



Article

Evaluation of the Biomechanical Effects and Mechanical Distribution of Stress and Strain in SiC-Reinforced PEEK Implants Compared to Titanium Under Oblique Loading: A Three-Dimensional Finite Element Analysis Study

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Abstract

This study compares the biomechanical impact and mechanical distribution of SiC-reinforced PEEK implants to titanium implants using three-dimensional finite element analysis (FEA). Five different implant materials were investigated: titanium, pure PEEK, and PEEK reinforced with silicon carbide (SiC) particles at 2%, 4%, and 6% ratios. A wide range of oblique forces (45°) from 100 N to 900 N was applied to simulate physiological to extreme masticatory loads. The distribution of maximum von Mises stress and total deformation within the implant was examined. Structural integrity metrics linked to yield strength, including factor of safety (FOS), were also investigated. The biological evaluation included an analysis of the behavior of the bone tissue surrounding the implant by assessing maximum principal strain and maximum principal stress in cortical bone. The results show that titanium exhibited the highest stiffness and FOS (>1 up to 500 N) but induced the lowest bone strains (755–2275 $\mu\epsilon$ at 100–300 N), indicating potential stress shielding. Pure PEEK resulted in excessive bone strains exceeding 4000 $\mu\epsilon$ at moderate loads, suggesting bone overload risk. Among reinforced groups, PEEK + 4%SiC demonstrated the most balanced performance, reducing maximum principal bone stress by 28% compared to pure PEEK at 200 N, while maintaining bone strains within the physiological adaptive range (1000–3000 $\mu\epsilon$) under moderate loads. PEEK + 6%SiC showed increased stiffness but reduced ductility and safety factor. Within the limitations of this computational study, PEEK reinforced with 4% SiC appears to offer an optimal trade-off between mechanical stability and biomechanical compatibility. Further in vitro and clinical studies are warranted to validate these findings.

Keywords: dental implant; biomechanical analysis; PEEK reinforced with SiC; FEA

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1. Introduction

Dental implantology has revolutionized the rehabilitation of edentulous patients, consistently demonstrating high long-term clinical survival rates and significantly improving oral health-related quality of life [1]. Despite these predictable clinical outcomes,

the long-term success of implant-supported restorations depends on a complex interaction of mechanical, biological, and clinical factors. Implant stability is influenced not only by the transfer of functional loads, but also by biological processes such as osseointegration, peri-implant bone remodeling, bone quality and density, surgical protocols, and host-related responses [2]. Nevertheless, from a biomechanical perspective, the distribution of stress and strain within the peri-implant bone remains one of the principal physical factors governing bone adaptation, maintenance, and long-term structural stability [3].

During functional mastication, dental implants are subjected to complex multidirectional loading conditions. Among these, oblique loading is widely recognized as the most critical biomechanical scenario because it generates elevated tensile, compressive, and shear stresses, particularly within the crestal cortical bone surrounding the implant neck [4,5]. Such loading conditions are commonly encountered during mastication, food penetration, and lateral mandibular movements [6]. Furthermore, the magnitude and complexity of these forces may increase considerably in patients exhibiting parafunctional habits such as bruxism and clenching, where occlusal loads frequently exceed normal physiological values and are applied at unfavorable angles [7,8]. Previous biomechanical investigations have demonstrated that these non-axial force vectors generate significant bending moments and localized stress concentrations that may compromise peri-implant bone stability over time [9].

To withstand these functional demands, commercially pure titanium (cp-Ti) and titanium alloys, particularly Ti-6Al-4V, have traditionally served as the gold standard materials for dental implant fabrication because of their excellent biocompatibility, corrosion resistance, and mechanical strength [10]. However, titanium exhibits a considerably higher elastic modulus (approximately 110 GPa) than cortical bone, which typically ranges between 15 and 20 GPa [11]. This substantial mechanical mismatch promotes the phenomenon known as stress shielding, whereby the implant absorbs a large proportion of the applied load while reducing the physiological mechanical stimulation experienced by the surrounding bone. Over time, this altered biomechanical environment may contribute to localized bone resorption, marginal bone loss, and reduced long-term implant stability [12].

To overcome the limitations associated with stress shielding, polyetheretherketone (PEEK) has emerged as a promising alternative biomaterial in implant dentistry due to its elastic modulus of approximately 3–4 GPa, which is closer to that of natural bone than titanium [13]. This characteristic allows a more favorable distribution of functional loads and may reduce the adverse biomechanical effects associated with highly rigid metallic implants. However, the relatively low stiffness of pure PEEK also represents a potential limitation. Under elevated functional loads, unreinforced PEEK may undergo greater elastic deformation, potentially increasing maximum principal stress and principal strains within the adjacent cortical bone [14]. Consequently, the challenge is not merely to increase the stiffness of PEEK, but to achieve an optimized balance between implant structural safety and the preservation of physiological bone stimulation, thereby maintaining favorable biomechanical conditions for long-term peri-implant bone health.

To address this challenge, numerous reinforcement strategies have been proposed for PEEK, including carbon fibers, hydroxyapatite (HA), and titanium dioxide (TiO₂). Although these reinforcements may improve selected material properties, each presents specific limitations. Carbon fibers can substantially increase stiffness but may introduce anisotropic mechanical behavior and aesthetic concerns related to their dark coloration [15]. Hydroxyapatite-based reinforcements may enhance bioactivity and cellular attachment but can negatively affect the fatigue resistance and overall mechanical integrity of the polymer matrix [16]. In contrast, silicon carbide (SiC) has attracted increasing attention as a reinforcement phase because of its high hardness, excellent fracture resistance, chemical

stability, and isotropic mechanical behavior [17]. In addition to its favorable mechanical properties, SiC exhibits excellent biocompatibility, minimal cytotoxicity, and the ability to support osteoblast adhesion and proliferation [18]. Moreover, the incorporation of SiC particles into the PEEK matrix may facilitate more homogeneous stress transfer throughout the composite structure. These combined characteristics suggest that SiC-reinforced PEEK may provide an intermediate biomechanical behavior between the excessive rigidity of titanium and the excessive compliance of pure PEEK [19].

Finite element analysis (FEA) has become an established and reliable computational approach for evaluating the biomechanical behavior of dental implants under various loading conditions. This technique enables detailed assessment of stress and strain distributions within both implant components and surrounding bone tissues without the limitations associated with *in vivo* experimentation. Recent numerical studies have investigated the biomechanical performance of polymer-based and composite implant systems under simulated osseointegrated conditions using fully bonded bone–implant interfaces [20]. Nevertheless, important gaps remain regarding the comprehensive biomechanical evaluation of SiC-reinforced PEEK implants subjected to progressively increasing oblique loads.

Although average physiological masticatory forces are generally lower than 900 N, substantially higher force magnitudes have been reported in posterior regions and in individuals presenting parafunctional habits such as bruxism and clenching [7,21]. Therefore, evaluating implant behavior under loads approaching 900 N provides valuable insight into structural safety and biomechanical performance under severe loading conditions rather than routine physiological scenarios.

Despite recent advances in implant biomaterials and numerical modeling, the current literature still lacks a comprehensive three-dimensional biomechanical comparison between titanium, pure PEEK, and SiC-reinforced PEEK implants evaluated under identical loading and boundary conditions. Furthermore, the influence of different SiC reinforcement ratios on implant structural behavior and peri-implant bone response under progressively increasing oblique loads remains insufficiently understood. Most previous investigations have focused either on implant stresses or on bone response separately, whereas integrated assessments considering implant mechanical performance together with peri-implant stress and strain behavior are relatively scarce. Consequently, the optimal SiC reinforcement percentage capable of balancing implant structural safety and physiological bone stimulation has not yet been clearly established.

To systematically contextualize this research gap and highlight the novelty of the present work, a concise summary of representative finite element studies on alternative polymer-based and composite dental implants is presented in Table 1. By comparing previous investigations with the current study, it becomes evident that a comprehensive evaluation of titanium, pure PEEK, and SiC-reinforced PEEK implants under progressive oblique loading conditions remains largely unexplored.

Table 1. Summary of representative finite element studies on polymer-based and composite dental implant systems and the research gap addressed by the present study.

