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# MODELING BRITTLE FRACTURE IN BONE CEMENT: COMPARATIVE STUDY OF XFEM AND PROGRESSIVE DAMAGE APPROACHES FOR ORTHOPEDIC DESIGN

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**Abstract**

This study presents a detailed numerical investigation into the fracture behavior of bone cement (PMMA) under uniaxial tensile loading, employing two advanced simulation methodologies: the Extended Finite Element Method (XFEM) and a progressive damage model implemented via the USDFLD user subroutine in Abaqus. Both modelling approaches were rigorously calibrated and validated against experimental tensile tests conducted on standardized PMMA specimens. The analysis primarily focused on predicting crack initiation, propagation pathways, and the material's overall stress–strain response. The findings demonstrate that XFEM delivers superior accuracy in predicting crack initiation sites and propagation directions, largely independent of mesh orientation, making it particularly effective for simulating discrete fracture events. Conversely, the progressive damage model offers a continuous depiction of material degradation, though it necessitates mesh sensitivity analysis and meticulous parameter calibration to ensure accuracy. Through this comparative analysis, the study elucidates the respective advantages and limitations of each modelling technique and underscores their potential in simulating fracture behavior in orthopedic cement applications. The outcomes contribute to the advancement of reliable computational tools for evaluating the mechanical integrity of cemented prostheses and inform the design optimization of future implant systems.

**Index Terms:** Otal Hip Arthroplasty, XFEM, Progressive Damage Modelling, Finite Element Analysis, Tensile Fracture.

## 1. INTRODUCTION

Total hip arthroplasty (THA) remains one of the most widely performed and clinically effective surgical procedures in modern orthopedics, significantly improving the quality of life for patients suffering from degenerative joint diseases such as osteoarthritis, rheumatoid arthritis, and complex femoral head fractures.

While the long-term clinical outcomes of hip prostheses have been largely satisfactory, implant longevity continues to be challenged by mechanical failures—especially in

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cemented prostheses, where the cement-implant interface is often identified as a structural weak point [1]. Polymethylmethacrylate (PMMA) is the most commonly used bone cement in cemented THA due to its favorable characteristics, including biocompatibility, radiopacity, and ease of intraoperative handling. However, PMMA is also well known for its quasi-brittle mechanical behavior: it lacks significant plastic deformation before failure and is highly sensitive to internal imperfections such as porosities and microcavities introduced during mixing or curing.

These defects serve as stress concentrators and promote crack initiation under physiological loading conditions [2], [3]. Clinical observations and experimental studies have consistently shown that the proximal region of the cement mantle—where the femoral stem transfers the highest mechanical loads—is particularly susceptible to damage. During activities of daily living (ADLs) such as walking, stair climbing, and sit-to-stand transitions, cyclic loads induce stress fluctuations that can lead to crack propagation, cement degradation, and ultimately, aseptic loosening of the implant [4], [5], [6]. To investigate and predict these failure mechanisms, computational modelling has become an indispensable tool.

The finite element method (FEM) has long been established in biomechanical engineering for analyzing complex structures, including hip prostheses. Early FEM models treated the cement mantle as a linear-elastic, homogeneous material, omitting the critical role of crack evolution. However, more recent studies have emphasized the importance of explicitly incorporating fracture mechanisms into the modelling framework to capture the actual in vivo response of PMMA under various loading conditions [7], [8].

In this context, two advanced numerical techniques have emerged as promising approaches for simulating crack formation and progression in PMMA. The first, the Extended Finite Element Method (XFEM), allows for the modelling of discontinuities such as cracks independently of the mesh. By incorporating enrichment functions and fracture criteria based on stress intensity factors (SIFs), XFEM has demonstrated a strong ability to predict arbitrary crack initiation and propagation paths in brittle and quasi-brittle media [9], [10].

The second approach involves progressive damage modelling, which is grounded in the theory of continuum damage mechanics. This method introduces evolving internal variables to represent material degradation under increasing mechanical load. Implemented in finite element codes such as Abaqus through user-defined subroutines (e.g., USDFLD), this framework enables the simulation of stiffness degradation, softening behavior, and eventual failure of PMMA. While this approach requires careful calibration and is sensitive to mesh refinement, it provides a powerful tool for simulating diffuse damage phenomena observed in experimental setups [3], [2].

In addition to mechanical degradation, the presence of residual stresses resulting from the exothermic polymerization of PMMA has been recognized as a significant contributor to early damage. These stresses whether tensile or compressive superimpose on the

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functional loads transmitted through the prosthesis and modify the stress field within the cement mantle. Studies have confirmed that these residual effects, especially in the proximal cement region, may substantially accelerate crack initiation and material failure [8]. Moreover, the type of external loading static versus dynamic—plays a critical role in the progression of damage. Simulations mimicking gait cycles and other dynamic loading conditions have revealed elevated stress peaks at the bone-cement and cement-stem interfaces compared to static loading. These findings underscore the need for simulation frameworks that incorporate loading histories and fatigue effects to assess long-term prosthesis performance accurately [5], [6].

Total hip arthroplasty (THA) has revolutionized the treatment of severe hip joint disorders, offering substantial improvements in patient mobility and quality of life. Among the fixation methods employed, cemented prostheses remain widely utilized due to their intraoperative versatility and immediate load-bearing capabilities.

