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An In-Vitro Study to Assess the Effect on Flexural Strength of Two Different Ceramic-Veneered Sub-Structures with Four Variable Thickness

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ABSTRACT
Background: Esthetic dentistry combines technical skill and artistic creativity to produce dental prostheses that restore function and enhance smiles. Over the years, dental materials have evolved from amalgams and gold alloys to advanced ceramics like zirconia, which offer superior aesthetics and strength. Porcelain-Fused-to-Metal (PFM) restorations, used since 1965, are durable but can compromise aesthetics due to light transmission issues. Zirconia ceramics, ideal for anterior and posterior restorations, combine strength and translucency similar to natural teeth. Advances in CAD/CAM and laser sintering technologies have improved the precision and durability of zirconia crowns. Understanding flexural strength, a material's resistance to deformation, is crucial for durable and aesthetically pleasing restorations.
This study examined the flexural strength of two different ceramic-veneered sub-structures with varying thicknesses, promoting the shift from PFM to Porcelain-Fused-to-Zirconia. The findings highlight improved mechanical performance, enhancing both the aesthetic value and overall well-being of patients.
Materials and Method: An In-Vitro study in which 80 samples were fabricated and divided equally into two groups, i.e., Metal and Zirconia Group. These two groups were further divided into four sub-groups of different thickness, i.e., 0.5mm, 0.7mm, 0.9mm and 1.2mm containing 10 samples in each sub-group. The Metal and Zirconia samples were fabricated using the Conventional Wax-Burnout and Computer-Assisted Milling Technique respectively. The thickness of the samples was later verified using a vernier calliper, followed by uniform layering of 1mm with porcelain of all the samples with the help of a silicone jig. The samples were later subjected to 3-Point Flexural Test in the Universal Testing Machine and the values of the flexural strength were obtained.
Results: The study revealed that the flexural strength of the core structures of various thickness kept increasing with an increase in the thickness. However, Group 1, i.e., Metal group values were significantly higher on comparison to its counterpart, i.e., Zirconia group of the same thickness.
Conclusion: These findings highlight the significance of thickness while fabrication of core structure in order to increase the overall functionality and aesthetics for the patient's well-being.

Keywords: Flexural strength, 3-Point Flexural Test, Porcelain-Fused-To-Metal, Porcelain-Fused-To-Zirconia

INTRODUCTION

Esthetic dentistrymerges the art and science of dental care, where meticulous technical skill complements artistic creativity to produce outstanding functional and aesthetic results. Success in esthetic dentistry requires practitioners to thoroughly understand the core principles of prosthetic dentistry. These principles are vital for designing dental prostheses like crowns and bridges, which not only restore oral function and replace missing teeth but also enhance the appearance of a patient's smile(1). A deep knowledge of various esthetic materials, especially ceramics and zirconia, is essential(3). Practitioners need to be well-informed about the clinical uses, contraindications, applications, and limitations of these materials to choose the most suitable options for each patient, ensuring optimal aesthetic and functional outcomes.

Over the past few decades, the field of dentistry has undergone remarkable transformations, especially in the realm of materials used for dental restorations[2]. Traditionally, materials like amalgams and gold alloys were the mainstays for filling cavities and constructing crowns[4,5]. These materials, while durable and effective in restoring function, often fell short in the esthetic department. Amalgams, with their silver hue, and gold alloys, despite their longevity, could not mimic the natural appearance of teeth, leaving patients with visibly unattractive dental work. The quest for materials that could offer both durability and natural-looking results led to the advent of porcelain-veneered ceramics, advanced ceramics, and composite resins. These materials revolutionized dental restorations by providing a more tooth-like appearance, enhancing patient satisfaction, and boosting confidence[6].

