STRESS AMPLIFICATION AND SHIELDING OF DOUBLE-EDGE CRACKS IN ALVEOLAR BONE UNDER MODE II LOADING: A COMPARATIVE ANALYSIS OF BONE MATERIAL HETEROGENEITY

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ABSTRACT

This paper aims to examine the response of double edge cracks in alveolar bone under Mode II loading with emphasis on differences in crack behaviour between homogeneous (cancellous) and heterogeneous (cortical-cancellous) bone types. Implant placement exerts load on the alveolar bone and consequently causes microcracks that would influence the stability of the implant and the bone. Such fractures and their relation to the composition of the human bones must be better understood to enhance the design of the implant. Crack behaviour was studied using a 2D continuum mechanics model of the dimension 1mm x 1mm. The crack length-to-width ratio of the upper crack varied in the range of 0.125 mm to 0.5 mm, and the lower crack was held constant at 0.125 mm. The goal of the study is to investigate Mode II loading of cancellous and cortical-cancellous bone materials where stress intensity factors (SIF) and normalized SIF values are a particular focus. In the homogeneous cancellous bone model, stress shielding occurred and normalized SIF values from 0.176 to 0.717 were consistently demonstrated. While the heterogeneous model initially showed similar shielding behavior (SIF ranging from 0.039 to 0.053), a transition was observed from shielding to stress amplification to SIF increasing from 0.053 to 1.205, with a unification point at a/W ≈ 0.3119. We observe that the cortical layer initially disperses the applied shear stress; however, as the crack length increases beyond a critical threshold, stress amplification occurs. Thus, the relevance of bone heterogeneity to the crack behavior is emphasized and the need to account for material composition in the implant design and placement for improving implant mechanical stability and durability is confirmed.

Keywords: *Stress Intensity Factor (SIF), Bone Material Heterogeneity, Mode II Loading, Double-Edge Cracks, Fracture Mechanics.*

1.0 INTRODUCTION

Dental implants are now considered to be a reliable treatment modality for the replacement of missing teeth, which provide both functional and aesthetic benefits, a highly desirable outcome among patients [1]. A growing interest in more dental implants means that there is a need to consider the biomechanical behaviour of implants within the alveolar bone space. Nonetheless, it is important to investigate how these interactions affect the implant stability and survival, more so since alveolar bone receives many forces during mastication

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and occlusion. These forces can put pressure, and in presence of pre-existing flaw, then can alter the mechanical characteristics of the bone which directly influences the stability of implant. Interestingly, as stated by other researchers, implantation procedures per se seem to cause microdamage in alveolus bone which may serve as the base for crack's further growth due to multiple loading [2].

Thus, shear loading referred to as Mode II loading, which is particularly critical for dental implants as it proves to be directly governing crack propagation along the bone surface, was considered. In contrast to axial or tensile forces, shear forces produce highly concentrated stress field resulting in a more efficient crack growth within the bone tissue. The forces that act upon pre-existing microcracks that may arise in the alveolar bone during normal chewing, if they accumulate over time can affect implant fixation. As cited in Bagheri *et al*., Ayatollahi and Hashemi's study earlier were all based on the Mode II loading that is considered to be the main loading factor in dental biomechanical systems. As a result, precise characterization crack behavior under shear loading conditions is needed for predicting the implant's longevity and providing the clinical treatment plans [3–5].

1.1 Mode II Loading in Dental Implant Biomechanics

Dental implants face various types of loading exposure within the mouth but shear forces (Mode II) stand out as the most important. Research demonstrates that shear forces prove more satisfactory in causing and extending alveolar bone cracks than axial or tensile stresses thus endangering implant durability [6,7]. The rise in microcrack prevalence after implant surgery warrants comprehensive knowledge of Mode II loading behavior to predict implant failure risks [8]. Furthermore, several experimental strategies involving Digital Image Correlation (DIC) and Micro-Computed Tomography (Micro-CT) used to measure bone response under shear forces. The obtained data through these methods supports computational model development and validation [9].

FEA is particularly useful in understanding Mode II loading in bone, which has gained popularity in biomechanical investigations because of flexural rigidity and allows modeling stress distributions and crack behaviours under controlled loading [10]. With FEA it can be considered such parameters as material inhomogeneity, boundary conditions, and geometrical characteristics of the implant implying stress distribution and crack initiation. This work applies the FEA to study the crack response under the Mode II loading condition, with particular focus on how shear stress influences the mechanical apposition between the implant and the bone. The Mode II Stress Intensity Factor (SIF), an effective parameter in crack mechanics, is employed to evaluate the crack growth propensity, which offers the understanding of the bone's resistance towards shear-induced crack extension. FEA facilitates the investigation of the influence of various parameters, including implant geometry and bone characteristics, on stress patterns and crack development when the structure is subjected to shear force. This versatile gadget can include geometries, material, and boundary conditions, making it a valuable asset in engineering [11–13].

Therefore, knowledge of fracture mechanics is essential when it comes to explaining the behaviour of the cracks in the bone under the Mode II loading. The SIF for Mode II loading quantifies the strength of the shear stress field about the crack tip. It is used as a measure for crack initiation and crack growth prediction [14,15]. To elucidate the behaviour of the bone under shear loading, it is essential to consider the fracture toughness, which is one of the key characteristics of the material's ability to resist cracks initiation and propagation.

1.2 Bone Heterogeneity

On the material level of understanding, bones are heterogeneous structures based on density, porosity, and microstructural properties that greatly influence the mechanical response to loading. These variations create new localized stress concentrations at interfaces between cortical and cancellous bone which can have an impact on crack initiation and propagation

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within alveolar bone [16]. As for the mechanical properties of the bones, cortical and cancellous bones showed different responses to the shear loading under which cancellous bones' properties are preferentially more effective than the cortical bones under the compressive loads. Such contrast results in further stress concentrations at those locations where stress concentrations are correlated with crack initiation [17]. Because bone at the material level has a high degree of variability, it is necessary to implement the variation into a range of predictive models to quantify crack dynamics surrounding dental implants.

