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Effect of Veneering Technique on Shear Strength of Porcelain Veneered Zirconia (PVZ): Finite Element Analysis

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ABSTRACT

Veneering technique is discussed as one of the reasons for chipping of porcelain veneered zirconia (PVZ) restorations, which impacts their longevity and success. This study aims to evaluate the effect of veneering technique; heat-pressed, and hand-layered, on the shear bond strength of PVZ ceramics through finite element analysis. Six cylindrical bilayer material model configurations were analysed; two types of zirconia, IPS e.max® ZirCad (Z) and Luxen Zr (L) and each veneered with three porcelain types, Shofu Vintage ZR (V), IPS e.max® Ceram (C), IPS e.max® Zirpress (P), with dimensions of (10 mm x 1.2 mm) and (5 mm x 3 mm), respectively. The force for three-dimensional model configurations were fixed at 5 kN. The results show that heat-pressed groups (ZP and LP) have slightly higher bond strength value 49.12 MPa and 49.03 MPa, compared to hand-layered groups (ZC, LC, ZV, and LV), measuring 48.87 MPa with 0.5% difference at maximum. Bond strength in MPa underwent variance analysis, revealing a significant influence of ceramic material on mean values (p = 0.0017). Thus, the highest stress concentrations occur at the edges of the load application points, gradually decreasing as the distance from the point of load application increases. Results indicate that heat-pressed technique is better than hand-layered veneering technique due to its effectiveness in strong adhering veneer to the zirconia core.

Keywords: Zirconia; veneer porcelain; shear bond strength; finite element analysis

INTRODUCTION

The introduction of zirconia as a core material has expanded the use of ceramics in dentistry via integration of computer-aided modelling (CAD/CAM) technology (Amat et al. 2018; Muchtar et al. 2012). One significant advantage of ceramic materials over metals in dental applications is their superior aesthetic properties, closely mimicking the natural appearance of teeth. Unlike metals, ceramics offer translucency that resembles natural teeth, enhancing the overall aesthetic outcome of dental restorations. Specifically, yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is known for its strong mechanical properties, meeting the requirements for high-stress dental restorations (Chin et al. 2018; Ma, Guess & Zhang 2013). However, Y-TZP, despite being a strong and durable material, its non-adhesive property had limited the translucency, making it fall short in replicating the inherent translucency of natural teeth (Kim 2020a; Salah et al. 2022). To achieve optimal aesthetics properties, a bilayer approach involving porcelain veneer over the zirconia core. Clinical studies on zirconia-based ceramic restorations have yielded promising results, highlighting their impressive clinical performance and high success rates (Komine, Strub & Matsumura 2012). In fact, it has been demonstrated that zirconia-based ceramic materials for restoration as anterior crown was safe and satisfactory, following ten years clinical study (Peumans M. 2004). Nevertheless, the veneering porcelain layer, responsible for the final optical appearance of fixed dental prostheses (FDPs), faces challenges due to its lower mechanical properties compared to zirconia. This disparity can lead to a noticeable occurrence of delamination and chipping effect (de Lima et al. 2015; Nistor et al. 2019). Despite the availability of monolithic Y-TZP as a strong alternative, there's ongoing interest in studying the mechanical properties of veneer porcelain on a zirconia core in zirconia veneered restorations.

Porcelain chipping in porcelain veneered zirconia (PVZ) restorations can be influenced by various factors, and among them, veneering techniques have been acknowledged as significant contributors, primarily because of their impact on residual stress (Rodrigues et al. 2021). The hand layering method has traditionally been a conventional technique to achieve an aesthetically pleasing and strong restoration. In this technique, a ceramic slurry is formed by mixing porcelain powder with distilled water, which is then layered directly onto the zirconia framework (Daud et al. 2017). Nonetheless, this method demands skill to prevent voids during layering and firing. Another known technique is heat-press or lost wax, where a wax model shapes the final porcelain layer on zirconia. This method achieves the final crown shape with just one firing, making it a less sensitive technique for veneering (Almoualimy et al. 2020). However, in an experimental study conducted by Teng et al. (2023) the shear bond strength of heat-pressed veneering was found to be lower yet comparable results, rather than superior, to conventional hand-layered veneering. This observation led researchers to favour the conventional hand-layered technique (Amat et al. 2020; Teng et al. 2023).