Since their introduction in 1965, porcelain-fused-to-metal (PFM) restorations have been a cornerstone in esthetic dental restoration. These restorations feature a strong metal core that supports the veneering ceramics, making them versatile for various applications, from single crowns to long-span fixed partial prostheses[7,8]. The core materials used in PFM restorations play a crucial role. They are designed to rebuild sufficient coronal anatomy of a vital or endodontically treated tooth, providing a solid foundation for a fixed dental prosthesis to be seated or cemented. This reinforcement not only enhances the strength of the prosthesis but also extends its lifespan, protecting the underlying tooth structure and surrounding soft tissues[9]. Furthermore, these core materials create a stable base for the ceramic material that is applied after the sintering process.

However, PFM restorations are not without their limitations. One significant drawback is their tendency to hinder light transmission, which can result in an opaque appearance that may compromise esthetic outcomes[10,11]. Despite this, PFM restorations have been widely used due to their durability and the reliable support they provide for veneering ceramics. Understanding the balance between the functional benefits and the esthetic limitations of PFM restorations is essential for practitioners, particularly those specializing in prosthodontics. By carefully selecting and applying these materials, dentists can optimize both the structural integrity and the visual appeal of dental restorations, achieving satisfactory results for patients[12].

In summary, while PFM restorations have been instrumental in the field of esthetic dentistry[13], ongoing advancements and careful material selection are vital to address their inherent limitations and enhance overall patient satisfaction.

Ceramics, particularly those used in crowns and bridges, have advanced significantly. Porcelain, a type of ceramic, offers excellent esthetic qualities, including translucency and color matching that closely resemble natural teeth[14]. However, the most significant advancement came with the introduction of zirconia ceramics. Zirconia combines the strength needed to withstand the forces of chewing with a translucency that rivals natural teeth, making it an ideal material for both anterior and posterior restorations[15,16]. The advent of digitalization, including technologies like CAD/CAM and laser sintering, has further enhanced the precision fitting and durability of zirconia crowns.

The shift from PFM to zirconia crowns underscores the importance of examining mechanical properties such as flexural strength. Flexural strength, also known as bend strength or transverse rupture strength, indicates the extent of deformation a material can endure before yielding or fracturing[17]. It is a critical material property defined as the stress in a material just before it yields in a flexure test. The transverse bending test, commonly employed in specimens with either circular or rectangular cross-sections, bends the material until fracture or yielding using a three-point flexural test technique[18]. The highest stress experienced within the material at its moment of yield is represented by the flexural strength .

Understanding the flexural strength of different core materials is essential for extending their clinical applicability from esthetic zones to high-stress or load-bearing areas such as the posterior region[19]. This ensures that dental restorations are not only aesthetically pleasing but also durable and functional. Zirconia's toughening transformation mechanism within its microstructure provides superior aesthetics by allowing better light transmission and reflection, similar to natural teeth. It also offers durability and biocompatibility, eliminating concerns about metal allergies or inflammation[20]. Moreover, advancements in technology have led to the precise fitting and enhanced longevity of zirconia crowns, making them a versatile and promising material for prosthetic dentistry[21].

Considering the pivotal role of aesthetics, durability, and functionality in material selection for prosthetic fabrication[22], it is essential to examine mechanical properties such as flexural and tensile strength.

In this study we had investigated the effect of flexural strength on two different ceramic-veneered sub-structures with four variable thicknesses. We have done so, in order to promote the generational shift from Porcelain-fused-to-Metal which has comparatively low esthetic value because of the opaque shade of the metallic sub-structure to Porcelain-fused-to-Zirconia which has a high esthetic value because of it's similarity to the tooth structure[23]. This studyprovided useful insights into the mechanical performance of these materials in the real-world conditions be it during mastication, speech, function or flexurewhich would enhance the overall emotional, social and biological well-being of the patient[24].