However, replicating each microstructural detail of the bone can be computationally expensive, and recon is probably not required in prediction of macroscopic mechanical responses. It is postulated hereby that porosity of the cancellous bone has negligible influence on its overall mechanical performance at macro level [18]. This assumption enables the model to capture few stress interactions and crack behaviours without compromising significantly on computational cost, in contrast to the studies' goals of modeling shear stress interplays relevant to clinical application.

1.3 Computational Analysis on Stress Interaction and SIF Evaluation Using Kachanov Theory

Numerous computational studies have demonstrated the importance of inter-crack stress interactions, particularly for the cases of closely spaced cracks, as in bone where closely spaced cracks can amplify or shield the stress at crack tips. The Kachanov theory of interaction provides a means to analyze such complex stress interactions in materials with multiple cracks, including bone [15]. Nevertheless, studies have shown that the presence of multiple cracks can alter SIF values at crack tips, either amplifying or minimizing the potential for crack growth which depends on various crack geometry and loading conditions. Such analyses demonstrate the importance of accounting for crack connections when evaluating material safety under complex loading patterns.

Previous research shows that additional cracks in proximity to each other either intensify or reduce the local stress around the crack tip which determines fracture initiation and propagation. Research on this topic primarily deals with uniform materials subjected to tensile (Mode I) loading conditions. Research about natural alveolar bone variations under Mode II loading remains scarce for understanding stress distributions and crack interactions. The heterogeneous nature of alveolar bone makes research complex because it includes cortical and cancellous components that have distinct mechanical properties as well as density levels and microstructural characteristics. Accurate predictions about crack initiation and growth behavior become challenging because of microstructural variability. Crack length together with position and material surrounding the crack has a considerable impact on how stress distributes through the bone matrix.

Therefore, the research objective of this study examines double-edge alveolar bone cracks under Mode II loading specifically regarding the effect of bone heterogeneity on stress intensity factors and crack interaction dynamics. The research develops a 2D finite element model to study stress deformations present in homogeneous (cancellous) along with heterogeneous (cortical-cancellous) bone compositions. The research uses normalized SIF calculation to find essential stress shielding-amplification shift points that advance knowledge of implant-related bone biomechanical fracture conduct. The analysis outcomes from this study will improve implant design parameters along with clinical placement criteria for different bone frameworks.

2.0 MATERIALS & METHODS

This study employs a 2D continuum mechanics model to analyze the behaviour of double-edge cracks in alveolar bone under Mode II loading, aiming to provide insight into the biomechanical interactions between dental implants and bone. By focusing on a

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computationally efficient 2D model, this research captures the essential stress interactions and crack propagation mechanics relevant to implant stability. The approach relies on FEA to simulate SIF and assess crack propagation in both homogeneous and heterogeneous bone structures under controlled loading conditions.

The researchers have modeled the flaws through pre-existing edge-cracks with zero-radius tips for which fracture mechanics approaches including J-integral and contour integral methods can be effectively applied. The analysis treats these geometrically similar notches as cracks according to basic principles of LEFM SIF analysis. The analysis considers these features as cracks due to their sharp geometrical properties and SIF methodology which applies to crack propagation even though some researchers might label them as notches.

2.1 Continuum Mechanics Model Framework

A continuum mechanics model is developed to investigate crack behaviour under Mode II loading. It is a 2D model that enables studying stress interactions at the implant bone interface based on important mechanical behaviours without the need of complicated anatomical detailing. This study utilizes a 3D porous alveolar bone structure although it analyzes Mode II loading through a 2D LEFM model. Various factors support the choice of implementing the 2D methodology. The model provides researchers with an isolated environment to study in-plane shear-induced crack interactions since they are the key investigative field of this research. The model enhances understanding of both stress patterns and crack progression especially how double-edge cracks affect each other during propagation. The model achieves accurate SIF computations with reduced computational cost while maintaining precision. The application of earlier bone mechanics studies supports the use of LEFM models to accurately assess SIF trends and calculate crack interaction behaviors especially when comparing different material heterogeneities and loading conditions [15, 18, 19].

The model consists of a 1 mm x 1 mm sized finite section of alveolar bone including two sharp edge cracks that model possible weak points in bone tissue. The lower crack length was constrained to a/W = 0.125 while the upper crack length was varied between 0.125 and 0.5 as a/W. The specified vertical interval between cracks remained constant at 0.1 mm for interaction effect examination. This type of crack reveals pre-existing flaws instead of blunt notches and follows LEFM theory. Computational fracture studies have previously proven methods which are comparable to this approach. [15]. The method presents shear tensile stress information and Mode II loading effects on crack growth in a 2D structure at reduced computational costs. The technique reduces dental implantological stress-specific behavior yet delivers a cost-effective numerical solution.

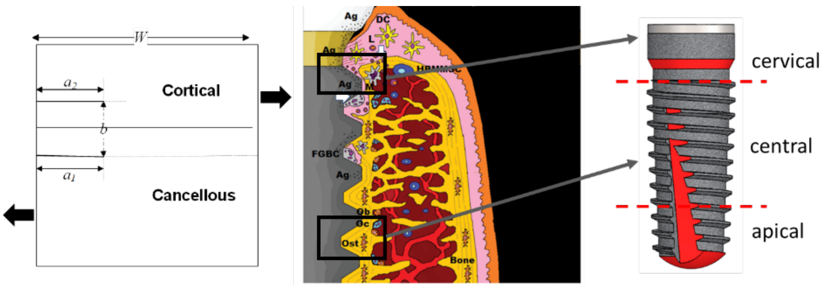

Figure 1: Schematic of potential microcrack interaction in cortical and cancellous regions around dental implants

Figure 1 demonstrates the potential interaction of microcracks in various sections of dental implant studies caused by the implant-bone interaction when subjected to shear load. The cortical bone represents the cervical region, while the cancellous bone represents the

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central and apical regions. This configuration emphasises the significance of material heterogeneity in the distribution of stress and behaviour of cracks.

