameter steel pressure bars as seen below in Figure 7.

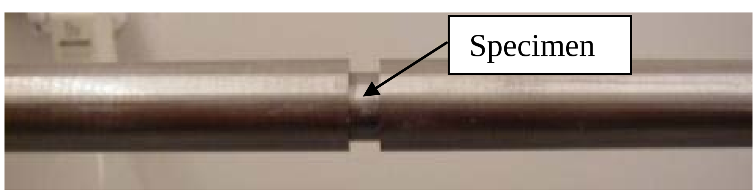

Figure 7: Specimen positioning

SHPB Results
A 30 cm striker bar was launched toward the incident bar using a pneumatic launcher operating at 138 kPa, and typical voltage pulses generated in the bars are shown in figure 8. The specimens fractured sometime between 20 and 30 μs after the incident pulse arrived at the specimen, as can be seen in the reflected pulse profile. The voltage pulses were converted to strain pulses which were used in equations 2 and 3 to calculate the dynamic stress-strain response of the specimen, shown in Figure 9.

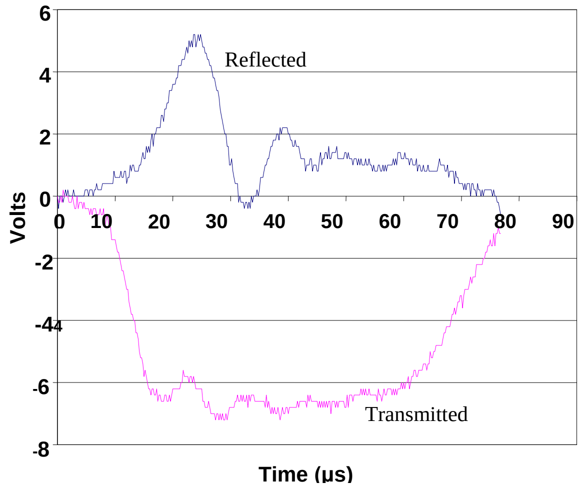

Figure 8: Voltage vs. Time Pulses

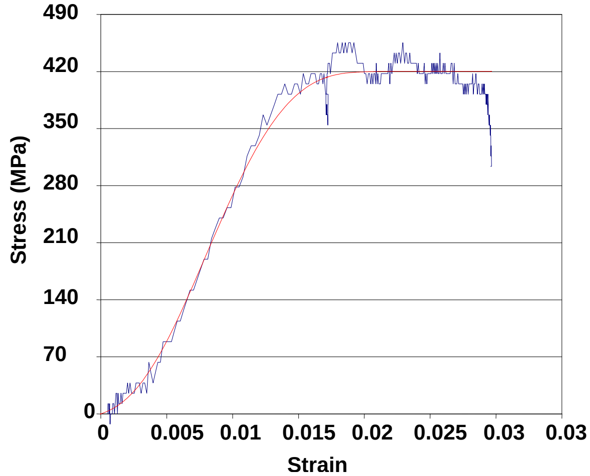

Figure 9: Dynamic SHPB stress-strain response

The specimens fractured as a result of the SHPB testing, and it is interesting to note that the specimens failed at approximately 80% of the quasistatic compressive strength of the material, indicating that the material is susceptible to brittle failure during impact. The resulting strain rate was calculated as 1559/s, far greater that that achieved in the drop tests. It is therefore concluded that strain rate dependence of material strength may be neglected, since an increase in strain rate of several orders of magnitude resulted in a decrease in strength of only 20%.

IV. IMPLICATIONS TO CROWN DESIGN

At the completion of the experimental portion of the project, the student was given the task of developing recommendations to improve crown performance. These improvements were first considered from an engineering perspective and involved methods of reducing crown stresses. Then methods for implementing the engineering plan needed to be translated into an action plan which could be implemented by the dentist.

The porcelain material is extremely brittle and displays very poor energy absorbing characteristics. For example, the porcelain material absorbed less than 1% of the energy absorbed by an aluminum specimen of the same geometry. However, the use of the dental adhesive nearly doubled the impact strength. It follows then that increasing the surface area of the bond is critical to crown durability. The brittle nature of this material also requires that the crown be shaped such that the majority of the material is placed in compression. Stress concentrations and relatively large, unsupported regions should be avoided. Gaps between the tooth and crown must also be eliminated to prevent localized areas of tensile loading from developing.