Recent advancements in CAD/CAM technology and software have transformed the design and analysis techniques for FDPs (Hosseini-Faradonbeh & Katoozian 2022), enabling comprehensive evaluation of zirconia veneered restoration's mechanical behaviour through finite element analysis (FEA). This analysis covers stress distribution, load-bearing capacity, and the identification of potential weak areas (Dhital et al. 2020; Fardin et al. 2022; Madruga et al. 2021; Tan et al. 2022), employing methods such as static, fatigue, thermal and bonding analyses. These methodologies are essential for enhancing the performance of zirconia veneered restorations in various clinical scenarios. However, the most significant concern contributing to veneer chipping often lies in the insufficient bond strength between the zirconia core and veneering ceramic (Almoualimy et al. 2021; Jadaan et al. 2023; Sailer et al. 2007, 2018; Solá-Ruíz et al. 2015). Thus, this study aims to evaluate the shear bond strength between various commercial PVZ, focusing on the porcelain veneering technique, specifically hand-layering and heat-pressing, using finite element analysis. By understanding how these two different veneering techniques influence the shear bond strength of the zirconia/veneering ceramic interface, this research seeks to provide insights that can lead to improved clinical outcomes and enhanced longevity of dental restorations.

MATERIALS AND METHODS

Figure 1 illustrates the process flow of this study. Ansys software (Ansys 2023 R2, Ansys Inc.) was employed to create 3D geometrical models and analyses stress at the bonding site.

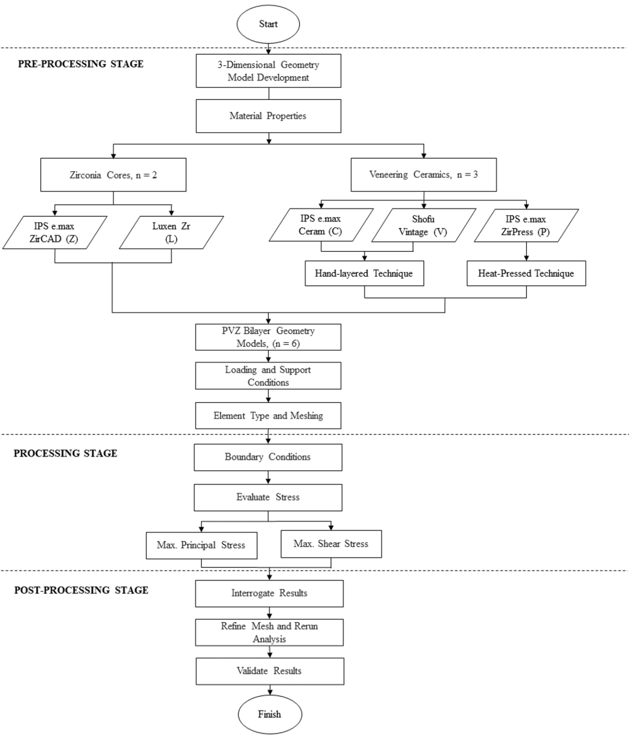

FIGURE 1. The process flow of this research

MATERIAL DETERMINATION FOR SIMULATION

In previous literatures, zirconia has been recognized for its excellence performance and properties in dental applications, particularly in cases where strength, durability, and resistance to fractures are of utmost importance (Daud et al. 2017). This makes it a highly recommended material for restorations like crowns and bridges. Besides, porcelain veneers serve as a complementary option to zirconia, providing a bilayer solution which combines aesthetic appeal with the strength of zirconia (Peumans M. 2004).

Therefore, the demand for both materials has led to various manufacturers producing them, making it imperative to compare their fabrication techniques. Thus, in this paper, six all-ceramic bi-layered test models were combined with identical configurations. The elastic modulus and Poisson's ratio were given as input into software according to common values (Dhital et al. 2020; Ereifej et al. 2011a; Heintze et al. 2018; Kim 2020a; Liu et al. 2010), as detailed in Table 1.

