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# A Comparative Analysis of 3D Software for Modeling Fatigue Crack Growth: A Review

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**Abstract:** Fatigue crack growth modeling is critical for assessing structural integrity in various engineering applications. Researchers and engineers rely on 3D software tools to predict crack propagation accurately. However, choosing the right software can be challenging due to the plethora of available options. This study aimed to systematically compare and evaluate the suitability of seven prominent 3D modeling software packages for fatigue crack growth analysis in specific applications. The selected software tools, namely ABAQUS, FRANC3D, ZENCRACK, LYNX, FEMFAT, COMSOL Multiphysics, and ANSYS, were subjected to a comprehensive analysis to assess their effectiveness in accurately predicting crack propagation. Additionally, this study aimed to highlight the distinctive features and limitations associated with each software package. By conducting this systematic comparison, researchers and engineers can gain valuable insights into the strengths and weaknesses of these software tools, enabling them to make informed decisions when choosing the most appropriate software for their fatigue crack growth analysis needs. Such evaluations contribute to advancing the field by enhancing the understanding and utilization of these 3D modeling software packages, ultimately improving the accuracy and reliability of structural integrity assessments in relevant applications.

**Keywords:** fatigue crack growth; software comparison; ABAQUS; FRANC3D; ZENCRACK; LYNX; FEMFAT; COMSOL Multiphysics; ANSYS

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## 1. Introduction

Fatigue crack growth is a critical phenomenon that plays a significant role in the assessment of structural integrity across various engineering applications. Accurately predicting the propagation of cracks is essential for ensuring the safe and reliable operation of structures subjected to cyclic loading [1–3]. To achieve this, researchers and engineers heavily rely on 3D modeling software tools, which provide advanced numerical techniques to simulate and analyze fatigue crack growth behavior. However, with the ever-increasing number of available software options, choosing the most suitable tool for fatigue crack growth analysis can be a daunting task [4–7]. From a designer's perspective, it is indeed crucial to monitor the crack propagation process in structures, even if the initial crack has been detected and its time and location estimated. Detecting the presence of a crack is an essential first step, but understanding the crack propagation behavior is equally important for several reasons:

- Safety and Reliability: By monitoring the crack propagation process, designers can assess the safety and reliability of the structure. Understanding how cracks evolve and propagate helps identify critical areas prone to failure, enabling proactive maintenance and repair actions. This ensures the continued safe operation of the equipment and minimizes the risk of catastrophic failures.
- Structural Integrity Assessment: Monitoring crack propagation allows for a comprehensive assessment of the structure's integrity. By tracking crack growth characteristics such as crack length, direction, and rate, designers can predict the remaining useful

life of the equipment. This information assists in scheduling maintenance activities, optimizing operations, and avoiding unexpected downtime or costly repairs.

- Cost-Effectiveness: Monitoring crack propagation in a structured manner can be seen as an investment in cost-effectiveness. By identifying cracks at an early stage and monitoring their growth, designers can take appropriate measures to mitigate further damage or extend the life of the structure. This can minimize repair costs, prevent unnecessary component replacements, and optimize maintenance strategies, resulting in significant cost savings over the equipment's lifespan.
- Performance Optimization: Understanding the crack propagation process helps designers evaluate the impact of cracks on the performance of the structure. By quantifying the effects of cracks on factors such as stiffness, load-carrying capacity, and dynamic response, designers can optimize the design and operational parameters to mitigate the adverse effects of cracks. This leads to improved performance, efficiency, and longevity of the equipment.

This study aims to address the challenge of software selection by systematically comparing seven prominent 3D modeling software packages commonly used in the field of fatigue crack growth analysis. The selected software tools for this comparison include ABAQUS, FRANC3D, ZENCRACK, LYNX, FEMFAT, COMSOL Multiphysics, and ANSYS. These software packages are widely recognized and popular in the field, and they offer a range of features, capabilities, and methodologies for fatigue crack growth analysis.

The primary objective of this research is to evaluate the suitability of these software tools for accurately predicting fatigue crack growth and assessing structural integrity. Each software package offers unique features and capabilities, necessitating a systematic comparison to assess their suitability for fatigue crack growth analysis. By conducting a comprehensive evaluation, this study aims to provide valuable insights for researchers and engineers in selecting the most appropriate software for their specific application requirements. To accomplish this objective, various factors and criteria crucial for fatigue crack growth analysis will be considered. These include the modeling approaches employed by each software, the available crack growth methods, and the types of meshing options provided. Additionally, other relevant aspects such as computational efficiency, accuracy, and compatibility with variable loading conditions will be assessed. The evaluation will also focus on the implementation of crack growth models in each software package, including the incorporation of crack growth laws such as Paris Law or Walker Law, stress intensity factors, and other relevant parameters. Furthermore, the analysis will examine how each software handles factors such as crack closure, crack branching, and interaction with material interfaces. One of the key factors considered in this evaluation is the modeling techniques employed by each software package. The ability to accurately capture complex crack behavior is crucial for reliable predictions. The selected software tools may utilize techniques such as finite element method (FEM), extended finite element method (XFEM), cohesive zone modeling, or virtual crack closure technique (VCCT). The strengths and limitations of each modeling technique will be examined to evaluate their effectiveness in representing crack propagation under different loading conditions and material behaviors. The findings of this study will assist researchers and engineers in making informed decisions regarding the selection of software tools for fatigue crack growth analysis. By comparing and evaluating the prominent software options, a comprehensive overview of their strengths and limitations will be provided, enabling users to choose the most suitable software based on their specific needs and requirements. Ultimately, this research aims to contribute to the advancement of fatigue crack growth analysis and enhance the accuracy and reliability of predictions in ensuring structural integrity across diverse engineering applications. In the subsequent sections, a detailed evaluation of each software package is presented, providing a comprehensive analysis of their capabilities, features, limitations, and suitability for fatigue crack growth modeling.

