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Matthew M. Stout

Assessing the feasibility of yttria-stabilized zirconia in novel designs as mandibular anterior fixed lingual retention following orthodontic treatment.

Matthew Stout

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Reading Committee:

Anne-Marie Bollen, Chair

Dwayne Arola

Hanson Fong

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Abstract

Assessing the feasibility of yttria-stabilized zirconia in novel designs as mandibular anterior fixed lingual retention following orthodontic treatment.

Matthew M. Stout

Chair of the Supervisory Committee:
Anne-Marie Bollen, Professor and Program Director
Department of Orthodontics

The purpose of this study is to explore the feasibility of yttria-stabilized zirconia (Y-TZP) in fixed lingual retention as an alternative to stainless steel. Exploratory Y-TZP specimens were milled to establish design parameters. Next, specimens were milled according to ASTM standard C1161-13 and subjected to four-point flexural test to determine materials properties. Finite Element (FE) Analysis was employed to evaluate nine novel cross-sectional designs and compared to stainless steel wire. Each design was analyzed under the loading conditions to determine von Mises and bond stress. The most promising design was fabricated to assess accuracy and precision of current CAD/CAM milling technology. The superior design had a 1.0 x 0.5 mm semi-elliptical cross section and was shown to be fabricated reliably. Overall, the milling indicated a maximum percent standard deviation of 9.3 and maximum percent error of 13.5 with a cost of \$30 per

specimen. Y-TZP can be reliably milled to dimensions comparable to currently available metallic retainer wires. Further research is necessary to determine the success of bonding protocol and clinical longevity of Y-TZP fixed retainers. Advanced technology is necessary to connect the intraoral scan to an aesthetic and patient-specific Y-TZP fixed retainer.

TABLE OF CONTENTS

List of Figures	ii
List of Tables	ii
Chapter 1. Introduction	1
Chapter 2. Material and methods	4
2.1 Milling Capabilities	4
2.2 Material Testing	5
2.3 Finite Element Analysis	5
Chapter 3. Results	8
3.1 Milling Capabilities	8
3.2 Material Testing	14
3.3 Finite Element Analysis	16
Chapter 4. Disussion	27
Chapter 5. Conclusion	36
Bibliography	37

LIST OF FIGURES

Figure 1. Five exploratory curved Y-TZP specimens with dimensions 1.0 x 0.9 x 36.0 mm and pictured on actual patient model	9
Figure 2. Design 4 Milled Specimens	13
Figure 3. Descriptions of Y-TZP designs and stainless steel control	18
Figure 4. Schematic of Bonding FE Model	22

LIST OF TABLES

Table 1. CAD-CAM Milling Overview	11
Table 2. Comparison of Experimental and FE Four Point Bend Data	15
Table 3. Mesh Convergence Study	20
Table 4. Maximum von Mises Stress and Safety Factor. Bonding Model	24
Table 5. Bond Shear Stress. Bonding Model	25
Table 6. Size and Cost Comparison	33

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Chapter 1. INTRODUCTION

Norman Kingsley was quoted over 100 years ago stating, “the success of orthodontia as a science and an art now lies in the retainer.”¹ As clinicians, we must consider the stability of our result which relies on retention as the long-term goal of treatment. As excited as patients are on debond day, we should ensure that our retention protocol can maintain the desired finish and prevent the patient from unnecessary retreatment. Treated patients are more cognizant than untreated peers when assessing crowding, incisor irregularity and alignment and crowding and incisor irregularity are the most cited reasons for seeking orthodontic treatment.^{2,3} It seems to follow that post-orthodontic retention would account for the mandibular anterior, a common site of crowding, as an aesthetic priority for patients and subsequently affect the orthodontist’s retention design and protocol.

Relapse can be defined as any undesired movement away from an ideal finish following initiation of retention protocol after orthodontic treatment, particularly in the mandibular anterior teeth.⁴ Various post-retention studies report movement toward arch constriction, decrease in intercanine width and increase in incisor irregularity and crowding with time.^{2,5,6} To counter relapse, mandibular fixed lingual retainers are the most commonly used appliance for mandibular retention in the United States among active AAO members as of 2010.⁷ Fixed retention may be achieved by bonding round stainless steel wire, multistrand flexible braided steel wire, rectangular steel wire or dead soft wire.⁸⁻¹³ Once a retention protocol and material is chosen, it is employed for as long as the patient is compliant and desires to maintain the orthodontic finish. Of current AAO members and 658 completed surveys, most orthodontists (75.9%) did not instruct patients to have fixed lingual retainers removed at a specific time.⁷

The motivation to explore novel retainer designs and materials stems from the desire to improve current retention protocol in terms of accuracy of fit, aesthetics, bonding and failure rate. Two recently published AJO-DO articles have highlighted the complications that can arise from improper fabrication, placement and irregular monitoring of fixed retention appliances.^{13,16} The overall failure rate of fixed retainers has been reported as high as 53% depending on placement technique and observation period.¹⁴⁻¹⁶ Failure of a bonded retainer can include debond, poor adaptation, and/or inadvertent activation, which may lead to crowding relapse, incisor irregularity, torque differences, bodily movement and/or root dehiscence.^{10,15-17} Kucera and Marek report a “twist effect” where the contralateral canines have opposite buccolingual inclinations, which are not categorized as relapse, as the most common complication.¹⁶ Though serious complications may be rare—up to 5% of cases—50% of these patients require retreatment.¹⁶ Thus, a new fixed retainer design and bonding protocol may mitigate the risk and better retain orthodontically-positioned teeth when compared to stainless steel.

