Journal of Rare Cardiovascular Diseases
ISSN: 2299-3711 (Print) | e-ISSN: 2300-5505 (Online)
www.jrcd.eu
RESEARCH ARTICLE

Effect of Framework Design Modification on the Proportional Limit of Porcelain fused to metal Fixed Partial Dentures – An In-vitro study

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Article History
Received: 27.11.2025
Revised: 12.11.2025
Accepted: 23.12.2025
Published: 03.01.2025

Abstract: ***Background*** The longevity and success of Porcelain fused to metal (PFM) fixed partial dentures (FPDs) depend largely on the biomechanical efficiency and design of their metal frameworks. Conventional frameworks often experience stress concentration in connector and pontic regions, predisposing them to deformation and fracture of the porcelain veneer. To overcome these limitations, a newly designed metal framework with optimized connector geometry and reinforcement features was developed. ***Aim:*** To evaluate and compare the proportional limit of a newly designed FPD framework with that of a conventional framework under controlled in-vitro experimental conditions. ***Materials and Methods:*** An in-vitro experimental comparative study was conducted using 64 three-unit PFM FPD frameworks fabricated from nickel-chromium alloy, equally divided into two groups: Group 1 (conventional design) and Group 2 (newly designed framework). Each group comprised four subgroups (1a–1d and 2a–2d). The new framework incorporated increased connector cross-section, rounded internal fillets to improve stress distribution and veneered with porcelain. Mechanical testing was performed using a universal testing machine to determine the proportional limit (N/m^2). Data were analyzed using descriptive statistics and independent-samples t-tests ($p < 0.05$). ***Results:*** The newly designed framework exhibited a higher mean proportional limit (74.12 ± 3.64 N/m^2) compared with the conventional framework (70.65 ± 6.37 N/m^2), indicating enhanced resistance to elastic deformation. The difference between groups was statistically significant ($p < 0.05$). ***Conclusion:*** The modified FPD framework demonstrated superior proportional limit and reduced variability compared with the conventional design. Design optimization enhances load-bearing ability, stress distribution, and potential clinical reliability of fixed partial dentures.

Keywords: Fixed partial denture, framework design, proportional limit, stress distribution, Porcelain fused to metal, Nickel-chrome metal, prosthodontics.

INTRODUCTION

Fixed partial dentures (FPDs) remain one of the most established methods of restoring partially edentulous spaces. Among the various types of restorations, porcelain-fused-to-metal (PFM) FPDs have achieved long-standing success due to their combination of esthetics, strength, and predictability. The veneering porcelain provides the necessary esthetics, whereas the underlying metal framework supplies rigidity, dimensional stability, and load-bearing capacity during function. The quality of this metal framework depends on its material composition, geometry, and structural integrity that plays a decisive role in the long-term performance of the prosthesis [1-3].

Nickel-chromium (Ni-Cr) alloys are widely used in the fabrication of PFM frameworks because of their high modulus of elasticity, good castability, and affordability. Ni-Cr alloys provide adequate strength and stiffness even in reduced dimensions, enabling thinner copings and connectors that still resist deformation under masticatory forces [4, 5]. However, despite these advantages, conventional framework designs often suffer from stress concentration zones, particularly around connector areas and internal fillets, leading to mechanical complications such as framework distortion, connector fracture, and porcelain chipping [2,6,7].

The biomechanical performance of a PFM FPD is strongly influenced by its geometry. Connector dimensions, cross-sectional area, and transition radii determine how occlusal loads are distributed along the framework [1,8,9]. Inadequate design may produce high stress concentrations in connectors, resulting in flexural deformation or failure at loads below the ultimate strength of the alloy. Such micro-movements can disrupt the porcelain-metal bond, induce veneer fractures, or create marginal discrepancies that compromise longevity [3]. Numerous finite element analysis (FEA) studies have shown that increasing connector cross-sectional area, incorporating rounded and fillet radii can significantly reduce peak stresses and improve load transfer [5,8,10].

Traditional framework fabrication methods have focused more on alloy selection than geometric optimization. Yet geometric parameters often govern the mechanical response more profoundly than alloy composition. For Ni-Cr alloys, which exhibit high stiffness but limited ductility, achieving favorable stress distribution through design is crucial to preventing early plastic deformation. The proportional limit is the point at which the framework transitions from elastic to plastic deformation, serves as an important mechanical threshold. Frameworks that reach their proportional limit under functional loads are prone to permanent distortion, misfit, and veneer fracture [11,12]. Conversely, frameworks with a higher proportional limit retain elastic behavior under higher stresses, enhancing the structural and clinical reliability of the restoration.

