Multi-axial Mullins effect in EPDM subjected to complex strain histories

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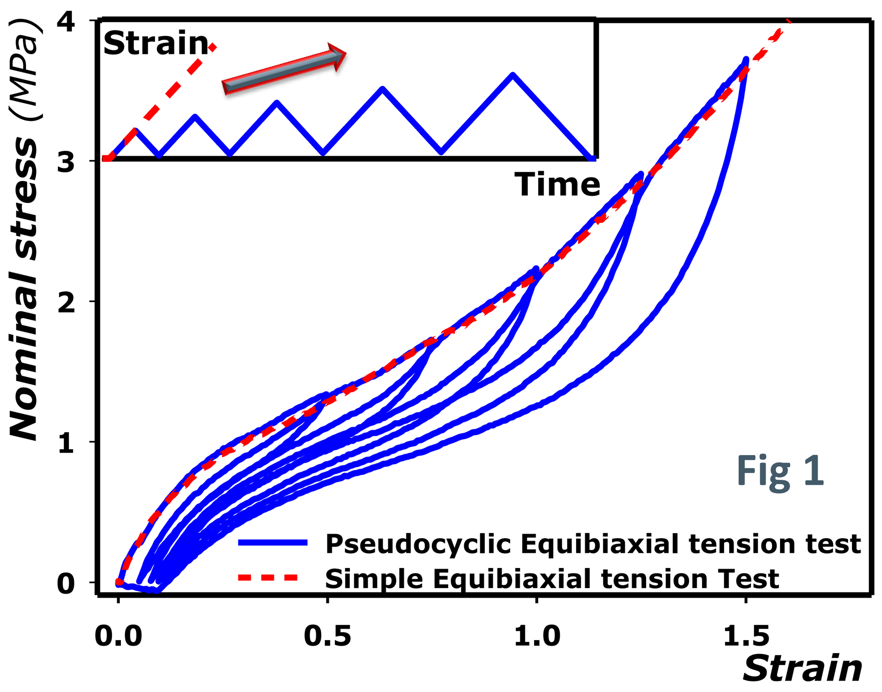
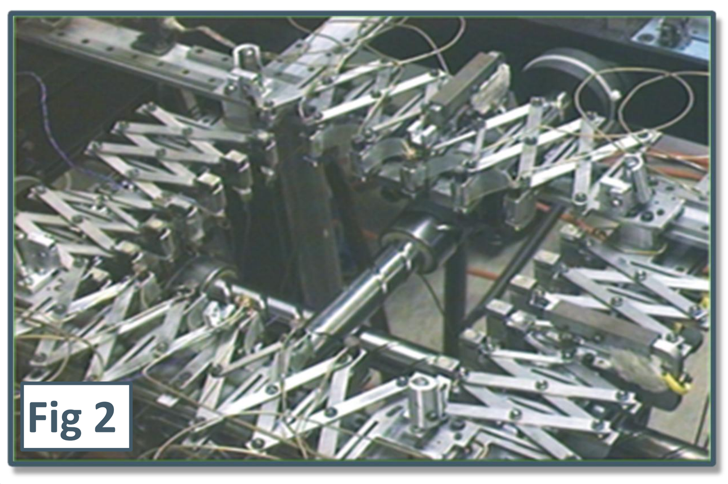
Introduction

The Mullins effect is a strain-softening phenomenon associated with filled elastomers in which, for simple cyclic loading, the material becomes softer (i.e. less stiff) on subsequent loadings within deformation envelopes it has previously experienced. This phenomenon is most frequently studied under uniaxial deformation, although it manifests itself in a similar fashion under biaxial deformation (eg. **Fig 1**). As is clearly visible in pseudo-cyclic deformation, the original stress-strain curve is followed unless the material has previously reached a given strain level. In this work we study the effect of previous multiaxial strain histories where the biaxiality ratio of the previous histories differs from the current deformation.





Materials and methods

A sulphur cross-linked carbon-black filled (50phr) oil extended **ethylene propylene diene (EPDM) rubber** [1] was tested at constant strain rate (0.03 s^{-1}) and room temperature using the Flexible Biaxial Film Tester [2] (**Fig 2**). Four cycles of constant width or equibiaxial deformation to varying maximum strains were applied, and followed by constant width deformation to 150% strain (in the perpendicular axis, in the case of previous constant width deformation).

