The Manufacture and Characterisation of a Novel, Low Modulus, Negative Poisson's Ratio Composite.

W Miller, PB Hook[†], CW Smith[*], X Wang, KE Evans.

School of Engineering, Computing and Mathematics.

University of Exeter, Exeter, UK. EX4 4QF.

[†]Auxetix Ltd., PO Box 140, Tiverton, EX16 0AY

Abstract.

Relatively few negative Poisson's ratio (auxetic) composites have been manufactured and characterised and none with inherently auxetic phases. This paper presents the use of a novel double helix yarn that is shown to be auxetic, and an auxetic composite made from this yarn in a woven textile structure. This is the first reported composite to exhibit auxetic behaviour using inherently auxetic yarns. Importantly, both the yarn and the composite are produced using standard manufacturing techniques and are therefore potentially useful in a wide range of engineering applications.

[*]Corresponding Author: c.w.smith@ex.ac.uk

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Introduction

In the past 20 years, materials with negative Poisson's ratios (auxetic materials), which expand laterally when stretched longitudinally, have been of significant scientific interest and have considerable practical applications [1-6]. It has been known to be theoretically possible since Love [7]. Auxetic behaviour has been observed in both naturally occurring and synthetic materials [8-13] and may provide many benefits over conventional positive Poisson's ratio behaviour, such as increased shear stiffness, synclastic curvature, increased fracture toughness and enhanced indentation resistance [5 and Scarpa [15]. Interestingly there are signs that auxetic materials may have advantages over conventional equivalents in damping applications [15]. It has been the goal to produce an auxetic composite for some time and some examples exist which rely upon specific stacking sequences of otherwise conventional lamina and fibres [16, 17], rather than fibres which are auxetic in their own right. Alderson *et al* [16, 18, 19] have also proposed the used of intrinsically auxetic fibres in composites to improve fibre pull out strength, however tests were conducted on single fibres potted in epoxy but a full composite sample was not characterised. There seems to be no other example in the research literature of an auxetic composite made from intrinsically auxetic fibres or yarns, though the possibility of and work towards such has been postulated before [18, 19].

In the present study, a new simple composite is made, using a novel helically wound yarn to achieve large negative Poisson's ratios, both by itself, in a textile, and in a fibrous composite. The yarn is based on a double-helix geometry where a relatively stiffer fibre, referred to as a ‘wrap’, is helically wound around a more compliant and initially straight elastomeric cylinder, referred to as a ‘core’, as shown in Figure 1 [20]. When this double-helix yarn (DHY) is stretched longitudinally, both the thin wrap and thick core are elongated. However, the much stiffer wrap laterally displaces the more compliant, and importantly, thicker core, causing an overall lateral expansion of the yarn’s maximal width. At zero strain the compliant core is a helix with zero pitch, and the stiff wrap is a helix with an internal helical diameter equal to that of the outer diameter of the core, as shown in Figure 1. Under a large tensile strain the situation becomes fully reversed, i.e. the wrap has become a helix with zero pitch, and the core has become a helix with the internal diameter equal to the external diameter of the wrap.

In such DHYs, the core performs two functions: to cause large lateral deformation when strain is applied, and to act as a ‘return spring’ to recover its former position and reform the original helix in the wrap when the load is removed. By means of appropriate co-registration of pitch phases between neighbouring yarns and material properties of the wrap and core components, auxetic behaviour in a textile type pre-preg may be achieved, and with a suitable modulus-matched matrix, an auxetic composite This paper reports the manufacture and experimental characterisation of the first auxetic composites using a woven auxetic fabric manufactured from an auxetic yarn.

Methods.

DHY samples were manufactured using a modified yarn-wrapper in which a 'wrap' fibre is helically wound around a central 'core' commercial fibre, allowing control over the geometrical parameters. The material properties of the wrap and core components and the yarn systems are as follows: diameter of 0.32 and 0.64 mm, Young's moduli of 6 GPa and 53 MPa and Poisson's ratio of 0.5 and 0.48 for the wrap and core respectively. Controlling the relative speeds of the wrap and core during manufacture allows alteration of the final yarn geometry. The wrap material used was a twisted ultra high molecular weight polyethylene (UHMWPE) fibre (220 dtex, where dtex is the mass in grammes per 1km length), and the core material used was a polyurethane (0.64 mm diameter) core with an approximate wrap angle of 70^{o}. The textile structures were woven using a plain weave, with the weft being the DHY and the warp being a meta-aramid fibre (approx 475 dtex) The DHY yarn was woven out of register to maximise the auxetic behaviour, see Figure 2. The matrix material for the composite samples was silicone rubber gel (Dow Corning 3-6512, 2 part elastomer).