MATERIALS AND METHODOLOGY

Sample Preparation

A total of 80 samples were prepared for the purpose of this study. Two groups were ofMetal and Zirconia Discs respectively with 40 samples in each group. These two groups will be further divided into 4 sub-groups of 10 samples each with varying thickness of the core structure for Porcelain-Fused-To-Metal Restorations(Fig. 1) and Porcelain-Fused-To-Zirconia Restorations(Fig. 2). A total of 4 thickness were chosen, the dimensions of the sample being 0.5mm, 0.7mm, 0.9mm and 1.2 mm respectively.
In this study, a total of 80 samples were fabricated, with 10 samples in each sub-group.

Table 1: Experimental Groups Abbreviations and their Associated Thickness

Material	Sub-Group	Abbr.	Sample Size	Thickness Of Sample(In Mm)
GROUP 1: METAL	Sub-Group 1A	M 0.5	10	0.5mm
	Sub-Group 1B	M 0.7	10	0.7mm
	Sub-Group 1C	M 0.9	10	0.9mm
	Sub-Group 1D	M 1.2	10	1.2mm
GROUP 2: ZIRCONIA	Sub-Group 2A	Z 0.5	10	0.5mm
	Sub-Group 2B	Z 0.7	10	0.7mm
	Sub-Group 2C	Z 0.9	10	0.9mm
	Sub-Group 2D	Z 1.2	10	1.2mm

Forty disc-shaped specimens were prepared having a diameter of 15mm for the metal core sub-structure. A wax pattern was prepared for each of the 40 samples and these sampleswerethen, invested and casted with Ni-Cr(Realloy N+, DIN EN ISO 22674) pellets to a thickness of 0.5mm, 0.7mm,0.9mm and 1.2mm respectively.
Another forty disc-shaped samples were designed in the CAD/CAM Software with a diameter of 15mm and of varying thickness for each sub-group (10 samples each).
These forty disc-shaped specimens were milled from a zirconia blank(AmannGirbachh AG CeraMill zolid ht+ preshade) using 5-Axis Milling Machine(AURM-5X-300-PRO). The dimension of the sample being a diameter of 15mm and of variable thicknesses ranging from 0.5mm, 0.7mm, 0.9mm and 1.2mm respectively with the help of a Machinable CAD/CAM Technique.
Dry Milling was done for preparation of the zirconia specimen and the final specimen were finished, polished and glazed.
Both the Metal Discs and Zirconia Discs were then be sintered at 1500˚C and 1550˚C in their respective furnaces(For Metal, For Zirconia).

Fabrication Of Silicone Jig & Layering Of The Samples With Porcelain

The dimensions of the discs (i.e., diameter and thickness of the sample) were verified using a Vernier Calliper (Rabbit Force Digital Calliper Eco 0-150mm DIGI-0150).
For the purpose of porcelain layering using the conventional method, a silicone jig(Fig. 3) was fabricated with the thickness of 1.5mm, 1.7mm, 1.9mm and 2.2mm for samples of thickness 0.5mm, 0.7mm, 0.9mm and 1.2mm respectively, in order to maintain a uniform thickness of 1mm for the study.

Testing Of The Samples

All the fabricated specimen were be tested for Flexural Strength using a Three-Point Flexure technique(Fig. 4) in a Universal Testing Machine (Zwick Roell, Germany Static UTM Z010) at Central Research Facility, Sonipat(Research Extension of IIT Delhi).

RESULTS

An In-Vitro Study was conducted at Santosh Deemed to be University, Ghaziabad in which 80 samples were fabricated for assessment of flexural strength on two different sub-structures of four variable thickness, i.e., 0.5mm, 0.7mm, 0.9mm and 1.2mm.
Forty Samples were fabricated each of Metal and Zirconia Sub-Structure using Conventional Casting technique and Dry Milling technique respectively.
These samples were later layered uniformly with porcelain of 1mm and sintered in a ceramic furnace. The uniformity in the layering process was obtained with the help of a Silicone Jig.
The Samples were tested for flexural strength using the Three-Point Flexure Test at Central Research Facility, Sonipat using the Universal Testing Machine with a load cell of 10kN.

