Chapter 2
Transverse Compression Response of Ultra-High Molecular Weight Polyethylene Single Fibers

Subramani Sockalingam, John W. Gillespie Jr., Michael Keefe, Dan Casem, and Tusit Weerasooriya

Abstract This work reports on the experimental quasi static transverse compression response of ultra-high molecular weight polyethylene (UHMWPE) Dyneema SK76 single fibers. The experimental nominal stress-strain response of single fibers exhibits nonlinear inelastic behavior under transverse compression with negligible strain recovery during unloading. Scanning electron microscopy (SEM) reveals the presence of significant voids along the length of the virgin and compressed fibers. The inelastic behavior is attributed to the microstructural damage within the fiber. The compressed fiber cross sectional area is found to increase to a maximum of 1.83 times the original area at 46 % applied nominal strains. The true stress strain behavior is determined by removing the geometric nonlinearity due to the growing contact area. The transverse compression experiments serve as validation experiments for fibril-length scale models.

Keywords UHMWPE • Ballistic impact • Transverse compression • Finite element analysis (FEA) • Constitutive model

2.1 Introduction

Ultra-high molecular weight polyethylene (UHMWPE) fibers are used in personnel protection ballistic impact applications [1] in the form flexible textile fabrics and laminated composites. UHMWPE fiber is made up of extremely long chains of polyethylene (monomer unit >250,000 per molecule) with a hierarchy of sizes and exhibits a fibrillar structure. Macro-fibrils [2] consist of bundles of micro-fibrils which in turn are composed of bundles of nano-fibrils. These fibers lend themselves to such applications due to their superior specific axial tensile strength and specific modulus. The fibers experience multi-axial loading [3] including axial tension, axial compression, transverse compression and transverse shear during impact. While axial specific toughness and longitudinal wave speed are important fiber properties contributing to the ballistic performance [4], the role of transverse properties and multi-axial loading during impact is not well understood. In this work we investigate the quasi static (QS) transverse deformation behavior of UHMWPE Dyneema SK76 single fibers.

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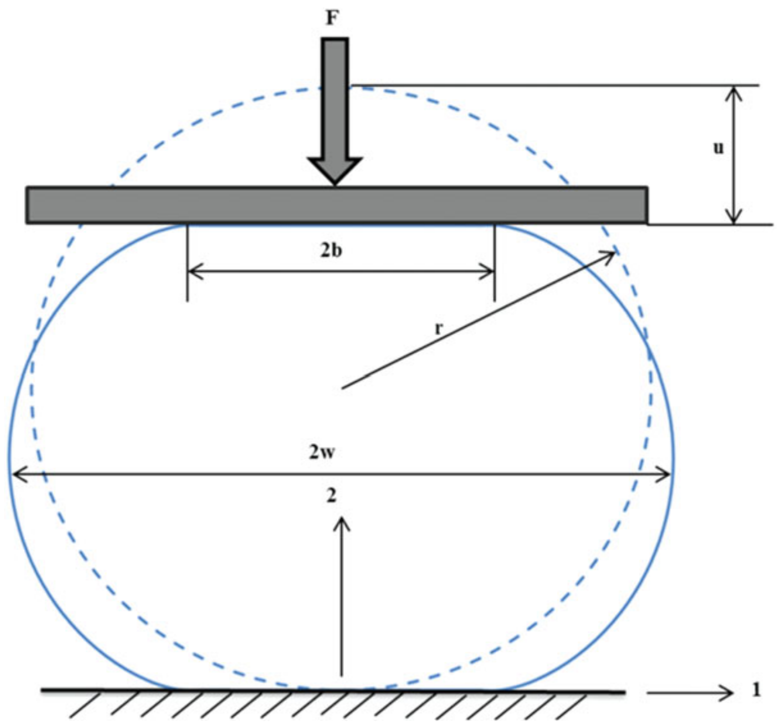

Fig. 2.1 Schematic of single fiber transverse compression

2.2 Experimental Set up

The QS experimental set up involves compressing a single fiber between rigid parallel platens (Sapphire substrates) in plane strain conditions as shown in the schematic in Fig. 2.1. The compressive load per unit length (F), platen displacement (u) and compressed width ($2w$) of the fiber are measured in real time. Contact width ($2b$) is measured post-test at different applied load levels. The fibers are compressed at 0.1 μm/s (average strain rate of 0.0059 s^{-1}). A more detailed explanation of the experimental set up is reported in [5].