The DHY samples were mechanically characterised in tension using a universal testing machine (Shimadzu AGS-10KN D) with capstan type clamps, at strain rates of $9.5x10^{-5}$ s^{-1} and sample lengths of 175 mm. Prior to data recording samples were stretched cyclically to 0.017 strain (3 mm deflection) at a rate of $9.5x10^{-5}$ s^{-1} (1 mm/min) for several cycles as a 'bedding in' process to minimise the pretension induced during fixation of the samples in the capstans. This conforms to ASTM standard WK12919 for characterisation of single fibres [21].

Axial and transversal strains were recorded in the central portion of the samples using a video extensometer system (Videoextensometer, Messphysik GmbH, Austria). Contrasting backgrounds and surface markers were arranged so that the edge following video-extensometer software could record strains in the main body of samples and avoid end effects as shown in Figure 3 [22]. Additionally, static tests were performed in which still photographs were taken at high magnification at several different strains in order to record the structure of the yarn and especially the wrap angle, as illustrated in Figure 4, but also to compare yarn length and width data as measured in the cyclical tests.

Results.

Figures 3 and 5 show that the maximal width of the DHY increases as it is stretched longitudinally, it has a negative Poisson's ratio of -2.1. A similar phenomenon can also be seen in the textile shown in Figure 6, however the yarns were able to overlap each other out of plane, causing an out of plane negative Poisson's ratio, so the in plane auxetic behaviour was lost and the textile contracted laterally, as shown in Figure 7. However due to the fibres overlapping the out of plane thickness of the sample increased as it was stretched, therefore demonstrating an out of plane negative Poisson's ratio but an in plane positive Poisson's ratio of 0.06. In order to prevent the out of plane overlapping the sample was re-tested whilst having the thickness constrained between two glass plates at constant separation. The extra constraint provided by the plates prevented the yarn from overlapping and a negative Poisson's ratio of -0.1 was observed, as shown in Figure 8.

Figure 9 shows an initial single layer composite sample, of the DHY textile and silicone rubber matrix. Similarly to the unconstrained textile layer this also had a positive Poisson's ratio of 0.27, see Figure 10. However, in multi layer form (visibly no different from the single layer form in Figure 9) the composite did have a negative Poisson's ratio, shown in Figures 11. Figure 11 shows that in the secondary quasi-linear portion of the strain-strain curve the Poisson's ratio was approximately -0.1. This value of Poisson's ratio was calculated using the rising portion of the curve, i.e. starting at length 25.2 mm, as the original length used in the calculation of the length and width strains. The preceding flat portion of the curve was assumed to be due to take up of slack within the DHY and/or the testing setup.

Discussion.

The DHY by itself is shown to be strongly auxetic, see Figures 4 and 5 with an approximate Poisson's ratio of -2.1. In addition an fabric can easily be manufactured from the auxetic DHY and can be auxetic in some circumstances, i.e. with suitable constraint. This requirement for the fibres to be constrained to remain in the plane was evidence to suggest that mutilayered composites may also show similar behaviour. Standard fibre materials are used to form this auxetic yarn and its manufacture is simple and via conventional textile manufacturing processes. A single layer composite was not auxetic, presumably since the constraint imposed by the matrix was not sufficient to prevent the fibres overlapping out of plane, see Figures 9 and 10. Importantly, the multilayer composite (shown in Figure 3) was shown to be auxetic, see Figure 11 with an approximate Poisson's ratio of -0.1. This was calculated assuming that the initial portion of the strain-strain curve was take up of slack and therefore the correct starting length was at a larger value (25.2 mm in this case). The auxetic effect in the composite is likely to be due to the extra constraint provided by the additional layers of DHY textile. It is usual for composites to be multilayered.

This work is of significant importance as it is the first time reported in the research literature that an auxetic composite has been produced from inherently auxetic fibres, and this has been achieved using standard manufacturing processes and commonly available materials [16, 17], though auxetic fibres have been reported and the possibility of such a composite postulated [18, 19]. It is therefore conceivable that composites of this nature could be manufactured commercially without the need for developing new manufacturing techniques. Auxetics are known to have many realised and potential benefits over positive Poisson's ratio equivalents [6-12] but these low modulus examples may be especially useful for damping applications [15], particularly in aerospace or automotive roles.

Conclusion.