For our novel retention protocol, we considered both material and design changes beyond round and flexible braided stainless steel. Yttria-stabilized zirconia, or Y-TZP, is an inert metal-oxide ceramic that has been used in dentistry as an aesthetic alternative to metallic alloys.¹⁸⁻²⁰ Zirconia possesses ideal properties for dental use, including high flexural strength, high fracture toughness, fatigue resistance, excellent wear properties, resistance to chemical corrosion, biocompatibility and aesthetic appearance.¹⁸⁻²⁴ We chose Y-TZP because, though it possesses some resiliency, it does not have the ability to store activation and enact orthodontic movement as stainless steel does. We also considered the current bonding protocol for Y-TZP involving MDP-containing luting agents to be clinically superior to current stainless steel bonding.

In addition to improved bonding technique, another advantage of employing zirconia as a retentive device is its ability to be milled to very specific dimensions and geometries. The advent of computer-aided design and computer-aided machine or manufacturing (CAD/CAM) systems have greatly improved the accessibility, design possibilities, accuracy of fit, sintering and milling of restorations with materials like Y-TZP.^{19,20} The level of customization that may be achieved by intraoral scanning could impart an individualized retention appliance that theoretically can be adapted much more precisely and deliberately to the lingual surfaces of teeth with appropriate technology. A personalized and adapted fixed retainer could possibly increase stability of anterior mandibular orthodontic results by minimizing the degrees of freedom a tooth has for incisor relapse and irregularity. Personalization is further advanced with the ability to shade-match the Y-TZP to the patient's dental shade imparting an aesthetic advantage over metallic options. As of a current literature search, zirconia has not been used in a CAD/CAM-fabricated fixed retainer following orthodontic treatment. The purpose of this study was to explore the feasibility of yttria-stabilized zirconia as mandibular anterior fixed retention by assessing milling capabilities, material properties and various designs with Finite Element (FE) Analysis followed by analyzing the cost and practicality of potential clinical use.

Chapter 2. MATERIAL AND METHODS

2.1 MILLING CAPABILITIES

To establish the parameters of current milling capabilities, ten straight and five curved exploratory specimens were milled (B&B Dental Lab, Renton, WA). These specimens shared the same rectangular cross-section and 1.0 x 0.9 x 36.0 mm dimensions. Standardized descriptive measurements were completed to ensure sufficient milling accuracy and precision before progressing to more refined designs. Descriptive measurements for the straight specimens were made at even intervals across each, while curved specimens were placed on a cast and marked at the mesio-distal midpoint of each crown. Initial exploratory curved specimens were based on geometric measurements of a well-aligned post-retention model while all subsequent curved dimensions were based on a well-aligned dentoform. We defined 0.018” and 0.036” type 304 18-8 austenitic stainless steel as our controls. The 0.9mm dimension was chosen as the closest millimetric measurement to 0.036” diameter round wire. The 1.0mm dimension was chosen to define a different measurement from 0.9mm and to test the milling capabilities within 0.1mm. All measurements were made with the same digital caliper (Carrera Precision 6” Digital Caliper Alloy) with the caliper arms placed perpendicular to the specimen surface where the measurement was being recorded.

Twelve yttria-stabilized zirconia (Y-TZP) specimens were fabricated (B&B Dental Lab, Renton, WA) according to ASTM standard C1161-13, which defines the Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature with a minimum requirement of ten specimens. Dimensions for each specimen were 2.0 mm width by 1.5 mm

height by 25 mm length. Standardized descriptive measurements were completed for each specimen to assess the milling capabilities. Height and width were measured at five evenly distributed areas on each specimen. Overall specimen length was also measured. All measurements were made with the same digital caliper (Carrera Precision 6" Digital Caliper Alloy) with the caliper arms placed perpendicular to the specimen surface where the measurement was being recorded.

Following FE analysis, the design with superior results in the shear bond strength model was sent to the dental lab (B&B Dental Ceramic Arts, Inc, Renton, WA) for fabrication. Ten specimens were fabricated and measured following the same aforementioned descriptive measurement protocol.

2.2 MATERIAL TESTING

Each of the twelve ASTM-standard specimens were loaded into a four-point flexural test attachment, placed in an Instron machine and loaded at a cross-head speed of 0.2 mm/minute in accordance with ASTM C1161-13. Extension at failure was recorded and maximum stress (MPa) and Flexural Modulus (GPa) were calculated for each specimen.

2.3 FINITE ELEMENT ANALYSIS

A straight specimen with ASTM-specified dimensions of 2.0 x 1.5 x 25.0 mm in rectangular cross-section was modeled in ANSYS Finite Element (FE) software. The specimen was subjected to a four-point bend test in accordance with ASTM C1161-13. This FE model was

used to evaluate the maximum stress as a comparison to the experimental values observed and to validate the FE model use for Y-TZP in the project.

Nine novel Y-TZP designs varying in cross-sectional geometry and dimensions as well as 0.018” and 0.036” round stainless steel wire were modeled using ANSYS software. Optimal mesh density was determined by a mesh convergence study. The overall length of each specimen and the defined height and width of each bonding area were defined according to tooth dimensions found in Wheeler’s Dental Anatomy, Physiology, and Occlusion textbook.²⁵ A standard dentoform with comparable tooth measurements to Wheeler’s was used to further define the geometric parameters of each design. The bonding area was measured as the flat lingual surface between marginal ridges at the inciso-gingival midway point of each crown. The dentoform was used to determine the depth, arch width and curvature of the lingual surfaces of the teeth for each design.