Reference	Materials Investigated	Loading Conditions	Key Biomechanical Findings/ Focus	Research Gap Addressed by Current Study
Fabris et al. [14]	Titanium, zirconia, PEEK, CFR-PEEK, and GFR-PEEK dental implants.	Three-dimensional finite element analysis (3D FEA) under simulated osseointegrated conditions	PEEK-based materials reduced the stiffness mismatch between implant and bone compared with titanium. Reinforced	Did not investigate ceramic particle reinforcement (e.g., SiC) or evaluate the effect of differ-

			PEEK materials improved mechanical behavior compared with unreinforced PEEK, with differences in stress and strain distribution.	ent reinforcement concentrations under progressive high oblique loading conditions.
Hong and Choi [20]	Titanium and PEEK-based implant prosthetic components	Three-dimensional FEA under functional loading conditions	PEEK components modified stress transfer characteristics due to their lower elastic modulus, influencing stress distribution in implant components and surrounding bone.	Evaluated PEEK components rather than SiC-reinforced PEEK implant structures and did not assess reinforcement-dependent optimization.
Altıparmak et al. [22]	Titanium and carbon fiber-reinforced PEEK (CFR-PEEK) implant systems	Three-dimensional FEA under vertical and oblique occlusal loading conditions	CFR-PEEK demonstrated biomechanical behavior comparable to titanium, with altered stress distribution patterns within the implant structure and surrounding bone.	Focused on fiber reinforcement; did not evaluate isotropic ceramic reinforcement such as SiC or determine biomechanical safety limits under severe loading conditions.
Current study	SiC-reinforced PEEK (2%, 4%, and 6%) versus titanium dental implants	Progressive static oblique loading up to 900 N using 3D FEA	Comprehensive evaluation of von Mises stress, deformation, principal strain, and biomechanical safety to identify the optimal SiC reinforcement level.	Addresses the lack of numerical studies directly comparing titanium and SiC-reinforced PEEK implant systems under severe oblique loading conditions.

Therefore, the present study aimed to perform a three-dimensional finite element analysis comparing commercially pure titanium, pure PEEK, and PEEK reinforced with 2%, 4%, and 6% silicon carbide under 45° oblique loads ranging from 100 to 900 N. Implant performance was assessed through von Mises stress distributions and structural safety considerations, while the biological response of the surrounding bone was evaluated using principal stress and principal strain. By integrating both mechanical and biological evaluation criteria, this study seeks to identify the reinforcement configuration that provides the most balanced biomechanical performance within the limitations of finite element modeling.

2. Materials and Methods

2.1. Creating a 3D Model

A three-dimensional model of a clinically utilized dental implant was created using SOLIDWORKS 2019. It was implanted within a replica of the jawbone, which has two different layers: cortical bone and cancellous bone. A complete real model of the dental implant was created (representing the design of the molar, abutment, and fixing screw, in addition to the dental implant and the surrounding bone tissue) in accordance with prior literature study recommendations, with the goal of conducting an accurate digital simulation that mimics the real case of the dental implant's operation and determining the forces acting on it as well as the interaction of the surrounding bone tissue.

The model was designed with the dimensions of the studied bone tissue section (14 mm, 22 mm), the thickness of the cortical bone tissue (1 mm), the height of the maxillary molar (5.5 mm), the diameter of the upper dental implant (5 mm) and the lower diameter (2.9 mm), the height of the implant (15 mm), and an angle of (0°).

To ensure design uniformity, this model will be used without any design modifications in all cases studied during the digital simulation, and will be reviewed by experienced and specialized dentists, with only the material used to make the dental implant changing while all loading conditions remain constant.

Finally, this model was exported to the (ANSYS 2020-R1) program for numerical modeling and simulation with the finite element method (FEA) (Figure 1).

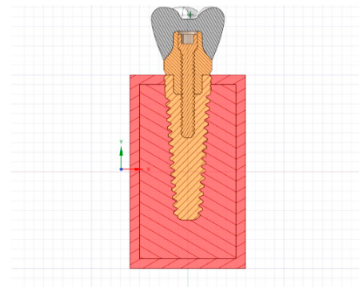


Figure 1. A cross-section of the implant model showing the abutment and screw, as well as the bone tissue used in the study.

2.2. Boundary Conditions

Using the finite element analysis program (Ansys 2020) (Canonsburg, PA, USA, Ansys Workbench), the model to be analyzed was imported, which represents the dental implant with the abutment and molar, in addition to the bone tissue surrounding the implant, in order to evaluate the behavior of the implant by comparing a group of different materials from which implants are made, as shown in Table 2, and determining the effect of each of these materials on bone.

Table 2. Physical properties (the Young's modulus, Poisson's ratio and yield strength) of the implant materials.

Component Material	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength/Mpa
Cortical bone	13.4 [23]	0.3	-
Cancellous bone	1.37 [23]	0.3	-
Y-TZP Zirconia (Molar)	210	0.3	-
Ti-6Al-4V alloy (Screw, Abutments)	110 [24]	0.33	795
Titanium (Implant)	115 [25]	0.35	680
PEEK (Implant)	3.85 [26]	0.395	100
PEEK + 2%SiC (Implant)	4.55 [26]	0.385	112
PEEK + 4%SiC (Implant)	5.15 [26]	0.372	122
PEEK + 6%SiC (Implant)	5.62 [26]	0.36	108

The boundary conditions were defined consistently across all implant models, and the designed structures were simulated with rigid connections (Figure 2). The cortical–cancellous bone interface was assumed to be perfectly bonded to focus primarily on the loading effects on the implant components, while frictional interactions within each component of the model were considered. A friction coefficient of 0.3 was assigned to the mechanical components of the implant. Conversely, the implant–bone interface was assumed to be perfectly bonded to simulate a state of complete osseointegration.

For this aim, five distinct implant materials will be defined, with the assumption that all solid structures are homogeneous, isotropic, and linearly elastic, with physical properties such as the Young’s modulus and Poisson’s ratio, as defined in Table 2.

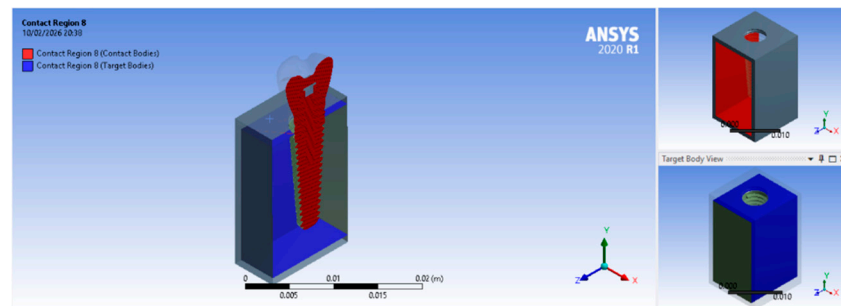


Figure 2. The model is within the ANSYS program, and the connection points.

The mechanical properties presented in Table 1 were adopted as input parameters for the finite element model. These parameters were selected based on the reported mechanical behavior of PEEK-based composites reinforced with SiC particles, considering the progressive effect of ceramic reinforcement on the elastic stiffness, strength, and ductility of the polymer matrix. The selected values represent realistic and representative mechanical properties for comparative biomechanical evaluation of PEEK/SiC composites with different SiC contents (2, 4, and 6%).

To depict the maximum load on a human molar, an oblique force at an angle of 45° was applied at the center of the molar (Figure 3), the magnitude of which is shown in Table 3.

Table 3. The value of the force applied in each test case.

Functional Interpretation	Compressive Force (N)	Case
Very Light Chewing	100	1
Normal Forward Chewing	150	2
Normal Chewing	200	3
Moderate Chewing	250	4
Strong Chewing	300	5
Normal Back Chewing	400	6
Strong Back Chewing	500	7
Strong Grinding	600	8
Subclinical Maximum Grinding	750	9
Maximum Potential Physiological Load	900	10

To study all conceivable scenarios separately, each of the five implant types (Titanium, PEEK + 6%SiC, PEEK + 4%SiC, PEEK + 2%SiC, and PEEK) were studied at each of the force levels listed in Table 3.

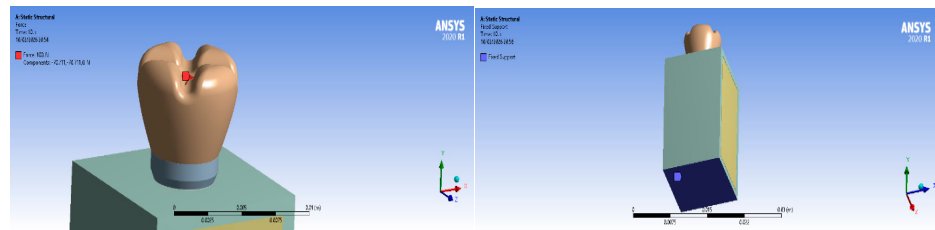


Figure 3. Fixation points and forces applied to the studied implant model.

2.3. Finite Element Model Analysis

After importing the model into the (ANSYS-2020) application for three-dimensional static analysis, first-order tetrahedra were used to construct the computational grid. The grid was smoothed in the prescribed region between the implant and the bone tissue, with the goal of capturing the greatest number of nodes to reflect the strain of the bone tissue as a result of force transfer via the implant. Table 4 summarizes the grid deflection and number of elements for the implant and model, ensuring the study's finite element model calculations are reliable and accurate.

Table 4. Mesh convergence and gride independence study parameters.