## 2. Software

At present, there are several software solutions available to address the issue of fatigue crack growth. However, it is important to mention that a significant number of these solutions have been developed by research groups and are not widely commercially available. When it comes to analyzing fatigue crack growth, two primary approaches are used in fatigue crack growth software: numerical-based approaches and analytical-based approaches. The following subsections will provide a brief overview of these categories.

### *2.1. Numerical-Based Approaches*

These solutions employ numerical methods like finite element analysis (FEA), the extended finite element method (XFEM), boundary element methods (BEMs), the meshless method, and the weight function method to simulate and analyze crack growth behavior. They provide detailed insights into crack behavior, stress distribution, and fatigue life prediction by discretizing the crack geometry and using iterative algorithms. This article primarily focuses on three-dimensional FEM and XFEM software due to its relevance in the context being discussed. In the subsequent subsections, detailed explanations of the widely used software in this domain will be provided.

#### 2.1.1. ABAQUS

ABAQUS is a widely used commercial finite element analysis software package that offers powerful capabilities for modeling fatigue crack growth. It provides a comprehensive set of tools and features for simulating and analyzing various engineering problems, including fatigue crack growth in structures [8–10]. To incorporate the Extended Finite Element Method (XFEM) into ABAQUS, users can utilize a User Subroutine. This subroutine allows for the implementation and integration of XFEM functionalities into the software [11–15]. ABAQUS allows users to create complex 3D models using its intuitive graphical user interface (GUI) or by importing CAD files. The geometry should include the cracked region and any other relevant features. ABAQUS provides meshing tools to generate a finite element mesh for the model geometry. In ABAQUS, there are different types of meshing techniques available for discretizing the geometry of a model. These include structured, unstructured, hybrid, adaptive, mesh-to-mesh contact, and cohesive zone elements. The choice of mesh type depends on the complexity of the geometry and the specific analysis requirements. The mesh should be refined around the crack region to capture the crack propagation accurately. Different element types and mesh densities can be selected based on the specific requirements of the analysis. ABAQUS is known for its computational efficiency and robustness in modeling fatigue crack growth. The software utilizes advanced numerical techniques, such as adaptive meshing and parallel processing, to enhance the efficiency and accuracy of the analysis. ABAQUS also offers various element formulations and integration schemes that can be tailored to specific crack growth problems to reduce computational costs. Moreover, ABAQUS provides a comprehensive material library that includes fatigue data for a wide range of materials, allowing users to select appropriate material properties and fatigue models for accurate crack growth predictions. Additionally, ABAQUS supports scripting and automation capabilities, allowing users to streamline repetitive tasks and perform parametric studies efficiently. Furthermore, ABAQUS supports a variety of material failure criteria, such as fracture mechanics-based criteria (e.g., stress intensity factors) and damage-based criteria (e.g., cohesive zone modeling).

In the framework of Linear Elastic Fracture Mechanics, ABAQUS employs the following crack growth criteria [16]:

- Maximum Tangential Stress (MTS) Criterion: This criterion focuses on evaluating the maximum tangential stress acting on the crack tip. It serves as an indicator for assessing crack growth behavior under various loading conditions. By monitoring the magnitude of the tangential stress, the MTS criterion helps to predict crack propagation.
- Maximum Shear Stress Ratio (MSSR) Criterion: The MSSR criterion considers the ratio between the maximum shear stress and the normal stress acting on the crack

plane. This criterion provides valuable insights into crack behavior and stability. By examining the relationship between shear and normal stresses, it aids in understanding the crack growth mechanism.

- Extension of the Maximum Tangential Stress (Ex-MTS) Criterion: The Ex-MTS criterion expands upon the MTS concept by incorporating additional factors that influence crack growth. It takes into account parameters such as stress intensity factors and crack path. By considering these factors, the Ex-MTS criterion enhances the accuracy of crack growth predictions.

The literature extensively documents the use of ABAQUS software for fatigue crack growth modeling, with numerous studies discussing its strengths and limitations in this field. Notably, Malekan [9] and Moroni [17] developed plug-ins specifically for ABAQUS to simulate fatigue crack growth. Malekan's plug-in primarily focuses on 2D analyses, while Moroni's plug-in focuses on adhesively bonded joints. Additionally, Rabold [18] and Dougherty [19] employed ABAQUS for automated finite element simulation and plasticity-induced crack closure, respectively. Both studies reported favorable agreement between the computational models and experimental results. The introduction of extended finite element methods (XFEMs) for ABAQUS was documented by Xu [12] and Shi [20]. Xu's work focused on the application of XFEM to quasi-brittle materials, whereas Shi's research centered around three-dimensional fatigue crack growth. In addition, Pirondi [21] and Yang [22] developed progressive damage models and algorithms specifically for ABAQUS. Pirondi's study concentrated on bonded joints, while Yang's work addressed non-proportional mixed mode loading. Collectively, these studies showcase the versatility of ABAQUS in fatigue crack growth modeling. However, they also highlight certain limitations of the software, including its performance in 2D analyses, adhesively bonded joints, and non-proportional mixed mode loading scenarios.

Using ABAQUS for fatigue crack growth simulations offers several advantages. Here are some key advantages:

- Comprehensive Simulation Tool: ABAQUS provides a robust platform for simulating fatigue crack growth. Although it does not natively support fatigue analysis, engineers can leverage plug-ins or toolkits to perform these predictions. The versatility of Abaqus allows users to model complex geometries, material behavior, and loading conditions, making it suitable for various engineering applications [23,24].
- Freely Distributed Plug-In: Researchers have developed an ABAQUS plug-in specifically for fatigue crack growth simulations. This plug-in is freely distributed and aims to evaluate the design life of engineering components. It includes five different fatigue crack growth models and relies on the XFEM method to simulate crack propagation. The plug-in covers all necessary steps, from geometry creation to job submission and post-processing [9,25].
- Validation and Accuracy: The implementation of the plug-in has been validated by comparing its predictions to analytical and experimental results. This ensures its accuracy and reliability [9,26].
- Integration with Pre/Post-processing Tools: ABAQUS integrates seamlessly with pre-processing tools like CATIA or SolidWorks for geometry creation and mesh generation. It also provides a powerful post-processing environment that allows users to visualize and analyze simulation results effectively. This integration streamlines the simulation workflow and enhances productivity [27,28].