2.2 Material Properties and Assumptions

The established mechanical properties used for cortical and cancellous bone are used in the continuum model to accurately represent the behaviour of bone under Mode II loading. Table 1 summarizes the properties of cortical bone to be assigned a Young's modulus of 15 GPa, and a Poisson's ratio of 0.3, and those of cancellous bone to have a Young's modulus of 1 GPa, and a Poisson's ratio of 0.25. These values based on standard literature allow a meaningful comparison between homogeneous (cancellous) and heterogeneous (cortical and cancellous) bone structures.

Table 1: Mechanical properties of cortical and cancellous alveolar bone [19]

Mechanical Properties	Cancellous bone	Cortical bone
Young Modulus	1 GPa	15 GPa
Poisson ratio	0.25	0.3
Occlusal load	11 Pa	11 Pa

Specific microstructural characteristics and cancellous bone porosity are excluded, and certain simplifications have been made such as bone being assumed to be a homogeneous and isotropic material. Alveolar bone's trabecular structure and porosity were excluded to create a simplified continuum model. Research by Chakraborty *et al*. [18] indicates that under LEFM assumptions the SIF remains unaffected by material porosity according to their findings. The modification enables better detection of stress amplification and shielding patterns. These features have little impact on the macroscopic mechanical properties and equally little impact on SIFs out of 2D continuum mechanics models. Such an assumption makes it possible to keep the computational error and complexity down in the form of larger scale stress interactions and the mechanics of crack propagation. Furthermore, the current study focuses on macro-level SIF interaction, where the continuum assumption holds valid. Finally, the result is that the continuum mechanics approach captures the leading physical elements of biomechanical behaviour without concomitant microstructural complexity.

The simulation evaluated stress intensity factors under Mode II loading through examination of two different modeled bone structures. Under the homogeneous configuration the entire 2D domain preserved the mechanical characteristics of cancellous bone while providing a simplified version of alveolar structure. A heterogeneous configuration was created to better display the natural multilayered structure which exists in alveolar bone. The model domain contained 0.25 mm cortical bone which overlay the lower 0.75 mm cancellous bone section. The modelled layered structure duplicates how human jaws arrange bone with cortical bone surrounding the cancellous interior throughout their cervical and apical regions. The simplified 2D model creates a biomechanically meaningful framework for studying the effects that material contrast has on crack-related stress distribution and behavior.

The structural analysis using ANSYS included module simulations that applied material data according to different vertical sections. The distinction between cortical and cancellous areas in the domain enables localized material contrast which represents the biomechanical differences seen in clinical cases. The simplified method enables detection of stiffness variations which directly modify the stress conditions near the crack tip.

2.3 Boundary Conditions and Loading Scenarios

To simulate relevant loading conditions, simplified boundary constraints were applied. The lower boundary of the model was fully constrained in all degrees of freedom, representing a stable support base, similar to the mandibular structure that supports an implant in clinical

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scenarios. The model simulates pure shear (Mode II) conditions. The lower boundary was fixed in all directions, while a uniform tangential load of 11 Pa was applied along the upper surface, simulating the average shear force exerted during mastication [19]. This controlled shear load represents typical forces in dental function and highlights the role of Mode II loading in crack propagation. The boundary replication method follows the standards defined in ASTM E1304 and E2472 to ensure unlimited bending or tensile effects. Shear loading performs its isolated analysis of crack propagation in this bone structure design which provides understanding about bone implant performance. The setup duplicates masticatory force shear contacts by following ASTM fracture test Mode II criteria. The system excludes limiting rotational motions coupled with asymmetric loading since these factors could trigger bending effects.

The model's simplified boundary conditions enable focused analysis on shear-induced stress distributions, which are a primary concern in implant stability. Although more complex, multi-directional forces are encountered in vivo, this setup isolates the effect of Mode II loading, yielding targeted insights into the bone's response to shear stress.

2.4 Finite Element Analysis (FEA) and Mesh Convergence

LEFM principles were used to perform FEA using ANSYS. The domain was meshed with quadrilateral PLANE183 elements which are known to be accurate in crack-tip modeling. A mesh sensitivity analysis was done to analyze the sensitivity of SIF values to the mesh density to find out which mesh density gives the most accurate SIF values particularly in the crack tip zone. Several mesh configurations were tested, including local and global refinements, to find the optimal compromise between accuracy and computational efficiency.

Mesh size was varied in the region near the crack tip from 0.002 mm to 0.02 mm producing various element densities in the region. The model was meshed to capture macro level stress distribution and concentrated refinement of it at the crack tip to capture stress concentration accurately. The results of the convergence analysis indicated that optimal mesh size for this study was 0.008 mm (as shown in Figure 2).

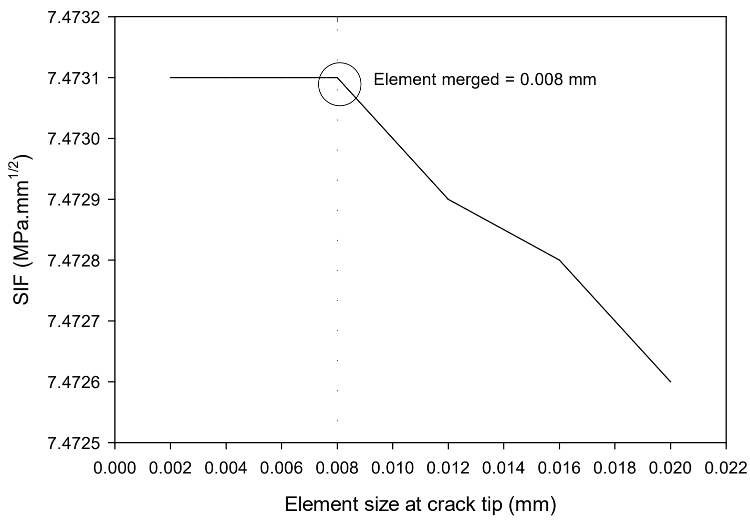

Figure 2: The meshing sensitivity analysis is based on the number of elements near the crack tip

SIF values below this mesh density following a sharp decline, confirming how critical mesh quality can be to model accuracy and the necessity of careful meshing in fracture mechanic's study. This meshing strategy follows established fracture mechanics best practice of having high density mesh close to critical stress points and in less critical

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areas. Guaranteeing a reliable and precise mesh configuration is also key to SIF calculation so that we can get robust insights into stress behaviour necessary to implant stability.