Table 2: Flexural Strength of all the samples tested for 3-Point Flexural Strength under UTM

S. No.	Flexural Strength of Metal(in MPa)				Flexural Strength of Zirconia(in MPa)			
	M 0.5	M 0.7	M 0.9	M 1.2	Z 0.5	Z 0.7	Z 0.9	Z 1.2
1st Sample	797	1006	1387	1733	701	801	985	1049
2nd Sample	802	998	1397	1701	726	805	973	1153
3rd Sample	785	1024	1413	1699	707	815	942	1170
4th Sample	799	993	1380	1664	691	795	959	1153
5th Sample	789	1004	1403	1727	706	810	991	1052
6th Sample	801	985	1390	1731	716	793	964	1033
7th Sample	811	1020	1420	1742	713	797	915	1008
8th Sample	805	1007	1407	1707	719	787	982	1091
9th Sample	815	986	1409	1713	694	791	933	1069
10th Sample	803	990	1403	1709	714	800	927	1109
MEAN	800.7	1001.3	1400.9	1712.6	708.7	799.4	957.1	1088.7

Table 3: Mean Value of Flexural Strength that was measured using Three-Point Flexure Test in the UTM for Metal Sample

Thickness	Mean (MPa)	SD	p-value	Pairwise comparison
0.5mm	800.70	8.57	<0.001*	0.5 vs 0.7, 0.9, 1.2 = <0.001* 0.7 vs 0.9, 1.2 = <0.001* 0.9 vs 1.2 = <0.001*
0.7mm	1001.30	12.78		
0.9mm	1400.90	11.77		
1.2mm	1712.60	21.33		

In Table 3, the mean flexural strength of various thickness of Group 1 i.e., Sub-group 1A is 800.70MPa (SD 8.57), Sub-group 1B is 1001.30MPa (SD 12.78), Sub-group 1C is 1400.90MPa (SD 11.77) and Sub-group 1D is 1712.60MPa (SD 21.33). In these groups, the highest flexural strength was noted in Sub-group 1D I.e. 1742 MPa and lowest flexural strength was noted in Sub-group 1A i.e., 785MPa. There was significant difference of 0.7 in the flexural strength (MPa) between the different thickness value in Group 1. Upon pairwise comparison it showed that flexural strength of metal samples of 0.5mm thickness was significantly lesser at a ratio of 0.79, 0.57 and 0.46 on relating with 0.7mm, 0.9mm and 1.2 mm respectively. 0.7mm was also significantly lesser at a ratio of 0.71 and 0.58 on relating with 0.9mm and 1.2 mm respectively. It was also seen that 0.9 mm was significantly lesser at a ratio of 0.81 on relating with 1.2mm thickness of metal samples.

Table 4: Mean Value of Flexural Strength that was measured using Three-Point Flexure Test in the UTM for Zirconia Sample

Thickness	Mean	SD	p-Value	Pairwise Comparison
0.5mm	708.70	10.50	<0.001*	0.5 vs 0.7, 0.9, 1.2 = <0.001* 0.7 vs 0.9, 1.2 = <0.001* 0.9 vs 1.2 = <0.001*
0.7mm	799.40	8.69		
0.9mm	957.10	25.17		
1.2mm	1088.70	53.12		

In the above given table, the mean flexural strength of various thickness of group 2, i.e., Sub-group 2A is 708.7MPa (SD 10.50), Sub-group 2B is 799.4MPa (SD 8.69), Sub-group 2C is 957.10MPa (SD 25.17) and Sub-group 2D is 1088.70MPa (SD 53.12). In Group 2, the highest flexural strength is seen in 1.2mm thickness, i.e., 1170 MPa and lowest flexural strength was seen in 0.5mm thickness, i.e., 691MPa. Flexural strength differed significantly by 0.8 between successive thickness values in group 2. Upon pairwise comparison, it showed that flexural strength of Zirconia samples of 0.5mm thickness was significantly lesser at the ratio of 0.88, 0.74 and 0.65 on relating with 0.7mm, 0.9mm and 1.2mm respectively. Also 0.7mm was significantly lesser at a ratio of 0.83 and 0.73 on relating with 0.9mm and 1.2mm respectively. It was also noted that 0.9mm was also lower at a ratio of 0.87 on relating with 1.2mm thickness of Zirconia sample.