In order to translate these improvements into an action plan which can be implemented by the dentist, the student first gained a thorough understanding of how crowns are developed and installed in patients. This involved several on-site discussions and demonstrations. At the same time, the basis for the recommendations was explained to the dentist. Quantities such as impact energy, quasistatic and dynamic strength and bonding effects were discussed. Through such meetings, an implementation plan was developed. The underlying tooth can be undercut to help hold the crown in place and increase the total bond area. While it is desirable to create a crown geometry which matched the original tooth as closely as possible, sharp fillet radii and unsupported regions can be reduced without sacrificing crown aesthetics. Eliminating gaps between the crown and underlying tooth my require higher resolution in the optical modeling software and CNC equipment to create a better match between the two. However, the dentist can strive to create cavities having relatively simple shapes to allow for simplified modeling. A slight excess of the adhesive which can fill gaps can also be used.

V. CONCLUSIONS

The successful completion of the project required that the student overcome several significant challenges. First, the student needed to fully understand the requirements of the dentist and patient in order to appreciate the physical requirements of the installed crown. This was accomplished through in depth discussions with the dentist and patients. This understanding of the application then needed to be translated into a series of mechanical requirements which could be evaluated and quantified. It was determined that dynamic properties were most relevant to performance and were not readily available in the literature. This required that the student develop a mechanical test plan for acquiring these properties. The extreme brittle nature of the crown material further complicated the development of such tests. As a result of this testing, it was determined that impact strength was most critical for reducing failures and that crown geometry and bonding area were most critical in improving durability. Finally, these mechanical parameters needed to be translated into an action plan which could be implemented by the dentist. Suggestions for modifying crown geometry and bond area were then made.

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AUTHOR BIOGRAPHIES

Glenn Vallee, Ph.D., P.E., Associate Professor of Mechanical Engineering, Western New England College, 1215 Wilbraham Rd, Springfield, MA 01119 (ph) (413) 782-1334, e-mail gvallee@wnec.edu

Dr. Glenn Vallee, Ph.D., P.E., is currently an Associate Professor of Mechanical Engineering at Western New England College in Springfield, MA. Dr. Vallee currently teaches graduate and undergraduate courses in engineering mechanics, experimental mechanics and machine design, and has published in the areas of nonlinear finite element analysis, experimental mechanics and the experimental determination of dynamic material properties. Dr. Vallee received a BS in Mechanical Engineering from the University of Rhode Island in 1985 and began working for the Fastening Systems Division of the Stanley Works in East Greenwich Rhode Island soon after. Beginning as an Engineering Lab Technician, he received a number of promotions, serving as a Test Engineer, Design Engineer, Product Development Engineer and finally as the Manager of the largest Engineering Laboratory at Stanley. He received both a Masters degree and Ph.D. in Mechanical Engineering from URI while working at Stanley, and served as an Adjunct Assistant Professor of Engineering at the University of Rhode Island and the Community College of Rhode Island. In 1997, Dr. Vallee accepted a position as Director of Engineering and Quality Assurance, Worldwide, with Remington Products Company in Bridgeport CT. Dr. Vallee was the senior corporate manager responsible for customer satisfaction and developed Quality Assurance and Engineering offices in both Hong Kong and mainland China. He also managed the Quality Assurance departments and Engineering Laboratories for Remington in the UK, Australia, and the Bridgeport Manufacturing facility. He accepted the position of Assistant Professor of Mechanical Engineering at Western New England College in 2002.

Dr. Richard P. Benoit, DMD is currently the Director of Dental Services for CMHC at the University of Connecticut Health Center. 263 Farmington Ave, Farmington CT, 06030-5386. (860) 679-5582, email rbenoit@uchc.edu. Dr. Benoit also maintains a private dental practice in Old Saybrook, CT practicing general dentistry with a focus on CEREC CAD/CAM restorative dentistry. 123 Elm St. Suite 1300, Old Saybrook, CT 06475, 860-388-2107, rpbdmd@comcast.net.

Dr. Benoit Graduated from Boston College in 1986 with a BS in Biology. He continued on to Tufts University School of Dental Medicine in Boston where he graduated in 1990 with his doctorate in dental medicine (DMD). After graduation Dr. Benoit served as a Lieutenant and Lieutenant Commander in the US Navy Dental Corp. He served at Parris Island and on board the USS George Washington CVN 73 as a dental officer. During this time he provided dental services to military personnel, and developed and ran the Quality Assurance program for the dental department. He also served as an assistant Moral Welfare and Recreation Officer for the ship's 5000 crew members.

Dr. Benoit left the active duty in 1993 and was honorably discharged from the Naval Reserves in 2006. He worked as a dental associate for Holyoke Dental Associates in Holyoke MA from 1993-1994. In 1994 he purchased a small dental practice in Old Saybrook CT where he continually introduces new dental technology to his patients. In 2009 he joined the staff at the University of Connecticut Health.