2.3 Results and Discussion

The QS experimental nominal stress $\overline{\sigma} = \frac{F}{d}$ nominal strain $\overline{\varepsilon} = \frac{u}{d}$ (d is undeformed fiber diameter) response due to monotonic and cyclic loading is shown in Fig. 2.2. The fibers exhibit a nonlinear inelastic response. The nonlinearity is attributed to both geometric stiffening due to growing contact area and material softening. After each load-unload cycle residual strains are measured.

Figure 2.3 shows scanning electron microscopy (SEM) images of fibers subjected to different levels of maximum nominal strains. The undeformed fiber shown in Fig. 2.3a indicates the presence of significant void like features on the surface and along the length of the fiber. Void like features are also observed on the surface of the compressed fibers.

The normalized contact width (b/r) and compressed width (w/r) growth is shown in Fig. 2.4. At maximum load the compressed width has increased by a factor of 4.5. It is also seen both 2b and 2w plateau at higher load levels to approximately four and a half fiber diameters. Negligible elastic recovery or reduction in width growth is observed during unloading.

The elastic modulus in transverse compression is determined using an analytical solution based on the Hertzian contact for a transversely isotropic fiber given by eqs. 2.1 [6] and 2.2 [7]. The experimental measurements are fitted into eqs. 2.1 and 2.2 to as shown in Fig. 2.5a using the properties in Table 2.1(v31 and v12 in Table 2.1 are assumed values). The analytical solution compares well with the experimental results until about 2 % nominal strains where material softening and damage may be on setting. A transverse modulus of 2.37 GPa and a Hertzian elastic limit of 2 % is determined.

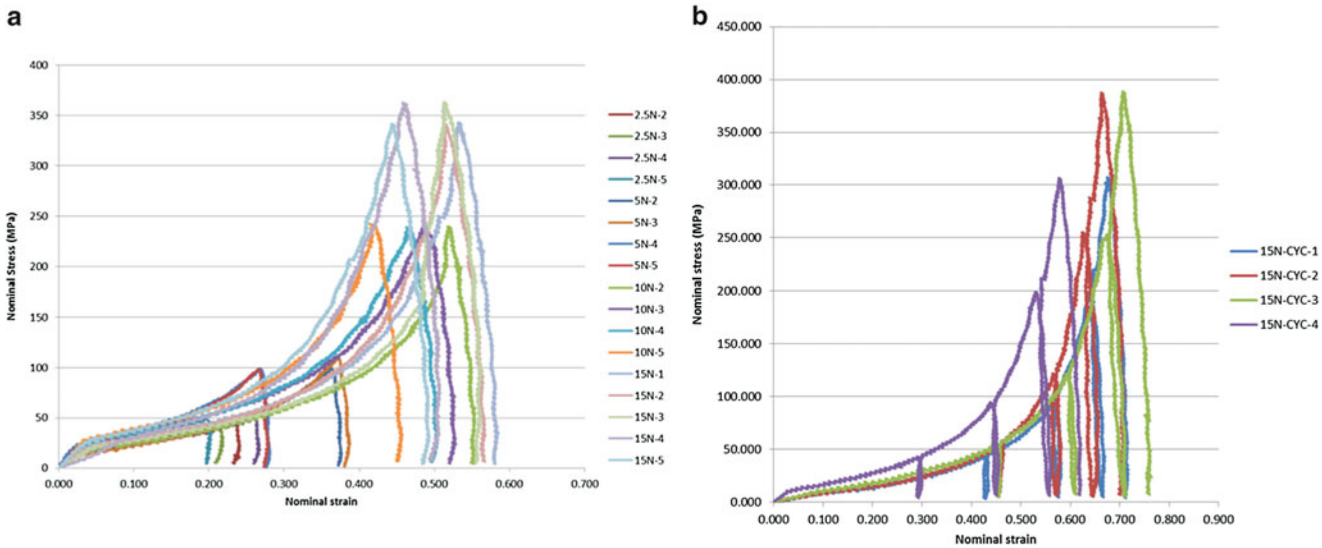

Fig. 2.2 QS experimental (**a**) one load unload cycle on different fibers (**b**) multiple load unload cycle on the same fiber