Eight of the nine different Y-TZP and two stainless steel designs were included in our model which assessed the bond strength to the tooth and the stress in the retainer resulting from an occlusal load. Design 2 was not included as it was judged not clinically applicable due to its large size. The model incorporated the materials properties determined from the experimental four-point flexural test for Y-TZP and published values for stainless steel.²⁶ The bonding area of all six mandibular anterior teeth were defined as fixed points. An anterior occlusal force of 285.3N was directed evenly across the superior-lingual aspect of each design.²⁷ This represented the occlusal force being transmitted directly to the retainer, a common mode of debond failure seen in anterior mandibular retainers. The reaction force at each fixed bonding site was determined and the shear stress at each bond was calculated for all six teeth using the bond areas for each design. The maximum von Mises stress in the retainer was compared to both

the experimental and FE-determined flexural strength values. If the von Mises stress is below the strength of the material than it is reasonable that the design will not fail. If the von Mises stress is above the material strength value, then it follows that the design is inadequate and will fail under the defined load. Furthermore, the safety factor (factor of safety, or FoS) was calculated for each design. Bond strength values were compared to literature values for Panavia F and Clearfil SE (Kuraray) with accepted bonding protocol to assess expected clinical bonding performance under the simulated occlusal force. The maximum shear stress at any bonding point was determined for each design and using 17.4 MPa as a reference, the safety factor was calculated and compared.²⁸ Using this information, we were able to determine the best design to pursue for milling. Once milled, the average dimensions of the milled specimens were modeled with the same cross-section as the corresponding design and run in the bonding model to determine the same aforementioned values.

Chapter 3. RESULTS

3.1 MILLING CAPABILITIES

Figure 1 shows the five exploratory curved specimens that were milled to assess the initial capabilities for current CAD/CAM technology for curved retainers at such dimension.



Figure 1. Five exploratory curved Y-TZP specimens with dimensions 1.0 x 0.9 x 36.0 mm and pictured on actual patient model

The average, standard deviation, percent standard deviation and percent error were calculated for all specimens in each milled group—exploratory straight, exploratory curved, ASTM-standardized and Design 4 (Table 1).

Table 1. CAD-CAM Milling Overview

Exploratory Straight		1.0 x 0.9 x 36.0 mm					
Average	0.96	SD	0.01	% SD	1.0	% Error	4.0
Average	0.87	SD	0.03	% SD	3.8	% Error	3.3
Average	36	SD	0.03	% SD	0.1	% Error	0.0
Exploratory Curved		1.0 x 0.9 x 36.0 mm					
Average	1.05	SD	0.02	% SD	2.1	% Error	5.0
Average	0.98	SD	0.01	% SD	1.0	% Error	8.9
ASTM		1.5 x 2.0 x 25.0 mm					
Average	1.45	SD	0.03	% SD	1.9	% Error	3.3
Average	2.04	SD	0.02	% SD	1.0	% Error	2.0
Average	25	SD	0.02	% SD	0.1	% Error	0.0
Design 4		1.0 x 0.5 x 27.75 mm					
Average	0.48	SD	0.01	% SD	2.6	% Error	4.0
Average	1.02	SD	0.08	% SD	8.1	% Error	2.0
Average	28.06	SD	0.15	% SD	0.5	% Error	1.1

From the data we recorded the maximum percent standard deviation and percent error for any one specimen within each group to determine the limit of milling capabilities. When assessing the milling for the initial exploratory straight Y-TZP specimens with rectangular cross-section (1.0 x 0.9 x 36.0 mm), the maximum percent standard deviation for any single specimen is 5.2 and the maximum percent error is 7.3. When assessing the milling for the initial exploratory curved Y-TZP specimens with rectangular cross-section (1.0 x 0.9 x 36.0 mm), the maximum percent standard deviation for any single specimen is 3.2 and the maximum percent error is 10.8. For ASTM-standard specimens the maximum percent standard deviation is 4.2 and the maximum percent error is 4.8 (same specimen). The maximum percent standard deviation and maximum percent error calculated for any single specimen of Design 4 are 9.3 and 13.5, respectively. Figure 2 shows the final ten specimens of Design 4 including the design's fit on the dentoform to highlight the adaptation and scale.