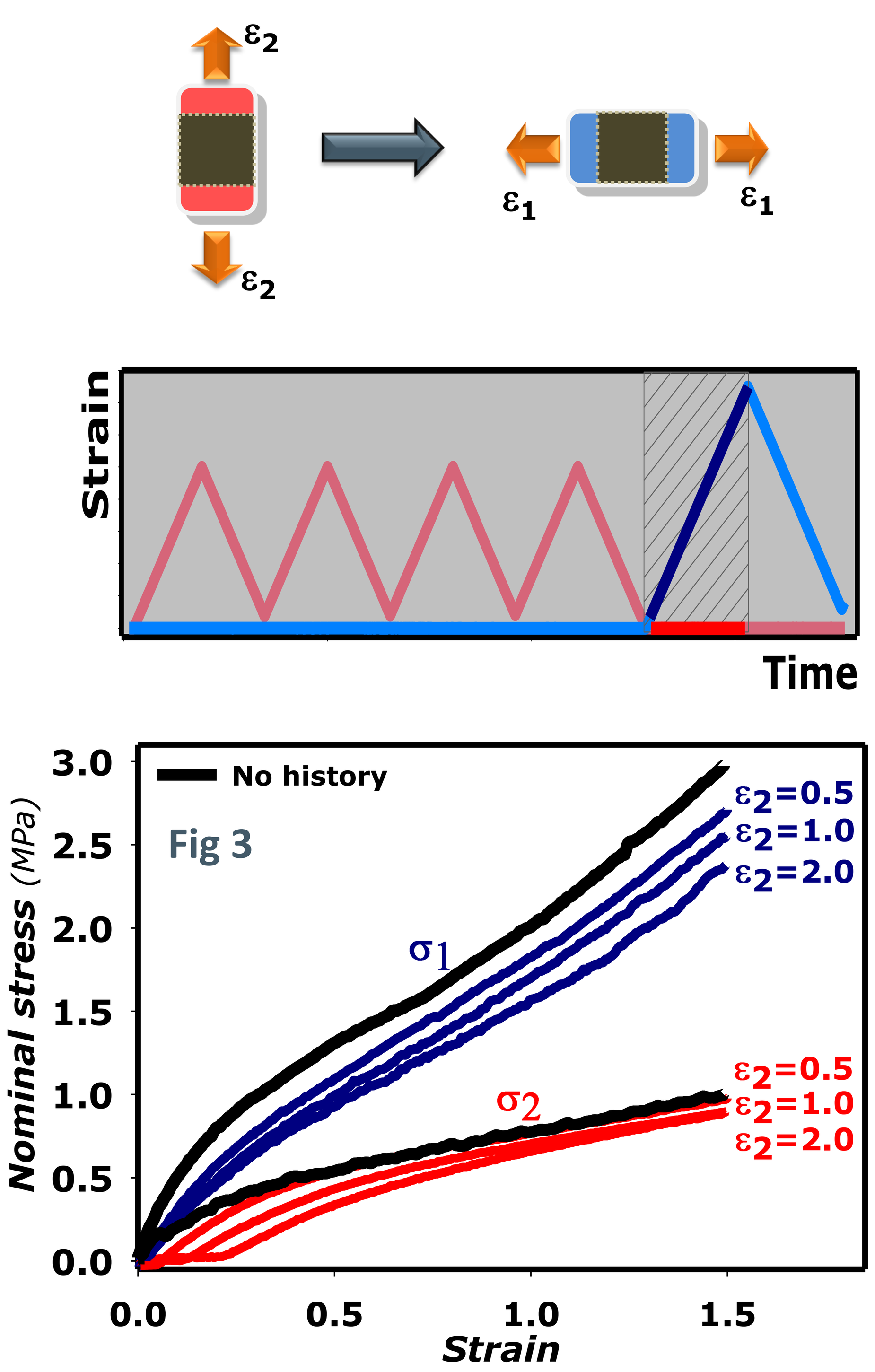
Results and analysis

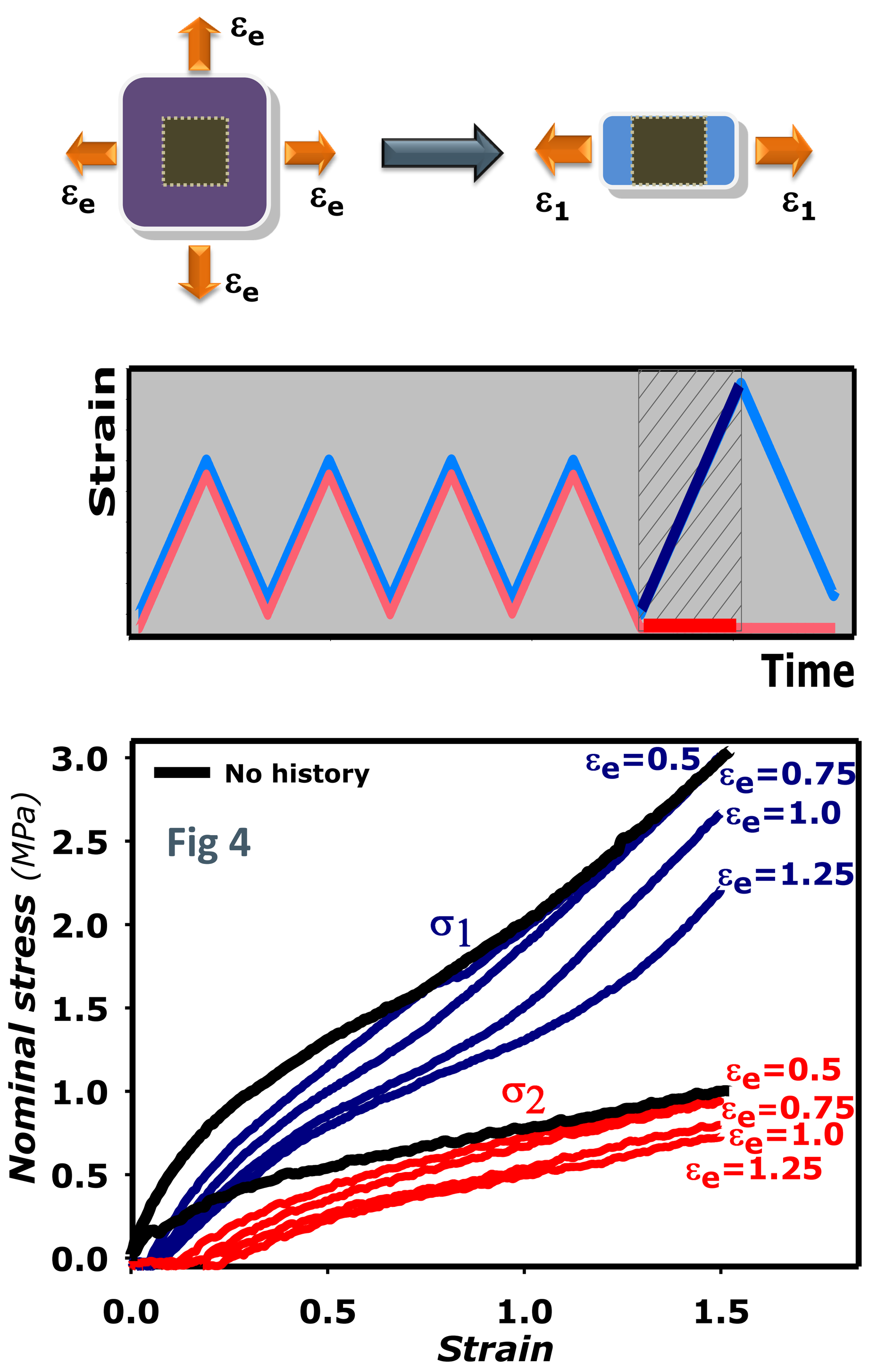
Effect of history on stress-strain curve

Nominal stresses measured in constant width deformation following perpendicular constant width (**⊥CW**) histories are shown in **Fig 3**, and following equibiaxial (**EB**) histories are shown in **Fig 4**.

The effect of **⊥CW** histories on σ_1 is a uniform softening throughout the strain range, whereas following **EB** histories softening is more pronounced in the early part of the curve. Surprisingly, a small (ε=0.5) **EB** history has no effect on large strains, whereas the same small **⊥CW** results in some softening.