Table 5: Comparison of Mean Value of Flexural Strength(MPa) between Metal and Zirconia Materials

Thickness	Metal		Zirconia		p-value
	Mean(in MPa)	SD	Mean(in MPa)	SD	
0.5mm	800.70	8.57	708.70	10.50	<0.001*
0.7mm	1001.30	12.78	799.40	8.69	<0.001*

0.9mm	1400.90	11.77	957.10	25.17	<0.001*
1.2mm	1712.60	21.33	1088.70	53.12	<0.001*

Table 5 compares the flexural strength of Metal and Zirconia across various thicknesses (0.5mm, 0.7mm, 0.9mm and 1.2mm), providing mean values, standard deviations (SD), and p-values indicating the significance oftheir differences. For each thickness, metal consistently exhibits higher flexural strength than zirconia. At 0.5mm, Metal's mean strength is 800.70MPa (SD 9.04) compared to Zirconia's 708.70MPa (SD 11.08), with a p-value<0.001. At 0.7mm, Metal shows a strength of 1001.30MPa (SD 13.47) versus Zirconia's 799.40MPa (SD 8.69), also with a p-value <0.001. For the 0.9mm thickness, Metal's strength is 1400.90MPa (SD 12.41) compared to Zirconia's 957.10MPa (SD 26.54), with a p-value <0.001. At 1.2mm, Metal reaches 1712.60MPa (SD 22.49) while Zirconia stands at 1088.70MPa (SD 56.00), with a p-value <0.001. These consistently low p-values (<0.001) indicate that the observed differences in flexural strength are statistically significant, underscoring that Metal has superior flexural strength over Zirconia across all thicknesses. Additionally, both materials exhibit an increasing trend in flexural strength with greater thickness, even though Metal consistently outperforms Zirconia at each thickness level.

DISCUSSION

Understanding the distribution and magnitude of masticatory forces is essential in designing Fixed Partial Dentures (FPDs) that can withstand functional loads, ensuring prosthesis durability. The occlusal forces differ between anterior and posterior regions due to variations in tooth morphology and function. The posterior teeth, responsible for mastication, face significantly higher forces, necessitating robust FPDs to prevent deformation and fracture. Tortopidis et al. reported that biting forces in the molar region range from 342 to 1280N, averaging 582N, highlighting the need for durable materials such as metal-ceramic or all-metal restorations to withstand these stresses.

In contrast, the anterior teeth experience lower occlusal forces, ranging from 10 to 40N, as stated by Rubio-Ferrer et al. However, these forces still require careful management to avoid stress on abutment teeth and prosthetic materials. Esthetic considerations are crucial in the anterior region, making material selection vital. Roberts HW et al. reported that 80.2% of metal-ceramic FPDs remained functional after 10 years, while Pjetursson et al. found a 90.4% survival rate for zirconia restorations over five years. Flexural strength testing is essential for predicting prosthesis survival, as it simulates real-world forces.

Materials like ceramics, metals, and their combinations are chosen based on strength, durability, and compatibility with oral tissues. Since the 1970s, Porcelain-Fused-to-Metal (PFM) restorations have been the gold standard due to their mechanical properties. The metal core provides strength, while the porcelain veneer offers a natural appearance. Ozcan M et al. emphasized that the success of PFM prostheses depends on the physical and mechanical properties of the metal substructure. For research purposes, PFM serves as a benchmark against which newer materials like zirconia are evaluated.

Comparing zirconia to PFM is crucial to determine if zirconia offers comparable or superior performance, particularly in flexural strength. Siarampi et al. noted that zirconia ceramics have excellent aesthetics, biocompatibility, low plaque accumulation, and high strength. Since the advent of CAD/CAM technology, the fabrication of aesthetic materials like zirconia has improved efficiency in dental treatments.