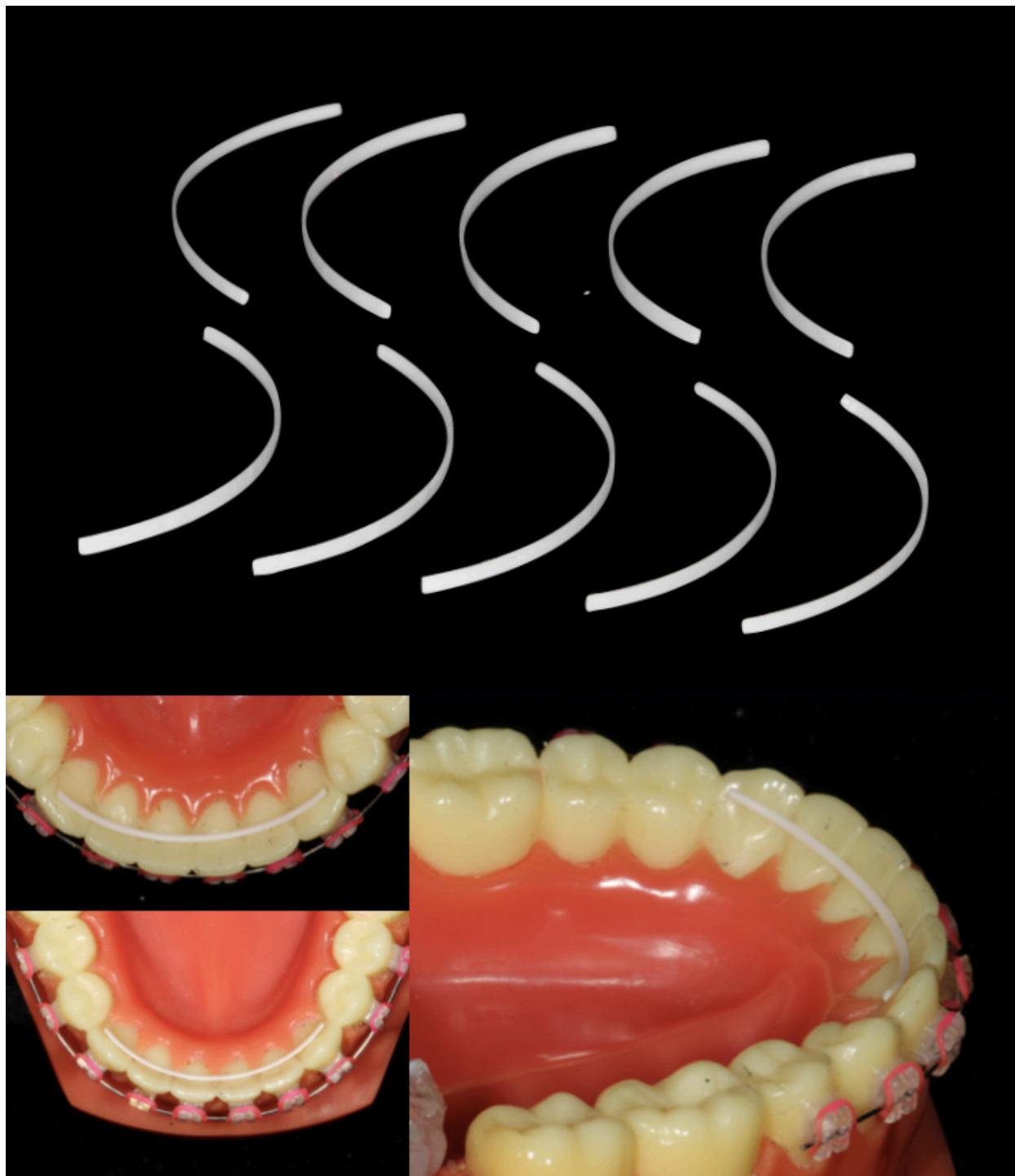


Figure 2. Design 4 Milled Specimens

Pictured with well-aligned dentofrom used for standardization of measurements for designs

3.2 MATERIAL TESTING

Table 2 summarizes the data obtained from the four-point bend tests.

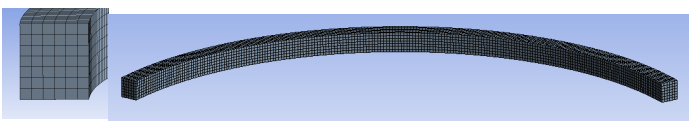
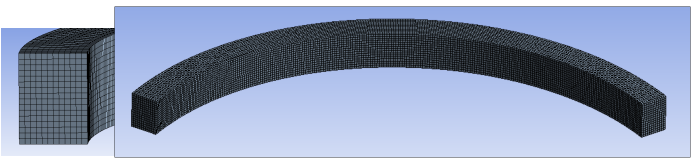


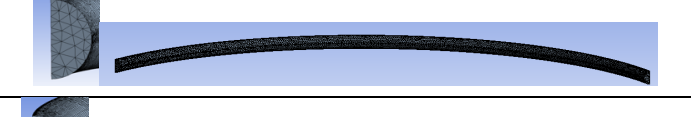
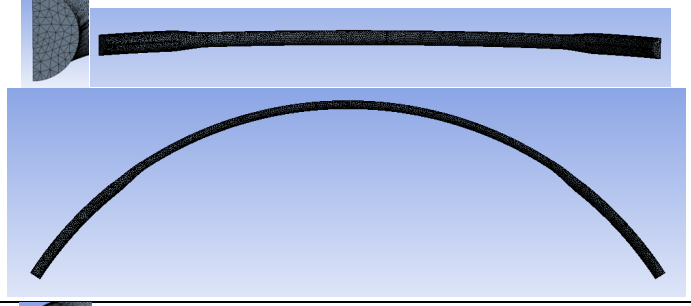
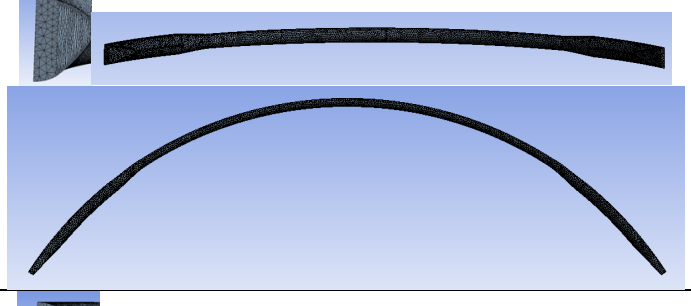
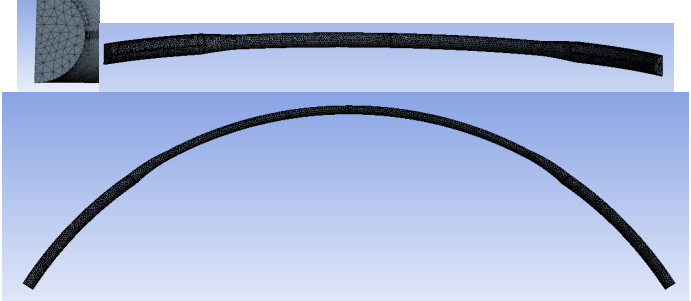
Table 2. Comparison of Experimental and FE Four Point Bend Data