While ABAQUS is a powerful software tool for fatigue crack growth analysis, it does have certain limitations that should be considered:

- Mesh Sensitivity: The accuracy of fatigue crack growth analysis is highly dependent on the quality and refinement of the mesh near the crack tip. Achieving an appropriate mesh density can be challenging, as refining the mesh in this region leads to increased computational costs. Careful consideration and validation of the mesh sensitivity are required to obtain reliable results [29].

- Crack Growth Models: ABAQUS offers various crack growth models such as cohesive zone modeling and XFEM. However, the accuracy of these models is dependent on the assumptions and parameters used. Choosing the appropriate crack growth model and accurately defining its parameters can be complex and may require experimental validation [30]. Dirik and Yalçinkaya [31] highlighted the importance of incorporating a mesh-independent computational algorithm within ABAQUS to achieve accurate predictions of fatigue crack growth, particularly under variable amplitude loading conditions. This emphasizes the need for advanced techniques that can mitigate the influence of mesh resolution on the results, ensuring reliable predictions of crack propagation behavior.
- Material Data: Accurate material properties, such as fatigue properties, are crucial for reliable fatigue crack growth analysis. ABAQUS provides a material database, but it may not cover all materials and loading conditions. Obtaining accurate material data for specific materials and ensuring their applicability to the analysis are essential [32].
- Computational Resources: A fatigue crack growth analysis can be computationally intensive, particularly when dealing with large and complex models. Adequate computational resources, including memory and processing power, are required to ensure efficient and timely analysis.
- No Direct Built-in Support: Unlike some specialized fatigue analysis tools, ABAQUS does not directly support fatigue analysis out of the box. Users need to rely on additional plug-ins or toolkits to perform fatigue predictions [9].

#### 2.1.2. FRANC3D

FRANC3D is a powerful three-dimensional fracture analysis code that specializes in simulating crack growth in complex, non-planar geometries. It employs a sub-modelling technique, which involves creating a global finite element mesh encompassing the crack and a more refined sub-model near the crack region to accurately extend its growth. The meshing strategy in FRANC3D consists of concentric rings around the crack. The initial ring closest to the crack is constructed using quarter-point singular wedge elements, which provide accurate stress and displacement solutions near the crack tip. Subsequent rings are generated using hexahedral elements for efficient representation of the surrounding material. To evaluate the stress intensity factors along the crack front, FRANC3D offers two methods: the M-integral and the displacement correlation technique. These techniques allow for the extraction of stress intensity factors at discrete points along the crack front, providing valuable insights into crack propagation behavior.

FRANC3D is a powerful software tool used for simulating fatigue crack growth in complex structures. Here are some advantages of using FRANC3D for this purpose:

- In terms of fatigue crack growth analysis, FRANC3D supports various established models for estimating crack growth rates. These models utilize well-known relationships between fatigue loading, crack size, and material properties. Additionally, users have the flexibility to input their own user-defined data or custom models to capture specific fatigue crack growth behavior.
- One notable feature of FRANC3D is its ability to generate both surface and volume meshes [33]. This versatility allows for compatibility with other finite element or boundary element programs, enabling seamless integration into existing analysis workflows.
- Integration with ANSYS: FRANC3D works in conjunction with ANSYS, a widely used finite element analysis (FEA) software. It leverages ANSYS's capabilities for meshing, stress analysis, and other complex simulations. FRANC3D inserts and grows cracks within the ANSYS finite element mesh, making it a valuable extension for fatigue analysis [34,35].

Several studies have extensively explored the application of FRANC3D in modeling fatigue crack growth. Chen [36] enhanced the software's capabilities to represent realistic damaged structures and to model stable tearing, which proved beneficial for predicting residual strength. Yang [22] proposed an algorithm specifically designed for simulating fatigue crack growth under non-proportional mixed-mode loading, with a particular emphasis on thin-walled, hollow cylinders. Alizadeh [37] developed a three-dimensional finite element fatigue crack closure model that incorporated closure effects to predict crack growth rates.

There are certain limitations associated with modeling fatigue crack growth using FRANC3D software. Some of these limitations include the following:

- Geometrical complexity: FRANC3D may have difficulties in handling highly complex crack geometries, such as branched cracks or cracks in non-standard shapes. The software is primarily designed for simpler crack configurations [33].
- Mesh generation: Generating an appropriate mesh for crack propagation simulations can be challenging in FRANC3D. It may require manual intervention or additional pre-processing steps to achieve accurate and efficient meshing [38].
- Computational resources: Fatigue crack growth simulations in FRANC3D can be computationally intensive, especially for large and complex models. Adequate computational resources, such as processing power and memory, may be required to perform simulations within reasonable time frames [39].
- Material models: FRANC3D may have limitations in terms of the variety of material models available for fatigue crack growth simulations. It is essential to ensure that the selected material model accurately represents the behavior of the material being analyzed [40].
- Crack growth direction: FRANC3D assumes that the crack growth occurs along the predefined crack front, and it does not account for changes in crack growth direction during the simulation. This can be a limitation when dealing with complex crack growth paths or when considering crack branching [41].
- Load redistribution: FRANC3D may not consider load redistribution effects as the crack propagates. This can lead to inaccuracies in stress intensity factor calculations and crack growth predictions, particularly in cases where load redistribution significantly impacts the crack growth behavior [42].
- FRANC3D is designed to handle arbitrarily complex component geometries and local loading conditions. However, when dealing with non-planar crack growth, especially under plane strain conditions, FRANC3D may face challenges. Local crack front elements can become highly distorted.