2.5 Stress Intensity Factor (SIF) Analysis and Stress Interaction Evaluation

The lower surface of the model was rigidly clamped in all degrees of freedom, to ensure a simple boundary condition as indicated by Figure 3(a). To obtain accurate results an analysis was done till the value converged as well as taking the element size near the crack tip into consideration. The type of stress intensity factor, SIF, which identifies the stress field at the crack tip and determines crack extension was under consideration. Thus, the SIF values were calculated using the contour integral method given in the ANSYS software. This approach allows for investigating the crack's geometry and stress distribution for Mode II loads in a model resembling the bone tissues when subjected to loading. There are a number of scholars including A.Kumar *et al*. [20] have employed comparable approaches to examine the crack interactions in other materials. Sequently, this approach has been found valid useful in getting more understanding of the complex dynamics of fractures.

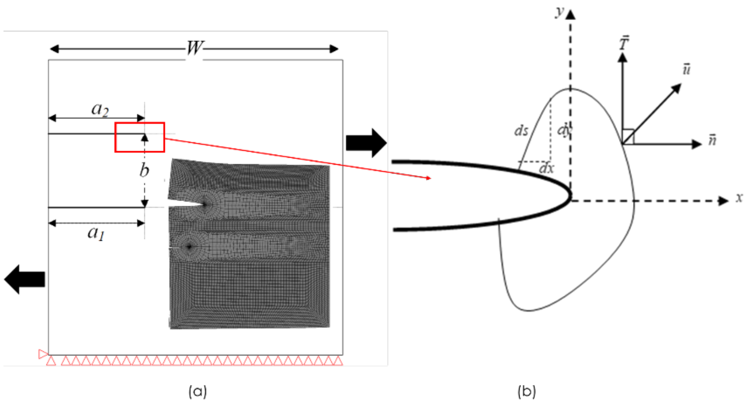

Figure 3: (a) Boundary conditions of the continuum mechanics model (b) Contour path plot used for SIF evaluation at the crack tip

In this model, crack propagation mechanics are understood via the SIFs calculated via the contour integral method in ANSYS. The SIF was quantified using Rice's path independent domain integral approach based on the J integral. The SIF calculation in Equation (1) quantifies the energy release rate at crack tips, the sole crack growth potential measure under shear loading [21].

$$J = \int_{\Gamma} \left(w\,dy - T_i \frac{\partial u_i}{\partial x} ds \right), w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}, \tag{1}$$

where Γ is the arbitrary contour path at the crack tip, w is the strain energy density, T_i is the traction component vectors, u_i is the displacement vectors, ds represents the length increment along the Γ path, σ_{ij} is the stress components, and ε_{ij} is the strain components of the model. The contour path of the integral method can be seen in Figure 3(b). The contour integral method is based on the domain integral approach and is conducted during the solution phase itself.

To investigate the impact of crack orientation on stress behaviour near the crack tip, the upper crack tip was aligned parallel, and different a/W values were adjusted in the numerical model that was created. The stress interaction was evaluated at the upper crack tip (Ct_1) and compared to a reference single-crack model (Ct_{ref}) to assess interaction effects. The findings of the numerical analysis are showcased for mode II loading. The Ct_{ref} is obtained from the single crack model and subsequently compared to the double edge crack model to analyse the amplification and shielding behaviour of the finite element (FE) model. The stress intensity component at the tip of the main crack can be altered by the presence of a microcrack, as explained by Equation (2)-(4). The estimation of stress interaction analysis is based on prior research [15,22]

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$$\frac{SIF_{Ct1}}{SIF_{Ctref}} > 1, \text{ Amplification} \tag{2}$$
$$\frac{SIF_{Ct1}}{SIF_{Ctref}} = 1, \text{ Unification} \tag{3}$$
$$\frac{SIF_{Ct1}}{SIF_{Ctref}} > 1, \text{ Shielding} \tag{4}$$

2.6 Validation and Model Limitations

Such continuum mechanics model does not include validation with experimental data nor detailed anatomical structures, yet it captures the essential biomechanical behaviours. While rooted in established fracture mechanics and continuum principles, this modified approach is limited to theoretical, model-based analysis, with void of in vivo data correlation. However, no experimental validation of a computational model is provided, and the model trends match the prior numerical studies that demonstrated other computational models could accurately replicate fundamentals stress interactions relevant to implantology (within controlled scope) and had the ability to provide meaningful predictive insights [9,15]. The simplicity of the continuum mechanics model strengthens its emphasis on the primary stress behaviour, allowing us to understand Mode II loading better in dental biomechanics.

3.0 RESULTS & DISCUSSIONS

This section discusses the results of SIF analysis under Mode II loading for both homogeneous (cancellous) and heterogeneous (cortical-cancellous) bone materials. The influence of bone heterogeneity on stress shielding and amplification, crack behaviour, and potential implications for dental implant stability is addressed. The results were obtained using a continuum mechanics model and a finite element approach, focusing on crack interactions and their biomechanical implications for implantology.