Specimen	Experimental Max Stress (MPa)	FE Max Stress (MPa)	Percent Difference (%)
1	547	556	1.7
2	530	539	1.6
3	591	600	1.7
4	506	514	1.6
5	534	543	1.6
6	563	572	1.6
7	519	528	1.6
8	556	565	1.7
9	601	617	2.7
10	574	583	1.7
11	534	542	1.7
12	613	623	1.6
Average	556	565	1.7

The average and standard deviation are highlighted—556 +/- 34 MPa for the experimentally-determined data and 565 +/- 35 MPa for data determined by FE modeling. The percent difference is listed for each specimen. The average percent difference is 1.7% with the values ranging between 1.6-2.7%. The extension at failure ranged from 0.2-0.31 mm in the experimental four-point bend test with an average of 0.24 mm and standard deviation of 0.03.

3.3 FINITE ELEMENT ANALYSIS

Figure 3 summarizes the nine Y-TZP designs and two stainless steel controls.

Design	Dimensions (mm)	Cross-section	Pictures
1	1.0 x 0.9	Rectangular Cross-Section	
2	2.0 x 1.5	Rectangular Cross-Section	
3	1.0 x 0.3	Semi-Elliptical Cross-Section	
4	1.0 x 0.5	Semi-Elliptical Cross-Section	
5	0.7 x 0.35	Semi-Elliptical Cross-Section	
6	1.0 x 0.5 tapering to 0.7 x 0.35	Semi-Elliptical Tapered Cross-Section	
7	1.0 x 0.5 tapering to 0.7 x 0.35	Semi-Elliptical Tapered Cross-Section with Edge Bevel	
8	1.0 x 0.5 tapering to 0.7 x 0.35	Semi-Elliptical Extended Taper Cross-Section	

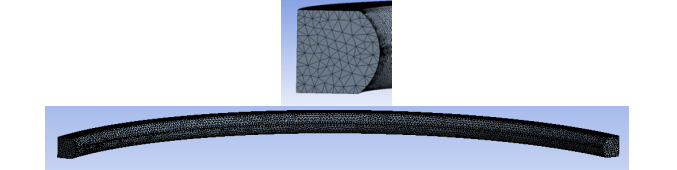

9	1.0 x 1.0	Semi-Ellipse with Square Top/Bottom Cross-Section	
SS 0.036" Wire SS 0.018" Wire	0.9144 0.4572	Type 304 18-8 Stainless Steel Round Wire	

Figure 3. Descriptions of Y-TZP designs and stainless steel control

Dimensions, cross-sectional geometry and pictures of each are included. Table 3 summarizes the results for the mesh convergence study used to determine mesh size for each design.

Table 3. Mesh Convergence Study

Mesh Size (mm)	Max von Mises Stress (MPa)	Percent Difference*	Nodes	Elements
0.5	92.222	n/a	820	205
0.2	63.501	36.9	4417	1759
0.1	62.622	1.4	19349	9638
0.075	61.109	2.4	32894	16933
0.05	60.669	0.7	79742	43272
0.04	60.577	0.2	119969	66129
0.03	60.501	0.1	222236	124971

A prescribed element size of 0.05mm was selected as appropriate for our modeling based on this analysis, which resulted in approximately 40,000 elements in each design. Figure 4 shows the schematic of the bonding model.