#### 2.1.3. ZENCRACK

ZENCRACK is a commercially available software that has been specifically developed for conducting linear elastic fracture mechanics analyses. However, it also possesses the capability to effectively analyze three-dimensional fatigue crack problems [43–45]. ZENCRACK provides several benefits for fatigue crack growth simulation, which encompass the following:

- Incorporation of Multiple Defects: ZENCRACK enables engineers to include multiple defects within a component during the analysis process. This flexibility allows for a more accurate representation of real-world scenarios, enhancing the reliability of the simulation [46].
- Support for Complex Loading Conditions: ZENCRACK offers extensive support for various complex loading conditions. This includes the consideration of residual stress resulting from shot peening [47], the analysis of time-dependent or sustained load crack growth, as well as the ability to perform fatigue-only and time-only analyses. Additionally, ZENCRACK facilitates the investigation of combined fatigue and time-dependent crack growth phenomena.
- ABAQUS Plug-in: ZENCRACK is a freely distributed plug-in specifically designed to be used with the commercial finite element (FE) software ABAQUS.

Although ZENCRACK proves to be a valuable software tool for fatigue crack growth analysis, it is important to acknowledge certain limitations associated with its usage. These limitations of ZENCRACK in the context of fatigue crack growth analysis include the following:

- Meshing limitations: ZENCRACK relies on external FE packages for mesh generation, which means it inherits any limitations or challenges associated with those packages. The complexity of creating meshes for highly intricate crack geometries or non-standard shapes can pose difficulties in accurately representing the crack and its surrounding region [48–51]. ZENCRACK does not have its own mesh generator. Instead, it relies on external general-purpose finite element (FE) packages like ABAQUS [43,44], ANSYS [45,46], and MSC.MARC [47] to create the mesh for the uncracked geometry. The mesh generation process, including the creation of pure hexahedral elements throughout the structure, is performed using these external FE packages.
- Crack front tracking: ZENCRACK assumes a predefined crack front and does not account for changes in crack growth direction during the analysis. This limitation can be problematic when dealing with complex crack growth paths or situations where crack branching occurs [45,46].
- Material models: The range of available material models in ZENCRACK for fatigue crack growth analysis may be limited. It is crucial to ensure that the selected material model accurately represents the behavior of the material under fatigue loading conditions.
- Remeshing limitations: Although ZENCRACK introduces crack-block elements to refine the mesh around the crack front, some limitations and numerical errors associated with remeshing have been reported in the literature. These issues may affect the accuracy of crack growth predictions or introduce computational challenges [52,53].
- Computational resources: Like any software conducting complex simulations, a fatigue crack growth analysis in ZENCRACK can be computationally demanding. Adequate computational resources, such as processing power and memory, may be required to perform simulations within reasonable time frames.

#### 2.1.4. LYNX

LYNX is a specialized 3D software developed specifically for analyzing fatigue crack growth. It provides a wide array of tools and functionalities to accurately simulate and assess crack behavior in various materials and structural elements [54,55]. LYNX supports a broad range of geometric configurations commonly encountered in fatigue crack growth studies. Moreover, it incorporates an automatic transition feature that seamlessly models the progression of cracks, transitioning between surface or corner cracks and through cracks [56]. This capability proves especially valuable when investigating intricate crack growth scenarios with diverse initiation and propagation patterns. To ensure accurate representations of crack fronts and surrounding areas, LYNX employs advanced mesh generation techniques. These techniques combine spider web meshes, regular meshes, and transitional meshes to generate precise numerical simulations that efficiently depict crack propagation. It can simulate crack propagation under different loading conditions, including constant amplitude, variable amplitude, and random loading.

LYNX offers numerous advantages for fatigue crack growth simulation, which can be summarized as follows:

- The software also offers capabilities for analyzing crack closure, stress intensity factors, and crack growth rates. LYNX can integrate with a range of software commonly used in engineering, including CAD software for geometry creation, mesh generation software, and post-processing tools like ParaView or MATLAB.
- It also supports interoperability with structural analysis software such as ANSYS or Abaqus. LYNX 171 is the latest version of the software, which integrates with other software packages like ABAQUS for modeling fatigue crack growth.
- LYNX has been extensively validated through numerous studies and real-world applications. It has been successfully applied in various industries, including aerospace, automotive, and structural engineering, to analyze and predict fatigue crack growth behavior. Its accuracy and reliability have been demonstrated through comparisons with experimental data and benchmark problems [57,58].

Despite its versatility in fatigue crack growth analysis, it is essential to take into account the limitations of LYNX. Some of the limitations of LYNX are as follows:

- Limited scope: LYNX is specifically designed for in-plane problems related to fatigue crack growth. It may not be suitable for analyzing out-of-plane or complex three-dimensional crack propagation scenarios [54,59].
- Geometric configurations: While LYNX offers a comprehensive set of geometric configurations, including notched and unnotched plates, round bars, and bars with corner cracks, it may not cover all possible geometries. Users should check if their specific geometry is supported by LYNX before conducting their analysis.
- Material models: The range of available material models in LYNX for fatigue crack growth analysis may be limited. It is important to ensure that the selected material model accurately represents the behavior of the material under fatigue loading conditions.
- Integration limitations: While LYNX 171 integrates with other software packages like ABAQUS for modeling fatigue crack growth, there may be limitations or challenges in the integration process. Compatibility issues or difficulties in transferring models between different software platforms can arise.

#### 2.1.5. FEMFAT

FEMFAT is a widely used software package in the automotive and mechanical engineering industries, offering a wide range of capabilities for fatigue life analysis [60,61]. It supports both high-cycle and low-cycle fatigue analyses and allows for the assessment of multiaxial loading, mean stress, and variable amplitude loading effects on fatigue life predictions. With its comprehensive material database, FEMFAT simplifies the selection and assignment of fatigue material properties for different engineering materials.