Zirconia has revolutionized dentistry since the 1990s, offering high flexural strength and fracture toughness. Its robustness ensures restorations can withstand masticatory stresses, contributing to long-term success. Zirconia’s biocompatibility integrates well with surrounding tissues, reducing adverse reactions and promoting stability. Unlike other ceramics, zirconia does not wear down opposing teeth, preserving dental structure and preventing additional wear. This hypoallergenic material is suitable for a wide range of patients, and its lower plaque affinity helps maintain periodontal health around restoration margins.

In this study, core structures of varying thicknesses (0.5mm, 0.7mm, 0.9mm, and 1.2mm) were analyzed to balance strength with minimal invasiveness. These incremental thicknesses help understand how slight changes affect material properties, guiding material selection for dental restorations. A core thickness of 0.5mm aligns with clinical norms, ensuring applicability while providing sufficient mechanical strength. Thicker cores, like 0.7mm, 0.9mm, and 1.2mm, were included to compare strength and aesthetics, ensuring a comprehensive assessment.

Flexural strength, critical for dental materials, reflects their ability to resist deformation and fracture under load. The study measured flexural strength using a 3-point flexure test, which simulates oral conditions by applying a load at the specimen's center, determining the material's failure point. The Universal Testing Machine (UTM) with a hydraulic mechanism was used to evaluate flexural strength, providing robust and accurate testing.

Results showed that increasing thickness significantly increased flexural strength for both metal and zirconia cores. Metal samples consistently outperformed zirconia across all thickness levels, with the highest flexural strength noted in metal samples at 1.2mm thickness (1712.60MPa) and the lowest in zirconia samples at 0.5mm

thickness (708.70MPa). A two-way ANOVA test revealed that both thickness and material type significantly impacted flexural strength.
Spintzyk et al. found that the mean flexural strength for 1.2mm thick zirconia was 1124MPa, emphasizing the impact of surface thickness on mechanical properties. Kelesi et al. reported a mean flexural strength of 1484.70MPa for 2.5mm thick zirconia with a 1mm layering, with no significant decrease in strength after aging.
The superior flexural strength of metal cores across all thicknesses indicates their suitability for posterior restorations where functional demands are high. Zirconia, despite its aesthetic advantages, may be better suited for anterior restorations where the functional load is lower. Clinicians must consider these factors and the patient's specific circumstances for the best outcomes.
The study emphasizes the importance of optimizing core dimensions based on clinical requirements, balancing strength and aesthetics. Thicker cores provide greater fracture resistance, ensuring restoration longevity. The results offer valuable insights into material selection and thickness optimization in prosthodontics, contributing to evidence-based clinical decision-making and enhancing patient care.