TABLE 1. The material properties of the tested models

Material	Abbr.	Young's Modulus (GPa)	Poisson's Ratio
Zirconia Cores	Z (Heintze et al. 2018)	210	0.30
	L (Kim 2020a)	208	0.25
Veneering Ceramics	V (Liu et al. 2010)	65	0.22
	C (Ereifej et al. 2011a)	68	0.24
	P (Dhital et al. 2020)	70	0.21

The bond strength test models were consisted of two sections, i.e., the zirconia core and porcelain veneer, where both sections representing five different material compositions and manufacturers. The selection of these materials was influenced by their different chemical compositions, fabrication techniques, and manufacturers, as detailed in Table 2. The commercial veneering ceramics used were Shofu Vintage ZR denoted as, (V), IPS e.max® Ceram (C) and IPS e.max® Zirpress, (P). To ensure research validity, both commercial zirconia materials with different chemical compositions; IPS e.max® ZirCad (Z) and Luxen Zr (L), were studied.

GEOMETRICAL MODEL DESIGN

The three-dimensional geometrical PVZ models of the zirconia core and veneering porcelain were precisely configured with dimensions of 10 mm x 1.2 mm and 5 mm x 3 mm, respectively (diameter, [d] x height, h). The dimensions of the zirconia core and veneering porcelain models were selected based on the experimental parameters outlined by Teng et al. (2023), enabling for a direct comparison between the experimental and simulation results. The models were designed perpendicular to the block material. Dimensions of the zirconia veneered porcelain for each type of model configuration are illustrated in Figure 2.

Structured meshing with 0.3 mm element size was selected, focusing on refining the bond interface of the zirconia veneer. This refinement produced 23,974 nodes and 110,352 tetrahedral elements, ensuring the necessary accuracy at the interface. A convergence test was conducted prior the mechanical simulation.

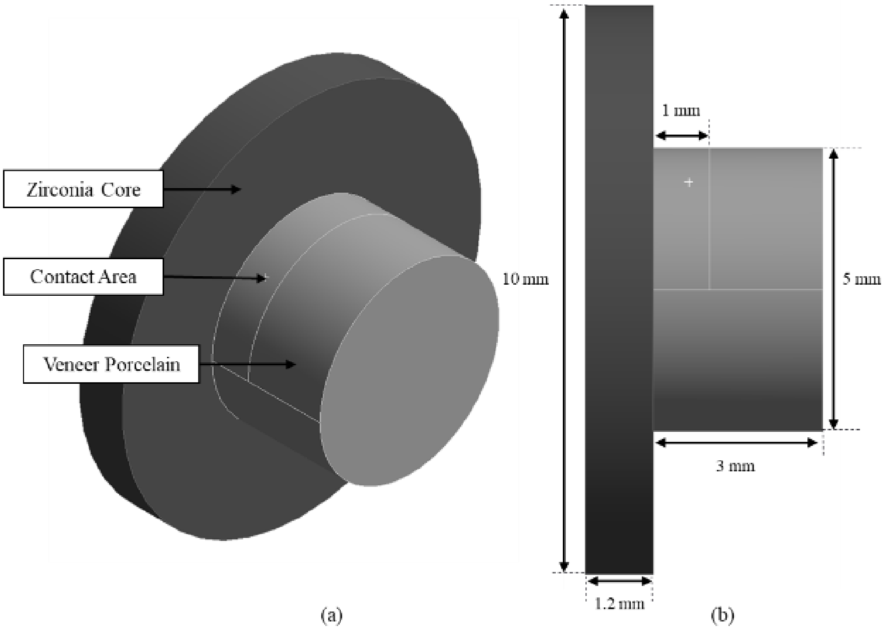

FIGURE 2. The three-dimensional zirconia veneered restoration (PVZ) geometrical model with size and dimension (a) isometric view; (b) front view

DETERMINATION OF BOUNDARY CONDITION

In the 3D analysis, all the listed materials were set to be isotropic, homogeneous, and linear elastic to simplify complex analyses. Additionally, it was presumed that the interfacial area between the zirconia core and porcelain veneer was bonded without any adhesion, and these interfacial regions were considered free of defects and voids. These assumptions were employed to establish a simplified and controlled environment, effectively eliminating numerous potential variables and sources of uncertainty in FEA. The models specifically focused on analysing stress distributions at the point of load application, comparing it with the experimental method results. This approach was chosen to focus primarily on the initial response and capturing the immediate effects of the veneering technique on the material's shear strength.