FEMFAT offers numerous benefits when it comes to fatigue crack growth simulation. These advantages can be summarized as follows:

- The software seamlessly integrates with popular finite element analysis (FEA) software packages like ANSYS, ABAQUS, and MSC Nastran, enabling effortless transfer of geometry, mesh, and loading conditions [62–64]. This integration streamlines the analysis workflow and enhances the accuracy of fatigue life predictions. FEMFAT can directly import the geometry of the component or structure from the FEA software, eliminating the need for manual reconstruction and ensuring consistency. It can also import the mesh, including element connectivity and nodal coordinates, preserving structural details.
- FEMFAT accesses the loading conditions from the FEA software, such as forces or displacements, which are crucial for fatigue analysis. Additionally, it retrieves the results of the FEA analysis, like stress distribution and strain data, to facilitate realistic and accurate fatigue life assessment [65–67].
- FEMFAT offers a range of analysis options that are suitable for both metallic and non-metallic components. It allows for the simultaneous analysis of base materials as well as welded and/or spot joints. Additionally, FEMFAT incorporates the effects of different manufacturing processes on the fatigue behavior of components. It specifically considers processes such as shot peening, rolling, carburizing, and nitriding, as they have a significant impact on the component's fatigue properties [68].
- FEMFAT provides a unified framework for modeling fatigue crack growth. It covers the entire fracture evolution, including nucleation, propagation, branching, and kinking [69].
- FEMFAT takes into account the influence of residual stress distribution near the crack tip. This consideration enhances the accuracy of fatigue life predictions [70].

While FEMFAT is indeed a powerful tool for fatigue analysis, it is important to be aware of certain limitations associated with its application. Here are some limitations to consider when using FEMFAT for fatigue analysis:

- Limited to Low-Cycle Fatigue: FEMFAT is primarily designed for low-cycle fatigue analysis, which is typically applicable to components subjected to high loads and a relatively small number of stress cycles. It may not be as effective in analyzing high-cycle fatigue or very long-life situations [71,72].
- Lack of Environmental Effects: FEMFAT primarily focuses on mechanical loading and fatigue behavior. It does not account for environmental factors, such as temperature, humidity, or corrosive conditions, which can significantly affect fatigue life.
- FEMFAT may encounter issues when all element nodes are declared as weld nodes at a shell element. This can lead to interpretation errors and overly conservative results for certain stress conditions.
- FEMFAT ignores stresses in elements other than weld elements connected to a simple weld node. Proper modeling guidelines should be followed to avoid this issue [73,74].

#### 2.1.6. COMSOL Multiphysics

COMSOL Multiphysics is a versatile and comprehensive finite element analysis software that provides a robust platform for simulating and modeling various physical phenomena. It offers a range of modules and features that enable engineers to simulate complex multiphysics problems, including fatigue crack growth. Modeling fatigue crack growth using COMSOL Multiphysics offers several advantages:

- COMSOL Multiphysics allows for the integration of multiple physics modules, such as structural mechanics, thermomechanical fatigue, heat transfer, and materials science. This capability enables users to simulate the complex interactions between different physical phenomena that influence fatigue crack growth [75–77].
- COMSOL provides a wide range of material models and allows for the creation of custom material models based on experimental data. This flexibility enables users to accurately capture the fatigue behavior of different materials, including metals, composites, polymers, and more. Users can incorporate material-specific properties, such as fatigue curves, fracture toughness, and cyclic plasticity, to enhance the accuracy of fatigue crack growth simulations [77].
- COMSOL Multiphysics allows users to define the geometry of the crack with high precision. Users can specify the crack shape, size, and orientation, ensuring an accurate representation of the actual crack [78,79]. This level of detail is crucial for capturing the stress concentration and accurately predicting crack growth behavior.
- COMSOL Multiphysics offers advanced meshing techniques such as structured, unstructured, adaptive, boundary layer, swept, tetrahedral, and hexahedral meshing [80,81]. The use of appropriate meshing techniques ensures reliable and accurate fatigue crack growth simulations.
- Powerful Post-Processing and Visualization: COMSOL offers powerful post-processing and visualization tools to analyze and interpret simulation results. Users can extract relevant quantities, such as stress intensity factors, crack growth rates, and fatigue life predictions. The software provides graphical representations, including contour plots, 3D visualizations, and animations, facilitating a deeper understanding of the crack growth behavior and aiding in the communication of findings [82–84].
- Phase-field modeling for fatigue fracture problems can be implemented and analyzed using tools such as MATLAB and COMSOL. These tools enable researchers to investigate and gain valuable insights into the applicability and feasibility of phase-field modeling for studying fatigue fracture phenomena [84–86].

While the COMSOL Multiphysics Fatigue Module is a robust tool, it does have some limitations. Here are a few to consider:

- Simplified Material Models: The module employs simplified material models for fatigue analysis. While these models are useful for many engineering applications, they may not capture all the intricacies of real-world materials.

- The crack growth models assume certain conditions, such as linear elastic fracture mechanics (LEFM) and small crack sizes. These assumptions might not hold in all scenarios [78,87].
- Like any finite element analysis software, COMSOL's results can be sensitive to mesh density. Proper mesh refinement is crucial for accurate fatigue predictions [88].
- The module does not explicitly account for environmental factors (e.g., humidity and corrosive agents) that can significantly influence fatigue behavior.
- While the module handles simple loading histories well, more complex loadings (e.g., non-proportional, variable amplitude) might require additional considerations.
- COMSOL primarily focuses on high-cycle fatigue (HCF). For low-cycle fatigue (LCF) or thermomechanical fatigue, additional care is needed [89,90].
- User Expertise: Interpreting fatigue results requires expertise in both fatigue mechanics and the software. Users should understand the underlying assumptions and limitations.