Grid Number	Mesh Size	Number of Nodes	Number of Cells	Deviation Value
1	0.3 mm	3,621,197	2,596,996	Default
2	0.1 mm	7,123,991	4,976,290	0.21
3	0.5 mm	1,848,491	1,311,404	0.28
4	0.2 mm	4,151,036	2,958,507	0.21

The contact area between the implant and the crown was the primary emphasis during the computational grid construction. As a result, the starting network element size in this area was set to 0.08 mm, with an average total network size of 0.3 mm. To test the network's sensitivity, the average network size was lowered to 0.1 mm, resulting in 4,976,290 elements and a variance of 0.21. The average mesh size was increased to 0.5 mm, the number of elements fell to 1,311,404, and the variation was 0.28 (Figure 4).

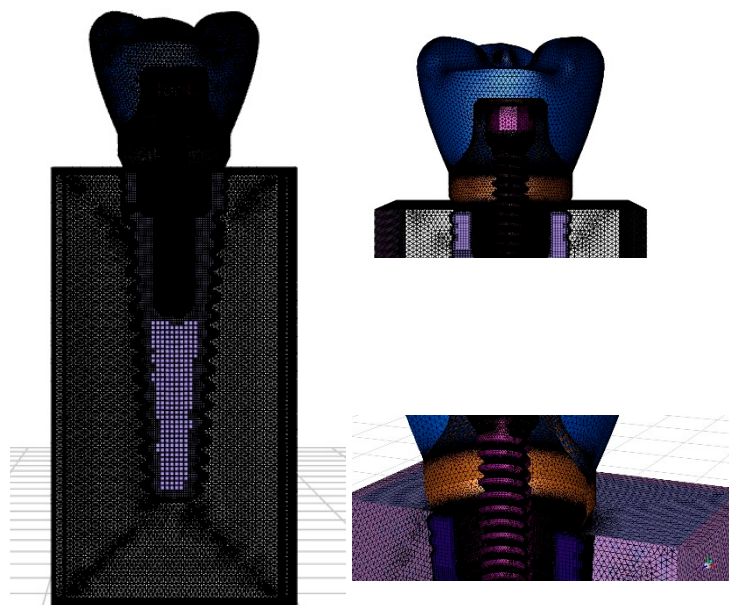


Figure 4. The computational grid used for the study.

As a result, an average total grid size of 0.2 mm was chosen, with 2,958,507 elements and a variation of 0.21. This is thought to be the best value for achieving the standard borderline grid. In addition, a numerical convergence test was performed between grid (1) and grid (4) by comparing the maximum values of von Mises stress in the implant and strain in the bone. The relative deviation was less than 1%, confirming the independence of the results from the computational grid and that grid (4) gives the most accurate numerical results at the shortest possible computation time. As a result, this grid served as the foundation for all studies.

3. Results

In this study, we investigated the numerical analysis of the finite element properties of dental implants made of titanium and pure PEEK materials reinforced with silicon carbide under the influence of oblique masticatory forces at a 45° angle, with magnitudes ranging from 100 to 900 N, as shown in Table 3. The mechanical response of the implants was evaluated by analyzing the distribution of maximum and average von Mises stress, total deformation values, and structural integrity indicators such as yield strength. The biological evaluation included an examination of the behavior of the bone tissue around the implant by measuring Maximum Principal Strain and Maximum Principal Stress, which are direct indicators of mechanical stimulation of the bone and the likelihood of bone resorption. The results were presented statistically and systematically across the different materials, demonstrating the influence of increasing the applied load and implant material type on both the structural performance of the implant and the biological response of the surrounding bone.

3.1. Mechanical Results of the Implant

3.1.1. Von Mises Stress Inside the Implant

The von Mises stress assessment within the implant is regarded as one of the most important indicators for determining the mechanical performance of implants under varying chewing loads. This indicator depicts the implant's ability to sustain stresses without yielding or mechanical failure, as well as the stress distribution inside the implant body and accompanying components like the abutment and screw.

Recent studies show that the type of implant material affects stress concentration. Solid implants like titanium have higher von Mises stress values within the implant body, while composite polymer materials like CF-PEEK and SIC-PEEK transfer load to surrounding bone more evenly, reducing stress concentration within the implant itself [27].

Loading angle significantly impacts stress distribution, with angled loads resulting in higher maximum von Mises stress values compared to axial loads. This provides a realistic simulation situation for evaluating implant mechanical performance under physiological settings. From this standpoint, von Mises stress analysis under oblique loads is a helpful technique for evaluating different implant materials and determining the mechanical design's safety prior to clinical implementation.

A finite element analysis of von Mises stress behavior under 45° angled loading, over the force range indicated in Table 3, demonstrated a clear pattern of increasing stress values with increasing applied forces in all implant types. Titanium implants had the highest stress concentrations, with a maximum of 132.69 MPa at 100 N and steadily increasing to 1237.2 MPa at 900 N. In contrast, PEEK implants and composites demonstrated much lower values, ranging from 45.7 MPa at 100 N for pure PEEK to 416.25 MPa at 900 N. The maximum principal stress for PEEK + 6%SiC implants was 473.06 MPa at 900 N, with stress gradually increasing with silicon carbide reinforcement (Figure 5). PEEK + 6%SiC

had the greatest von Mises stress values among polymer materials, followed by PEEK + 4%SiC, PEEK + 2%SiC, and pure PEEK, as shown in Table 5.

Table 5. The maximum von Mises stress values are expressed in MPa for each applied force and implant.

Force [N]	Titanium	PEEK	PEEK + 2%SiC	PEEK + 4%SiC	PEEK + 6%SiC
100	132.69	45.7	45.88	46.08	46.35
150	194.33	70.1	70.71	71.04	71.41
200	254.61	95	96.49	96.63	97.06
250	320.74	119.68	122.64	122.75	123.3
300	389.48	143.93	149.26	149.4	150
400	528.66	192.19	202.47	202.84	203.81
500	668.22	238.94	255.76	256.52	257.75
600	808.01	280.76	308.62	310.09	312.03
750	1020	351.39	386.98	389.77	392.91
900	1237.2	416.25	464.26	468.55	473.06

The average von Mises stress values were much lower than the maximum values in all implants, with stresses concentrated mainly at the implant neck and in the first turns. This pattern is consistent with recent studies indicating that implants under oblique loads show higher stress concentrations in the neck and component contact points.

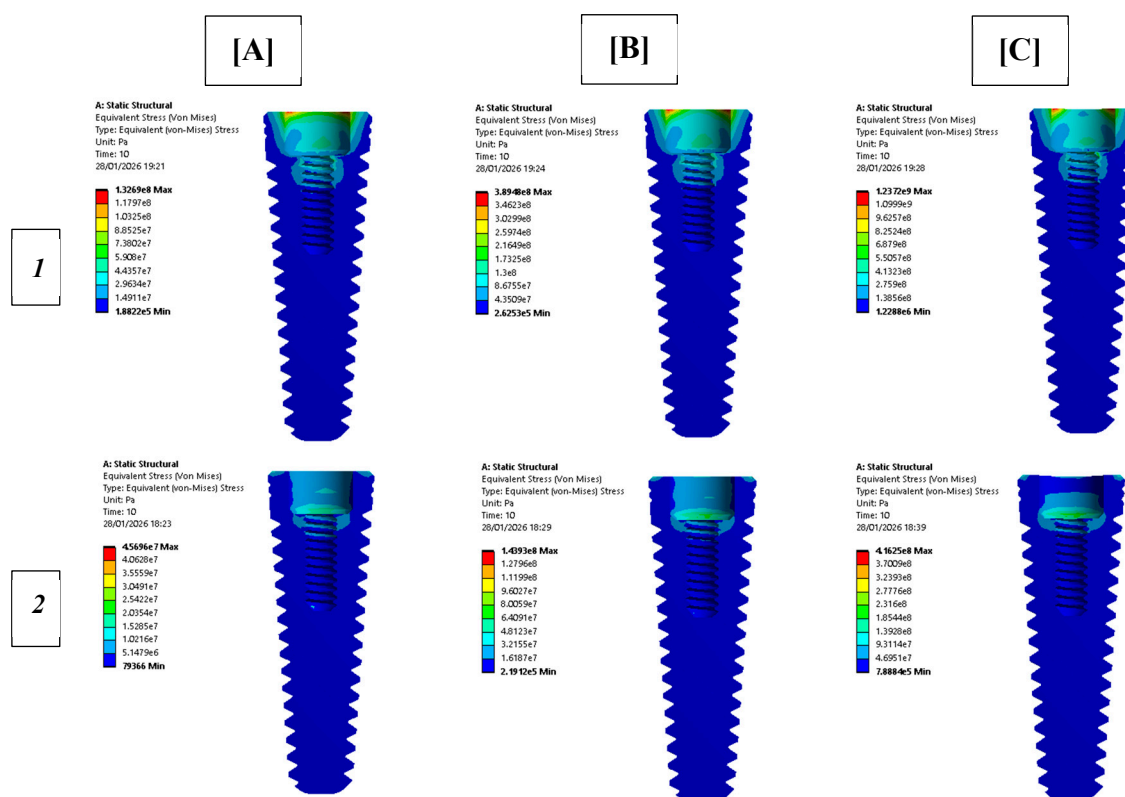
Titanium implants, assuming a yield strength of approximately 680–795 Mpa, have high safety coefficients at low loads (greater than 2 at 100 N to 250 N), gradually decreasing with increasing load to approach one at 500 N (≈ 1.02), and then falling below one at higher loads, indicating a theoretical entry into the yield range at very high loads. For PEEK, assuming a yield strength of around 100 Mpa, the results showed acceptable safety coefficients only at low pressures, which decreased to less than one at medium and high loads. PEEK composites reinforced with SiC showed a small improvement in the safety coefficient with increasing reinforcement ratio Figure 6. However, this gain did not reach the performance level of titanium at high loads, as shown in Table 6.