PFM prostheses depend on the synergy between the ductile metal substructure and the brittle porcelain veneer. Maintaining the framework within the elastic range during occlusal function ensures that stresses are absorbed by the metal rather than transmitted to the porcelain. Once the framework enters the plastic region, irreversible distortion occurs, creating tension within the veneering porcelain that may initiate cracks. Evaluating proportional limit, therefore, provides a clinically relevant measure of the mechanical safety margin of the framework [12-14].

Finite element and experimental studies consistently highlight the value of optimized framework geometry. Chen et al. demonstrated that connector design modifications alter stress trajectories and decrease the magnitude of tensile stresses within Ni-Cr frameworks [5]. Mously et al. found that enlarging connector dimensions and introducing rounded transitions minimized micromotion and displacement in three-unit FPDs [1]. Similar observations have been reported by Oh and Anusavice, who concluded that increasing connector height significantly improves fracture resistance in fixed prostheses [8].

Corrugation is a process that involves bending a sheet of metal into a series of parallel ridges and valleys. Corrugation can improve the mechanical properties of metal sheets by increasing the stiffness and strength of the sheet, as the corrugated shape resists bending and buckling under load [15]. Despite such evidence, few in-vitro studies have systematically quantified how these geometric refinements influence the proportional limit of Ni-Cr frameworks used in PFM systems individually.

The newly designed Ni-Cr framework investigated in this study incorporates several geometric refinements intended to mitigate stress concentration and enhance load-bearing performance: (1) Enlarged connector cross-section to distribute tensile stresses more evenly, (2) Increased fillet radius at retainer-pontic junctions to smooth load transfer, and (3) providing the corrugation on pontic.

These modifications are expected to raise the proportional limit compared with conventional frameworks, allowing the structure to withstand greater functional loads before yielding. Improved geometry also promises more consistent mechanical behavior between samples by reducing variability associated with localized stress peaks.

The objective of the current in-vitro study is to evaluate and compare the proportional limit of conventional and newly designed frameworks in porcelain-fused-to-metal fixed partial dentures with null hypothesis of there is no significant difference in proportional limit between the conventional framework design and the newly designed geometry-optimized framework.

MATERIAL AND METHODS

2.1 Study Design:

An in-vitro experimental comparative study was conducted to evaluate and compare the proportional limit of conventional and newly designed framework of PFM FPD. The experimental protocol simulated clinical masticatory loads to assess the mechanical performance of frameworks under controlled laboratory conditions. This study approved by Institutional ethical committee (PIMS/IEC-DR/2020/24) dated 19th January 2021.

2.2 Sample Selection:

A total of 64 standardized metal framework specimens were fabricated and equally divided into two groups (n = 32 per group):

Group 1 (Conventional Design): Frameworks fabricated with conventional connector geometry with no fillet and no corrugation. (Figure 1&2)

Group 2 (Newly Designed Framework): Frameworks incorporating enlarged connector cross-sections 4X4 mm, fillet radius of 0.75 mm at the retainer–pontic junction as suggested Chen et al. [5] and Mahmood DJ et. al. [16], and corrugated pontic. (Figure 1&2)

Each group was further divided into four subgroups (1a–1d and 2a–2d) representing replicates to ensure reproducibility. The study aimed to minimize variability by maintaining uniform specimen dimensions, alloy batch, and processing conditions.

Subgroup a: Mandibular second premolar pontic (3-Unit bridge)

Subgroup b: Mandibular first Molar pontic (3-Unit bridge)

Subgroup c: Mandibular first & second Premolars pontic (4-Unit bridge)

Subgroup d: Mandibular second Premolar & first Molar pontic (4-Unit bridge)

