Biaxial Response of Composite Propellant at Low Temperature: Effect of Displacement Rate and Biaxiality Ratio

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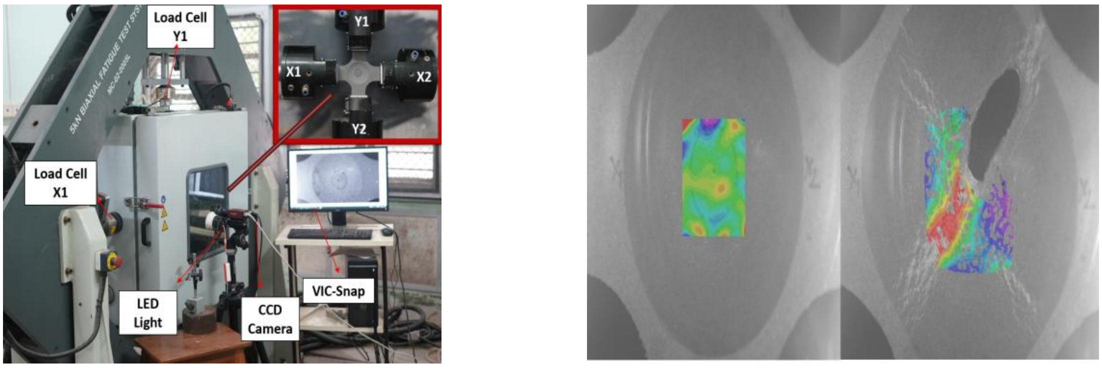
Abstract. This study investigates the biaxial tensile behaviour of hydroxyl-terminated polybutadiene (HTPB)-based composite solid propellants (CSPs) at low temperature (−40°C). Biaxial tensile tests were performed on optimized cruciform specimens, and full-field strain measurements at the gauge section were carried out using Digital Image Correlation (DIC). The low-temperature response was systematically compared with that at room temperature (20°C) to assess the influence of thermal conditions on the mechanical behaviour. Furthermore, to examine the effects of displacement rate and biaxiality ratio, experiments were conducted at 1, 50, and 1000 mm/min and biaxiality ratios of 1:1 and 0.5:1. The results demonstrate a nonlinear, temperature-dependent stress-strain response, with the material exhibiting increased stiffness and failure stress but reduced failure strain at −40°C compared to 20°C. Increasing displacement rate results in a corresponding rise in stiffness, failure stress, and failure strain. Variation in the biaxiality ratio significantly alters the material's stress distribution and deformation response. Under a biaxiality ratio of 0.5:1, deformation in the Y-direction strongly influences the response in the x-direction, leading to interdependent strain development between the two orthogonal axes. This asymmetric loading condition promotes earlier damage initiation in the x-direction and results in a progressive change in stiffness, attributed to pre-strain effects arising from the dominant deformation in the y-direction.

Introduction

Composite solid propellants (CSPs) are energetic materials widely used in solid rocket motors (SRMs) and consist of a polymeric binder matrix containing oxidizers, metallic fuels, and additives. This heterogeneous composition provides high energy output while maintaining structural integrity under operational conditions. The mechanical behaviour of CSPs is governed by the interaction between the binder and dispersed particles, which can be tailored through microstructural design. During service, propellant grains are subjected to combined thermal and mechanical loads, which may lead to stress and strain levels exceeding material limits. This can result in crack initiation and propagation, increasing the effective burning surface area and potentially causing combustion instability and failure of the motor [3]. Uniaxial tests are commonly used to characterize CSPs. However, they are insufficient for capturing the response under realistic multiaxial stress states. Although CSPs are initially quasi-isotropic, large deformations lead to microvoid formation and particle-matrix debonding, resulting in damage-induced anisotropy [2]. Consequently, the mechanical response becomes direction-dependent.



(a) Biaxial experimental setup (b) Variation of strain ϵ_{yy} obtained from DIC analysis.

Figure 1: Biaxial testing setup and corresponding DIC-based strain field analysis.

Biaxial testing provides a representative assessment by imposing loads along two perpendicular directions, enabling reliable characterization of deformation behaviour and failure mechanisms under multiaxial loading conditions. Several experimental approaches have been used to achieve biaxial loading such as bulge tests, combined tension and torsion tests, combined bending and in-plane tests, and combined axial load with internal pressure tests, but many of them provide limited control over the applied stress state and often result in non-uniform deformation. Cruciform specimens overcome these issues by allowing independent loading in two directions and ensuring a well-defined stress state in the gauge [5].

Results and Discussion

The tensile response of CSPs is strongly influenced by both displacement rate and temperature [1, 4]. The stress-strain behaviour remains nonlinear across all test conditions, with higher displacement rates resulting in increased stiffness and higher stress levels at a given strain (refer fig. 2), consistent with the rate-dependent viscoelastic response of the binder. Additionally, the failure strain increases with displacement rate due to the limited time available for void growth and coalescence, which delays damage localization and the onset of macroscopic failure. In contrast, at −40°C, stiffness and failure stress increase, while failure strain decreases, indicating a transition in failure mechanism. Under non-equibiaxial (0.5:1) loading, a consistently higher initial slope in the x-direction was observed, attributed to Poisson-driven pre-strain induced by greater deformation in the y-direction, leading to enhanced stiffness in the transverse direction during early loading. This phenomenon reflects anisotropic coupling between strain directions, in which lateral contraction or expansion influences the local stress state and microstructural response. Such behavior can also be linked to the interaction between particle-matrix debonding and microvoid formation, which are direction-dependent and affect stiffness differently along each axis.

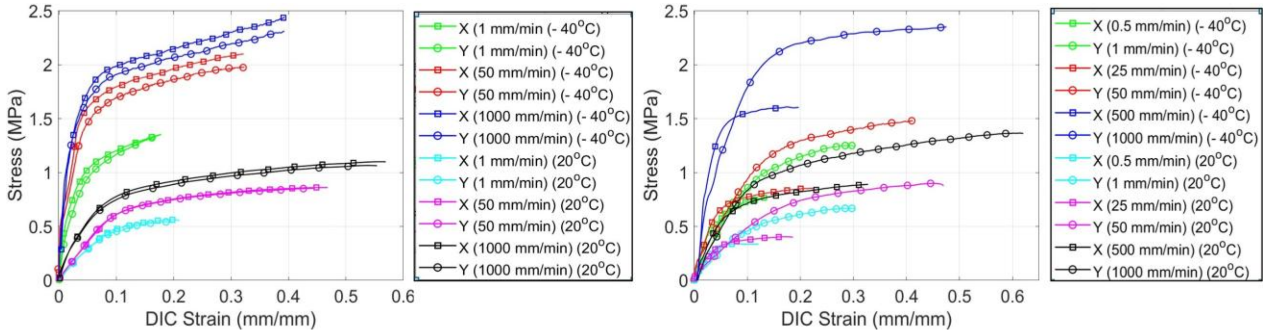


Figure 2: Stress–strain response for Biaxiality ratios of 1:1 and 0.5:1

These observations demonstrate the coupled influence of displacement rate, temperature, and biaxiality ratio on the deformation and failure behaviour of CSPs, where stiffness evolution and macroscopic response are strongly governed by these factors. Such behaviour cannot be captured through uniaxial testing, as it does not account for the interaction between deformation in orthogonal directions and the associated stress redistribution. The present work, therefore, emphasizes the need for biaxial characterization to better describe service conditions and accurately evaluate the macroscopic response of CSPs.

References

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