Table 6. The safety factor (FOS) values are determined for each applied force and implant.

Force [N]	Titanium	PEEK	PEEK + 2%SiC	PEEK + 4%SiC	PEEK + 6%SiC
100	5.12	2.19	2.44	2.65	2.33
150	3.5	1.43	1.58	1.72	1.51
200	2.67	1.05	1.16	1.26	1.11
250	2.12	0.84	0.91	0.99	0.88
300	1.75	0.69	0.75	0.82	0.72
400	1.29	0.52	0.55	0.6	0.53
500	1.02	0.42	0.44	0.48	0.42
600	0.84	0.36	0.36	0.39	0.35
750	0.67	0.28	0.29	0.31	0.27
900	0.55	0.24	0.24	0.26	0.23

These findings suggest that the difference in modulus of elasticity and stiffness between titanium and reinforced polymer has a direct impact on the stress distribution pattern and safety factor. The high stiffness of titanium causes bigger localized stress concentrations under oblique loading, whereas polymer materials give a more uniform stress distribution, albeit at a lower overall yield strength than titanium. This is consistent with

current research on how loading angle and material parameters affect the mechanical behavior of implants.



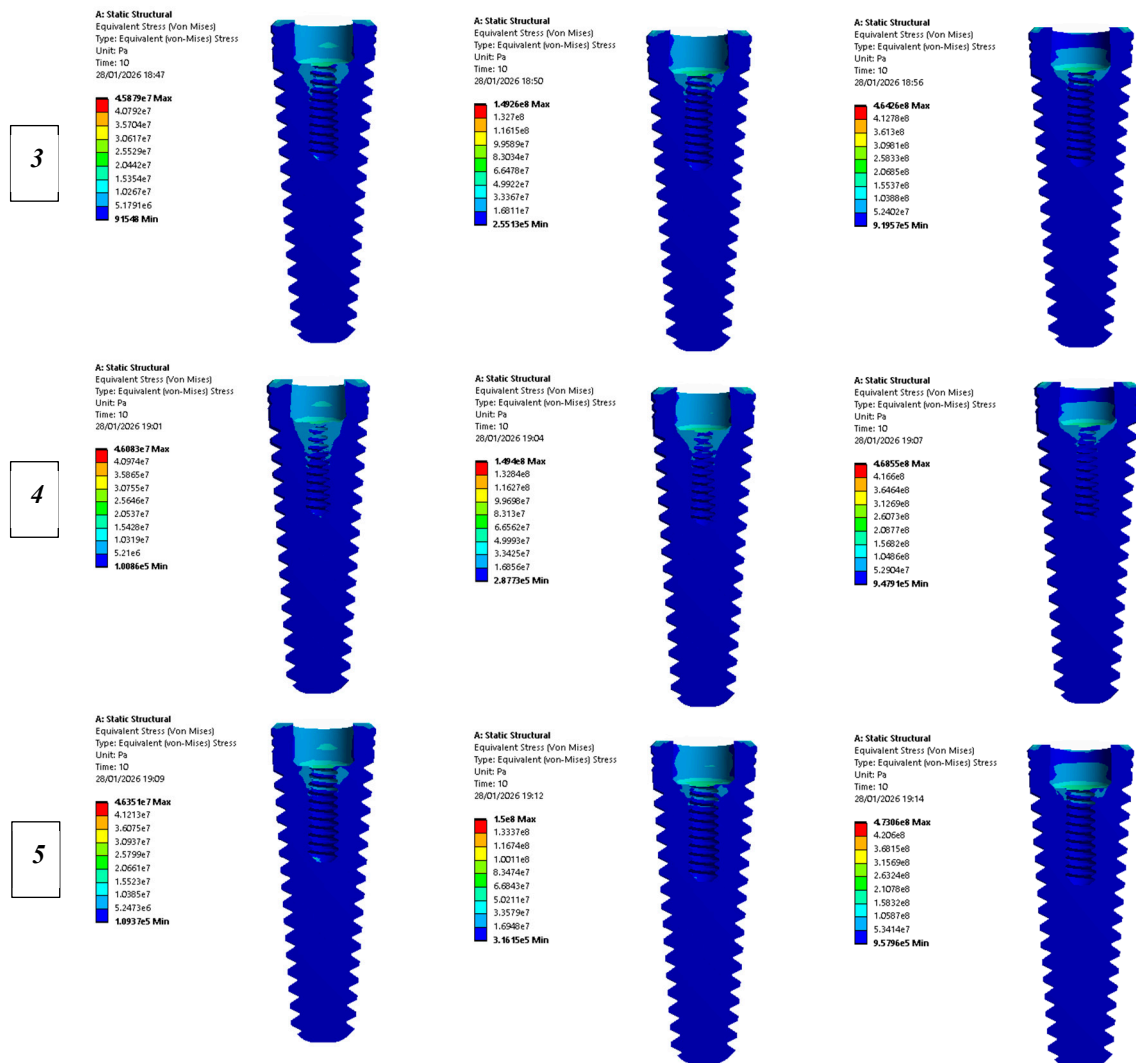


Figure 5. The maximum von Mises stress values are indicated by the numbers (1, 2, 3, 4, 5) which denote the order of implants as follows: (Titanium, PEEK, PEEK + 2%sic, PEEK + 4%sic, PEEK + 6%sic), where (A = 100 N), (B = 300 N), and (C = 900 N).

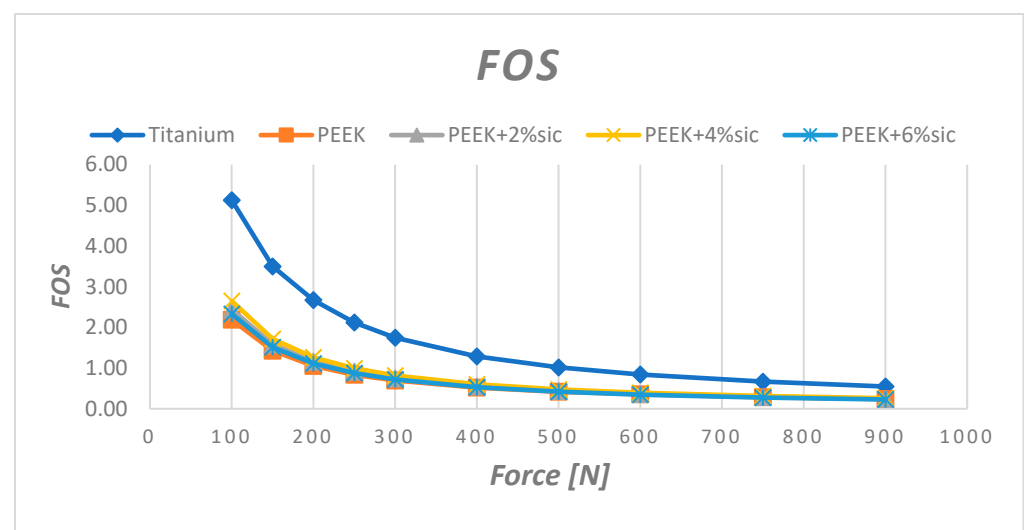


Figure 6. Factor of safety (FOS) for different implant materials under 45° oblique loading as a function of applied force.

3.1.2. Total Deformation Within the Implant

The evaluation of maximal deformation in finite element analysis is an important mechanical indicator for assessing implant performance under occlusal load. It depicts the total deformation caused by loading and is used to predict initial mechanical stability and the possibility of micromotion at the osteo-implant contact site. It also enables the comparison of the effects of various materials and elastic properties on implant performance under identical loading conditions.

The results under a 45° oblique load showed a regular increase in maximum deformation with increasing applied force from 100 to 900 N for all materials, indicating linear elastic behavior within the numerical analysis range. The titanium implant reported the lowest deflection values, with deformation ranging from 26.57 µm at 100 N to 241.28 µm at 900 N, reflecting its high stiffness and modulus of elasticity.

PEEK has the largest mechanical deformation values compared to other materials, reaching 38.38 µm at 100 N and 364.11 µm at 900 N. This is due to its lower modulus of elasticity compared to titanium, which causes higher deformation under angled stress (Figure 7).