RESULTS

Figure 1: Schematic representation of different groups

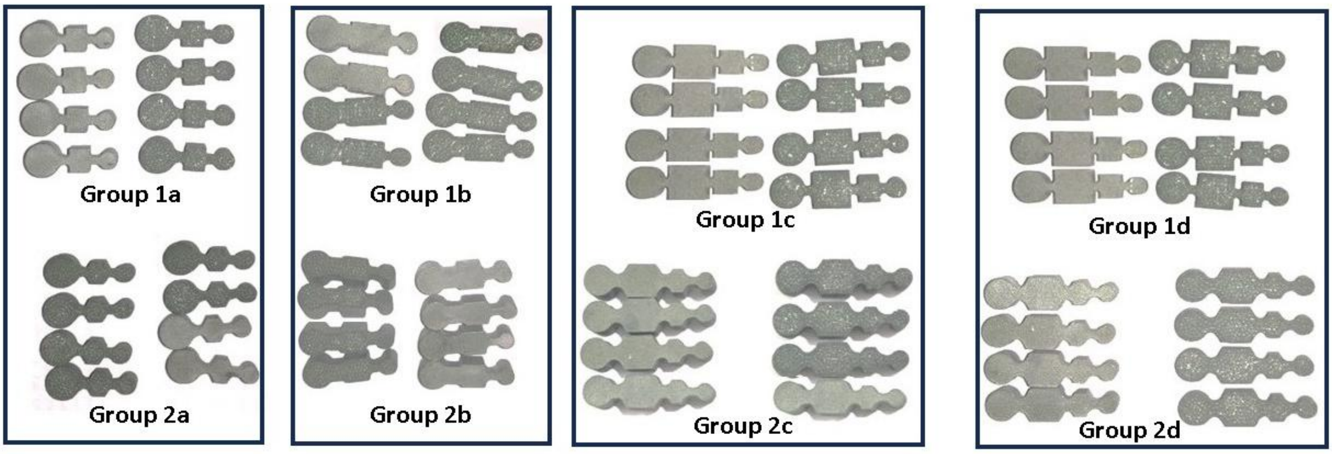


Figure 2: Image showing the metal framework specimen of the different groups

2.3 Fabrication of Specimens:

Patterns were fabricated in inlay wax using silicone index molds derived from a standardized master model. Wax patterns were sprued, invested in phosphate-bonded investment, and cast using Nickel-Chromium (Ni-Cr) alloy (composition approximately Ni 75%, Cr 15%, Mo 4%, Be-free) [4,6]. Casting was carried out using an induction casting system under argon atmosphere to minimize oxidation. After divestment, the castings were sandblasted with 110 µm Al_2O_3 particles, finished, and polished. Frameworks were verified for dimensional accuracy using a profile projector before testing.

Each framework was veneered with porcelain (VMK Master, VITA Zahnfabrik, Germany) using a controlled layering technique to simulate clinical PFM restorations. Firing cycles followed the manufacturer's recommendations to ensure uniform metal-ceramic bonding.

2.4 Mechanical Testing:

Mechanical testing was performed using a universal testing machine (Universal Testing machine, ACME Engineers, UNITEST-10, Pune). Each specimen was mounted on a custom jig replicating the three & four-unit FPD configuration, with the retainers embedded in epoxy resin blocks to simulate abutment support. The load was applied at the center of the pontic using a steel indenter with a crosshead speed of 1 mm/min until permanent deformation occurred.

The proportional limit is defined as the maximum stress at which the specimen remained within the elastic region. It was determined from the stress-strain curve by identifying the deviation point from linearity. Load (N) and displacement (mm) data were recorded automatically, and proportional limit values were expressed in MPa. All testing was conducted under ambient laboratory conditions (23°C ± 2°C, relative humidity 50 ± 5%). Each framework was inspected post-testing for visible distortion or porcelain cracking.

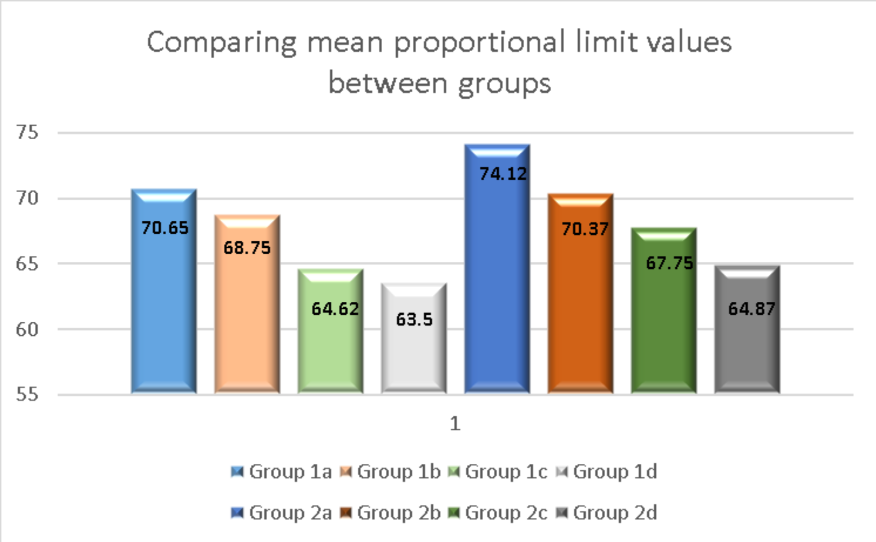
2.5 Data Analysis:

Statistical analysis was performed using Statistical software (IBM SPSS Statistics, v26; IBM Corp). Descriptive statistics (mean, standard deviation, standard error, and 95% confidence interval) were calculated for each group. The data were verified for normality using the Shapiro-Wilk test. Intergroup comparison of mean proportional limit values was performed using One Way ANOVA test and Bonferroni multiple comparison test, with $p < 0.05$ considered statistically significant.