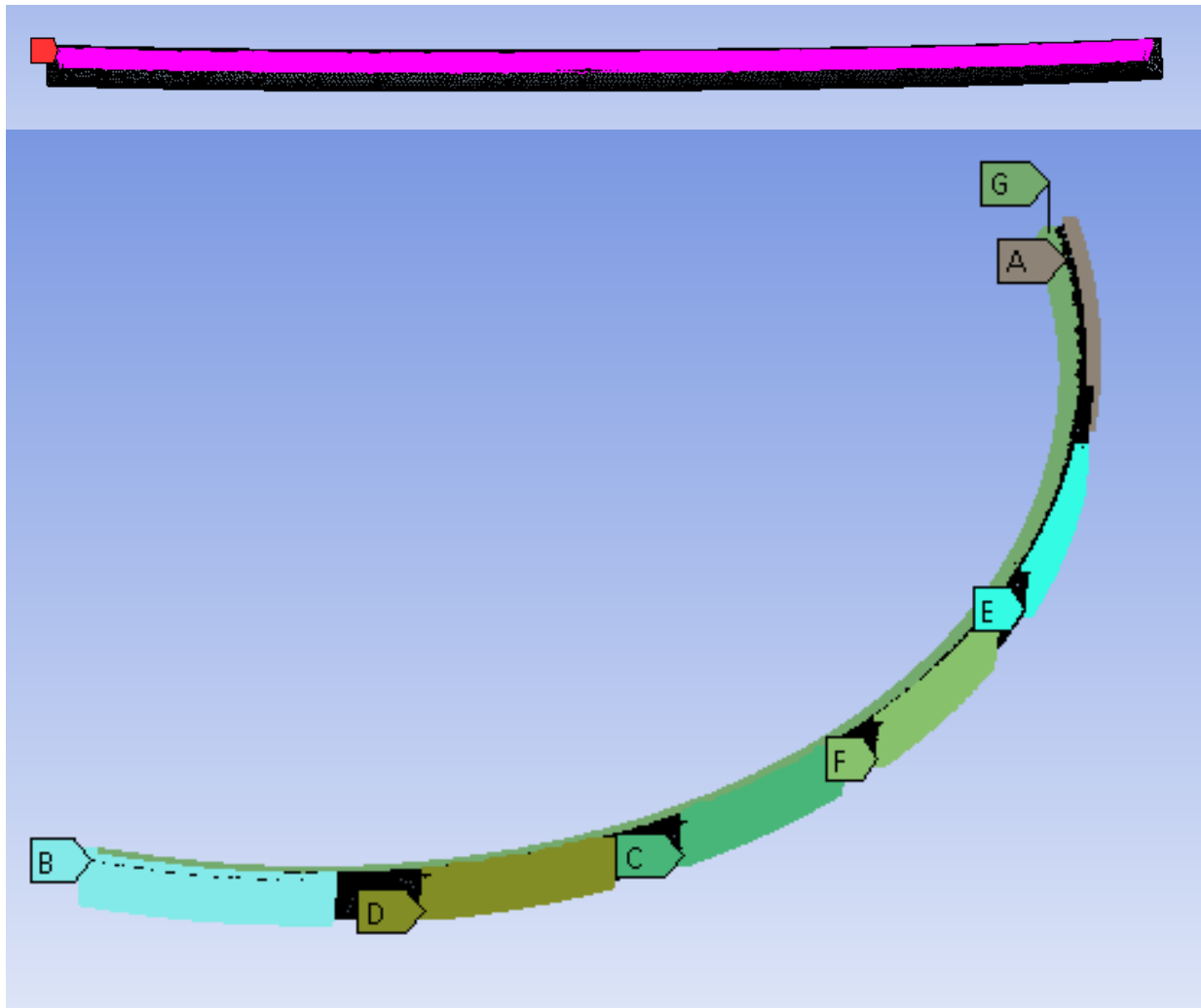


Figure 4. Schematic of Bonding FE Model

Highlighted lingual region corresponds to area of force application. Highlighted lingual region depicts the area of force application. Six highlighted segments correspond to the fixed bonding area.

Bonding areas are highlighted as well as the superior-lingual aspect of the retainer where the occlusal force was applied. Tables 4 and 5 summarize the data obtained from the bonding model.

Table 4. Maximum von Mises Stress and Safety Factor. Bonding Model

Design	Max von Mises Stress (MPa)	Safety Factor (Experimental Value)	Safety Factor (FE Value)
1	222	2.5	2.5
3	476	1.2	1.2
4	494	1.1	1.1
4 Milled	452	1.2	1.3
5	760	0.7	0.7
6	758	0.7	0.7
7	657	0.8	0.9
8	579	1.0	1.0
9	333	1.7	1.7
SS 0.036" Wire	313	1.6	1.6
SS 0.018" Wire	779	0.6	0.6

Safety factor compared to an experimentally determined flexural strength for Zirconia of 556 +/- 34 MPa (from 4pt bend materials testing), and a tensile strength for 304 18-8 Stainless Steel of 505 MPa.

Table 5. Bond Shear Stress. Bonding Model

Design	Maximum Bond Stress (MPa)	Minimum Safety Factor (Experimental)
1	12.9	1.3
3	13.1	1.3
4	13	1.3
4 Milled	12.3	1.4
5	19.3	0.9
6	17.2	1.0
7	17.1	1.0
8	17.1	1.0
9	12.6	1.4
SS 0.036" Wire	15.8	1.1
SS 0.018" Wire	30.1	0.6

Bond strength compared to Panavia F, Clearfil SE bond (Kururay), air-abraded, 180 days' storage and thermocycling, where the mean experimentally determined bond failure stress was

17.4 MPa.

Safety Factor is calculated using both the experimentally- and FE- determined stress for the material. The values for both calculations are included in the table and used to determine the best design(s). Designs 1, 3, 4, 4 Milled and 9 as well as the 0.036" SS control have a calculated Safety Factor greater than 1.0 and are highlighted. Designs 1, 3, 4, 4 Milled and 9 as well as the 0.036" SS control have maximum bond stress values less than the literature-reported value of 17.4 MPa and calculated Safety Factors greater than 1.0 and are highlighted.²⁸

Chapter 4. DISUSSION

Advantages of Y-TZP over stainless steel include: lack of inherent activation nor the potential for such activation when flexed, which can cause inadvertent orthodontic tooth movement as stainless steel does, improved aesthetics, and potentially improved bonding protocol. Kucera and Marek report the possibility of wire fatigue and mechanical deformation from masticatory forces and hard food particles as a probable contributing factor in undesired fixed retainer complications.¹⁶ It is also reported that “even small deflections of the retainer wire can produce forces high enough to cause undesired tooth movement in the retainer segment.”^{16,17} Undesired effects include incisor rotations, tipping and torque differences. Of these, 89.5% of canine inclinations, or “twist effect,” complications reported had the same asymmetrical effect suggesting the mechanical properties of the wires used may be etiologic.¹⁶ In assessing the apparent issues with current stainless steel wire designs, protocols and bonding this project aimed to explore the feasibility of yttria-stabilized zirconia as an alternative to round and flexible braided stainless steel in mandibular anterior fixed retention. Through testing and final milling of Design 4 we confirmed the accuracy and precision that is achievable with current CAD/CAM technology and Y-TZP to create a practical initial prototype.