Polymethylmethacrylate (PMMA) bone cement plays a critical role in ensuring mechanical stability between the femoral stem and the surrounding bone [7]. However, despite its favorable biocompatibility and handling properties, PMMA is characterized by a quasi-brittle mechanical behavior, with limited plasticity and pronounced sensitivity to microstructural defects such as pores and inclusions introduced during mixing or polymerization [8], [9].

The structural failure of the cement mantle remains a major cause of aseptic loosening and revision surgeries in cemented THA [9]. Clinical studies and retrieval analyses have consistently shown that cracks often initiate at pre-existing defects or near stress concentration zones, particularly in the proximal cement mantle subjected to complex loading [10], [11]. Consequently, there is a pressing need to develop robust computational models capable of accurately simulating the crack initiation and propagation mechanisms within PMMA under physiological loading conditions. Traditional finite element models of bone cement primarily treated it as a homogeneous, linear-elastic material, neglecting critical aspects of fracture behavior.

However, modern approaches increasingly emphasize the need to model discontinuities explicitly to replicate in vivo damage progression. Among the advanced methods, the Extended Finite Element Method (XFEM) has emerged as a powerful tool, allowing for the simulation of arbitrary crack initiation and growth independent of the mesh topology [11]. XFEM leverages enrichment functions based on asymptotic crack-tip fields to represent discontinuities, providing significant advantages in simulating brittle fracture in heterogeneous materials like PMMA [8]. In parallel, progressive damage, models based on continuum damage mechanics have been widely explored.

These models introduce internal variables that evolve with mechanical loading, representing material degradation and enabling simulation of stiffness loss, strain softening, and eventual failure [9]. While progressive damage frameworks, implemented for instance via user subroutines like USDFLD in Abaqus, offer computational efficiency,

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they are inherently sensitive to mesh discretization and damage localization phenomena [10].

Recent developments have further extended modeling capabilities. Phase-field models offer a diffuse representation of crack surfaces, naturally regularizing the solution and capturing complex crack patterns without requiring ad hoc tracking techniques [11]. Nonlocal and gradient-enhanced damage theories have also been introduced to mitigate mesh dependency, improving numerical stability and physical realism in damage evolution predictions [12]. For biomedical polymers like PMMA, recent studies have emphasized the importance of coupling accurate material characterization with advanced numerical techniques.

Xu et al. [1] demonstrated the capability of XFEM in predicting crack paths in biomedical-grade polymers under dynamic loading conditions. Similarly, Patel et al. [2] proposed a progressive damage approach accounting for nonlocal effects to better represent fracture initiation in bone cements. Despite these advances, significant challenges remain. Predicting the onset of fracture, accurately capturing the transition from microcracks nucleation to macroscopic crack propagation, and modeling fatigue-induced damage accumulation in PMMA require further refinement of existing models. Moreover, environmental factors such as humidity and thermal stresses generated during polymerization can exacerbate damage mechanisms, influencing long-term mechanical performance [13], [14].

The present study aims to perform a comparative analysis of two advanced numerical approaches XFEM and progressive damage modeling—in simulating the tensile fracture behavior of PMMA. Both methods are calibrated and validated against experimental uniaxial tensile tests on standard PMMA specimens. The comparative evaluation focuses on key metrics including stress strain correlation, crack path accuracy, mesh sensitivity, computational cost, and predictive fidelity of fracture mechanisms. By identifying the strengths and limitations of each approach, this study contributes to the development of more reliable computational frameworks for simulating cement mantle failure in orthopedic applications and beyond.

## 2. MATERIALS AND METHODS

### 2.1. Specimen Preparation and Testing Protocol

Standardized tensile specimens were fabricated from commercially available (PMMA) resin, following ISO 527-2 Type 1A geometries to ensure consistency and reproducibility. The PMMA material was thermally polymerized under controlled laboratory conditions to minimize residual stresses and internal defects. Special care was taken during the mixing and molding processes to avoid the introduction of air bubbles, which could act as crack initiation sites during mechanical testing (Figure 1).

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**Figure 1: Geometry and dimensions of the ISO 527 PMMA specimen**

Specimens were visually inspected for surface defects and measured using a digital micrometer to verify dimensional tolerances according to ISO standards. Only specimens exhibiting no visible imperfections and within ±1% of nominal dimensions were retained for mechanical testing.

Tensile tests were performed using a ZwickRoell Z020 universal testing machine equipped with 05 kN high-precision load cell. The crosshead displacement rate was set at 1 mm/min to replicate quasi-static loading conditions and minimize strain rate effects on the fracture behavior. Axial displacement and strain evolution were measured using a clip-on extensometer positioned across the gauge length, ensuring accurate strain capture up to specimen failure (Figure 2).