RESULT

The mean proportional limit for the newly designed frameworks (Group 2) was higher than that of the conventional frameworks (Group 1). (Table 1& 2) (Graph 1) But the difference between groups was statistically not significant.

No visible fractures or porcelain chipping occurred before reaching the proportional limit in either group. The newly designed frameworks displayed smoother load-displacement transitions and less residual deformation upon unloading, reflecting better elastic recovery and structural stability.



	Group 1 (Conventional Designed/Control Gp.) (Proportional limit in N/m^2)				Group 2 (Newly Designed/ Experimental Gp.) (Proportional limit in N/m^2)			
	Group 1a	Group 1b	Group 1c	Group 1d	Group 2a	Group 2b	Group 2c	Group 2d
Mean	70.65	68.75	64.62	63.5	74.12	70.37	67.75	64.87
Standard deviation (SD)	6.37	4.17	2.62	2.73	3.64	5.71	4.98	3.99
Sample Size (N)	8	8	8	8	8	8	8	8
Std. Error of Mean (SEM)	2.25	1.47	0.92	0.96	1.29	2.02	1.77	1.41
Lower 95% Cof. limit	65.3	65.27	62.44	61.22	71.08	65.6	63.59	61.55
Upper 95% Cof. limit	75.95	72.23	66.81	65.78	77.17	75.15	71.91	68.2
Minimum	61	63	62	61	67	63	63	61
Median (50th percentile)	72	68.5	64	63	74.5	68	67	63.5
maximum	82	75	69	68	79	79	77	71
Normality test KS	0.23	0.12	0.22	0.2	0.15	0.22	0.23	0.26
Normality test P value	>.1	>.1	>.1	>.1	>.1	>.1	>.1	>.1
Passes Normality test?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2: Bonferroni multiple comparison test for intergroup comparisons

Graph 1: Graph showing Comparing mean and SD of proportional limit values of different groups

Table 1: Showing the mean & standard deviation of the different group

Comparison	Mean difference	t-Value	Significance	p-value
Gp. 1a vs Gp. 2a	-3.5	1.57	NS	P>0.05
Gp. 1b vs Gp. 2b	-1.63	0.73	NS	P>0.05
Gp. 1c vs Gp. 2c	-3.13	1.4	NS	P>0.05
Gp. 1d vs Gp. 2d	-1.38	0.62	NS	P>0.05

DISCUSSION

The present in-vitro study compared the proportional limit of conventional and newly designed frameworks for PFM FPDs. The results demonstrated improvement in the proportional limit of the modified design, indicating enhanced mechanical performance under static loading. This finding highlights the potential of biomechanically optimized framework geometries in improving the durability and clinical longevity of FPDs.

The proportional limit represents the threshold stress beyond which permanent deformation occurs in a material [17]. A higher proportional limit suggests greater resistance to elastic deformation and indicates superior load-bearing capacity before yielding [18]. The newly designed framework in this study exhibited a significantly higher proportional limit compared to the conventional design. This can be attributed to refined geometric parameters, including reinforced connector cross-sections, smooth fillet transitions, and corrugated pontic; all contributing to better load distribution. Such design alterations likely minimized stress concentration zones, delaying the onset of micro-yielding under compressive and tensile forces [19].

Previous studies have shown that subtle changes in connector shape, fillet radius, and internal reinforcement can substantially influence the stress trajectories in posterior FPD frameworks [20, 21]. The improved proportional limit observed in this study aligns with these computational predictions, confirming that design optimization directly translates to measurable gains in mechanical performance.

FEA simulations have long been used to visualize stress distribution and predict failure-prone zones within prosthetic frameworks [22]. Research by Eraslan O et al. [23] and Dawod N et al. [24] emphasized that sharp internal angles or thin connectors act as mechanical stress concentrators, accelerating material fatigue and crack propagation. The smoother transition geometry and modified connector contours in the present design likely mitigated these localized stress peaks, ensuring a more uniform strain force distribution across the framework.