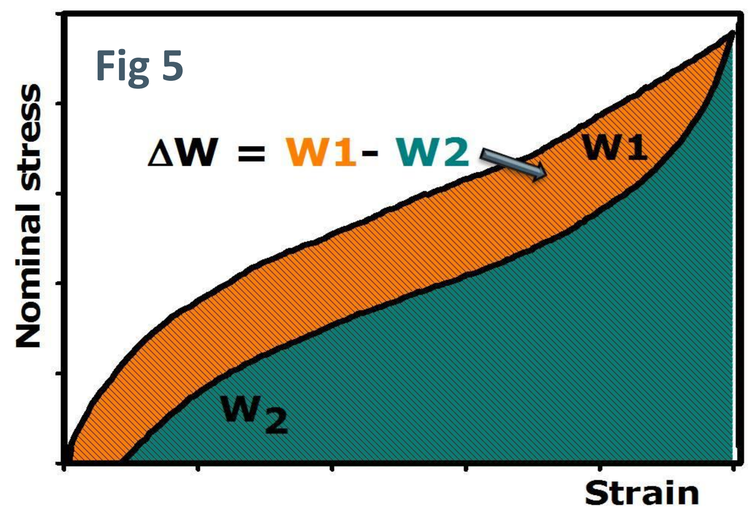
The effect of history on σ_2 is dominated by permanent set, but **⊥CW** and **EB** histories of the same magnitude lead to different responses. The experiments demonstrate that Mullins softening can occur even if the deformation history takes place in another axis, but also that the response of one axis depends on the history of both axes.