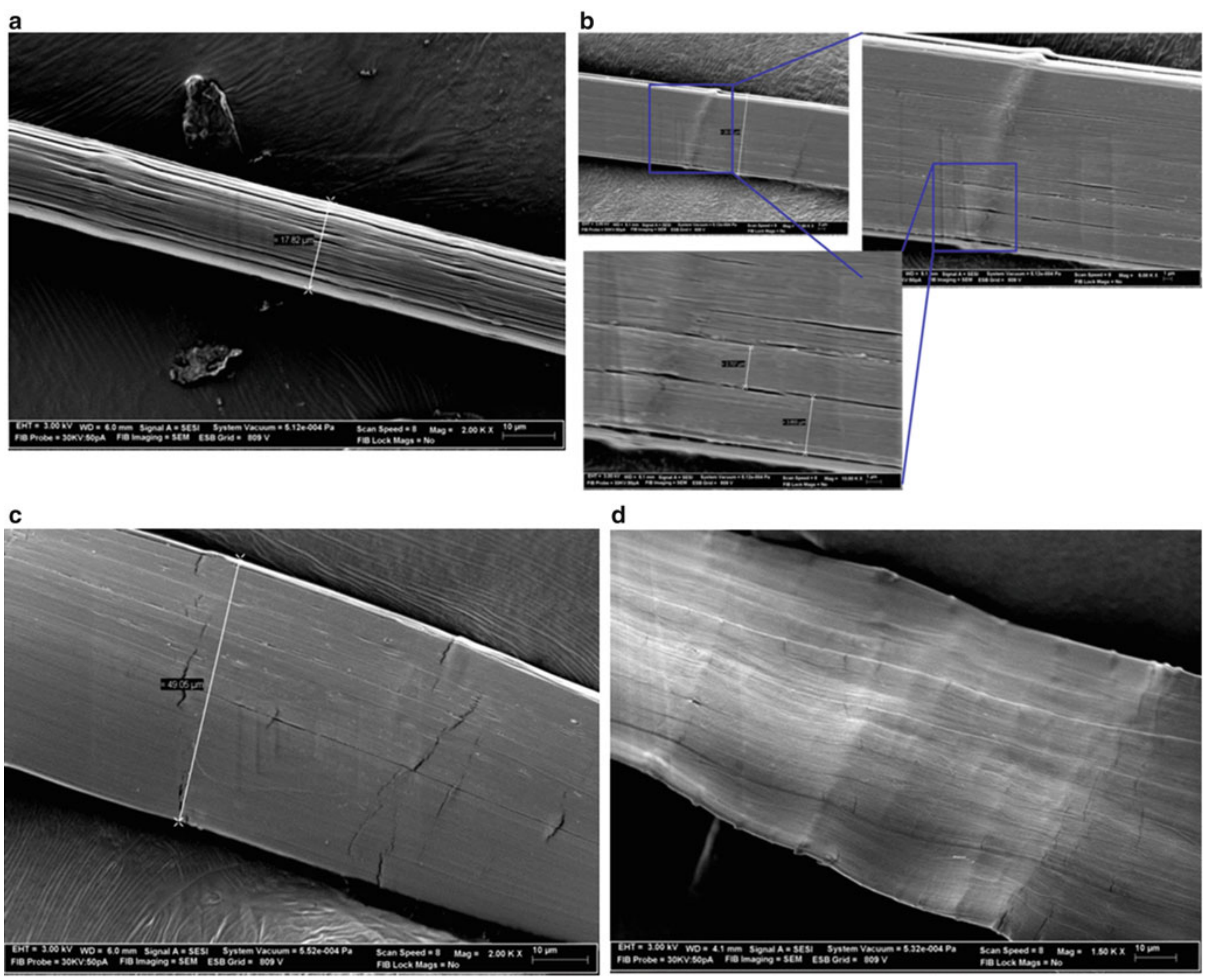

Fig. 2.3 SEM images of deformed fibers at nominal strain levels (**a**) 0 % (**b**) 22 % (**c**) 51 % (**d**) 71 %