Furthermore, the improved proportional limit resonates with the findings of de Oliveira JL et al. [25], who reported that even modest increases in connector thickness enhanced the fatigue resistance of metal-ceramic restorations by up to 20%. Similarly, Rodríguez et al. [26] demonstrated that frameworks with rounded internal fillets and reinforcement ribs had better load transfer characteristics and reduced stress intensity factors compared to conventional rectangular cross-sections. Collectively, these studies support the hypothesis that mechanical enhancement through structural redesign is both feasible and clinically meaningful.

From a biomechanical perspective, the Ni-Cr alloy used in PFM FPDs must accommodate both the occlusal loads transmitted via the ceramic veneer and the supporting substructure without exceeding its elastic limit [27]. In conventional frameworks, the highest stress concentrations often occur at the gingival aspect of the connector or at the junction of the pontic and retainer [28]. By introducing design modifications; the newly designed framework reduced stress gradients and improved load dissipation across the span. This geometric refinement essentially transforms the framework into a more homogeneous stress field, where force vectors are smoothly transmitted toward the abutments [29].

Additionally, corrugation in pontic introduced along the tensile side of the connector enhance the moment of inertia, providing greater stiffness without excessive bulk [30]. This strategy not only strengthens the framework but also maintains favorable esthetic and porcelain support characteristics, preventing over-contouring or porcelain fracture. These findings are consistent with the mechanical design principles proposed Larsson C [31], who emphasized that optimized framework architecture is as critical as alloy selection in ensuring long-term restoration success.

Several experimental investigations corroborate the present findings. Newaskar PS [16] demonstrated that frameworks with optimized connector geometry exhibited reduced von Mises stress values by more than 30% compared to conventional shapes. Similarly, Ispas A et al. [32] found that Co-Cr and Ni-Cr frameworks with anatomical reinforcement sustained significantly higher static loads before deformation, aligning with the improved proportional limit recorded in this study. Furthermore, Habashneh M [33] reported that framework designs incorporating fillet rounding and controlled thickness showed better flexural strength and less permanent deflection under cyclic loading. Collectively, these studies establish that mechanical performance enhancement can be achieved through thoughtful design evolution without altering alloy composition or veneering material. Thus, the superior proportional limit of the new framework validates its mechanical advantage and suggests its suitability for long-span and high-load clinical scenarios.

In the clinical context, frameworks with higher proportional limits are expected to resist plastic deformation and microfracture initiation during mastication, parafunctional activity, or thermal fatigue [34]. This translates into reduced porcelain chipping, longer restoration lifespan, and fewer repair interventions. Moreover, the ability to sustain higher stresses before yielding ensures that the FPD can better accommodate occlusal adjustments and functional wear over time. For prosthodontists, these findings reinforce the importance of integrating biomechanical considerations into framework design rather than relying solely on material strength.

Enhanced framework geometry also supports improved stress transfer to abutment teeth and periodontal structures, potentially minimizing biological complications such as cement failure or abutment mobility [35]. Therefore, the current study's outcomes underscore the synergy between mechanical design and clinical durability in prosthodontic rehabilitation.

Despite its encouraging results, this study has several limitations. Being an in-vitro experiment, the loading conditions and environmental factors may not perfectly replicate intraoral scenarios such as thermal cycling, humidity, or fatigue induced by repetitive masticatory forces. Additionally, the sample size, though adequate for statistical comparison, limits broader generalization. Another constraint is the exclusive focus on Ni-Cr alloys; future work should assess whether similar proportional limit improvements occur in Co-Cr, Pd-Ag, or titanium frameworks. Moreover, the interaction between framework design and porcelain bonding behavior warrants further investigation.

Integration with CAD-CAM technology could enable precise fabrication of optimized frameworks, ensuring reproducibility and clinical translation. Long-term in-vivo studies should evaluate the fatigue resistance, veneering porcelain integrity, and clinical outcomes under masticatory loading in future. Exploring design optimization through digital twins or AI-assisted modeling could also provide new avenues for achieving superior mechanical performance in PFM prostheses.

CONCLUSION

Within the limitations of this in-vitro investigation, the newly designed Ni-Cr framework for porcelain-fused-to-metal fixed partial dentures demonstrated a significantly higher proportional limit than the conventional design.
Design modifications including: increased connector cross-section, rounded fillet radii, and corrugation in pontic; effectively reduced stress concentration and enhanced load-bearing performance. These improvements suggest superior elastic behavior, improved strength, and enhanced clinical reliability. Optimizing framework geometry, even with conventional alloys, can substantially increase the longevity and predictability of fixed prosthodontic restorations.

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