To validate the experimental data by Teng et al. (2023), a constant force of 5 kN was applied to the contact surface of the interface, as depicted in Figure 3(a). The application area of the force was designed in the form of a shear blade, a semi-circle indentation area of 1 mm thickness and radius of 5 mm as demonstrated in Figure 3(b) and (c). The interaction between the zirconia and veneer porcelain was characterized as bonded contact, and a fixed support was employed on the rear surface of the zirconia block, thereby immobilizing it in all directions, as seen from Figure 3(d).

STATISTICAL ANALYSIS

Statistical analysis of the shear bond strength data was carried out using an independent t-test to compare the means between the simulation and experimental groups. The independent t-test was chosen due to its suitability for comparing two independent groups. Prior to executing the t-test, the assumptions of normal data distribution and homogeneity of variances were verified. Adjustments to the p-values resulting from the independent t-test were made using the Holm post hoc test to control the familywise error rate during multiple comparisons. A significance level of $p < 0.05$ was considered statistically significant for all tests (White et al. 2022). The statistical analyses were carried out using ANOVA to examine the group data.

TABLE 2. Description of the materials used as zirconia core and veneering porcelain (Kim 2020b; Pantić et al. 2019)

Material	Name	Abbreviation	Manufacturer, Country of Origin	Composition (wt%)	Material Type	Fabrication Technique
Zirconia Cores	IPS e.max® ZirCad	Z	Ivoclar Vivadent; Schaan, Liechtenstein	Zr(87-95), Y_2O_3(4-6), Hf(1-5), Al(0.1-1)	3 mol% Yttrium High Strength Zirconia	CAD-CAM Milling
	Luxen Zr	L	DentalMax, Seoul, Korea	Zr(91.68), Y(5.44), Hf(2.76), Fe(0.05), Al(0.05)	3 mol% Yttrium High Strength Zirconia	CAD-CAM Milling
Veneering Ceramics	Shofu Vintage ZR	V	Shofu, Kyoto, Japan	Aluminosilicate glass, Leucite ($KAlSi2O_6$), etc	Feldspathic Veneering Porcelain	Hand-Layered
	IPS e.max® Ceram	C	Ivoclar Vivadent; Schaan, Liechtenstein	SiO_2, Al_2O_3, Na_2O, K_2O, ZnO, CaO, P_2O_5, F, other oxides, Pigments	Nano-Fluorapatite Veneering Porcelain	Hand-Layered
	IPS e.max® Zirpress	P	Ivoclar Vivadent; Schaan, Liechtenstein	SiO2, Li_2O, Na_2O, K_2O, MgO, Al_2O_3, CaO, ZrO_2, P_2O_5 and other oxides	Fluorapatite Veneering Porcelain	Heat-pressed