PEEK composites reinforced with SiC particles showed a progressive improvement in mechanical behavior as the reinforcement % increased. At 900 N, PEEK + 2%SiC displaced 316.23 µm, while PEEK + 4%SiC and PEEK + 6%SiC displaced 310.47 µm and 306.8 µm, respectively. This implies that raising the reinforcing percentage results in higher stiffness and lower deformation. The materials with the least mechanical distortion are ranked as follows:

$$\text{Titanium} < \text{PEEK} + 6\%\text{SiC} < \text{PEEK} + 4\%\text{SiC} < \text{PEEK} + 2\%\text{SiC} < \text{PEEK}$$

At physiological loads (100–300 N), deformation values for all materials were less than 150 µm. However, at high loads (600–900 N), they exceeded this limit, which is consistent with the nature of the oblique loading and its high intensity. These findings show that reinforcing PEEK with SiC particles improves mechanical stability and reduces deformation when compared to the unreinforced material, with titanium retaining the highest resistance to displacement across all load levels studied, as shown in Table 7.



Figure 7. Total deformation (µm) for different implant materials under 45° oblique loading as a function of applied force.

Table 7. Maximum deformation values in μm for the studied implants at the loads shown in Table 3.

Force [N]	Titanium	PEEK	PEEK + 2%SiC	PEEK + 4%SiC	PEEK + 6%SiC
100	26.57	38.38	36.8	35.94	35.39
150	39.8	56.77	54.83	53.55	52.74
200	53.05	75.31	72.78	71.1	70.03
250	66.3	93.83	90.7	88.62	87.31
300	79.58	112.3	108.59	106.13	104.56
400	106.29	148.41	144.05	141.04	139
500	132.99	184.04	178.77	175.23	172.96
600	159.87	219.48	213.35	209.2	206.55
750	200.42	272.3	264.96	259.96	256.76
900	241.28	364.11	316.23	310.47	306.8

3.2. Biological Response of Bone Tissue

3.2.1. Maximum Principal Strain in Bone

When assessing the biological response of bone tissue around implants, one of the key biomechanical variables to consider is the Maximum Principal Strain, which provides a direct indication of the level of mechanical stimulation to which bone tissue is exposed under functional loads. Frost's mechanostat hypothesis states that strains within a certain range (1000–3000 $\mu\epsilon$) stimulate bone remodeling activity, while higher strains can overload and cause excessive resorption of bone tissue. This can exceed the bone's ability to self-correct and restore normal structure, potentially accelerating bone resorption rather than promoting physiological bone growth [28].

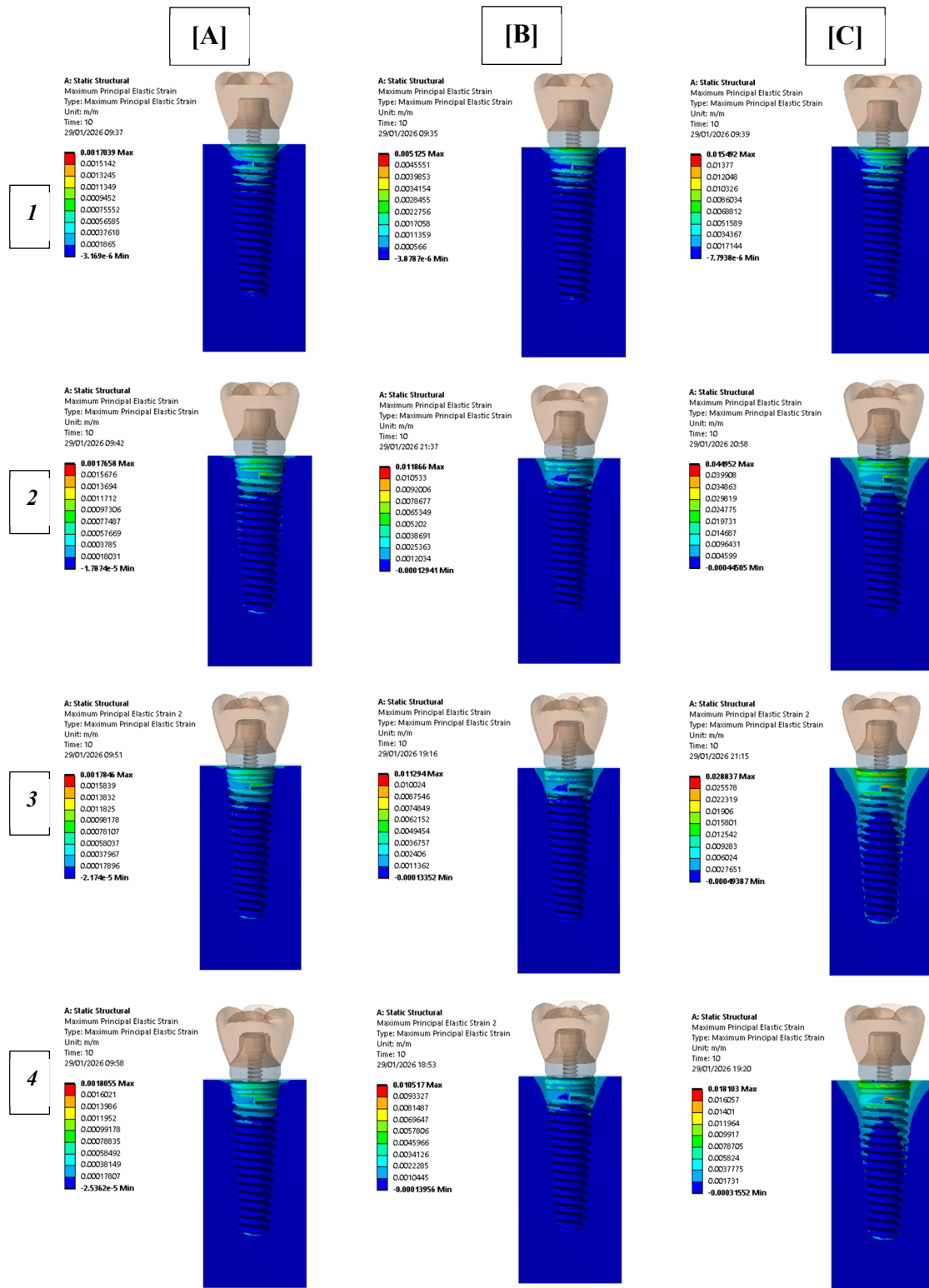
Recent numerical studies using finite element analysis (FEA) in dental implant models have confirmed the importance of strain as a more expressive variable of biological stimulation of bone tissue than equivalent stress indices alone, particularly when the properties of the materials used to manufacture the implants or abutments, the loading angle, and the applied force field differ. For example, studies have shown that polymer materials such as realistic PEEK cause higher strains in cortical bone than solid titanium, indicating more physiological mechanical load transfer and a reduction in the stress shielding effect commonly observed with high-strength titanium, which affects the dynamics of the bone response surrounding the implant [29]. Taking this into account, estimating the maximum principal strain in this study under 45° oblique loading and within a force range between the materials used (titanium, PEEK, and PEEK reinforced with SiC particles) provides an accurate framework for linking numerical results to bone's biological response behavior. This assessment allows for the determination of whether the strains recorded in cortical bone are close to the physiological stimulation ranges or exceed them to the limits of overload, while taking into account the difference in modulus of elasticity between the materials and its role in load distribution across the implant–bone interface, which helps to explain the possibility of bone remodeling or excessive bone resorption in critical sites under clinical loads.

The analysis of the Maximum Principal Strain behavior in the bone surrounding implants under 45° oblique loading and within the force range shown in Table 3 revealed a clear gradual increase in strain values with increasing load in all models studied, while maintaining a quasi-linear relationship between the amount of force applied and the recorded strain value. The titanium implant showed the lowest strain values at all loading levels, ranging from 755.52 $\mu\epsilon$ at 100 N to 8603.4 $\mu\epsilon$ at 900 N. Pure PEEK demonstrated

the greatest results, with a maximum principal strain of 1171.2 $\mu\epsilon$ at 100 N and steadily increasing to 22,239 $\mu\epsilon$ at 900 N.

PEEK composites reinforced with silicon carbide showed a gradual decrease in strain values with increasing reinforcement ratio, with maximum values for the PEEK + 2%SiC composite at (900 N) reaching 16,756 $\mu\epsilon$, 15,879 $\mu\epsilon$ for the PEEK + 4%SiC composite, and 15,330 $\mu\epsilon$ for the PEEK + 6%SiC composite, with PEEK + 6%SiC remaining the least strained among the polymer materials. This trend indicates the direct effect of raising the effective stiffness of the composite by increasing the reinforcement ratio, which resulted in a reduction in the amount of deformation imparted to the bone under the same loading circumstances, as shown in Table 8.

Maximum strain values were concentrated in the cortical bone region surrounding the implant neck and the first turns of the thread, gradually decreasing toward regions further from the neck level. This pattern is consistent with the regions of maximum load transmission under oblique loading. The modulus of elasticity of materials affects both stress levels within the implant and the amount of strain generated in the surrounding bone. Less rigid materials increase mechanical stimulation, while more rigid materials reduce deformities, resulting in a clear difference in expected bone response under high loads (Figure 8).