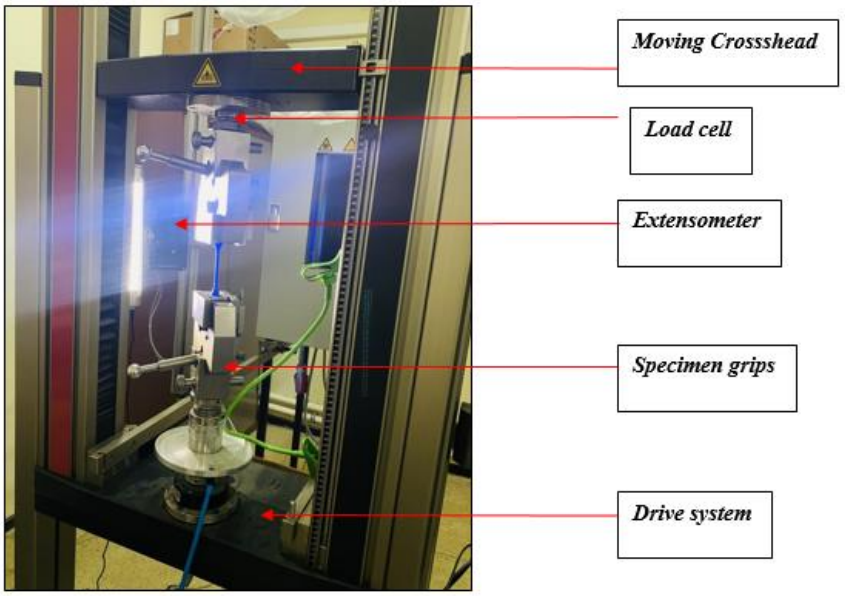


**Figure 2: Schematic diagram of the tensile test setup (ZwickRoell Z20)**

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Each specimen aligned carefully within self-centering grips to avoid the introduction of bending moments or shear stresses. Mechanical tests were conducted at ambient laboratory conditions (23 ± 2°C; 50 ± 5% relative humidity). A minimum of three valid specimens were tested to capture experimental variability and assess the repeatability of the results. Real-time data acquisition of load and displacement was performed using TestXpert II software, enabling high-fidelity recording of the stress–strain response (Figure 3).

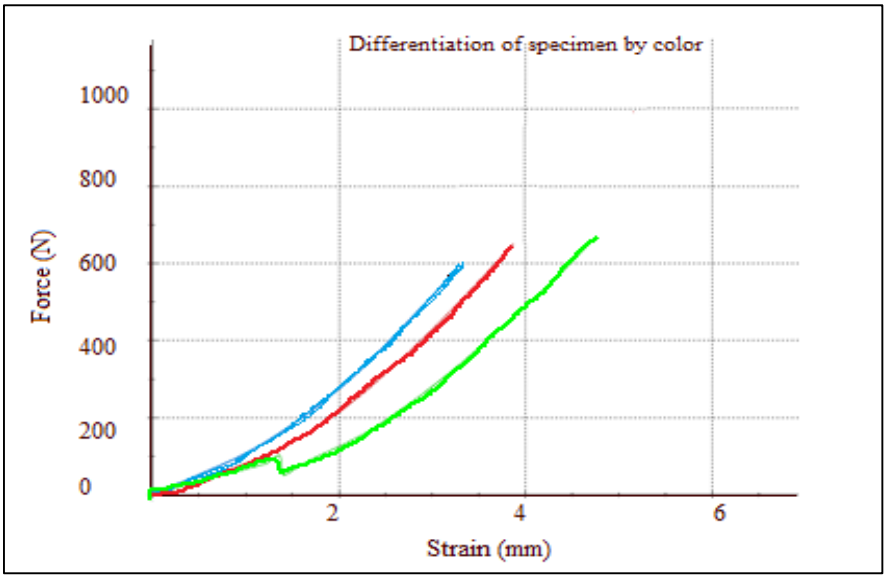


**Figure 3: Experimental stress–strain curves for the three PMMA specimens**

Additionally, digital image correlation (DIC) techniques employed to monitor local strain fields and detect early damage localization phenomena. Specimens were speckled with a stochastic black-and-white paint pattern to enable accurate DIC measurements throughout the loading process, providing supplementary insight into deformation and fracture behavior beyond extensometer readings.

### 2.2. Finite Element Modeling Overview

The finite element analyses conducted using Abaqus/Standard. Two distinct simulation strategies were implemented: (1) XFEM with cohesive segment modeling, (2) progressive damage modeling via a user-defined field variable (USDFLD). A 3D model of the specimen was developed, and the mechanical response was analyzed under the same boundary conditions and displacement rate as the experiments.

The model utilized C3D8R elements (8-node linear brick elements with reduced integration and hourglass control). The mesh consisted of 47,520 elements with refinement near the expected crack path. Boundary conditions were defined to replicate the experimental test setup, with one end of the specimen fixed and the opposite subjected to a prescribed displacement in the loading direction (Figure 4).

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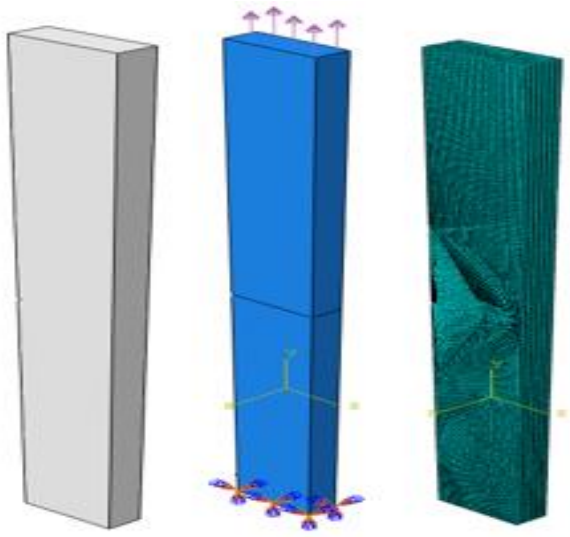

**Figure 4: 3D mesh of the specimen (47,520 C3D8R elements) and boundary conditions**

### 2.3. XFEM Implementation

The material parameters used in the numerical simulations were directly calibrated from experimental uniaxial tensile tests conducted on bone cement specimens. The initial elastic modulus (E_0) was determined to be approximately 23800 MPa, based on the linear slope of the stress–strain curves within the elastic regime. The maximum tensile stress ($\sigma_{max}$) was observed to range between 23 MPa and 24 MPa across the specimens, while the corresponding fracture strain ($\varepsilon_f$) was approximately 1.0% (($\varepsilon_f$=0.010).

