

Lifetime prediction of a typical rocket combustion chamber by means of viscoplastic damage modeling

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To Sebastian

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Summary

The lifetime of a launch vehicle is determined by the cyclic lifetime of its major components. In this regard, the combustion chamber of a rocket engine is one of the most important components of a launch vehicle. It undergoes extreme cyclic thermomechanical loading during its operation. Due to its high thermal conductivity and ductile behavior, the application of copper alloy as the liner material of the cooling channels is well established. However, it is well known that after several engine cycles the wall of the cooling channels becomes thinner and bulges towards the interior of the chamber before crack of the cooling channel wall eventually occurs. This failure mode which limits the lifetime of the thrust chamber is known as the "doghouse" effect.

Due to the high cost of experimental studies, efficient numerical analysis methods for lifetime prediction of a combustion chamber are becoming more and more important. In this context, an accurate lifetime prediction of the combustion chamber requires a material model which takes viscous behavior, hardening phenomena and damage into account.

This dissertation focuses on the development of viscoplastic damage models for the lifetime prediction of a typical rocket combustion chamber. Two types of unified viscoplastic damage models were developed and implemented into a finite element software. The first type is based on a scalar damage variable (isotropic damage). The second type considers damage through a damage tensor of second order (anisotropic damage). Both types are suitable for failure prediction of ductile metallic materials.

Thermomechanical analyses of a combustion chamber segment incorporating these material models were performed to numerically describe the doghouse failure mode. The investigations show that with the help of the developed damage models, the observed doghouse effect can be described numerically. Moreover the models are suitable to be used for lifetime prediction of structures subject to low cycle fatigue failure.

The developed viscoplastic damage model coupled with isotropic damage is implemented into a computational environment which is specially developed for fluid-structure interaction analysis of a rocket nozzle defined by Astrium Space Transportation GmbH. The computation is carried out for one engine cycle and is able to predict the location of the damage downstream of the throat. With this implementation the potential of the combined numerical schemes for lifetime prediction of the combustion chamber could be shown.

Zusammenfassung

Die Lebensdauer einer Trägerrakete ist durch die zyklische Lebensdauer der Hauptkomponenten begrenzt. In dieser Hinsicht ist die Brennkammer eines Raketentreibwerks eine der wichtigsten Komponenten einer Trägerrakete. Sie ist während des Betriebs extremer zyklischer thermomechanischer Belastung ausgesetzt. Aufgrund der hohen Wärmeleitfähigkeit und des duktilen Verhaltens hat sich die Anwendung von Kupferlegierungen als Auskleidungsmaterial der Kühlkanäle etabliert. Es ist jedoch bekannt, dass nach mehreren Betriebszyklen die Wand der Kühlkanäle dünner wird und sich in Richtung der Kammer ausbeult, bevor es letztendlich zum Bruch der Kühlkanalwand kommt. Dieser Versagensmodus, der die Lebensdauer der Brennkammer begrenzt, wird als "Doghouse"-Effekt bezeichnet.

Aufgrund der hohen Kosten für experimentelle Untersuchungen gewinnen effiziente numerische Verfahren zur Lebensdauervorhersage einer Brennkammer immer mehr an Bedeutung. In diesem Zusammenhang erfordert eine genaue Vorhersage der Lebensdauer der Brennkammer ein Materialmodell, das sowohl viskosos Verhalten als auch Verfestigung und Schädigung berücksichtigt.

Diese Dissertation konzentriert sich auf die Entwicklung von viskoplastischen Schädigungsmodellen für die Lebensdauervorhersage einer typischen Raketenbrennkammer. Zwei Arten von viskoplastischen Schädigungsmodellen wurden entwickelt und in ein FE-Programm implementiert. Die erste Variante basiert auf einer skalaren Schädigungsvariablen (isotrope Schädigung). Die zweite Variante berücksichtigt die Schädigung durch einen Schädigungstensor zweiter Ordnung (anisotrope Schädigung). Beide Varianten eignen sich für die Lebensdauervorhersage von duktilen metallischen Werkstoffen.

Thermomechanische Analysen eines Segmentes der Brennkammer wurden mit diesen Materialmodellen durchgeführt, um den Versagensmodus ("Doghouse"-Effekt) numerisch zu beschreiben. Die Untersuchungen zeigen, dass mit Hilfe der entwickelten Schädigungsmodelle der beobachtete Versagensmodus ("Doghouse"-Effekt) numerisch abbildungbar ist. Des weiteren eignen sich die Modelle zur effizienten Lebensdauervorhersage von Strukturen, die durch Niedrig-Lastwechsel-Ermüdung versagen.

Das entwickelte viskoplastische Schädigungsmodell gekoppelt mit isotroper Schädigung wurde in eine Rechenumgebung implementiert, die speziell für die Strömungs-Struktur-Wechselwirkungs-Analyse einer Raketendüse von Astrium Space Transportation GmbH entwickelt wurde. Die Berechnung wurde für einen Betriebszyklus durchgeführt. Sie ist in der Lage, den Schädigungsort stromabwärts des Brennkammerhalses vorherzusagen. Mit dieser Implementierung konnte das Potenzial der kombinierten numerischen Verfahren zur Lebensdauervorhersage von Brennkammern aufgezeigt werden.

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