3.1 SIF Analysis in Homogeneous and Heterogeneous Bone

Examining the SIF analysis revealed major differences in crack behaviour between a homogeneous bone and a heterogeneous bone model during Mode II loading. In the homogeneous (cancellous) model, normalized SIF values exhibit stress shielding at all crack lengths to width ratios (*a/W*), for SIF values between 0.176 to 0.717 as seen in Table 2. Such an environment makes it apparent that cancellous bone is a stable environment to support implants, shielding effect is used to mitigate the possibility of crack propagation [23]. On the other hand, bone resorption may be over time if there is excessive shielding in order to maintain bone density [24].

Conversely, the heterogeneous model showed a change from stress shielding to stress amplification with increasing *a/W*. The SIF values for this model were from 0.053 to 1.205 with an obvious unification at approximately *a/W* = 0.3119 as seen in Figure 4 as normalized SIF reached 1.0. SIF values greater than this threshold were indicative of amplification (a condition in which crack propagation is more likely). It’s consistent with studies that show cortical bone initially acts as a stress shielding effect, and thereafter cracks elongate and this stress shielding effect is diminished, causing stress amplification [17]. The emphasis on the role of material heterogeneity in stress behaviour rightly highlights the initial role of the cortical layer in crack shielding before the cortical layer amplifies stress under prolonged shear.

Table 2: Comparison of stress condition between homogeneous and heterogeneous materials

a/W	SIF, ct_1	SIF, ct_{ref}	SIF, ct_1 /ct_{ref}	S/A
Homogeneous				
0.125	1.031	5.846	0.176	S
0.175	3.452	6.937	0.498	S
0.225	5.096	7.910	0.644	S
0.275	6.195	8.906	0.696	S
0.325	7.128	9.995	0.713	S
0.375	8.063	11.245	0.717	S
0.425	9.084	12.737	0.713	S
0.475	10.277	14.573	0.705	S
0.5	10.968	15.661	0.700	S
Heterogeneous				
0.125	3.902	5.405	0.722	S
0.175	0.334	6.336	0.053	S
0.225	4.251	7.250	0.586	S
0.275	7.578	9.255	0.819	S
0.325	9.884	9.255	1.068	A
0.375	12.539	10.476	1.197	A
0.425	14.395	11.949	1.205	A
0.475	14.395	13.776	1.045	A
0.5	17.199	14.865	1.157	A
S=Shielding, A=Amplification				

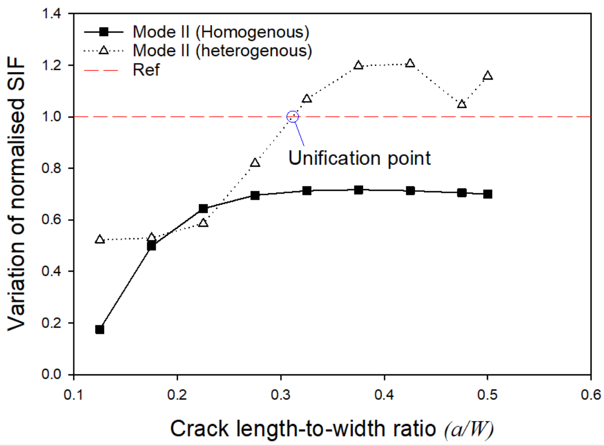

Figure 4: Normalised SIF between homogeneous and heterogeneous alveolar bone towards the increment of crack length to width ratio

3.2 Stress Interaction and Bone Heterogeneity

Stress interaction between double edge cracks in homogeneous and heterogeneous bone models are analyzed and such double edge cracks exhibit distinct behaviour. Both bone types also experienced stress shielding at lower *a/W* ratios, and crack propagation risks are also minimized due to the distributed stress field in cancellous bone [23]. Nevertheless, the SIF values from the heterogeneous model tended to shift from shielding to amplification as the crack length increased, until the stress interaction between cracks resembled the behaviour of a single crack, and SIF values increased significantly.

The transition in this study corresponds to how the cortical layer affects the stress distribution initially dispersing stress and then amplifying with larger crack length. The importance of this behaviour is specifically important for the understanding of how cortical

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bone alters stress environments, as research has shown they are critical in predicting crack propagation under shear loading [25].

3.3 Contour Plot Analysis and Crack Opening Displacement

The contour plots of von Mises stress in homogeneous and heterogeneous models illustrated the different stress responses in each bone type. In homogeneous bone, the crack openings were larger, indicating higher SIF values and an increased likelihood of crack propagation. Conversely, in the heterogeneous model, the cortical layer effectively minimized crack opening displacement at lower *a/W* ratios, supporting the shielding effect. As the crack length increased, however, the opening displacement in heterogeneous bone widened, signifying the shift to stress amplification.

This behaviour aligns with findings in other computational studies, which show that the cortical layer initially limits crack displacement but, at higher stress levels, amplifies stress and promotes crack propagation [26]. The role of cortical bone in controlling crack displacement underscores the importance of material heterogeneity in alveolar bone and highlights its impact on stress behaviour under Mode II loading.

The contour plot comparison between different types of bone materials highlights the differences in their properties. From the Figure 5 - Figure 10, it is evident that the crack opening in the upper crack (found in cortical bone) is smaller in heterogeneous material when compared to homogeneous material. It has been observed that the cortical layer in heterogeneous bone has a significant impact on reducing crack opening displacement, resulting in a shielding effect.