For the XFEM implementation, crack initiation was controlled by a maximum principal strain criterion with a critical threshold set at 0.2% strain ($\varepsilon_0$=0.002), calibrated from the point where the experimental stress–strain curves deviated from linearity. The traction-separation law parameters, including the maximum traction and the fracture energy ($G_f$), were set to match the experimentally observed peak stress and estimated energy dissipation during fracture, with approximated at 120 J/m².

In the progressive damage model implemented via USDFLD, the degradation of stiffness was governed by a linear damage evolution law between the same critical strain thresholds: damage initiation at $\varepsilon_0$=0.002 and complete failure at $\varepsilon_f$=0.010. This approach allowed the progressive damage model to replicate the gradual stiffness reduction leading to final fracture observed experimentally, albeit in a smeared manner compared to the sharp fracture captured by XFEM.

### 2.4. Progressive Damage Modeling via USDFLD

A progressive damage model implemented in Abaqus/Standard using the user subroutine USDFLD to simulate the degradation of the mechanical properties of PMMA under uniaxial tensile loading. The damage mechanism was assumed to be driven primarily by

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the accumulation of tensile strain, consistent with the brittle and quasi-brittle fracture behavior observed experimentally.

The damage variable $D \in [0,1]$ was introduced as a scalar field variable controlling the progressive reduction of the effective Young's modulus according to the relation:

$$E_{\text{eff}} = E_0(1 - D) \qquad (1)$$

Where:

$E_{\text{eff}}$ is the degraded elastic modulus,

$E_0$ is the initial undamaged Young's modulus (2380 MPa),

$D$ represents the material damage.

Damage initiation was defined based on a critical equivalent tensile strain threshold $\varepsilon_0$, with subsequent linear damage evolution up to a final fracture strain $\varepsilon_f$, at which complete material failure was assumed.

The parameters used for the damage model were calibrated as follows:

Initial elastic modulus: $E_0 = 2380$ MPa

Damage initiation strain: $\varepsilon_0 = 0.002$ (2.0% strain).

Fracture strain: $\varepsilon_f = 0.010$ (1.0% strain).

The evolution of the damage variable $D$ as a function of the equivalent strain was defined by:

$$D = \frac{\varepsilon_{eq} - \varepsilon_0}{\varepsilon_f - \varepsilon_0}, \qquad \text{for} \varepsilon_{eq} \geq \varepsilon_0 \qquad (2)$$

Outside this range:

For $\varepsilon_{eq} < \varepsilon_0$, the material remains intact ($D = 0$)

For $\varepsilon_{eq} \geq \varepsilon_f$, the material is considered completely fractured ($D = 1$)

This linear degradation law allowed a progressive reduction of stiffness during loading, simulating the accumulation of micro-damage until macroscopic fracture occurred. The field variable $D$ was updated at each increment within USDFLD based on the current equivalent strain, and subsequently used to modify the elastic properties via the material definition in Abaqus.

Although this approach does not explicitly represent discrete crack surfaces, it enables an efficient and computationally tractable simulation of material degradation, which is suitable for capturing the global mechanical response of PMMA under tensile loading. However, as discussed later, this model has intrinsic limitations in representing sharp, localized fracture events, and therefore may not fully replicate the abrupt brittle failure modes observed experimentally.

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### 2.5. Model Calibration and Validation

Both XFEM and damage model parameters were calibrated against the experimental stress–strain curves. Validation was performed by comparing:

Mesh convergence studies were conducted to ensure numerical stability, and the models were verified to be insensitive to element size in the crack propagation region.

## 3. RESULTS

This section presents the experimental and numerical results obtained from tensile tests and corresponding simulations using XFEM and progressive damage modeling. The comparison focuses on global mechanical response, fracture onset and evolution, and agreement with observed failure modes.

### 3.1 Quantitative Comparison

**Table 1: Quantitative comparison of experimental, XFEM, and damage model results**

| Model | Stress Prediction | Strain at Failure | Fracture Mode | Post-Peak Behavior | Suitability |
|---|---|---|---|---|---|
| **Experimental (Avg)** | ~23.4 MPa (mean) | ~0.010 | Abrupt, localized fracture | Sudden stress drop | Validation baseline |
| **XFEM** | Slightly overestimated (~24 MPa) | ~0.009 | Localized, sharp crack | Sudden drop captured | High-fidelity fracture prediction |
| **Damage Model** | Slightly overestimated (~25.5 MPa) | ~0.012 | Diffuse damage zone | Gradual softening | Efficient for global degradation trends |

The comparative analysis between experimental results, XFEM simulations, and progressive damage model simulations provides valuable insights into the predictive capabilities and limitations of each approach.

The experimental data, serving as the validation baseline, confirmed the quasi-brittle behavior of PMMA bone cement, characterized by a high initial stiffness, a peak tensile strength of approximately 23.4 MPa, and a very low failure strain (~0.010). The mechanical response exhibited a sharp, sudden stress drop post-peak, indicating catastrophic and localized fracture with minimal plastic deformation.