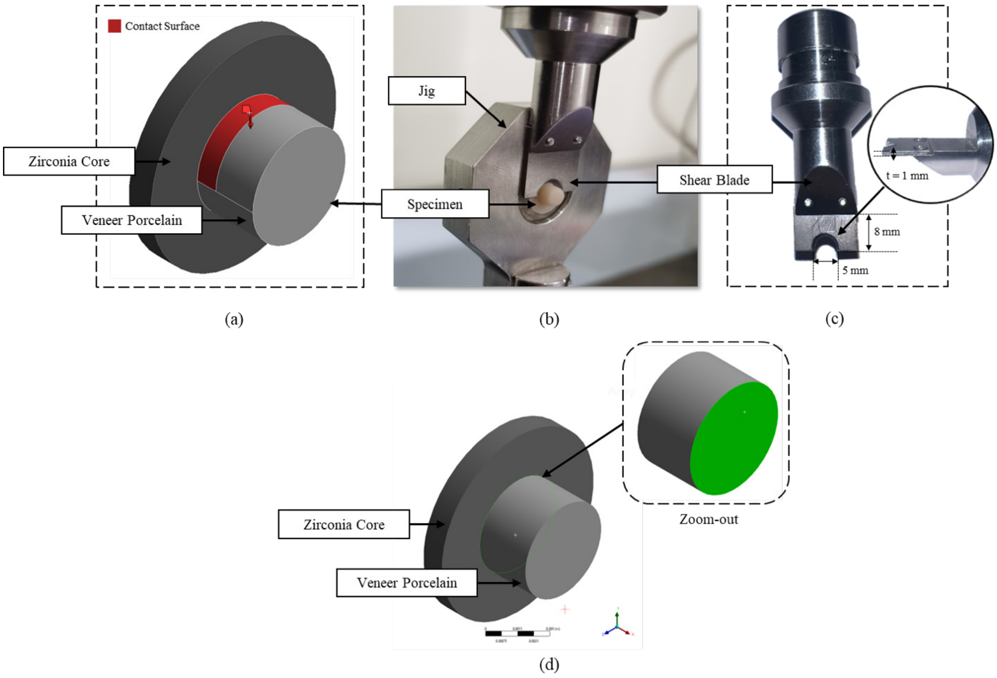

FIGURE 3. The complete setup for both experimental and simulation methods; (a) contact surface area for force and (b) shear bond strength test setup using the Autograph AGS-X Series by Shimadzu, Japan; (c) shear blade dimensions in (mm) (d) area of the interface bond (highlighted in green) between zirconia and veneer

RESULTS AND DISCUSSION

SHEAR BOND STRENGTH

Table 3 displays the outcomes of the maximum shear stress analysis conducted through FEA the six bi-layered geometrical models. Among these models, the heat-pressed groups ZirCad-ZirPress (ZP) and Luxen-ZirPress (LP) configuration demonstrated a higher shear strength value, at 49.12 MPa and 49.03 MPa, respectively, while the hand-layered groups ZirCad-Ceram (ZC), Luxen-Ceram (LC), ZirCad-Vintage (ZV), and Luxen-Vintage (LV) configuration exhibited lower shear bond strength values, with the lowest being LC at 48.87 MPa, with 0.5% maximum difference with heat-pressed group, ZP. Exhibit there is no statistically significant differences were observed among the six groups. These findings align with prior research conducted by Al-Dohan et al. and Ereifej et al. (Al-Dohan et al. 2003; Ereifej et al. 2011b), who evaluated the shear bond strength of different zirconia core/veneer PVZ combinations, including Ceram, ZirCad, and Empress CAD. In their investigations, they similarly discerned no statistically significant differences in bond strength between the groups. Thus, the minor differences in shear bond strength value among these six groups were negligible that they can be considered to have similar strength during clinical service, thereby supporting the acceptance of the first hypothesis.

However, the results of this study emphasize the influence of veneering techniques on shear bond strength. In specific, the veneering technique employed, involving two heat-pressed groups, LP and ZP, exhibited slightly higher bond strength in comparison to the hand-layered counterparts, LC, LV, ZV, and ZC. This finding led to the rejection of the second hypothesis, suggesting that using the heat-pressed method may not be optimal for bi-layered dental restorations. Heat-pressed techniques have the potential to yield a stronger bond between the two layers because they allow for better adaptation and intimate contact between the veneer and the core material (Cheng, Yang & Yan 2018). In contrast, hand-layered techniques involve the manual application of veneering material in layers, followed by firing process to achieve the desired shape and aesthetics (Almoualimy et al. 2021).While this method portrays better manual control over the restoration’s appearance, may not consistently result in the same level of bond strength as heat-pressed techniques. Therefore, the achieving of uniformity and strong adhesion between the veneer and core can be even challenging. Thus, the study suggests that both heat-pressed and hand-layered methods are viable options for bi-layered dental restorations, with each offering its own set of advantages and considerations.