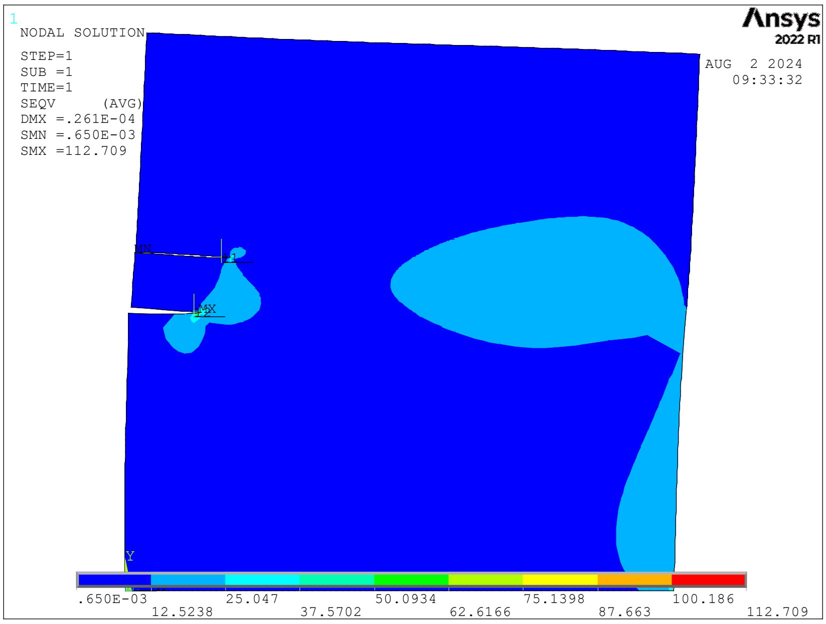

Figure 5: Contour plot of von Mises stress (MPa) in homogeneous, *a/W* = 0.125 mm (shielding stress interaction)

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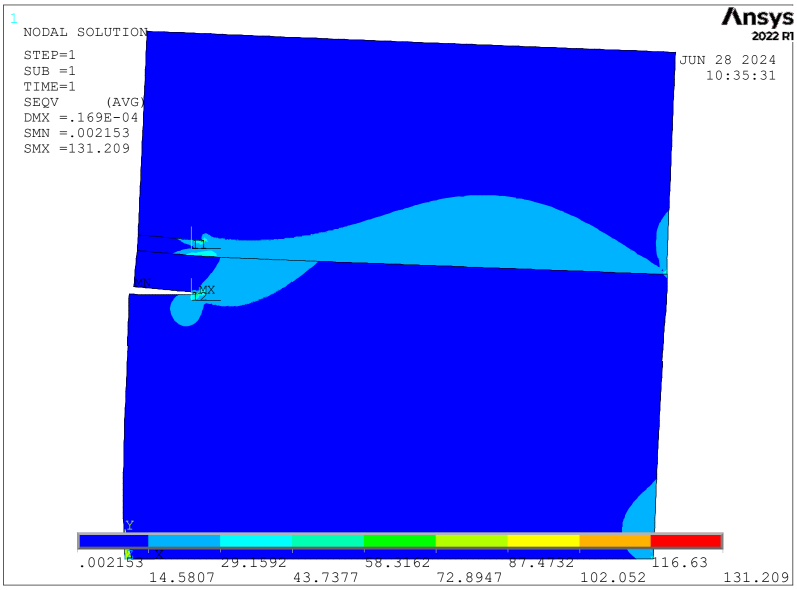

Figure 6: Contour plot of von Mises stress (MPa) in heterogeneous, *a/W* = 0.125 mm (shielding stress interaction)

On the other hand, in homogeneous bone, the crack opening is more noticeable, resulting in higher SIF values and suggesting an increased likelihood of crack propagation. The significance of the cortical layer in stress distribution and crack propagation dynamics is highlighted by this behaviour.

At *a/W* = 0.125 mm as seen in Figure 5 and Figure 6, there is a noticeable stress interaction between the double-edge cracks in both homogeneous and heterogeneous materials. Nevertheless, the crack opening in homogeneous material is slightly larger than in heterogeneous material, which emphasises the initial effectiveness of the cortical layer in limiting crack propagation.

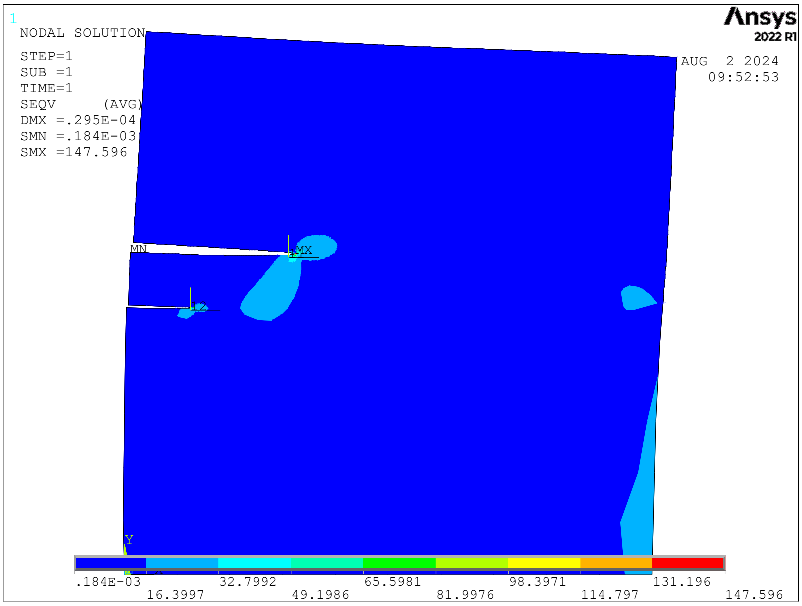

Figure 7: Contour plot of von Mises stress (MPa) in homogeneous, *a/W* = 0.3119 mm (shielding stress interaction)

At *a/W* = 0.3119 mm as seen in Figure 7 and Figure 8 a noticeable disparity is evident. The consistent material demonstrates its effectiveness in providing protection, while the heterogeneous bone material experiences a significant level of stress interaction between the double-edge cracks. In this study, it can be observed that the size of the crack

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opening is larger in homogeneous materials compared to heterogeneous ones. This finding highlights the point at which the presence of the cortical layer in heterogeneous bone starts to have a significant impact on stress distribution.