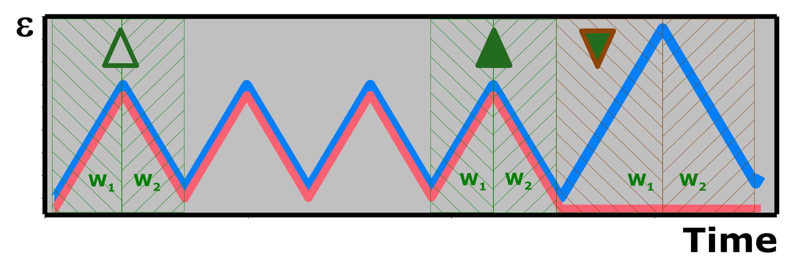


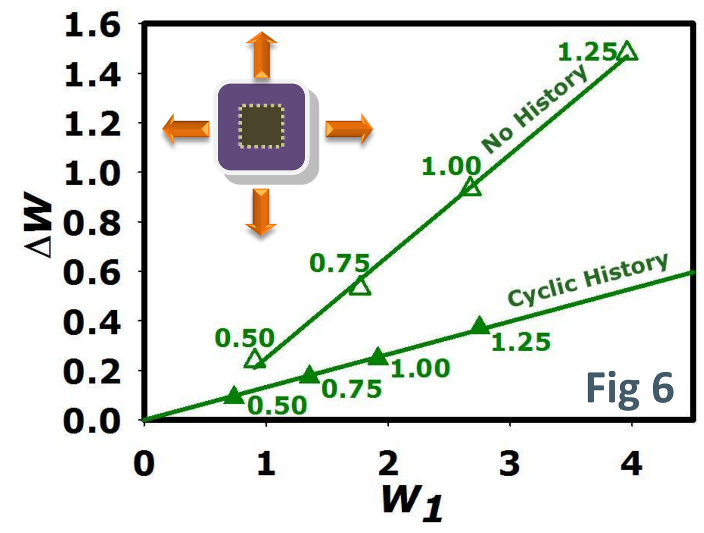


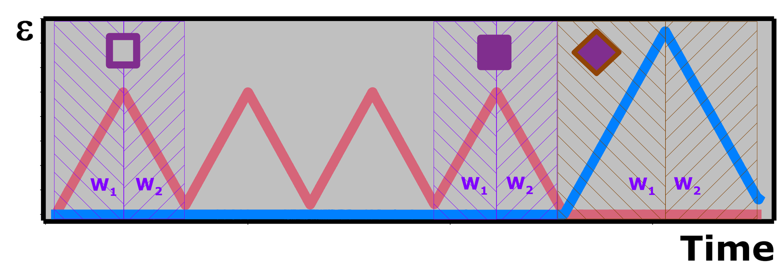
Hysteresis

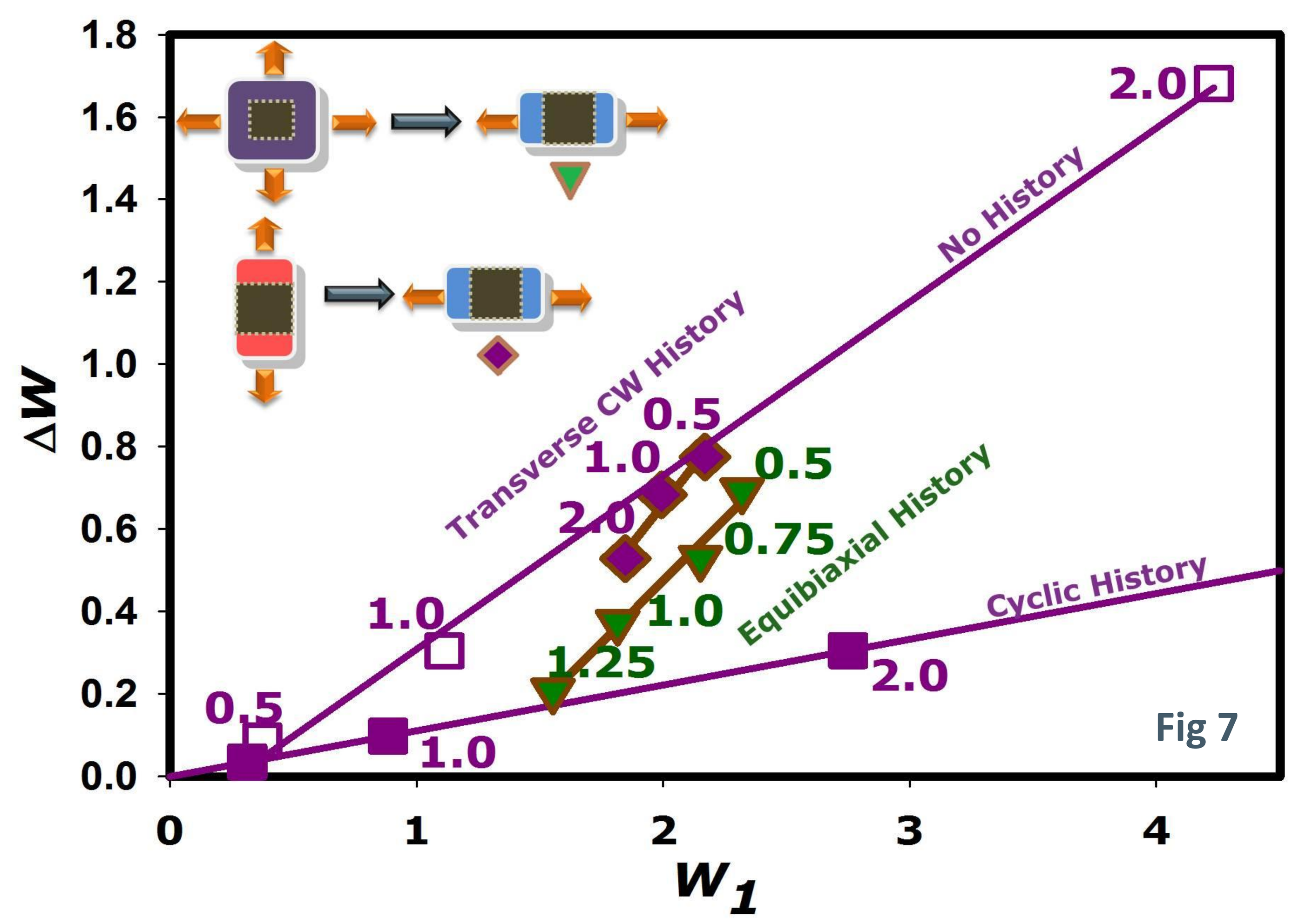
Here we follow the approach of Buckley et al. [3,4] in examining the hysteresis following complex loadings, by plotting the work input W_1 as a function of the hysteresis ΔW following a range of histories (**Fig 5**). In simple histories (where the strain state remains the same) ΔW is a linear function of W_1 for all measured strain levels: with a steeper gradient on first loading, and with a shallower gradient on subsequent loadings (cycle 4 shown, **Fig 6,7**). For complex loadings, we observe that the measured data lie between the *no history* and the *cyclic history* measurements (**Fig 7**).











Conclusions

It is apparent from these experiments that a fully 3D model for the Mullins effect cannot treat the deformation history as a simple scalar quantity. Future work will focus on developing such a model, by considering the manner in which changes in hysteresis manifest themselves following complex histories.

References

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[4] BUCKLEY, C. P., PRISACARIU, C. and MARTIN, C. 2010. *Elasticity and inelasticity of thermoplastic polyurethane elastomers: Sensitivity to chemical and physical structure*. Polymer, 51, 3213-3224.

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