This paper presents the first experimental verification of an auxetic composite made from auxetic fibres or yarns, and confirms via microscopy the mechanism underlying this behaviour. A novel composite containing multiple layers of a textile produced from the DHY is presented and shown to exhibit a large negative Poisson's ratio. This is the first time that a composite displaying a negative Poisson's ratio has been manufactured using inherently auxetic fibres. The simplicity of its manufacture is of significant practical interest for a wide variety of potential applications.

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Figure Legends

Figure. 1 Illustration of the auxetic double-helix yarn: (a) at zero strain a stiffer wrap is helically wound around an elastomeric core and (b) at a larger strain, the core has become a helix around the wrap.

Figure 2. Sketch of double helix yarns, a) out of register and, b) in register.

Figure 3. Picture of double helix yarn multi layer composite in tensile test clamps with video extensometry markers affixed.

Figure 4. Schematic illustration for measurement of deformation of the auxetic double-helix yarn: (a) a small longitudinal strain and (b) a larger longitudinal strain.

Figure 5. Graph of longitudinal against lateral strain for single DHY.

Figure 6. Picture of DHY textile under load, showing fibres overlapping out of plane.

Figure 7. Graph of longitudinal against lateral strain for single DHY textile under load, showing the width of the sample decreasing as it is stretched.

Figure 8. Graph of longitudinal against lateral strain for single DHY textile under load, constrained between 2 plates, showing width of sample increasing as it is stretched. The spike in the data is due to vibration of the camera equipment used in the video extensometry.

Figure 9. Composite containing single layer of DHY.

Figure 10. Graph of length against width for composite containing single layer of DHY. The solid line is the best fit slope used in calculation of the Poisson's ratio.

Figure 11. Graph of longitudinal against lateral strain for composite containing three layers of DHY, showing initial bedding in of sample.

Figure1

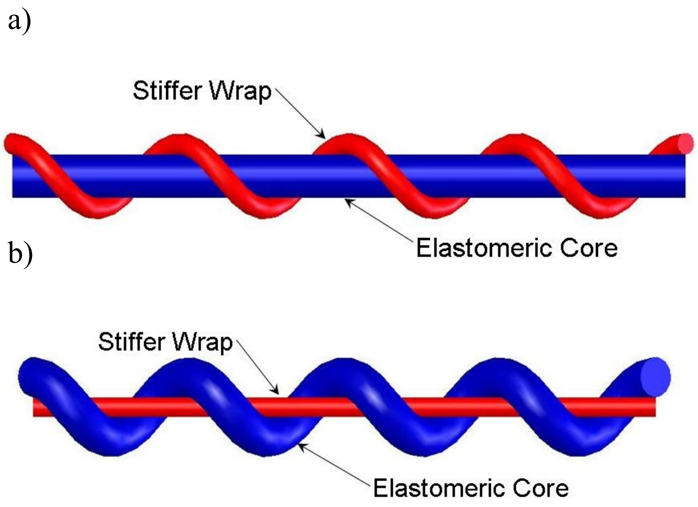
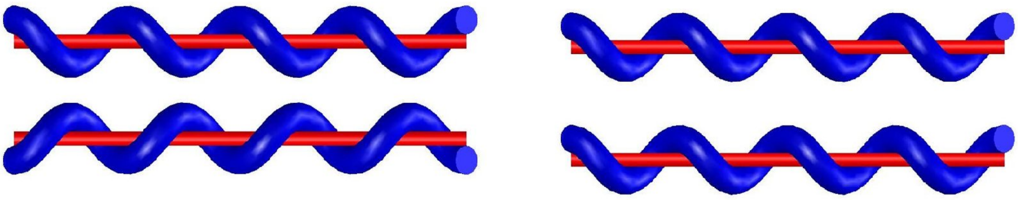


Figure. 1

Figure2



a) b)

Figure 2.

Figure3

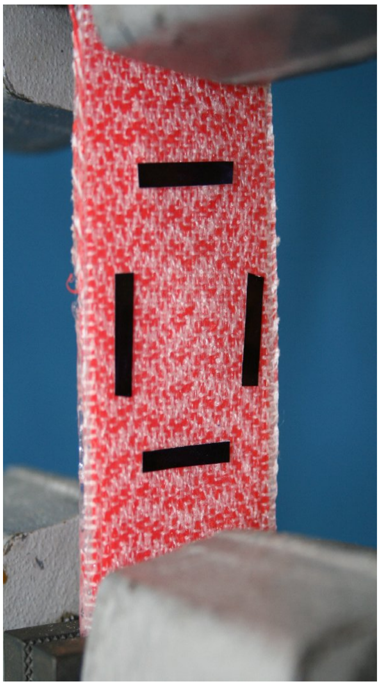


Figure 3.