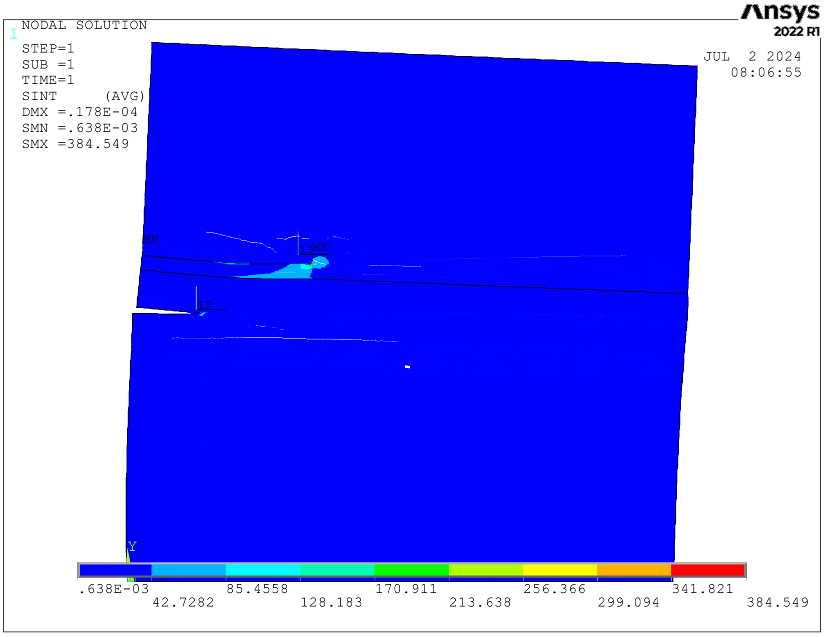

Figure 8: Contour plot of von Mises stress (MPa) in heterogeneous, *a/W* = 0.3119 mm (unification stress interaction)

When the *a/W* = 0.5 mm as seen in Figure 9 and Figure 10, the homogeneous material continues to demonstrate shielding, while the heterogeneous material displays an intensified stress interaction between the double-edge cracks. Crack opening in different types of materials varies significantly, highlighting the crucial role of the cortical layer in preventing crack propagation, even when subjected to higher stress levels. This comparison clearly shows the difference in stress environments between the cortical layer in heterogeneous bone and homogeneous cancellous bone, highlighting the advantage of the former in reducing the risk of excessive crack propagation.

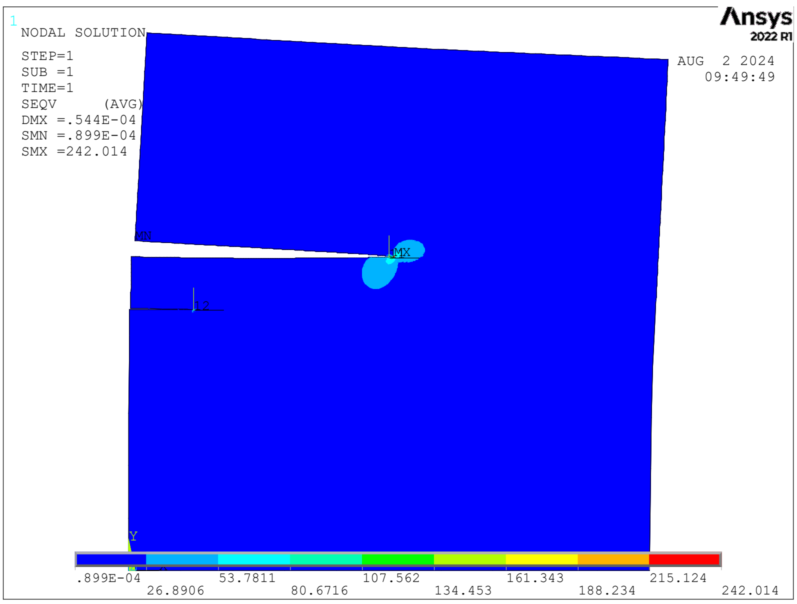

Figure 9: Contour plot of von Mises stress (MPa) in homogeneous, *a/W* = 0.5 mm (shielding stress interaction)

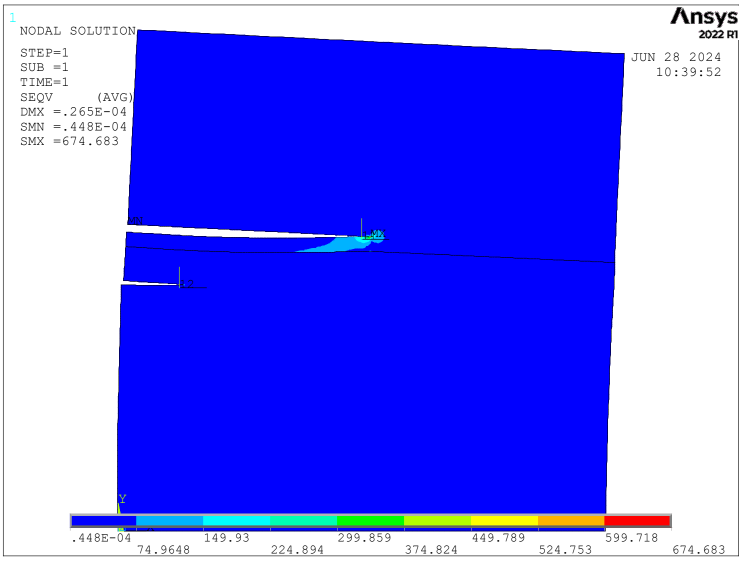

Figure 10: Contour plot of von Mises stress (MPa) in heterogeneous, a/W = 0.5 mm (amplification stress interaction)

The homogeneous model exhibited larger crack openings when compared to the heterogeneous bone material model, as can be observed in the contour plots. At a/W = 0.3119 mm, the crack opening in the upper crack is greater in size when compared to a/W = 0.125 mm. As the width increases to 0.5 mm, the crack opening expands further. Nevertheless, the observed trend persists, with the uniform crack opening being greater in magnitude when compared to the non-uniform bone material. The disparity in crack openings can be ascribed to the diverse material characteristics in the heterogeneous model, resulting in distinct stress distribution patterns.