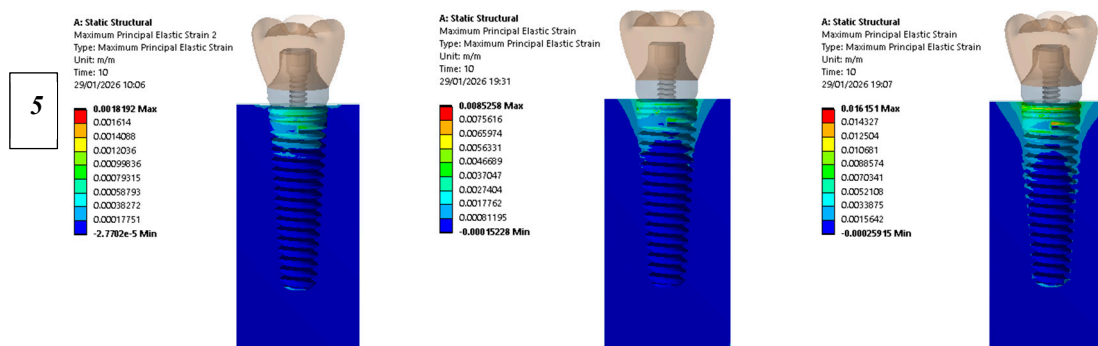


Figure 8. The Maximum Principal Strain values (1, 2, 3, 4, 5) reflect the order of the implants (Titanium, PEEK, PEEK + 2%SiC, PEEK + 4%SiC, PEEK + 6%SiC), where (A = 100 N), (B = 300 N), and (C = 900 N).

Table 8. The Maximum Principal Strain values (in $\mu\epsilon$) for each applied force and implant used.

Force [N]	Titanium	PEEK	PEEK + 2%SiC	PEEK + 4%SiC	PEEK + 6%SiC
100	755.52	1171.2	981.78	972.02	958.36
150	1134.3	1706.1	1403.6	1249.9	1181
200	1513.9	2771.1	2303.7	2158.4	2062.1
250	1894.4	3863.9	3242.4	3057.1	2940.8
300	2275.6	5050.4	4196.2	3972.5	3835
400	3037.6	7451.6	6122	5820.9	5609.8
500	3800.9	9978.3	8068.8	7685.1	7439.4
600	4567	13,674	10,083	9579.1	9272.4
750	5721.4	17,318	13,361	12,669	12,234
900	8603.4	22,239	16,756	15,879	15,330

3.2.2. Maximum Principal Stress in Bone

Maximum Principal Stress (MPST) analysis of bone surrounding the implant provides a direct mechanical indication for determining bone tissue behavior under non-axial stresses. It represents the maximum tensile or compressive value to which the bone is subjected at any specific place. Because bone is a relatively brittle material that is more sensitive to maximum principal stress than shear stresses, studying the MPST is more appropriate for determining the likelihood of initiating microcracks or stimulating bone remodeling processes in areas with high stress concentrations, particularly in cervical cortical bone.

The analysis of the maximum primary stress under a 45° slanted load and a force range of (100–900 N) revealed a consistent steady increase in all tested models. The titanium model had the lowest stress values at all load levels, ranging from MPa8.45 at N100 to MPa75.87 at N900. This suggests that the material's high rigidity reduces the transmission of maximum principal stress to bone. Pure PEEK, on the other hand, had the highest recorded values, with the maximum main stress increasing from 13.08 MPa at 100 N to 324.48 MPa at N900, showing that more load was transferred to the cortical bone as the applied force increased, as shown in Table 9. At N900, the maximum values for silicon carbide-reinforced PEEK composites decreased with increasing reinforcement percentage. At N900, the values were 233.12 MPa for (PEEK + 2%SiC), 219.24 MPa for (PEEK + 4%SiC), and 210.72 MPa for (PEEK + 6%SiC), with PEEK + 6%SiC remaining the least stress-intensive among the polymer materials (Figure 9).

The largest primary stress values were centered in the cortical bone region surrounding the implant neck and initial threads, gradually decreasing toward more distant locations, consistent with the load transfer process under oblique loading. The average values were substantially lower than the maximum values, indicating a localized stress concentration. These findings indicate that decreasing the modulus of elasticity of polymer materials increases the amount of tensile stress passed to the bone, whereas increasing stiffness by reinforcing PEEK with SiC particles gradually reduces these values without reaching titanium-level stress.

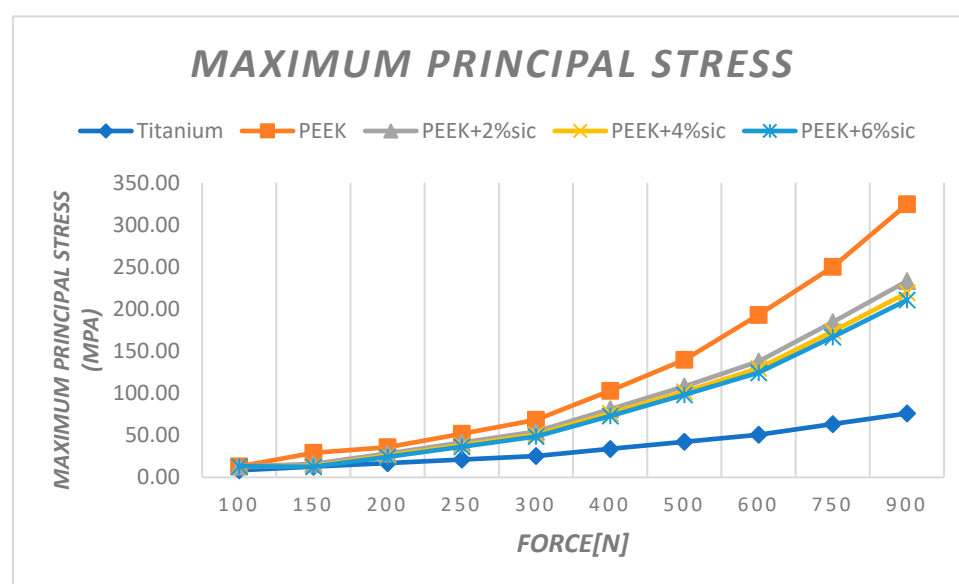


Figure 9. Maximum Principal Stress values (MPa) for different implant materials under 45° oblique loading as a function of applied force.

Table 9. Maximum Principal Stress values (MPa) for each applied force and implant type.

Force [N]	Titanium	PEEK	PEEK + 2%SiC	PEEK + 4%SiC	PEEK + 6%SiC
100	8.45	13.08	13.07	13.05	13.03
150	12.67	29.1	15.91	13.49	12.62
200	16.89	35.78	28.23	25.86	24.36
250	21.11	51.73	41.18	38.19	36.32
300	25.33	68.3	54.35	50.78	48.54
400	33.77	102.76	80.95	76.21	72.82
500	42.2	139.64	107.89	101.79	98.03
600	50.63	192.95	137.59	129.41	124.33
750	63.26	250.09	184.35	173.38	166.68
900	75.87	324.48	233.12	219.24	210.72

4. Discussion

The findings of this study revealed considerable disparities in stress distribution patterns amongst dental implants with varied material architectures. It emphasized the contrasts in behavior between traditional and highly reliable titanium implants and contemporary polymeric implants, notably PEEK. Furthermore, this study includes reinforcing PEEK with silicon carbide in various quantities in order to improve the mechanical qualities of pure PEEK implants. Therefore, five different implants were studied (titanium, PEEK + 6% SiC, PEEK + 4% SiC, PEEK + 2% SiC, PEEK) throughout a wide range of stresses, as shown in Table 3, to reflect as many of the circumstances that dental implants

may be subjected to as feasible. All forces were measured at a 45° angle to reflect the greatest stress load and to test the implants' strength under the most extreme conditions, with each evaluated individually. Before interpreting the results, it is important to acknowledge the limitations of the linear elastic assumption adopted in this study. For PEEK-based implants, the von Mises stresses at loads exceeding 200 N approached or surpassed the yield strength of the material (approximately 100–122 MPa, depending on the SiC content). Under such conditions, the material would undergo plastic deformation, and the linear elastic analysis no longer reflects the actual mechanical behavior. Therefore, the numerical results at loads above 200 N should be interpreted as theoretical trends for comparative purposes only, and not as predictions of actual elastic performance. The clinically relevant interpretation of this study focuses on the load range up to 200 N, where all materials remain within their safe elastic limits.

It is important to note that under high masticatory forces exceeding the yield thresholds of the PEEK composites (above 200 N) and titanium (approaching 500 N), the quantitative stress and strain magnitudes derived from the linear elastic simulation must be interpreted with scientific caution. These high-load data have been intentionally maintained in the discussion to serve as theoretical comparative trends, establishing a standardized baseline to evaluate the relative mechanical hierarchy and macro-structural stiffness among the investigated implant configurations. While a non-linear material analysis would be required to accurately map localized plastic deformation and true post-yield structural failure, the linear outcomes at these upper limits remain scientifically valuable strictly for comparative biomechanical screening under identical loading conditions.