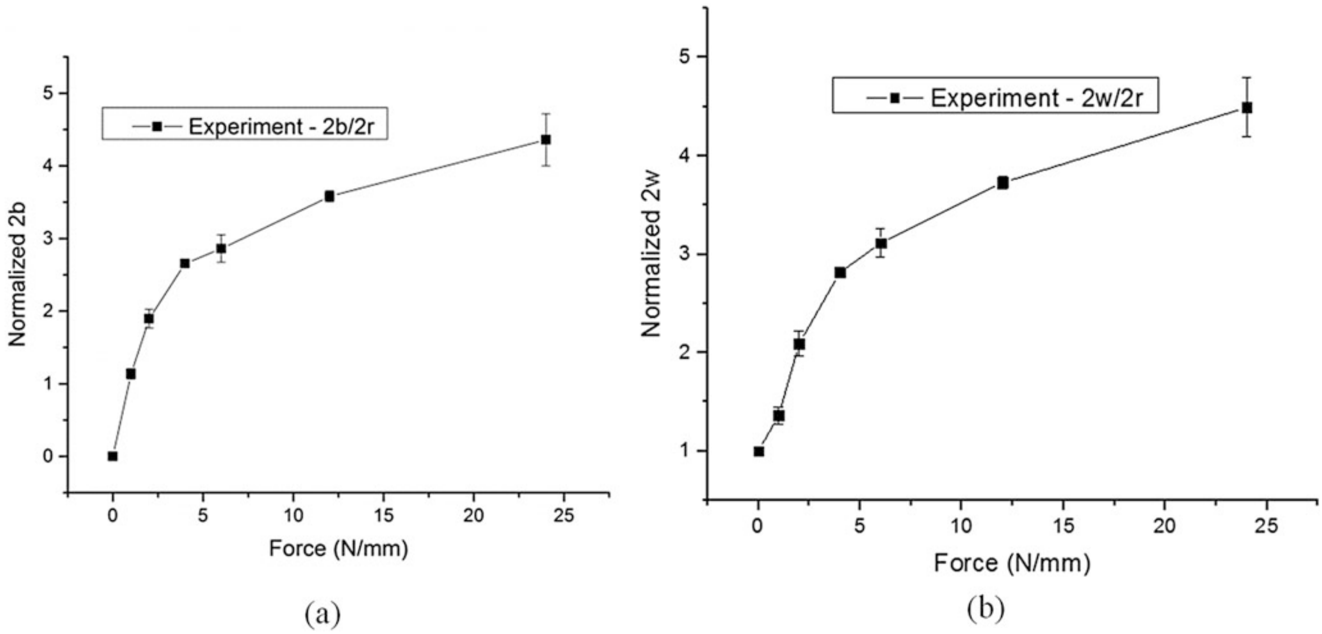

Fig. 2.4 Normalized 2b and 2w

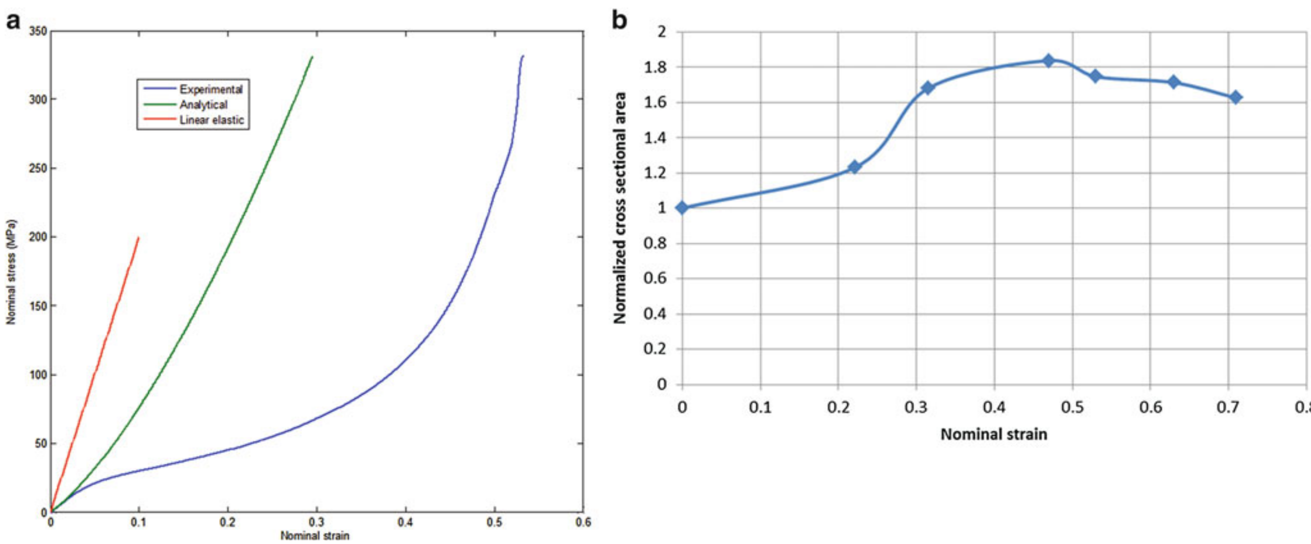

Fig. 2.5 (**a**) Nominal stress strain (**b**) normalized cross sectional area

Table 2.1 Transversely isotropic properties of Dyneema SK76

ρ (g/cm^3)	D (μm)	E_3 (GPa)	ν_{31}	ν_{12}	E_1 (GPa)	Hertzian elastic limit	True elastic limit
0.97	17.0	116.0	0.60	0.40	2.37	2 %	0.5 %

$$u = \frac{4F}{\pi}\left(s_{11} - \frac{s_{13}^2}{s_{33}}\right)\left[0.19 + \sinh^{-1}\left({}^{r}/_{b}\right)\right] \tag{2.1}$$

$$b^2 = \frac{4Fr}{\pi}\left(\frac{1}{E_1} - \frac{\nu_{31}^2}{E_3}\right) \tag{2.2}$$

where,
F—load per unit length along the fiber longitudinal direction
u—platen displacement
L—length of the compressed fiber
r—radius of the fiber
b—contact half width
E_1—Young's modulus in 1–2 plane of transverse isotropy
E_3—longitudinal Young's modulus in the fiber direction
w—compressed half width

$$s_{11} = \frac{1}{E_1} \quad s_{12} = -\frac{\nu_{12}}{E_1} \quad s_{13} = -\frac{\nu_{13}}{E_1} \quad s_{33} = \frac{1}{E_3}$$

The intrinsic material behavior is isolated from the total response by defining true stress as $\sigma = \frac{F}{2w_{eff}}$ where the effective width $w_{eff} = \frac{w+b}{2}$. The original fiber cross section is assumed to be a circle and the compressed fiber cross section is assumed to be a rectangle. The compressed cross sectional area is estimated using $2w_{eff} \times (2r - u)$. The normalized compressed apparent cross sectional area is found to increase to a maximum of 1.83 times the original area at 46 % nominal strain and then plateau at higher strain levels as shown in Fig. 2.5b. A more detailed study is required to understand the increase in cross sectional area.