If we compare the experimentally observed stress values for the four-point bend test with the stress values from the FE four-point validation model, the differences are within 1.7% of one another. This small difference may be due to the assumption of linear elasticity of the material for FE modeling, whereas in actuality there may be potential nonlinearity at the fracture point of the ceramic specimens, resulting in a higher stress for the FE model. It should be noted that all specimens of zirconia fractured within the loading span during the experimental four-point bend test confirming validity of the test. Each specimen fractured cleanly in to two individual pieces

which were retrieved and measured to ensure that their combined lengths added up to the original length and there were no additional fragments. One concern for clinical performance is the potentially sharp ends of segments following a fracture of the appliance. We must bear in mind that our FE bonding model exaggerated the clinical force and some designs still performed well leading us to believe that a fracture would be less common clinically. We must, however, consider additional investigation prior to any clinical application due to the potential for injury should a fracture occur.

We feel that zirconia proved to be an adequate material for the purposes of this study. The average maximum stress and flexural modulus were 556 MPa and 214 GPa, respectively, as determined in our four-point bend test. In comparison, the literature values for both are 900 MPa and 210 GPa, respectively.³¹ The maximum stress value of Y-TZP experimentally obtained in this project was considerably less than the literature value and yet Design 4 still performed well in the FE model using the experimentally-determined materials properties. Thus, it would follow that a higher quality zirconia may perform even better under the defined loading conditions and perhaps produce an even better prototype.

Furthermore, the evaluation of mechanical properties following aging and/or toughening need to be evaluated for comparison as the processes can decrease mechanical properties. It must be stated that different brands and protocols for zirconia can result in different mechanical properties. Therefore, the results and conclusions of this project apply to the specific in-house lab brand, system and milling machine we used and cannot be extrapolated to other brands, systems, or milling protocol.

To evaluate our new designs, we utilized FE Analysis commonly used in engineering. FE Analysis was developed as a method for solving structural mechanical problems by

subdividing a complex geometry into standard, or “finite”, elements such as tetrahedrons, to form a mesh.³² A displacement or force is prescribed at selected nodes, and the model is solved to yield data such as resultant stress and strain.³² FE Analysis may be used to model complex biologic systems and has been employed in dental research prior to this project.³²⁻³⁵ By creating a standardized FE model we are able to effectively compare stainless steel with zirconia specimens of varying cross-sectional geometries under a simulated shear debonding clinical force. Two previous iterations of FE models simulating exaggerated clinical situations were created and evaluated, but deemed inappropriate given their parameters. The data and analysis from these first two models are available upon request.

When evaluating the bond strength model, the decision to evenly distribute the occlusal force was made to replicate common incising of food that could cause bond failure. This was deemed more appropriate than arbitrarily choosing one or a select few bonding areas to focus the whole occlusal force.

The safety factor was calculated as a standard comparative measure for the various designs. The safety factor (factor of safety or FoS) is the ratio of the material load capacity to the applied load. In this project it is the average flexural strength of the material—determined experimentally as 556 MPa and as 565 MPa in FE modeling—over the maximum von Mises stress observed for each design. A ratio of 1.0 means the design will withstand only the experimentally applied load, with any greater load causing failure. Accordingly, a ratio of 2.0, for example, means the design can withstand two times the experimentally applied load. Therefore, we defined a safety factor greater than 1.0 as more ideal than a ratio of 1.0 or below. The safety factor was also calculated for maximum bond stress by taking the literature value of 17.4 MPa and dividing by the maximum bond stress found for each design.²⁸ The safety factor

values in each table serve as a measure to compare the different designs and aided our decision to pursue Design 4 for fabrication.

Overall, Designs 1, 3, 4, and 9 performed the best when compared to literature values and when evaluating safety factors. We considered a rounded geometry on the lingual of the retainer as an advantage over rectangular cross-sections for the patient's lingual comfort. Design 1 is rectangular in cross-section and therefore less ideal in comparison to rounded designs. After discussion with multiple dental labs, Design 3 was determined to be too small to mill due to its 0.3mm dimension. Thus, Design 4 and 9 will be considered for further discussion.

Design 4 is 0.5mm thick in a buccolingual dimension compared to 1.0mm for Design 9 in the same dimension. In the bonding model, the stainless steel control performed best while Design 9 outperformed Design 4 in terms of maximum von Mises stress and safety factor value. Similarly, Design 9 outperformed Design 4 when evaluated the maximum bond stress. Stainless steel, however, performed the worst of the three in this case. Considering both Design 4 and 9 in relation to the 0.036" stainless steel round wire, the smaller dimensions of Design 4 are more clinically advantageous. Therefore, Design 4 was selected to be fabricated and evaluated as the smallest and theoretically most comfortable design that performed well in our FE model.

Design 4 was milled with average dimensions of 1.02 x 0.48 x 28.06 mm. These milled specimens had a maximum percent standard deviation of 9.3 and maximum percent error of 13.5. We feel this is reasonable for such small dimensions and any such difference would not affect clinical performance. Using these milled dimensions, we modeled the same cross-section, input it in to the bonding model and calculated the safety factor for the maximum von Mises stress and bond shear stress for confirmation. Both calculated values had safety factors greater than 1.0 leading us to conclude that the actual milled specimens would be successful under the parameters

of our bonding model. Interestingly, the 0.018” SS control had calculated safety factor values less than 1.0. Even though 0.018” stainless steel wire is anecdotally applied clinically with success, it would fail under the defined parameters of our model. We believe the difference between our model and what actually occurs clinically during function accounts for the difference in success seen in each instance. Perhaps the actual clinical force(s) experienced by the appliance is better distributed across multiple bonding sites and the bonding material itself, thus dissipating the force so each bonding area experiences a decreased force leading to a higher chance of clinical success.