The XFEM simulation closely replicated the experimental behavior. It slightly overestimated the peak stress (~24 MPa) but maintained an excellent match in predicting the abrupt transition from elastic behavior to complete failure. The fracture was highly localized, consistent with experimental observations, and the post-peak behavior was accurately captured as a sudden loss of mechanical integrity. This reinforces XFEM's suitability for modeling materials where discrete, sharp crack propagation is the dominant failure mode, and where mesh independence is critical for simulating complex crack paths.

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In contrast, the progressive damage model, while also slightly overestimating the maximum stress (~25.5 MPa), predicted a more ductile response with an extended strain at failure (~0.012). The damage field evolution revealed a broader, more diffuse damage zone rather than a discrete crack. Consequently, the post-peak softening was gradual rather than abrupt. Although this model does not faithfully reproduce the localized, catastrophic fracture observed experimentally, it remains valuable for capturing the global trend of material degradation and stiffness reduction, especially in simulations where computational efficiency outweighs the need for detailed fracture morphology.

Overall, XFEM is identified as the most accurate approach for simulating brittle fracture in PMMA, particularly for applications requiring precise failure localization, such as in orthopedic implant reliability studies. Conversely, the progressive damage model is better suited for large-scale analyses where an approximate but computationally efficient prediction of material degradation is sufficient. The experimental results emphasize the necessity of selecting the appropriate modeling approach based on the specific requirements of the simulation—precision versus computational cost.

### 3.2 Model Validation Summary

- XFEM provided the most faithful replication of brittle fracture, accurately reproducing crack initiation timing, orientation, and propagation speed.
- The damage model offered qualitative insight into progressive stiffness loss but failed to localize the fracture sharply and exhibited deviations in post-peak behavior.

Visual comparisons (Figure. 5) highlight the differences in crack morphology between the two numerical methods and their alignment with experimentally observed fracture surfaces.

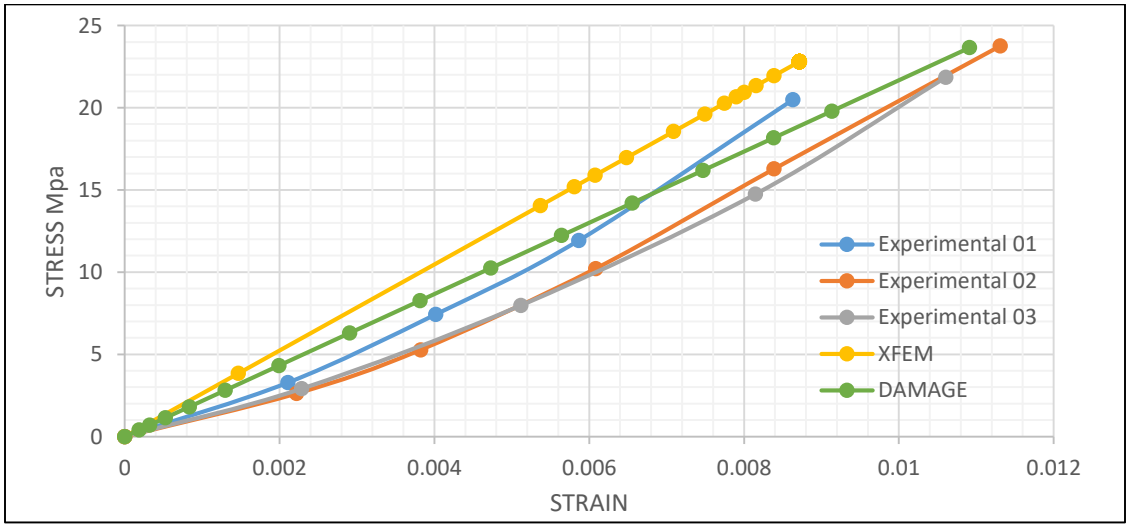


**Figure 5: Comparison of simulated vs experimental stress–strain curves**

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The stress–strain curves obtained from the experimental tensile tests and the numerical simulations (XFEM and DAMAGE models) provide valuable insights into the fracture behavior of PMMA bone cement under uniaxial loading. All experimental curves exhibit a characteristic brittle response with a near-linear elastic region followed by an abrupt drop in stress, indicating catastrophic failure. Numerical results, while capturing the general trend, exhibit differences in both stiffness and failure stress, reflecting the limitations inherent to each modeling approach. The three experimental replicates (Experimental 01, 02, and 03) demonstrate a relatively low degree of scatter, confirming the reproducibility of the material behavior under tensile loading. Slight variations in ultimate stress and strain at failure are observed, which can be attributed to material heterogeneity, defects, or minor inconsistencies in specimen preparation and alignment. Nonetheless, the overall mechanical response, characterized by a high modulus of elasticity and low ductility, remains consistent across samples, validating the experimental procedure. Comparing the XFEM simulation to the experimental results, the model accurately predicts the initial stiffness, as evidenced by the slope of the stress–strain curve. However, the XFEM simulation slightly overestimates the peak tensile strength relative to the experimental mean value. Moreover, the failure strain predicted by XFEM is marginally higher, suggesting that crack initiation occurs later in the simulation than observed experimentally. This discrepancy could stem from the predefined cohesive parameters used in the XFEM implementation, which may not fully replicate the local material flaws or porosity influencing early crack initiation in the real material.