The true strain is obtained by equating the internal energy to the external work done given by eq. 2.3. The true strains are computed incrementally using trapezoidal rule to evaluate the integrals in eq. 2.3.

$$\int_{V_0}^{V}\int_{0}^{\varepsilon_{eff}} \sigma_{eff}\, d\varepsilon_{eff}\, dV = \int_{0}^{u} F\, du \tag{2.3}$$

The true stress strain response obtained by imposing a constant volume along with a linear elastic behavior with a stiffness of 2.37 GPa is shown in Fig. 2.6. The true elastic limit of 0.5 % is identified as the point at which the instantaneous stiffness is lower than the elastic stiffness of 2.37 GPa.

The single fiber transverse compression experiment is modeled using a quarter symmetric finite element (FE) model shown in Fig. 2.6b in the commercial FE code LS-DYNA. The fiber is modeled as a nonlinear inelastic continuum material with a user defined constitutive model [5] UMAT. The yield stress-effective plastic strain required as input to the model is determined by subtracting the elastic portion of the true stress-strain curve (Fig. 2.6a). The UMAT force displacement predictions are much better correlation to the experimental results compared to a linear elastic behavior with stiffness of 2.37 GPa. However the model under predicts contact area compared to the experiments as shown in Fig. 2.6d. This deviation may be attributed to the increase in fiber cross sectional area observed in the experiments which is a topic for future studies.