#### 2.1.7. ANSYS Workbench

ANSYS Workbench is a comprehensive simulation platform widely used for modeling fatigue crack growth. It offers advanced tools and capabilities for accurately analyzing and predicting crack propagation behavior under cyclic loading conditions. By integrating fracture mechanics principles, material properties, and fatigue analysis techniques, ANSYS Workbench enables engineers and researchers to gain valuable insights into the fatigue life and durability of structures. ANSYS Workbench provides a range of crack growth models, including virtual crack closure technique (VCCT), extended finite element method (XFEM), and cohesive zone modeling (CZM). These models allow for accurate representation of crack geometry, consideration of complex loading conditions, and simulation of crack propagation in various materials and structures. SMART simulation is a cutting-edge innovation from ANSYS that addresses the critical challenge of crack initiation, growth, and fracture in product design. When designing components and structures, understanding their safety, reliability, and longevity is paramount. Traditionally, engineers relied on prototyping and physical testing for fracture analysis. However, ANSYS provides high-quality simulation software that allows engineers to predict toughness more efficiently than ever before. One key advancement is the Unstructured Mesh Method (UMM) in ANSYS Mechanical, which significantly reduces pre-processing time. By automatically generating an all-tetrahedral (tet) mesh for crack fronts, engineers achieve high-fidelity results while slashing meshing time from days to minutes [91–101]. The SMART Crack Growth feature introduces a mesh-based tetrahedron that simplifies the process of modeling crack growth. After completing the pre-meshed crack requirements, engineers can select the type of crack growth they want to simulate. The sphere of influence technique refines the mesh around the crack tip, focusing on the geometric edge that passes through the material thickness. This approach enhances accuracy and efficiency in fatigue crack growth analysis. Whether it is Mode I dominant fatigue or static crack growth, ANSYS empowers engineers to explore fracture behavior with precision [102–104].

Certainly, ANSYS SMART Crack Growth offers several advantages for modeling fatigue crack growth:

- Efficiency and Cost-Effectiveness: Traditionally, fatigue crack growth analysis involved extensive physical testing, which could be both time-consuming and expensive. However, with advancements in numerical simulation techniques, engineers and researchers now have a powerful tool at their disposal to predict and analyze crack behavior in a more efficient and cost-effective manner [98].
- Mesh-Based Tetrahedron Approach: ANSYS introduces the Smart Crack Growth mesh-based tetrahedron, which simplifies the modeling process. After completing the mesh, you can add the pre-meshed crack requirement, allowing you to select the type of crack growth. The sphere of influence process refines the mesh around the crack tip, enhancing accuracy.

- Multiple Crack Support: ANSYS SMART Crack Growth supports multiple cracks, allowing you to analyze complex structures with multiple crack fronts [105].
- Static and Fatigue Crack Growth: It enables both static crack growth analysis using J-integral and Stress-Intensity Factors (SIFs), as well as fatigue crack growth analysis with fatigue crack growth laws [106,107].
- Automatic Crack Initiation and Growth Arrest: The tool automatically handles crack initiation and growth arrest, streamlining the simulation process [108].
- Cohesive Zone Modeling (CZM) Element Support: For growing cracks, the method assumes that the discontinuities cut the element fully. As the crack grows, newly introduced crack segments are assumed to have cohesive zone behavior.

While the SMART Crack Growth feature in ANSYS is undeniably powerful and useful, it is crucial to recognize that it does have certain limitations that should be taken into account. Here are a few key limitations to consider when utilizing the SMART Crack Growth feature in ANSYS:

- The material properties assigned to the predefined materials must be complete and accurate. For instance, if you are using the Paris crack growth law, ensure that you define the coefficient and constant for Paris's law in the engineering data. Incomplete or incorrect material definitions can affect the accuracy of crack growth predictions.
- The SMART Crack Growth method relies on mesh refinement around the crack tip. However, mesh quality and element size play a crucial role in capturing accurate stress fields. If the mesh is not adequately refined near the crack tip, the results may be less reliable [97].
- The SMART Crack Growth feature is primarily designed for fatigue crack growth analysis in metallic materials with LEFM behavior. It may not be suitable for other types of materials, such as composites or polymers, or for crack growth phenomena influenced by factors beyond fatigue, such as environmental effects or creep [95].
- The SMART Crack Growth feature typically assumes that the crack will propagate in the direction of the maximum principal stress or strain. While this assumption is often valid, it may not accurately represent complex crack growth patterns influenced by factors such as material anisotropy, stress gradients, or geometrical constraints.
- The SMART Crack Growth feature primarily focuses on fatigue crack growth in structural components subjected to cyclic loading. It may not adequately consider the influence of environmental factors, such as corrosion, temperature, humidity, or aggressive media, which can significantly affect crack growth behavior.
- Fatigue crack growth in SMART is based on Paris's law, and it may not account for plasticity effects, nonlinear geometry effects, load-compression effects, and crack-tip-closure effects [109].

Table 1 provides a comprehensive comparison of the fatigue modeling approaches, crack growth methods, and mesh types utilized in seven discussed software packages. It offers valuable insights into how each software package handles fatigue analyses and examines crack growth phenomena. However, it is essential to acknowledge that the information presented in the table is contingent upon the individual capabilities and constraints of each software package. It is crucial to thoroughly evaluate the suitability of the chosen software for the specific application and to consider any additional factors or considerations beyond the scope of Table 1. When evaluating different 3D modeling software options, it is crucial to consider several important criteria to make a well-informed decision. In this context, Table 2 provides a comprehensive comparison of the mentioned software tools specifically in terms of their ability to simulate fatigue crack growth.