Maximum von Mises stress values in implants differed significantly between titanium, PEEK, and their composites at all loading levels. Titanium showed a clear, continuously increasing value—a steep upward curve, demonstrating the material's high stiffness and modulus of elasticity as compared to bone. Unreinforced PEEK exhibited significantly lower values within the same force range, with a gradual increase. Reinforcement of PEEK with 2%, 4%, and 6% SiC particles resulted in somewhat higher von Mises stress than pure PEEK.

The safety factor investigation also revealed that titanium implants had high safety factors under low and medium loads. This is due to their great stiffness, as titanium implants have a safety factor of 5.12 at 100 N and remain above 1 up to 500 N. In contrast, PEEK implants had a safety factor of around 2.19 at 100 N and 0.84 at 250 N. PEEK + 4%SiC implants had the highest safety factor among PEEK implants, measuring 2.65 at 100 N and around 1 at 250 N. The superiority of PEEK + 4%SiC implants stems from the fact that the tensile and flexural strength of PEEK composites reinforced with silicon carbide declines when the percentage exceeds 4%, as does their elasticity. Despite this, PEEK implants were unable to meet the necessary safety standards for titanium implants.

Titanium's high modulus of elasticity (~115 GPa) causes increased stress within the implant body due to its resistance to elastic deformation [30]. Although titanium has a high yield strength (often ranging between 680 and 800 MPa), exceeding the calculated values of yield stress at theoretically high loads indicates that the safety factor is approaching critical limits under high-load conditions. This calls for careful analysis of the safety factor in the context of clinical design [31].

PEEK implants have a low modulus of elasticity (~3–4 GPa), which reduces von Mises stress by absorbing elastic deformation and distributing the load over a larger surface [32]. However, this decrease in internal stress is followed by a relative rise in strain, which is consistent with the behavior of semi-elastic polymer materials. Reinforcing PEEK with ceramic particles such as SiC leads in a minor increase in stiffness and a limited rise in von Mises stress, but not to the levels of titanium, indicating the possibility of striking a compromise between mechanical stiffness and stress shielding [33].

Recent finite element analysis studies indicate that titanium implants have higher stresses within the implant body compared to high-performance polymer materials. PEEK materials, on the other hand, have a more uniform stress distribution with lower maximum values within the implant [13,34]. Furthermore, recent research suggests that modifying PEEK with ceramic or fibrous additives gradually improves its mechanical performance without reaching titanium's modulus of elasticity, making it a promising option for improving mechanical compatibility with bone and reducing hyperstimulation-induced bone resorption [14]. As a result, the observed mechanical behavior can be interpreted as follows: titanium provides very high resistance to deformation with high internal stresses, whereas PEEK systems—particularly partially reinforced ones—provide a more balanced approach that reduces maximum principal stresses within the implant while gradually improving stiffness, which may have a positive impact on the surrounding biological response in the long run.

Maximum deformation is an integrative indication that reflects the total mechanical reaction of the implant–bone system when loaded. Its significance goes beyond just evaluating the degree of deformation; it also evaluates the level of initial stability and the possibility of micromobility development at the bone–implant interface. The results indicated a constant upward trend in deformation with increasing load for all materials, indicating linear elastic behavior within the examined domain and supporting the numerical model's consistency. However, the differences between the materials were both quantitative and qualitative in terms of mechanical reaction pattern. Titanium has the lowest sensitivity to deformation across all loading levels, which is a direct result of its high rigidity. While this conclusion supports the concept of structural stability, it is mechanically tied to the system's higher stiffness, which may limit the degree of mechanical stimulation delivered to the surrounding bone, as earlier finite element analysis studies have shown [3,35].

In contrast, PEEK demonstrated more elastic behavior, with a fall in modulus of elasticity accompanied by a large rise in displacement, particularly at high loads. This behavior represents a larger capacity for elastic energy absorption. However, it may increase the chance of micromotion when the deformation surpasses clinically tolerable limits (100–150 μm) under non-axial loading circumstances [36]. However, because PEEK's modulus of elasticity is similar to that of cortical bone, it has a potential advantage in terms of increased mechanical compatibility and reduced stress transmission heterogeneity, as indicated by current biopolymer material research [13].

The reinforcement of PEEK with SiC particles caused a gradual change in the material's structural behavior. With increasing reinforcement, performance tended to decrease distortion but did not achieve titanium's metallic rigidity. This progressive improvement demonstrates the ceramic particles' effectiveness in increasing the composite modulus of elasticity and improving flexural strength under oblique loads. Mechanically, these results indicate that the material's structural qualities can be tuned to strike a compromise between sufficient stiffness for initial stability and the elasticity required to avoid stress shielding.

Analyzing the results within the physiological load range reveals that all materials maintained deformation within the mechanically acceptable range at low and medium load stages, whereas differences became more pronounced at high forces, where the effect of varying elastic moduli became more apparent. This pattern is consistent with earlier research demonstrating that the effect of material type is more responsive to angled loading than axial loading [37,38]. As a result, the findings can be interpreted in terms of optimal elastic compatibility; titanium has the highest resistance to deformation, whereas PEEK/SiC composites provide an intermediate response, combining improved stiffness

and reduced displacement compared to pure PEEK while remaining closer to bone's elastic properties. Thus, reinforcing PEEK with SiC particles is a viable method for increasing mechanical stability under oblique loads while maintaining biomechanical compatibility.

The bone strain data reveal that all materials retained linear elastic behavior under oblique loading, although qualitative differences emerged when interpreted within the framework of Frost's mechanostat theory. Titanium achieved physiological catalytic values at low and medium loads (755–2275 $\mu\epsilon$) up to 300 N, indicating a strong ability to restrict initial deformations. However, its high modulus of elasticity is associated with increased load concentration in the cervical cortical bone, a pattern documented in classical finite element analyses such as those by Geng JP [3] and [38], which showed that high-strength materials improve localized load transfer under non-axial loading.

Pure PEEK demonstrated high values, exceeding 2771.1 $\mu\epsilon$ at 200 N. This puts the bone in the overload range for medium to high forces. This is consistent with [13] systematic study, which found that PEEK's lower modulus of elasticity causes more bone strain than titanium.

The reinforced PEEK composites improved gradually with increasing SiC content. The PEEK + 4% SiC composition achieved remarkable mechanical equilibrium, reducing strain by approximately 28–30% compared to pure PEEK at high loads and maintaining values close to the upper limit of the physiological range at moderate loads (~2158 $\mu\epsilon$ at 200 N). This behavior reflects an increase in effective elastic modulus without reaching the high stiffness of titanium, which may reduce the stress shielding phenomenon traditionally associated with high-strength metallic materials, as discussed by [37] in his analysis of mechanical factors affecting the bone–implant interface. When comparing these values to the physiological strain ranges proposed in the bone biomechanical theory (Frost's mechanostat), the range of approximately (100–3000 $\mu\epsilon$) is considered the optimal bone stimulation range, while exceeding (4000 $\mu\epsilon$) may lead to overloading and bone resorption. At moderate loads (200–300 N), titanium stayed within the physiological range (1513.9–2771.1 $\mu\epsilon$), but pure PEEK exceeded this range early (2771.1–5050.4 $\mu\epsilon$), indicating the likelihood of high stimulatory stresses that may lead to imbalanced bone remodeling. Reinforcing PEEK using SiC particles improved mechanical behavior, particularly at a 4% concentration (2158.4–3972.5 $\mu\epsilon$) at moderate loads.

Titanium had the lowest absolute strain values in the examined range, indicating its strong stiffness and ability to limit deformation. However, this drop may be due to stress shielding in the long-term therapeutic term. In contrast, pure PEEK has excessive elasticity, resulting in strains that exceed physiological limitations at high loads, potentially increasing the risk of micro-bone resorption. PEEK/SiC composites, particularly at a 4% ratio, provide superior mechanical balance by lowering strain compared to pure PEEK while retaining elastic characteristics equivalent to cortical bone. As a result, reinforcing with ceramic particles is a viable alternative for improving mechanical compatibility between the implant and bone while minimizing the possibility of overloading and stress shielding within the examined physiological load range. The integrated biomechanical assessment, which considers load distribution, the physiological field of bone stimulation, and the risks of stress blocking, suggests that PEEK + 4% SiC may be the most balanced option for creating a stimulating and stable mechanical environment at the same time, particularly under oblique loading conditions.

The maximum primary stress results demonstrate mechanical behavior that is compatible with the load transfer principles in implant systems under oblique loading. All models showed a consistent increase in values as force increased, demonstrating a steady elastic response without numerical breakdown. The biomechanical importance of these data goes beyond the rising trend and includes the interpretation of values within the limits of cortical bone's resistance to maximum principal stress.

