A multi-stage inverse Finite Element method for determining the constitutive model for human heel pad under high rate axial loading

Jean Sebastian Giudice, Lee Gabler, Matthew B. Panzer

Center for Applied Biomechanics, Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA

Abstract

A primary injury mechanism for troops in armored vehicles exposed to an underbody blast (UBB) event is high-rate axial loading to the foot caused by rapid intrusions of the vehicle's deforming floor. Previous analysis using finite element (FE) human body models has demonstrated that the non-linear and viscoelastic properties of the heel pad material significantly influence the force response of the tibia in high rate axial loading of the foot. While material characterization of heel pad provides some insight into the constitutive material behavior, suitable closed-form analytical solutions do not exist for determining the constitutive relationship of the material due to the complex boundary conditions, sample dimensions, inertial effects, and the temporal nature of these types of test. This poses a significant challenge for implementing appropriate material models in FE.

One technique that is gaining popularity for determining constitutive models from non-analytical mechanical tests is inverse finite element analysis (iFE). This method involves optimization of constitutive model parameters to reduce the error between simulation and experimental response. Due to the iterative nature of this method, and the likelihood for a substantial number of long-duration simulations that track the time history of the material, the success of iFE for non-linear, viscoelastic materials in the literature is limited to simplistic constitutive models with few time constants and few experimental samples. To overcome feasibility issues associated with non-linear, viscoelastic iFE, we have developed a multi-stage method that utilizes the viscoelastic relaxation process to reduce the complexity of the optimization process and the overall computational cost of iFE.

This method was applied to a previously reported experimental dataset from seventeen human heel pad tissue samples tested in compressive stress-relaxation (loading rate up to 60 s-1, holding time 30s). A constitutive model framework based on a Fung Quasi-Linear Viscoelastic (QLV) model that was implemented in Ls-Dyna as a user material. The relaxation function of the QLV consisted of 5 time constants ranging from 1 ms to 10 s. FE models of each test specimen were developed, and displacement loading conditions from each experiment were applied directly to the specific model. Elastic and viscoelastic material coefficients were determined via *a conjugate gradient method by minimization of the sum of squared errors between the force time-histories of the FE model and the experiment, up to the entire 30s history of the test.*

All iFE model fits showed good agreement with the experimental data, and were comparable to the model fits previously developed analytically for this data under a number of simplifying assumptions. However, the coefficients of the elastic and viscoelastic portions of the constitutive models were substantially different between the iFE and analytical fitting methods. In general, the iFE method was not as sensitive to the short time-constants as the analytical method, resulting in lower stiffness elastic response and a delayed relaxation response. Additionally, the existing analytically-derived constitutive model, when implemented in the FE model, did not reproduce the experimental force time-histories as well as the iFE constitutive model.