The DAMAGE model, implemented via the USDFLD subroutine, provides a closer match to the experimental peak stress but underestimates the initial stiffness compared to both experiments and XFEM. The progressive damage evolution captured by this model results in a more gradual post-peak softening behavior, contrasting with the abrupt stress drop observed experimentally. This difference suggests that while the DAMAGE model effectively simulates the strength degradation, it may overly smooth the transition from elastic behavior to failure due to its underlying damage accumulation laws and regularization techniques. In critically comparing both modeling strategies, XFEM shows superiority in capturing the elastic behavior and the sharp transition to failure, aligning better with the brittle nature of PMMA. However, it tends to predict a delayed failure onset, possibly due to idealized cohesive zone assumptions. Conversely, the DAMAGE model provides a realistic ultimate stress prediction but fails to replicate the abrupt fracture characteristics, indicating a limitation in capturing the highly localized damage mechanisms intrinsic to brittle polymers.

The shape of the stress–strain curves further reveals insights into the failure mechanisms. Experimentally, the abrupt stress drop suggests a single dominant crack rapidly propagating through the specimen. XFEM captures this mechanism qualitatively, as evidenced by the sudden decrease in stress. The DAMAGE model, by contrast, suggests a more distributed damage evolution, inconsistent with the experimentally observed brittle fracture but potentially reflective of more ductile damage mechanisms if different polymers were modeled. Several factors could explain the discrepancies between numerical and

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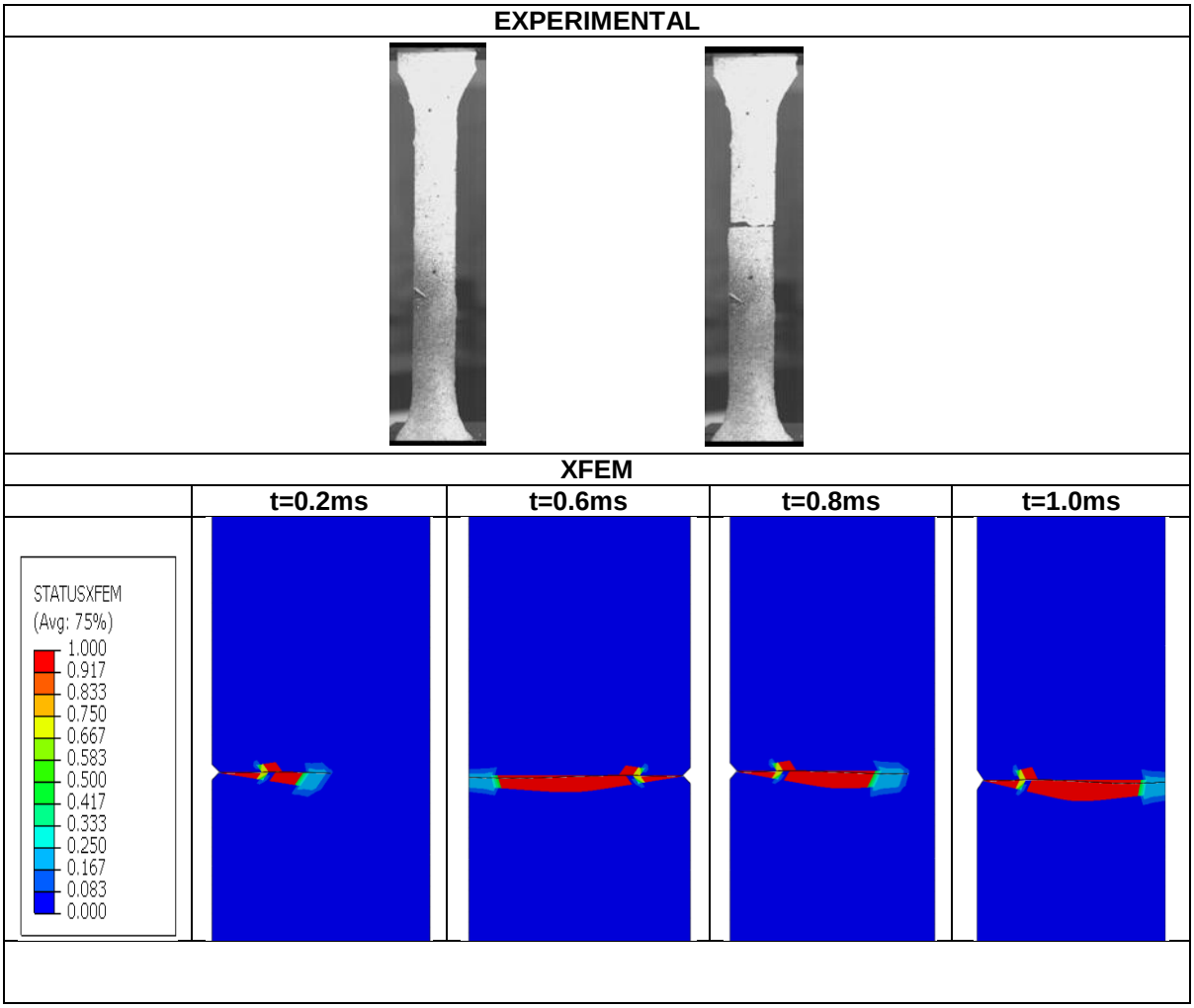
experimental results. In XFEM, the definition of traction–separation laws, element size at the crack front, and crack initiation criteria strongly influence failure prediction. For the DAMAGE model, parameters such as damage initiation thresholds, energy dissipation rates, and field variable interpolation play crucial roles. Additionally, experimental scatter, including surface defects or slight misalignments, cannot be fully captured in deterministic simulations and contribute to observed differences.