Cortical bone's tensile strength is commonly estimated to be between 80 and 130 MPa, depending on density and microstructure, although shear strength is lower. Titanium values ranging from 8.45 MPa to 25.33 MPa remained safe at N300, demonstrating that the material's high stiffness prevents tensile stress transmission to the bone. Finite element analysis investigations by Geng JP et al. indicate that materials with high modulus of elasticity lower absolute stress values in cortical bone, but may increase localized stress concentration in the neck region under non-axial loading.

Pure PEEK, on the other hand, showed a significant rise in stress, topping 65 MPa at 300 N and reaching 139.64 MPa at 500 N—a number considerably exceeding the physiological limits of cortical bone tolerance to tensile stress. Such levels may be associated with a risk of microcrack development or localized resorption, especially under repeated oblique stress. This trend is consistent with the findings of [13] about higher load transmission to bone when employing lower-strength materials than titanium.

PEEK/SiC composites showed a significant and steady improvement; the ultimate stress at 200 N fell from 35.78 MPa in pure PEEK to 28.23 MPa in PEEK + 2% SiC, 25.86 MPa in PEEK + 4% SiC and 24.36 MPa in PEEK + 6% SiC, showing a reduction of roughly 21–32% relative to the unreinforced material, indicating a balance between elasticity and lowered ultimate maximum principal stress.

Although titanium exhibited the lowest absolute stress values, the biomechanical performance of an implant material cannot be determined solely by minimizing stress magnitude. Instead, it requires a balanced consideration of implant structural safety, stiffness mismatch, and the ability to provide an appropriate mechanical environment for the surrounding bone. While the high rigidity of titanium effectively limits implant deformation and stress accumulation, its substantial difference in elastic modulus compared with bone may reduce physiological mechanical stimulation and contribute to stress-shielding phenomena. Therefore, the optimal implant material should achieve sufficient mechanical strength while maintaining a more favorable load-transfer behavior.

Within the investigated composite configurations, PEEK + 4%SiC demonstrated the most balanced biomechanical response. Compared with unreinforced PEEK, the incorporation of SiC particles substantially improved the structural performance by reducing stress concentration within the implant system. Furthermore, PEEK + 4%SiC exhibited lower von Mises stress within the implant body and higher factor of safety values compared with PEEK + 6%SiC under the investigated loading conditions, indicating improved structural reliability without excessive stiffness increase. Although PEEK + 6%SiC provided slightly lower deformation and reduced stress values in some regions of the surrounding bone due to its higher stiffness, the overall biomechanical improvement was limited compared with the potential disadvantages associated with excessive ceramic reinforcement.

This comparative trade-off can be explained by the material behavior of high-performance polymer composites. Previous studies have indicated that SiC reinforcement levels within approximately the 2–4% range can provide significant improvements in tensile strength, flexural strength, and elastic modulus of PEEK-based composites. Increasing the ceramic content beyond this range may increase the probability of particle agglomeration and micro-clustering within the polymer matrix, which can act as local stress concentration sites and reduce the efficiency of stress transfer. In addition, excessive ceramic loading may progressively reduce composite ductility and deformation tolerance by restricting polymer chain mobility. Therefore, although higher SiC contents can further increase stiffness, they may not necessarily provide proportional biomechanical benefits [39,40].

Considering that the stress and strain distributions of PEEK + 4%SiC and PEEK + 6%SiC remained comparable in the present numerical analysis, the 4% SiC configuration

represents a more favorable compromise between mechanical reinforcement and biomechanical compatibility. This configuration achieved reduced implant von Mises stress, increased factor of safety, and a more balanced elastic response compared with higher SiC reinforcement, suggesting that moderate SiC incorporation may provide an intermediate mechanical behavior between the excessive rigidity of titanium and the excessive compliance of pure PEEK. Consequently, PEEK reinforced with 4% SiC may represent a promising biomechanical alternative for improving stress distribution under oblique loading conditions within the limitations of the present linear elastic analysis.

While this study provides valuable insights into the biomechanical performance of SiC-reinforced PEEK dental implants using finite element analysis (FEA), several limitations should be acknowledged. First, the assumption of perfectly bonded and homogeneous, isotropic, linearly elastic materials for both the implants and bone represents an idealization. In reality, bone tissue is anisotropic and exhibits heterogeneous, time-dependent (viscoelastic) behavior, and the osseointegration interface is more complex than a perfect bond. Second, the applied loads were static and monotonic, ranging from 100 N to 900 N at a fixed 45° angle. This does not fully replicate the dynamic, cyclic, and variable nature of masticatory forces *in vivo*, which can lead to fatigue failure over time. Third, the study focused solely on the immediate biomechanical response and did not simulate long-term biological processes such as bone remodeling, resorption, or the effects of the implant's surface topography on osseointegration. Fourth, the finite element model, despite a rigorous mesh convergence study, remains a simplified representation of the complex oral environment and cannot capture all clinical variables, such as the quality of the surrounding bone, patient-specific anatomy, or the presence of a microgap at the implant–abutment connection. Fifth, the analysis assumed linear elastic material behavior for all implant materials. This assumption becomes invalid when stresses exceed the yield strength of the material, as observed for PEEK-based implants at loads exceeding 200 N and for titanium at loads approaching 500 N. Under such conditions, plastic deformation would occur, and the linear elastic model no longer reflects the actual mechanical response. Therefore, the numerical results at loads above the elastic limit should be interpreted as theoretical trends for comparative purposes only, and non-linear analysis would be required to accurately simulate post-yield behavior. Sixth, the current simulation utilized a static load configuration rather than dynamic, multi-axial cyclic loading. Clinical mastication introduces millions of load–unload cycles annually, which induces material fatigue, structural degradation, and viscoelastic behavior in polymeric matrices like PEEK. While static FEA is a vital and standard screening tool for assessing peak stress–strain limits and predicting immediate mechanical failure risks, it cannot fully replicate long-term dynamic wear or fatigue life. Future investigations focusing on fatigue testing and dynamic cycling simulations are strongly recommended to bridge the gap between numerical models and real-world clinical performance. Finally, these findings are computational and require validation through *in vitro* experiments and, ultimately, long-term controlled clinical trials to confirm the safety and efficacy of PEEK/SiC composites in a clinical setting. Therefore, the results should be interpreted with caution, and the conclusions drawn are primarily indicative of comparative biomechanical trends rather than absolute clinical predictions.

5. Conclusions

This study was carried out using a three-dimensional finite element method to evaluate the biomechanical performance of SiC-reinforced PEEK dental implants compared to titanium and pure PEEK. Based on the findings within the limitations of this computational study, the following conclusions can be drawn:

- The modulus of elasticity of the implant material significantly affects the distribution of stress and strain in the surrounding cortical bone. Titanium exhibited the lowest

bone strains (755–2275 $\mu\epsilon$ at 100–300 N) but at the cost of potential stress shielding, while pure PEEK induced excessively high bone strains ($>4000 \mu\epsilon$), indicating a risk of bone overload.

- Under high loads (600–900 N), both titanium and PEEK-based implants exceeded their theoretical yield strength, indicating a risk of mechanical failure. Therefore, the clinically relevant safe working range for all implant materials tested is up to 200 N, where the factor of safety remains above 1 for titanium and above 1 for reinforced PEEK composites (FOS = 1.11 for PEEK + 4%SiC at 200 N).
- Reinforcing PEEK using silicon carbide particles resulted in a considerable reduction in ultimate stresses and bone strains when compared to the unreinforced material, with the improvement proportional to reinforcement ratio.
- Within the physiologically relevant load range (100–200 N), PEEK reinforced with 4% SiC demonstrated the most balanced biomechanical performance. It reduced maximum principal bone stress by 32–35% compared to pure PEEK while maintaining bone strains within the adaptive physiological range (1000–3000 $\mu\epsilon$) under moderate loads, showing improved biomechanical compatibility.
- Increasing SiC reinforcement beyond 4% (i.e., 6%) led to increased stiffness but reduced ductility and safety factor, likely due to particle agglomeration. Thus, 4% SiC appears to be the optimal reinforcement ratio for balancing mechanical integrity and biomechanical compatibility.
- The cortical bone surrounding the implant neck and first turns had the highest main stress values, indicating that oblique loading is the most mechanically critical scenario. A material that balances reducing maximum principal stress and preventing long-term stress blockage is recommended.
- Within the limitations of this computational study (linear elastic analysis, simplified bone properties, static loading), PEEK reinforced with 4% SiC offers a promising alternative to titanium for load-bearing dental applications, particularly in the physiological load range (100–200 N). However, further in vitro and clinical studies are necessary to validate these findings and assess long-term fatigue performance.

In conclusion, the development of advanced dental implant materials is crucial for prolonging their functional lifespan by minimizing bone resorption while maintaining the necessary mechanical durability to ensure optimal clinical performance. Further studies are warranted to validate the findings obtained from the current FEA.

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