TABLE 3. A summary results of the study

	Materials					
Geometrical Models	ZV	ZC	ZP	LV	LC	LP
Max. Principal Stress (MPa)	61.12	61.27	61.00	61.18	61.34	61.07
Shear Bond Strength (MPa)	48.89	48.95	49.12	48.91	48.87	49.03

STRESS DISTRIBUTION

The stress distribution in the adhesive area between the surface layers of PVZ was determined using the principal stress criterion. The methodology reveals the interface bond area between zirconia and the veneer porcelain, with the green region depicting the area where the contour plot is observed. By discerning regions of elevated stress, the principal stress analysis identifies critical areas for restoration durability. Figure 4 illustrates the maximum principal stress and maximum shear stress results, offering an overview of the performance of PVZ across all six-bilayer model configurations. The heat-pressed groups (ZP and LP) demonstrate higher principal stress values at 61 MPa and 61.07 MPa, respectively, compared to the hand-layered group, which LC exhibits the lowest value at 61.34 MPa. This represents a 0.6% difference compared to the highest heat-pressed model, ZP. These model configurations consistently exhibit only slight differences in stress levels. Similar to the shear stress results, these findings suggest that, even with variations in elastic modulus, density, and mechanical properties among ceramic materials, and assuming ideal adhesion conditions, there is minimal to no discernible difference in their behaviour at the interfaces. However, it is obvious that the highest stress concentrations occur at the edges of the load application points, gradually decreasing as the distance from the point of load application increases.

Variations in elastic modulus between core and veneering materials can impact stress distribution. A stiffer zirconia core (higher elastic modulus) may endure greater compressive stresses, while a more compliant veneering material (lower elastic modulus) may face higher tensile stresses. The stress results suggest that ceramic materials exhibit consistent behaviour at interfaces, irrespective of their physical differences Although the stress values were not excessively high, there was still an increase in stress observed in a specific part of the core. This increase in stress, even if moderate, could have played a role in making that area of the core more susceptible to fracturing during the in-vitro experiment. This stress distribution pattern closely aligns with the findings reported by Al-Dohan et al. (2003), Ereifej et al. (2011), as well as studies conducted over the past 14 years (2006 – 2020) that were reviewed systematically by Maria et al. (2020). The review concluded that both heat-pressed and hand-layered veneering technique on Y-TZP cores achieved similar bond strength results. They also previously highlighted the flexural momentum resulting from high tensile stresses near the load application area were reported as "Saint-Venant effect", an engineering concept in the field of solid mechanics and structural engineering (Al-Dohan et al. 2003; Ereifej et al. 2011b; Maria et al. 2020). To mitigate stress concentration effects, the singularity point was excluded from further analysis.

Consequently, results indicate that both heat-pressed and hand-layered veneering technique exhibited comparable bonding strength, implying their equal effectiveness in securely adhering veneer to the zirconia core. This equivalence permits a choice between these two techniques. One of the limitations of this study is the inability to investigate stress distributions and crack behaviour after crack initiation. This limitation arises due to stress concentration effects within the samples and the technique-sensitive nature of failure in brittle materials like ceramics. Static bond strength tests can only offer general qualitative insights into stress concentrations, which can vary under different testing conditions, parameters, and material properties. This method can offer early detection of chipping or delamination by analysing stress distribution in the adhesive area, without the need for crack or fracture modelling.

STATISTICAL ANALYSIS

The shear bond strength analysis, utilizing independent t-tests and Holm post hoc corrections, revealed a significant difference between simulation and experimental methods ($p < 0.05$, adjusted $p = 0.0017$). This highly significant dissimilarity indicates a genuine distinction in shear bond strength, supported by the compelling evidence to reject the null hypothesis. The mean shear bond strength of the simulation method (48.95 ± 0.09 MPa) was notably higher compared to the experimental method (36.25 ± 6.80 MPa), as illustrated in Figure 5, a pattern observed across distinct sample sets (ZV, ZC, ZP, LV, LC, LP). This difference, highlighted by the t-test results, suggests that the simulation method consistently yields stronger shear bond strength values than the experimental method.

Additionally, the Holm post hoc corrections were applied to account for the multiple comparisons inherent in the analysis. The adjusted p-value of 0.0017 further reinforces the significance of the observed difference, maintaining a rigorous control over the familywise error rate. The substantial dissimilarity in shear bond strength between the two methods is not only statistically supported but also carries practical importance. The simulation method appears to produce consistently higher shear bond strength values, indicating its potential superiority or efficiency in achieving stronger material bonds.