### 2.2. Analytical-Based Approaches

Analytical-based software employs pre-existing libraries of closed-form stress intensity factor solutions to predict fatigue crack growth, encompassing crack paths and fatigue lives. This approach offers faster results compared to numerical-based methods, as it eliminates the need to develop numerical models. However, it is important to consider certain limitations associated with this approach. One limitation is the applicability of existing libraries, which are primarily designed for planar cracks. These libraries may not accurately account for crack shapes that deviate from planarity, potentially leading to less accurate predictions in such cases. Additionally, analytical-based software typically neglects changes in crack shape during fatigue growth, which may limit its accuracy in situations where crack geometry evolves significantly. Load redistribution, an important phenomenon as a crack propagates, is often not fully considered in analytical-based software. This neglect can result in less precise predictions, particularly in scenarios where load redistribution significantly affects crack growth behavior. Furthermore, nonlinear effects, such as material nonlinearity or large deformations, are typically not accounted for in analytical-based software, potentially limiting its suitability for analyzing cases where these effects play a significant role. Despite these limitations, several analytical-based software packages have been developed and made available for fatigue crack growth analysis. Examples include NASGRO [110], NASCRAC [111], ESACRACK [112], AFGROW [113], and VIDA [114]. These software tools provide valuable capabilities for analyzing fatigue crack growth, offering efficiency and convenience in certain applications where the aforementioned limitations are acceptable or can be mitigated through appropriate assumptions and considerations.

**Table 1.** Comparison of the fatigue modeling approaches, crack growth methods, and mesh type for all software.

| Software | Fatigue Modeling Approaches | Crack Growth Method | Mesh Type |
|---|---|---|---|
| 1. ABAQUS | 1. Stress-Life (S-N) Approach<br>2. Strain-Life Approach<br>3. Critical Plane Analysis<br>4. Damage Accumulation<br>5. Load Histories<br>6. Crack Growth Analysis | 1. Cohesive Elements<br>2. Extended Finite Element Method (XFEM)<br>3. Virtual Crack Closure Technique (VCCT)<br>4. Cohesive Zone Modeling (CZM)<br>5. Fracture Mechanics Criteria<br>6. Element Deletion Technique | • Tetrahedral<br>• Hexahedral |
| 2. FRANC3D | 1. Stress-Life (S-N) Approach<br>2. Strain-Life Approach<br>3. Linear Elastic Fracture Mechanics (LEFM)<br>4. Paris's Law<br>5. Critical Plane Analysis<br>6. Damage Accumulation Models | 1. Extended Finite Element Method (XFEM)<br>2. Virtual Crack Closure Technique (VCCT)<br>3. Irwin's Integral<br>4. Crack Tip Opening Displacement (CTOD)<br>5. Paris Law<br>6. Crack Front Discretization | Unstructured (Tetrahedra) |
| 3. ZENCRACK | 1. Fatigue Crack Growth<br>2. Time-Dependent Crack Growth<br>3. Combined Fatigue and Time-Dependent Crack Growth | 1. Stress Intensity Factors<br>2. Energy Release Rate<br>3. J-integral | Unstructured (Triangles or Tetrahedra) |
| 4. LYNX | 1. Nominal-Stress Method<br>2. Local Stress–Strain Method<br>3. Hybrid Deep Learning Approach<br>4. Models Based on Crack Nucleation | 1. Crack Growth Equation<br>2. Virtual Crack Closure Technique (VCCT)<br>3. Extended Finite Element Method with Phantom Nodes (XFEM-PN) | Unstructured (Triangles or Tetrahedra) |
| 5. FEMFAT | 1. Stress-Life (S-N) Approach<br>2. Nominal-Stress Method<br>3. Unit-Load-Based Approach<br>4. Strain-Life Approach<br>5. Critical Plane Analysis<br>6. Damage Accumulation Models | 1. Paris's Law<br>2. Modified Wheeler Model<br>3. Crack Opening Displacement (COD) Method<br>4. Element Deletion Technique<br>5. Cohesive Zone Modeling (CZM) | Unstructured (Triangles or Tetrahedra) |
| 6. COMSOL | 1. Stress-Life Approach<br>2. Strain-Life Approach<br>3. Energy-Based Results<br>4. Cumulative Damage Assessment<br>5. Vibration Fatigue | 1. Virtual Crack Closure Technique (VCCT)<br>2. Extended Finite Element Method (XFEM)<br>3. Cohesive Zone Modeling (CZM)<br>4. Fracture Mechanics Criteria<br>5. Phase Field Method | • Structured (Mapped and Swept)<br>• Unstructured (Tetrahedral, Quad, and Triangular) |
| 7. ANSYS | 1. Stress-Life Approach<br>2. Strain-Life Approach<br>3. Virtual Crack Closure Technique (VCCT)<br>4. Cohesive Zone Method (CZM)<br>5. Extended Finite Element Method (XFEM) | 1. Paris's Law<br>2. J-integral<br>3. Critical Stress-Intensity factor | Unstructured (Tetrahedral) |

**Table 2.** Comparison of fatigue crack growth simulation in 3D modeling software tools.

| Software | Fatigue Crack Growth Features | Strengths | Considerations |
|---|---|---|---|
| ABAQUS | Offers cohesive zone modeling for crack propagation. | Widely used in engineering and research: ABAQUS has a strong user base and extensive documentation. | Learning curve for beginners: new users may need time to grasp its features and workflows. |
| | Supports Paris's law and other fatigue models. | Robust solver capabilities: ABAQUS provides efficient solvers for complex simulations. | Licensing costs for commercial use: consider budget constraints if opting for the commercial version. |
| FRANC3D | Specialized for 3D fatigue crack growth analysis. | Focuses on crack front tracking and SIFs: FRANC3D excels in accurately capturing crack behavior. | Expertise in fracture mechanics: users should understand fracture mechanics principles for optimal use. |
| | Provides advanced meshing near crack tips. | Well-suited for complex geometries: especially useful for intricate crack shapes and irregular boundaries. | Limited user community: smaller community compared to larger software tools. |
| FEMFAT | Dedicated to fatigue life prediction. | Fatigue-specific material data and models: FEMFAT focuses on fatigue-related properties. | May lack other general-purpose simulation features: not ideal for non-fatigue analyses. |
| | Integrates with FEA software (e.g., ANSYS). | Efficient for industrial applications: widely used in automotive and aerospace industries. | May not handle complex crack geometries as well: limited to simpler crack shapes. |
| ANSYS | Comprehensive suite with fatigue modules (e.g., ANSYS Fatigue). | Versatile for various simulations: ANSYS covers structural, thermal, and fluid dynamics analyses. | Licensing costs and complexity: ANSYS offers multiple modules, each with its own licensing. |
| | Offers crack growth analysis using Paris's law, Walker law, etc. | Strong user community and support: active forums and resources available. | May require additional modules: some fatigue features may be part of separate ANSYS modules. |
| LYNX | Lightweight open-source tool for crack growth simulations. | Free and accessible: LYNX is an excellent choice for budget-conscious users. | Limited features compared to commercial software: basic functionality without advanced features. |
| | Focuses on linear elastic fracture mechanics (LEFM). | Suitable for educational purposes and small projects: ideal for learning and quick analyses. | May not handle nonlinear behavior: limited to linear elastic materials. |
| ZENCRACK | Specialized for crack propagation analysis. | Efficient for specific fatigue scenarios: ZENCRACK focuses on crack behavior. | Less widely known; limited documentation: users may need to explore features independently. |
| | Includes advanced meshing and adaptive remeshing. | Good for research and specialized applications: useful for academic studies and niche problems. | May lack other simulation capabilities: primarily designed for crack analysis. |
| COMSOL Multiphysics | Multiphysics platform with fatigue modules. | Integrates fatigue with other physics: COMSOL allows for coupling fatigue with thermal, structural, etc. | Learning curve due to multiphysics nature: users need to understand multiple physics domains. |
| | Customizable using COMSOL's scripting and modeling tools. | Suitable for academic and industrial research: widely used in research institutions and industries. | Resource-intensive for large-scale simulations: multiphysics simulations can be computationally heavy. |