CONCLUSION

The primary objective of this study was to investigate the effect of flexural strength on two ceramic-veneered sub-structures—Metal (Ni-Cr) and Zirconia—across four variable thickness(0.5mm, 0.7mm, 0.9mm, and 1.2mm). Through meticulous planning and execution, eighty 15mm discs were fabricated from Metal (Ni-Cr) and Zirconia, layered uniformly with 1mm porcelain using customized silicone jigs. The uniformity of the porcelain layering was crucial to ensure consistent and reliable results, which was verified using a vernier caliper before subjecting the samples to a 3-point bending test in a Universal Testing Machine.
The results of this rigorous experimental process revealed a significant finding: the flexural strength of Metal (Ni-Cr) samples was consistently higher than that of Zirconia samples across all thicknesses tested. This outcome underscores the inherent strength characteristics of Metal (Ni-Cr) as a sub-structure material, highlighting its potential advantages in applications where high flexural strength is paramount. This finding has substantial implications, particularly in the field of dental restorations, where the choice of sub-structure material can significantly influence the durability and longevity of the restoration.
The implications of these findings extend beyond the immediate context of the study. The superior flexural strength of Metal (Ni-Cr) suggests that it may be more suitable for applications that demand high mechanical performance. This insight can inform material selection processes in various engineering and biomedical applications, potentially leading to the development of more robust and reliable products.
However, it is essential to acknowledge the limitations of this study. One significant limitation is the uniform porcelain layering technique employed, which, while ensuring consistency, may not perfectly mimic real-world conditions where variations in layering and application techniques are common. Additionally, the study focused solely on one type of ceramic and one layering technique, which may limit the generalizability of the results. Future research should consider exploring a wider range of ceramics and layering techniques to provide a more comprehensive understanding of the performance characteristics of these materials.
In conclusion, this study provides valuable insights into the flexural strength characteristics of Metal (Ni-Cr) and Zirconia as sub-structure materials. The findings suggest that Metal (Ni-Cr) demonstrates superior flexural strength, making it a more suitable choice for applications requiring high mechanical performance. This study's methodology and findings contribute to the broader body of knowledge in material science and engineering, offering a foundation for future research to build upon. As the field continues to evolve, ongoing research and innovation will be crucial in uncovering new materials and techniques that further enhance the performance and application of ceramic-veneered sub-structures.
Overall, the study highlights the importance of material selection in engineering and biomedical applications, emphasizing the need for continued research to optimize material properties and performance. The findings presented here serve as a stepping stone for future investigations, encouraging a deeper exploration of the factors that influence flexural strength and other critical material properties. By addressing the limitations and expanding the scope of future research, we can achieve a more comprehensive understanding of these materials and their potential applications, ultimately leading to the development of more advanced and reliable products.

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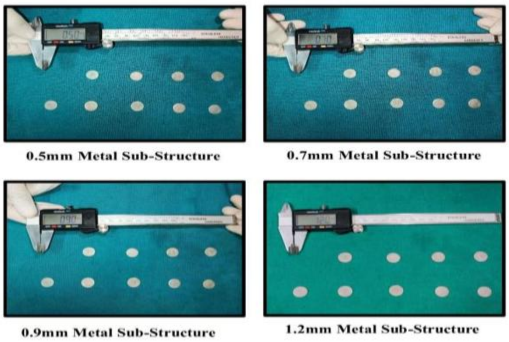


Fig 1: Metal Samples of Various Thickness

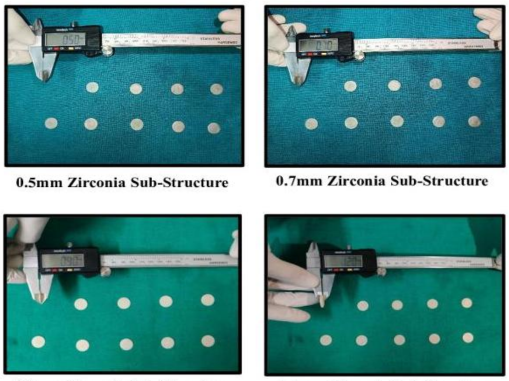
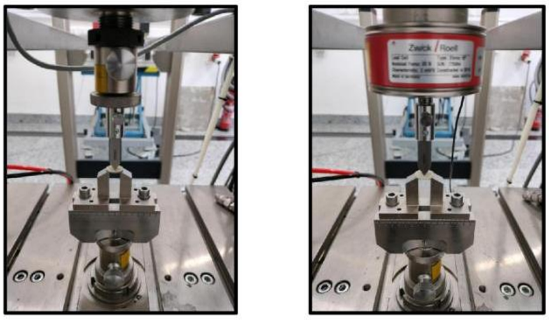


Fig 2: Zirconia Samples of Various Thickness

Fig 3: Silicone Jig for Uniform Layering of 1mm



3-Point Flexure Test of PFM and PFZ sample In UTM

Fig 4: 3-Point Flexure Test of both PFM & PFZ samples in Universal Testing Machine(UTM)