Figure4

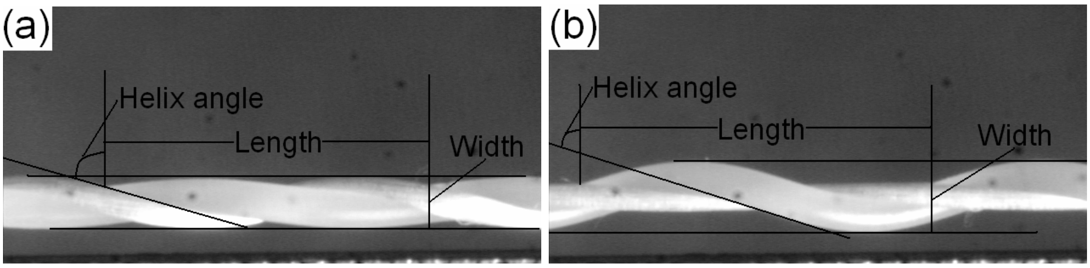


Figure 4.

Figure5

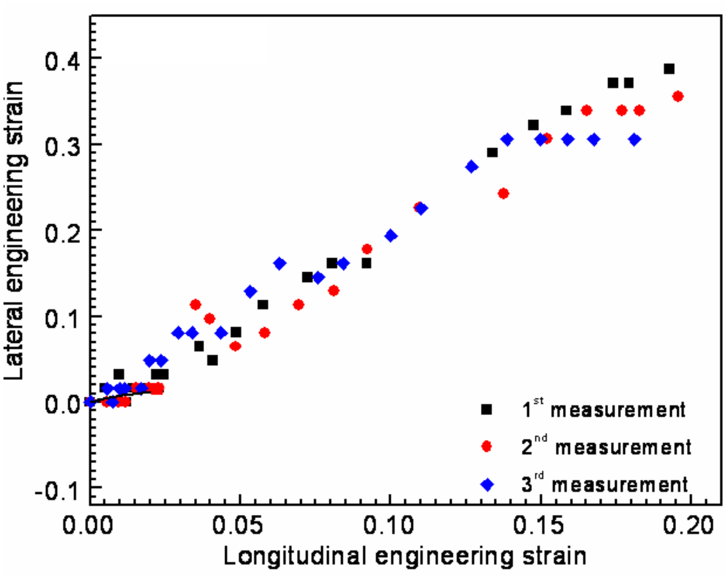


Figure 5.

Figure6

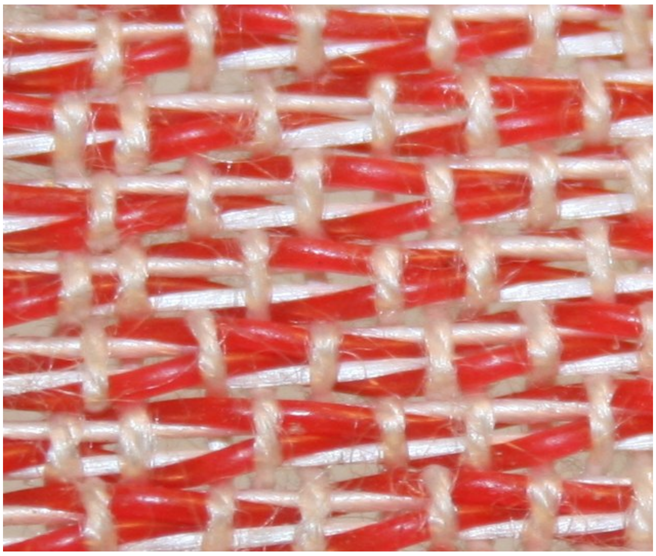


Figure 6.