2.4 Conclusions

This paper presented the quasi-static transverse compression response of UHMWPE Dyneema SK76 ballistic fibers. The fibers exhibit nonlinear inelastic behavior under large compressive strains. The true stress strain behavior of the fiber is determined by removing the geometric nonlinearity using the measured contact area. The true elastic limit of these fibers in transverse compression is found to be 0.5 % and the Hertzian elastic limit is found to be 2 %. The numerical FE model

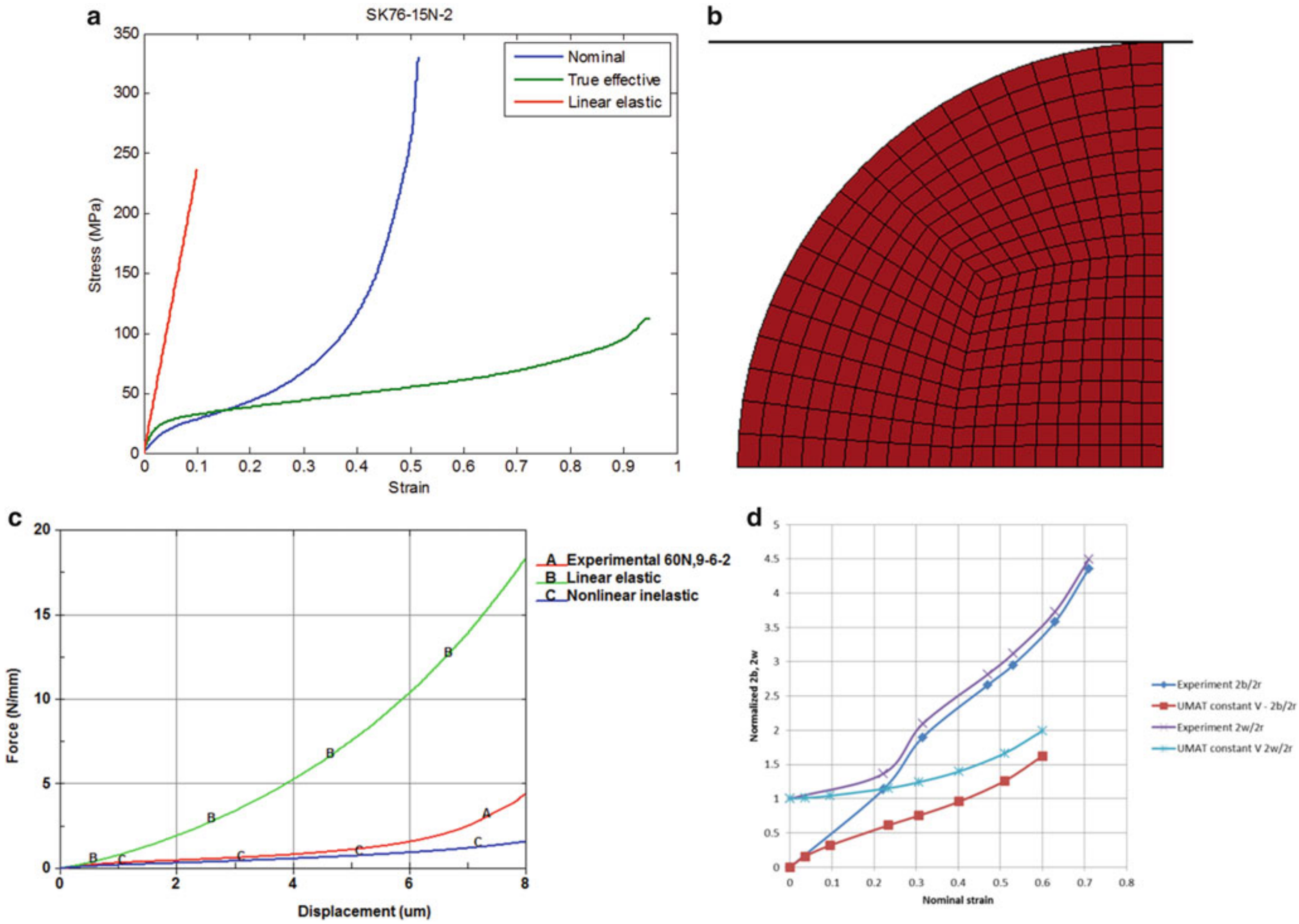

Fig. 2.6 (**a**) True stress strain behavior (**b**) FE model (**c**) comparison of model and experiments (**d**) normalized contact and compressed width

predictions using true stress-strain curve is found to be in a much better correlation to the experimental force displacement response compared to a linear elastic assumption. Both virgin and compressed fibers are found to possess void like features on the fiber surface. Further investigation is required to better understand the increase in apparent fiber cross sectional area during transverse compression.

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