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Mechanistic Fatigue Damage in Double-Network and Granular Double-Network Elastomers Under Force and Strain Controlled Cyclic Loading

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Abstract

Double network (DNE) and double network granular elastomers (DNGE) are emerging soft materials with high toughness and strong dissipation through sacrificial network mechanisms. Despite their promise, their long term durability under different cyclic loading conditions is not well understood. This work presents a systematic comparison of fatigue damage in DNEs and DNGEs under both strain controlled and force controlled cyclic loading, supported by independent tests probing hardening, stress relaxation, creep, and Mullins type softening. Notably, this study includes the first force controlled fatigue experiments conducted on soft materials. Fatigue tests are performed across a range of maximum stretch ratios (λ_max), stress ratios, and R ratios to characterize how loading mode and stress amplitude influence damage accumulation. Strain controlled tests isolate intrinsic microstructural degradation by maintaining constant deformation amplitude, enabling clear evaluation of stiffness changes, hysteresis evolution, and internal damage growth. In contrast, force controlled tests reveal stress driven mechanisms such as cycle dependent strain drift, amplification of deformation near critical stress levels, and transitions toward instability, highlighting how DNEs and DNGEs respond when stress is the dominant driving factor. To interpret these behaviors, we conduct a series of complementary mechanical tests. Hardening experiments, involving repeated cycling between −10% and +10% strain, quantify stiffness evolution and provide a baseline for early-cycle microstructural rearrangements. Stress relaxation tests at identical peak stresses but different λ_{max} and R ratios demonstrate how loading history influences internal stress redistribution. Creep experiments quantify time dependent deformation and reveal residual damage that persists after unloading. Mullins effect tests capture irreversible softening associated with sacrificial bond breakage. Together, these experiments create a unified picture of fatigue damage in DNEs and DNGEs. DNGEs exhibit reduced Mullins softening, slower strain drift under force control, and greater stability at high stress ratios, suggesting enhanced ability to redistribute stresses through granular bridging. DNEs, in contrast, show stronger sensitivity to R ratio and more pronounced stress softening. Overall, this study provides the first comprehensive mechanical and fatigue evaluation of double network and double network granular elastomers under both deformation and stress controlled loading. The results establish fundamental mechanistic links between microstructural architecture and long-term cyclic durability, offering key guidelines for the design of next-generation fatigue resistant soft materials.

Keywords:

Double network granular elastomers Double network elastomers Fatigue damage Force controlled cyclic loading Strain controlled cyclic loading R-ratio