Expanding on bonding, one further consideration for the use of zirconia clinically is the need for improved bonding to enamel. For this, we looked to the prosthodontic literature for zirconia bonding protocol. Bonding of zirconia to enamel has progressed using various products often containing 10-methylacryloyloxydecyl dihydrogen phosphate, otherwise known as “MDP.” The 2015 review by Kern compared the clinical and laboratory success of various zirconia bonding protocols using non-retentive prostheses such as resin-bonded fixed dental prostheses—which “rely solely on adhesion”—or minimally-retentive inlay-retained designs.³⁶ In this regard, a resin-bonded fixed dental prosthesis can be considered comparable to a bonded lingual retainer. Over 20-64 month observation periods, debond rates with the two best bonding methods ranged from 4.8-7.1% with failures caused by traumatic incidents and of mixed adhesive failure meaning resin on both enamel and zirconia surfaces.³⁶ The overall recommendation in the review for the best bonding of zirconia to enamel is acid etching of the enamel, 50µm alumina particle abrasion at 0.25 MPa or less pressure of the zirconia, followed by MDP-containing primer and/or luting resin.³⁶ We considered this as the reference for bonding technique for the purpose of this project. The 17.4 MPa literature value used and referenced throughout this paper

was obtained using the Kern protocol.^{28,36} We recognize the need for further studies looking at aging Y-TZP specimens and bonds through thermocycling and then bonding to enamel for evaluation.

Current bonding of stainless steel round wire or braided flexible gold or stainless steel wire requires a mass of composite to cover the retainer at each bonding site providing some mechanical retention. While this same technique could perhaps be used for the Y-TZP retainer, the aforementioned zirconia bonding protocol does not require the luting agent to cover the retainer. Instead, the retainer is fixed to the enamel much like a veneer, requiring only etching of the enamel surface. If in further testing this bonding protocol is clinically acceptable it would impart a lower profile fixed retention design with less bonding material covering the tooth surface. Overall, this would be a smaller and less obstructive retention design capable of withstanding the maximum recorded anterior occlusal force.

To assess the practicality of Y-TZP fixed retainers, we analyzed the size and cost compared to our 0.018” and 0.036” round stainless steel controls and commonly used flexible braided wire such as OrthoFlex from Reliance Orthodontics. A summary of the analysis may be seen in Table 6.

Table 6. Size and Cost Comparison

Retainer	Size (mm)	Cost
0.036" SS	0.9144	\$0.03
0.036" SS Lab-Fabricated	0.9144	\$24.00
OrthoFlex (Reliance Orthodontics)	1.0 x 0.4	\$2.78
OrthoFlex Gold (Reliance Orthodontics)	1.0 x 0.4	\$5.56
Design 4	1.0 x 0.5	\$30.00

Design 4 was defined with semi-elliptical cross-sectional dimensions of 1.0 x 0.5mm. The round stainless steel wires equate to 0.9144 mm (0.036”) and 0.4572 mm (0.018”). Reliance Orthodontics OrthoFlex material measures approximately 1.0mm high by 0.4mm thick. In comparison, one can see that Design 4 has similar dimensions to 0.018” round steel and OrthoFlex.

To analyze cost we included only the retention appliance itself and did not include the cost of bonding materials. Stainless steel wire cost us \$3.25 for a 10 pack of 14” (355.6 mm) wires. From this length we are able to get 12 retainers based on the dimensions of our dentoform and, assuming no waste, gave us an approximate cost per round stainless steel retainer of \$0.03. A lab-fabricated stainless steel retainer cost us \$24. Likewise, OrthoFlex Stainless Steel costs \$75 for thirty inches (762mm). Calculating the cost for a retainer of the same size as the Y-TZP Design 4 retainer, and assuming no waste of material, the Orthoflex material yields 27 retainers at a cost of \$2.78 per retainer. For further comparison, Reliance Ortho FlexTech (gold) costs \$150 for thirty inches (762mm). Similar calculations yield a cost of \$5.56 per retainer. The cost of the Y-TZP retainer is considerably increased at \$30 when compared to these other available products and materials. The cost, however, is reasonable if considering the benefits to the patient in terms of potential comfort, aesthetics, bonding and adaptation. The cost is also reasonable if compared to the typical cost of a removable mandibular retainer.

The vision for clinical application of Design 4 or further refined designs is to scan the patient at or just prior to debond and have the lab mill a shade-matched Y-TZP retainer that is contoured to the lingual aspect of all six mandibular anterior teeth to be bonded using the recommended protocol. At this time, we are unaware of a software that is designed to connect an intraoral scan to the CAD/CAM machine for this specific purpose. The eventual goal of this

investigation is to bridge this gap to aid orthodontists in providing a Y-TZP alternative to stainless steel and gold fixed retention appliances. Regardless of the fixed retention protocol one chooses, careful fabrication, delivery and regular monitoring are imperative for clinical success and minimizing undesired effects and complications.

Chapter 5. CONCLUSION

Yttria-stabilized zirconia is an adequate material for retention and offers an aesthetic alternative to currently available stainless steel retainer materials. Y-TZP can be reliably milled to 0.48mm in a curved geometry to approximate the lingual aspect of the mandibular canines and incisors as a bonded retainer. Further research is necessary to determine the success of bonding protocol and clinical longevity of Y-TZP fixed retainers. Advanced technology is necessary to take full advantage of the possibilities of a milled retainer personalized to a patient's unique lingual anatomy, alignment and arch form. The overall cost is increased but reasonable considering the proposed advantages in aesthetics, size, bonding and patient comfort.

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