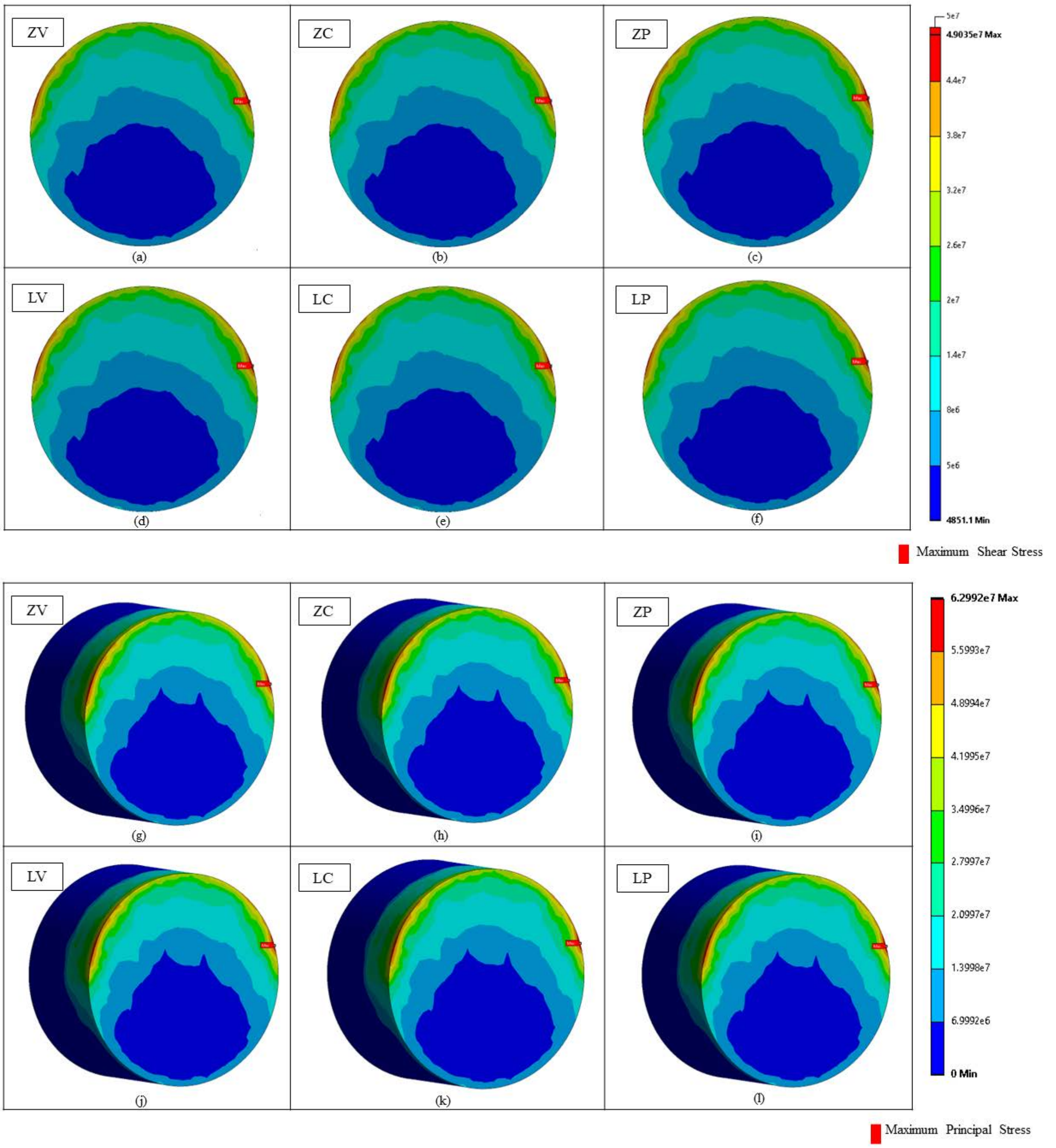

FIGURE 4. Results of stresses at the veneer porcelain interface for all six groups: maximum shear stress (a) ZV, (b) ZC, (c) ZP, (d) LV, (e) LC, and (f) LP. and maximum principal stress (g) ZV, (h) ZC, (i) ZP, (j) LV, (k) LC, and (l) LP