In conclusion, both numerical approaches successfully replicate key aspects of PMMA's tensile behavior but exhibit specific limitations. XFEM offers a better representation of the abrupt brittle fracture, although it slightly overpredicts failure strain, while the DAMAGE model excels in predicting ultimate tensile strength but does not capture the catastrophic failure mode. Future improvements could include calibrating the cohesive parameters more precisely based on fracture toughness data, implementing stochastic defect modeling, or using micromechanical modeling approaches to better simulate localized damage initiation and propagation. (Figure 6).



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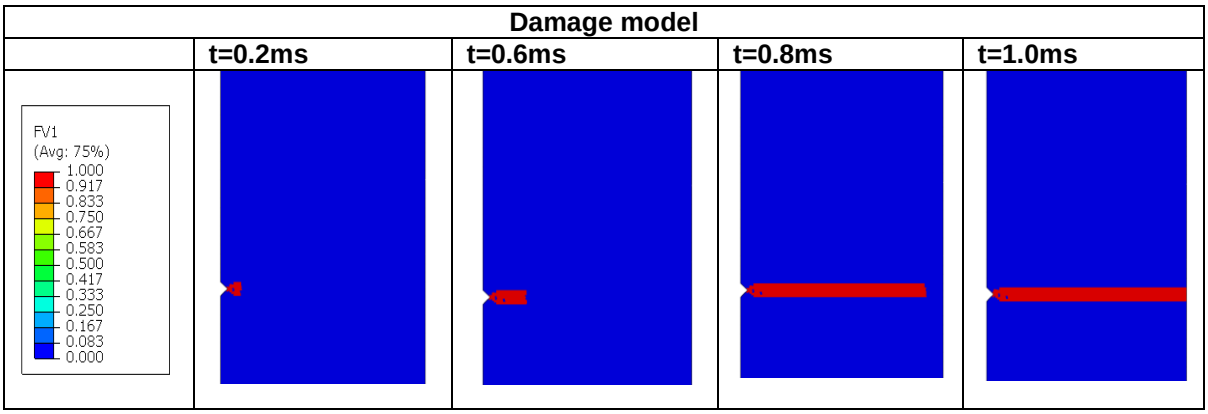


**Figure 6: Comparison between Experimental, XFEM crack evolution damage field plots at different times (t = 0.2 ms, 0.6 ms, 0.8 ms and 1.0 ms)**

The crack propagation patterns observed experimentally and numerically using the XFEM and the progressive damage model provide further insights into the fracture mechanisms of PMMA bone cement under uniaxial tension. The experimental images reveal a sudden and catastrophic crack propagation, consistent with the brittle behavior inferred from the stress–strain response. The failure initiates at the necked region and propagates rapidly across the specimen width, leading to a clean and sharp fracture surface (Figure 6).

In the XFEM simulations, the crack initiation is captured at approximately t = 0.2 ms, indicated by the development of localized damage regions (STATUSXFEM > 0.6). As time progresses (t = 0.6 ms to 1.0 ms), the crack propagates along a defined path, maintaining a concentrated damage zone. The crack front advances sharply and remains localized, reproducing the experimental observations of a dominant single-crack failure mechanism. The XFEM accurately models the abrupt propagation and limited plastic deformation, although some minor asymmetry is observed, potentially attributable to numerical mesh discretization effects.

Conversely, the progressive damage model exhibits a different crack evolution behavior. At t = 0.2 ms, localized damage starts to appear; however, the damage field is more diffuse compared to XFEM. By t = 0.6 ms, damage spreads significantly before coalescing into a primary crack path by t = 0.8 ms and 1.0 ms. The damage distribution is broader and less sharply defined than in XFEM, indicating a more gradual degradation of material properties. This suggests that the progressive damage model captures the accumulation of micro-damages preceding macroscopic crack formation, a phenomenon that is not prominently observed experimentally for this brittle PMMA material.

The difference between XFEM and the progressive damage model reflects fundamental distinctions in how each method handles damage localization and crack propagation. XFEM inherently models a discrete crack by enriching the displacement field, leading to a sharper representation of fracture surfaces. In contrast, the damage model relies on

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gradual stiffness degradation based on a field variable, resulting in a smeared crack appearance that may be more appropriate for ductile or quasi-brittle materials.

Overall, the XFEM results show better agreement with experimental crack morphology and propagation kinetics, capturing the sudden and localized nature of fracture in PMMA bone cement. The progressive damage model, while providing valuable insights into the progressive failure process, appears less suited to capturing the catastrophic failure mode of highly brittle materials under tensile loading.

## 4. DISCUSSION

### 4.1. Predictive Accuracy of Numerical Approaches

The results from the experimental and numerical investigations confirm that XFEM provides superior predictive capabilities in capturing the brittle fracture behavior of PMMA under tensile loading. The XFEM simulations closely matched experimental observations, both in terms of the mechanical response and crack morphology. Specifically, the stress–strain curves exhibited excellent correlation with experimental data up to the point of fracture, followed by an abrupt load drop indicative of catastrophic failure. XFEM's ability to accurately predict crack initiation and arbitrary propagation paths, independent of mesh discretization, aligns well with previous findings on XFEM performance in brittle and quasi-brittle materials [1], [7].

Conversely, the progressive damage model, although successful in replicating the general trend of material degradation, failed to capture the abruptness of fracture. The model predicted a smoother softening behavior with an extended post-peak response, suggesting a gradual loss of stiffness inconsistent with the catastrophic fracture mode observed experimentally. This divergence highlights the intrinsic limitations of scalar damage models when applied to highly brittle polymers like PMMA, where plastic deformation prior to failure is minimal [2], [9].

