# Continuum Damage Modeling of Biaxial Fatigue Failure in Whole Bone: Influence of Anisotropy on Experimental Agreement

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## Summary

The mechanical fatigue behavior of whole bone is key to understanding stress fractures. This study compared experimental measurements of biaxial fatigue failure in rabbit tibiae, to continuum damage models using isotropic verses anisotropic material properties. Experimental data and anisotropic models illustrated a notable decrease in fatigue-life with higher levels of torsion ($p < 0.05$), whereas isotropic models showed no significant variation to loading conditions. The anisotropic approach accounted for 76% of the experimental variability, outperforming the 39% explained by isotropy. These findings highlight the importance of considering anisotropic material properties to improve fatigue failure predictions of whole bone in biaxial loading scenarios.

## Introduction

Fatigue failure in whole bone, caused by repetitive mechanical loading, is critical to understanding the development of stress fractures and their prevention[1]. We have developed a finite element (FE)-based continuum damage model to simulate fatigue loading and failure in rabbit tibiae[2]. This study compared experimental measurements of biaxial fatigue failure in rabbit tibiae, to continuum damage models using isotropic versus anisotropic material properties.

## Methods

Twenty-one rabbit tibiae were previously tested under cyclic biaxial loading until failure: 0% (n = 10), 25% (n = 6), and 50% (n = 5) of ultimate torsion (3.4 Nm) superposed on 50% of ultimate axial compression (2500 N) at 2 Hz[3]. FE models were generated from CT scans, meshed (~70,000 elements), and assigned axial elastic moduli ($E_3$) based on local density. Isotropic FE models were described by $E_3$ only and a Poisson's ratio of $\nu=0.3$. Anisotropy was defined as $E_1=0.574\times E_3$, $E_2=0.577\times E_3$, $G_{12}=0.195\times E_3$, $G_{23}=0.265\times E_3$, $G_{31}=0.216\ E_3$, $\nu_{12}=0.427$, $\nu_{23}=0.234$, and $\nu_{31}=0.405$[4]. Here, subscripts 1 and 2 denote the medial and anterior directions, respectively. Continuum damage models of rabbit tibiae (Dimnik et. al[2]) were implemented in a user material subroutine (UMAT) in Abaqus. The model used von Mises equivalent strains to calculate the damage rate [5], leading to elastic modulus degradation. A 25% reduction in whole-bone stiffness was assumed as the failure criterion. Statistical differences between loading groups were analyzed using the Kruskal-Wallis test, subsequent to a Shapiro-Wilk test for normality.

## Results and Discussion

Both experimental data and anisotropic FE models showed a significant reduction in fatigue-life with increasing superposed torsion ($p < 0.05$), while isotropic FE models showed no significant differences among groups. Anisotropy explained 76% of the experimental variation compared to 39% for isotropy. Both models showed consistent fracture locations with the experiment. In pure compression, the fracture occurred at the proximal end, while with superposed torsion, the fracture occurred more distally. Both models overpredicted fatigue-life, highlighting the need for further calibration of the damage model.

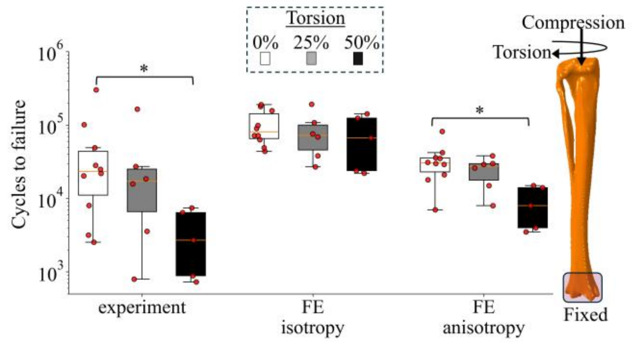


**Figure 1**: Fatigue-life of whole rabbit tibiae under 0%, 25%, and 50% of ultimate torsion (3.4 Nm) superposed on 50% of ultimate axial compression (2500 N).

## Conclusions

FE-based continuum damage models of whole bone with anisotropic material properties demonstrated enhanced precision in replicating experimental biaxial fatigue-life measurements when compared to isotropic models. These findings emphasize the importance of incorporating anisotropy into simulations of whole-bone biaxial fatigue failure, which is relevant to *vivo* loading conditions.

## Acknowledgments

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## References

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