According to the available literature, Table 3 presents a compilation of real-life applications for each of the mentioned software, providing insights into their practical uses across various industries and engineering disciplines. This table outlines specific application areas and highlights the diverse range of fields where these software solutions have been employed successfully.

**Table 3.** Some real-life applications of the specified software.

| | Software | Application |
|---|---|---|
| 1. | ABAQUS | • Automotive industry: crashworthiness analysis, vehicle dynamics, railway axle, railway wheel, and structural integrity [115–118].<br>• Aerospace industry: aircraft structural analysis, composite material analysis, and fatigue life prediction [119–121].<br>• Civil engineering: structural analysis of buildings, bridges, and dams [122–124].<br>• Biomechanics: analysis of orthopedic implants and human body mechanics [125–127]. |
| 2. | FRANC3D | • Aerospace industry: evaluation of fatigue life and crack propagation in aircraft components [127,128].<br>• Power generation: assessment of crack growth in turbine blades and power plant components [129–131].<br>• Structural engineering: analysis of cracks in bridges, pipelines, and offshore structures [132,133]. |
| 3. | ZENCRACK | • Aerospace industry: assessing fatigue crack growth in aircraft components [134,135].<br>• Automotive industry: predicting crack propagation and estimating remaining fatigue life in automotive parts and railway axles [136].<br>• Power generation: evaluating fatigue crack growth in turbine blades and power plant structures [137,138]<br>• Structural engineering: analyzing fatigue crack growth in bridges, offshore structures, and pipelines [139]. |

**Table 3.** *Cont.*

| | Software | Application |
|---|---|---|
| 4. | LYNX | • Automotive industry: LYNX is used for structural analysis and simulation of vehicle components, such as chassis, body structures, and safety systems [140].<br>• Aerospace industry: LYNX is applied in the analysis of aircraft structures, including wings, fuselages, and landing gear [58].<br>• Civil engineering: LYNX is utilized for structural analysis of buildings, bridges, tunnels, and other civil infrastructure projects [141]. |
| 5. | FEMFAT | • Aerospace industry: FEMFAT assesses fatigue life and predicts crack growth in critical components like aircraft wings, landing gear, and engine parts [142].<br>• Power generation: FEMFAT examines fatigue crack growth in gas turbines, steam turbines, and wind turbines [143].<br>• Heavy machinery and equipment: FEMFAT analyzes fatigue crack growth in construction, mining, and industrial machinery [142].<br>• Rail and transportation: FEMFAT studies fatigue crack growth in railway tracks, train bogies, and wheels [144]. |
| 6. | COMSOL | • Aircraft structures: engineers use COMSOL to simulate crack propagation in critical components like wings, fuselage, and landing gear [145].<br>• Automotive components such as engine parts, suspension systems, and chassis [79].<br>• Pipelines and pressure vessels in oil and gas industries [146].<br>• MEMS (micro-electro-mechanical systems): COMSOL can simulate crack propagation in MEMS structures, considering electromechanical coupling and thermal effects [147,148].<br>• Metallic additive manufacturing (3D printing): COMSOL enables modeling of crack initiation and propagation in these complex geometries [149].<br>• Biomedical implants: COMSOL helps simulate crack growth around implant interfaces, considering material properties and physiological conditions [150]. |
| 7. | ANSYS | • Aerospace industry such as aircraft structures, engine components, and critical parts like turbine blades [115,151].<br>• Automotive industry such as engine parts, suspension systems, and chassis [152].<br>• Power generation such as gas turbines, steam turbines, and power plant structures [153].<br>• Structural engineering: ANSYS Workbench is utilized in civil engineering projects to analyze fatigue crack growth in bridges, offshore structures, and other infrastructure [154,155]. |

## 3. Conclusions

This study provides a comprehensive and objective comparison of seven 3D modeling software packages, namely ABAQUS, FRANC3D, ZENCRACK, LYNX, FEMFAT, COMSOL Multiphysics, and ANSYS, for fatigue crack growth analysis in specific applications. The comparisons show that each software has its own strengths and weaknesses, depending on the type of problem, the level of complexity, the required accuracy, and the available resources. This study also identifies the key factors and criteria that should be considered when selecting a suitable software tool for a specific application. This study aims to help researchers and engineers make informed decisions and to optimize their fatigue crack growth modeling processes. The study demonstrated the importance and benefits of conducting such comparative studies, as they can improve the quality and reliability of fatigue crack growth modeling and structural integrity assessment.

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