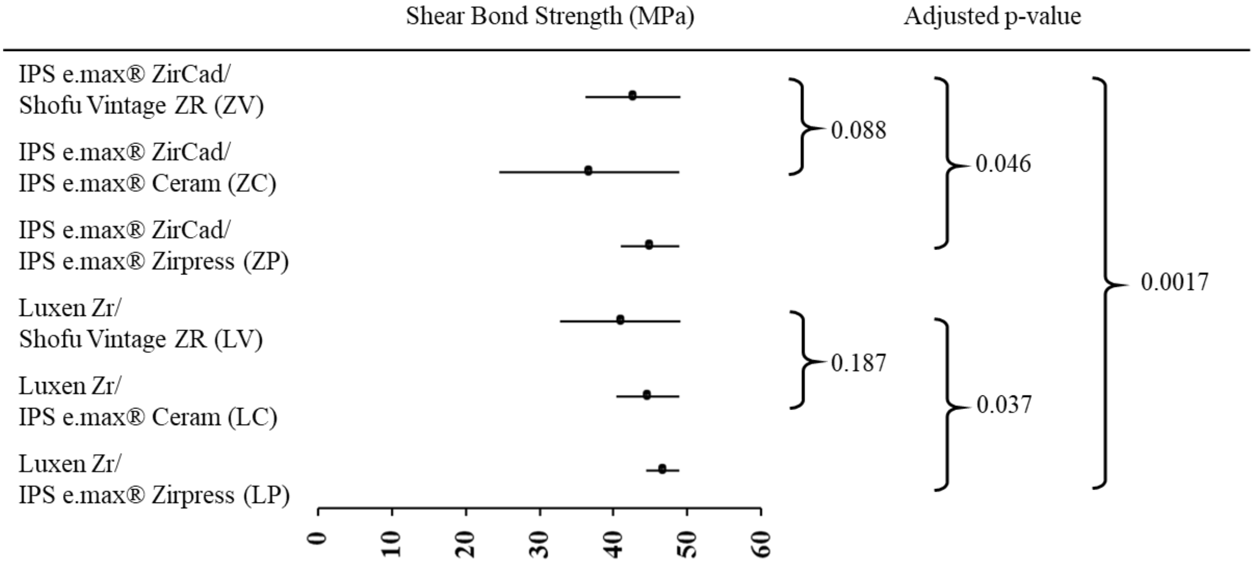

FIGURE 5. The estimated means of shear bond strength measurement for all six geometrical bilayers with adjusted p-values

CONCLUSION

Within the limitations of this study, the following conclusions were drawn:

1. The shear strength analysis was studied under static loading condition with a 5kN force, showing comparable results for both techniques: hand-layered and heat-pressed.
2. Heat-pressed group ZP and LP model configuration demonstrated a higher shear strength value, registering at 49.12 MPa and 49.03 MPa, with only 0.5% difference at maximum, compared to the lowest in hand-layered group, LC 48.87 MPa.
3. The independent t-tests, supported by Holm post hoc corrections, confirm a significant and consistent superiority of the simulation method over the experimental in shear bond strength ($p < 0.05$, adjusted $p = 0.0017$). With the simulation method producing markedly higher values (48.95 ± 0.09 MPa) compared to the experimental method (36.25 ± 6.80 MPa), this observed difference is not only statistically robust but also practically significant, suggesting the simulation method's efficiency in achieving stronger material bonds.
4. The stress concentration between the zirconia and veneer porcelain (PVZ) decreases with distance from the load points. While a larger adhesive area enhances bonding, it can still induce stress in the core, potentially contributing to fractures during experiments. This method allows for early detection of issues such as chipping or delamination by analysing stress and deformation in the adhesive area, without the need for crack or fracture modelling.
5. Heat-pressed are a comparable technique to hand- layered veneering technique implying their equal effectiveness in securely adhering veneer to the zirconia core. delamination by

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DECLARATION OF COMPETING INTEREST

None.

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