### 4.2. Computational Efficiency and Practical Trade-Offs

While XFEM demonstrated superior predictive fidelity, it comes at a cost of higher computational requirements. The implementation of enrichment functions and the need for refined meshes in the vicinity of potential crack paths increase both the model complexity and computational time. Such limitations must be considered when applying XFEM to large-scale or patient-specific simulations in clinical settings, where computational resources and time constraints may be prohibitive [3], [7].

In contrast, the progressive damage model is computationally efficient, requiring only scalar field variables and avoiding the need for enrichment schemes. This simplicity makes it attractive for large-scale analyses where detailed crack morphology is less critical. Nevertheless, its mesh-dependent behavior and tendency to smear damage highlight the importance of implementing nonlocal or gradient-enhanced formulations when simulating brittle materials [8], [12].

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### 4.3. Sensitivity to Material and Numerical Parameters

Both numerical strategies exhibited sensitivity to key model parameters. In XFEM, the fracture energy (Gf), maximum principal strain threshold, and the cohesive law definition significantly influenced crack initiation and propagation predictions. Incorrect calibration of these parameters may lead to either premature crack nucleation or delayed failure [4], [10].

The progressive damage model was particularly sensitive to the damage initiation strain and failure strain parameters. Fine-tuning these thresholds was necessary to align the simulated stress–strain curves with experimental results. Additionally, damage localization was highly mesh-dependent, emphasizing the need for regularization strategies to minimize artificial effects of element size on the damage zone [9], [10].

### 4.4. Implications for Orthopedic Applications

From an orthopedic engineering perspective, accurately predicting the initiation and growth of cracks in PMMA bone cement is critical for ensuring the longevity of cemented prostheses. XFEM's capacity to predict fracture surfaces and failure loads makes it an invaluable tool for virtual prototyping of implants, surgical planning, and failure risk assessment [11], [12].

However, for clinical applications requiring rapid evaluation of multiple implant configurations, progressive damage modeling may remain valuable due to its computational efficiency, provided its limitations are recognized. For instance, global assessments of cement mantle integrity under physiological loading cycles may tolerate some inaccuracies in local fracture representation if overall trends are captured [13], [14].

### 4.5. Opportunities for Future Model Enhancements

Several promising avenues could further enhance numerical modeling of PMMA fracture behavior:

- Phase-Field Models: By diffusing the crack surface representation over a finite width, phase-field approaches naturally regularize crack propagation and eliminate the need for explicit crack tracking [15].
- Micromechanical Modeling: Incorporating explicit representations of pores, microcavities, and material heterogeneity could improve fracture predictions by accounting for localized stress concentrations [13], [16].
- Fatigue and Cyclic Loading Analysis: Extending current models to simulate cyclic damage accumulation would better reflect in vivo conditions, where implants are subjected to millions of gait cycles annually [17], [18]. [22]. [23].
- Environmental Effects: Incorporating the influence of thermal residual stresses from polymerization and environmental factors such as moisture uptake could enhance long-term predictive reliability [19].

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Overall, integrating advanced fracture models such as XFEM or phase-field methods with multiscale micromechanical approaches offers a promising strategy to improve the predictive capabilities of numerical

## 5. CONCLUSION

This study provided a comprehensive comparative analysis of two advanced numerical approaches—Extended Finite Element Method (XFEM) and progressive damage modeling—for simulating the quasi-brittle tensile fracture behavior of PMMA bone cement. Experimental uniaxial tensile tests served as the validation baseline, revealing a characteristic linear-elastic regime followed by catastrophic failure with minimal plastic deformation.

XFEM demonstrated an exceptional ability to predict crack initiation, propagation, and failure modes with high fidelity, closely matching experimental observations. The model successfully captured the abrupt load drop associated with brittle fracture and accurately represented the fracture surfaces independent of mesh topology. Despite the increased computational cost and the need for careful calibration of fracture parameters, XFEM stands out as a highly effective predictive tool, particularly for applications requiring precise failure analysis, such as orthopedic implant design and failure risk assessment.

In contrast, the progressive damage model offered computational efficiency and simplicity of implementation, making it suitable for large-scale or preliminary simulations. However, its reliance on scalar damage variables and sensitivity to mesh discretization resulted in a smoother, more diffuse damage progression that failed to replicate the sudden fracture observed experimentally. This model may nevertheless be valuable for applications where global trends in material degradation are of interest, provided its inherent limitations are acknowledged.

Beyond the comparative assessment, the study highlights several avenues for improving the predictive modeling of PMMA failure. Integration of phase-field models presents a promising solution to the challenges of mesh sensitivity and crack tracking, enabling the natural emergence of complex crack patterns. Additionally, micromechanical modeling approaches incorporating material heterogeneities, porosity, and environmental effects could further refine fracture predictions and enhance the understanding of failure mechanisms. Future research directions should also focus on simulating fatigue damage accumulation under cyclic loading conditions, as bone cements in vivo experience millions of load cycles throughout the prosthesis lifespan. Investigating the combined influence of thermal residual stresses from polymerization, moisture uptake, and biological aging on mechanical performance will be crucial for developing next-generation bone cement formulations with improved durability. Ultimately, the insights gained from this study contribute to the advancement of computational fracture mechanics in biomedical materials, supporting the design of safer, more reliable orthopedic implants and guiding strategies to minimize the incidence of implant loosening and failure in clinical practice.

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