This study highlights the importance of bone material heterogeneity in influencing crack behaviour during Mode II loading. The shift from shielding to amplification in the diverse bone indicates that although the cortical layer initially disperses stress to offer protection, it also presents a potential for crack propagation once the unification point is exceeded. This emphasises the contrasting impact of the cortical layer's influence: it serves as a safeguard in the cervical region but can pose a risk if stress conditions surpass specific thresholds.

The findings of this study have significant implications for research in dental implantology. The results suggest that due to the uniform shielding effect of the homogeneous cancellous bone, it will be easy to guarantee the implant stability. However, what is seen here is a change in roles of the heterogeneous bone from shielding to amplification, stressing the need for one to make a proper assessment and incorporate ideal stress controlling measures. This is particularly important in the cervical region where cortical layer has been identified. Understanding of these factors can be used to decide on the orientation and placement of dental implants where cracks are not likely to propagate and lead to implant failure.

Comparing these findings with the previous literature, we can again conclude that the cortical layer is critical for stress distribution, which matches the prior knowledge [27]. However, the transition analysis in heterogeneous bone from shielding to amplification is informative to understand the complex response of bone in stress which has not been reported significantly. This new knowledge underlines the importance of accounting for the variation of the bone material density in biomechanical studies and in implant development.

3.4 Clinical Implications for Dental Implants

Practical implications of these findings include their role in the design and placement of dental implants. Instead, homogeneous cancellous bone demonstrates consistent stress shielding suggesting implants placed preferentially on cancellous bone will be under more stable mechanical environments except for the increased risk of crack propagation. The

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deviations from shielding to amplification, especially at larger crack lengths, in the heterogeneous bone model point to the pitfalls associated with cortical rich areas. This implies that implant placement should take the bone type and distribution into consideration when implanting to reduce the risk of stress amplification, particularly in cortical areas [7]. Therefore, implant placement in cortically-dominant areas must incorporate regular monitoring or proper load management systems to lower the risk of instability which can stem from fracture formation.

All these insights are clinically relevant and support the need for implant designs that minimize shear forces, especially at the cortical bone. Improved stress distribution within cortical regions would help mitigate the associated risks of stress amplification, and implant materials or configurations that optimize stress distribution could lengthen implant longevity. Clinicians may also wish to monitor crack development in high risk cortical regions, where acoustic amplification may lead to instability of the implant [10].

3.5 Stress Shielding to Amplification Transition: Mechanistic Insights

The observed transition from stress shielding to amplification in this heterogeneous bone model demonstrates the dual role of the cortical layer in stress dynamics. First, dispersal of the cortical layer prevents crack propagation. Despite this, in the case where the crack length exceeds a critical threshold, the cortical layer acts as a stress shielded, reduces amplification of the stress throughout it, and decreases the risk of fracture at the interface with the implant [14]. This shift emphasizes the relevance of characterizing bone heterogeneity for dental implantology since material differences influence crack behaviour under load.

This mechanistic insight agrees with continuum mechanics principles that demonstrate that even the most simplified 2D models can capture the most important stress interactions for real world applications. This study identifies when stress shielding is expected to transition to amplification to provide a theoretical basis for developing more rational implant designs and placement strategies, particularly for implants within complex bone composition.

4.0 CONCLUSION

A detailed analysis of stress interactions and crack propagation of alveolar bone with double edge crack subjected to Mode II loading is presented and its bone material heterogeneity is examined in this study. The research shows that the behaviour of SIF between homogeneous (cancellous) and heterogeneous (cortical-cancellous) bone is dramatically different in a finite element model, and that the material composition is critical to shielding and amplification of a crack.

These findings reinforce the idea that homogeneous cancellous bone can offer stable shielding effects and SIF values normalized below unity, thus possibly contributing to implant stability with limited crack propagation risk. Excessive shielding, however, could cause bone resorption in time due to a lack of mechanical stress that is required for normal bone remodeling. In contrast, shielding shifted from amplification to a sharply increased risk of crack propagation in the heterogeneous model at a critical transition point at a/W = 0.3119. This transition signifies the dual role of the cortical layer in heterogeneous bone: Dispersing stress initially makes it protective, but later amplifies stress when thresholds are exceeded and is a threat to implant longevity in clinical scenarios.

Clinically, these findings suggest that implant placement strategies should consider the type and distribution of bone tissue. Implants placed in cancellous-dominant regions may benefit from stable stress shielding, whereas in cortical-rich regions, careful monitoring is required to prevent stress amplification and potential crack propagation. Additionally, implant designs that minimize shear forces in cortical areas could help reduce

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stress amplification risks, thereby enhancing implant stability and patient outcomes. The insights gained here can inform clinicians about optimal placement zones and implant configurations that accommodate bone heterogeneity.

Combining this new material characterization capability and crack behaviour in heterogeneous bone under Mode II loading, this research provides new insights into crack behaviour in heterogeneous alveolar bone under Mode II loading, an area which has been almost overlooked in earlier studies. A novel contribution of this study is the identification of a specific transition point from stress shielding to amplification in cortical–cancellous alveolar bone surrounding implants. Together, these two behaviours driven by the bone heterogeneity give a more nuanced view of the process of implant-bone interactions and cortical layer role, untraced in the previous models that, predominantly, only considered homogeneous bone.

Ultimately, these findings ought to be validated experimentally, and more detailed models of stress interaction with the bone microstructure and porosity ought to be explored. This knowledge can be extended to improve implant design and placement strategies, enhance clinical performance and ultimately, dental implants will benefit from increased efficacy, stability and overall longevity.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

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