Figure7

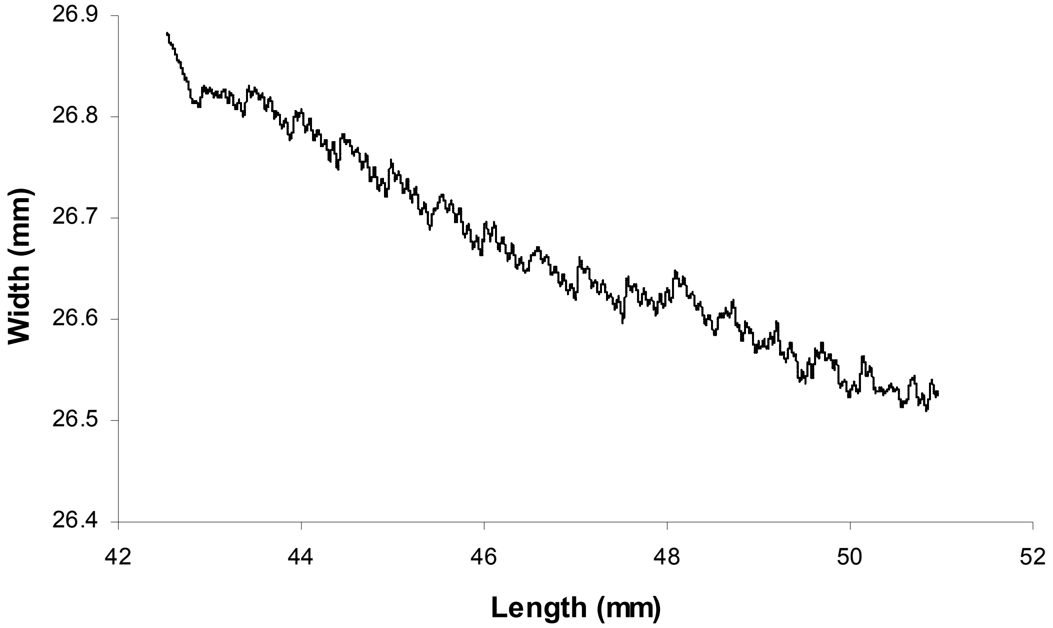


Figure 7.

Figure8

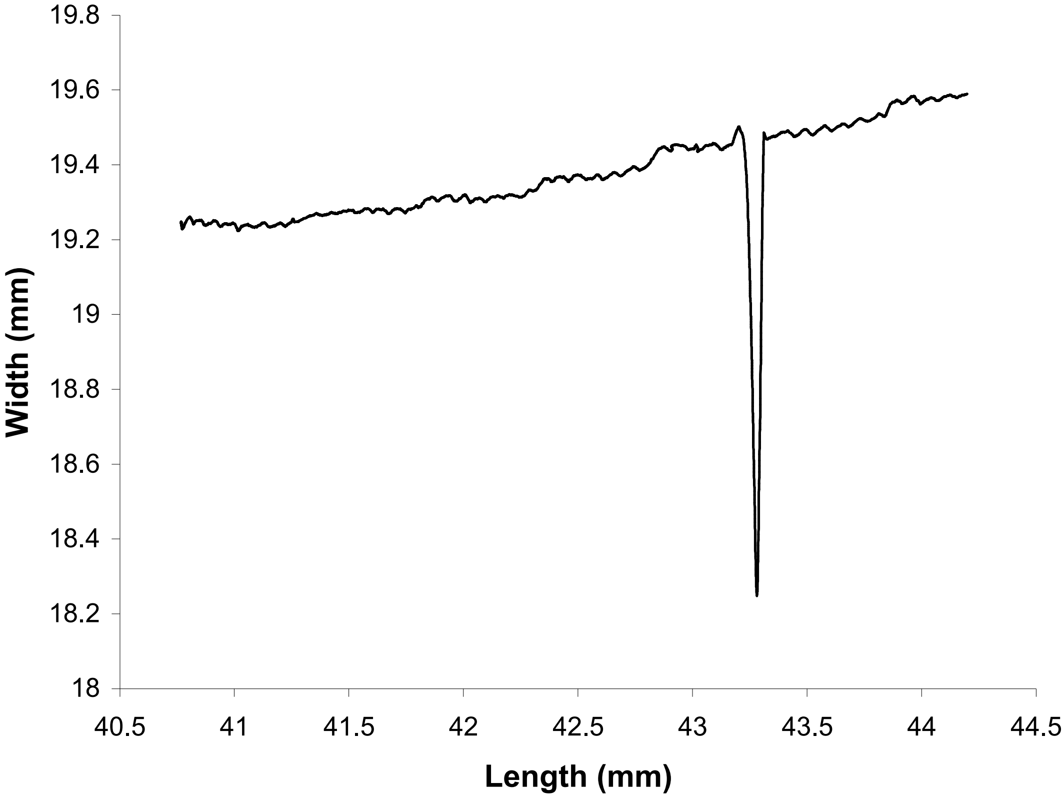


Figure 8.

Figure9

Figure 9.

Figure10

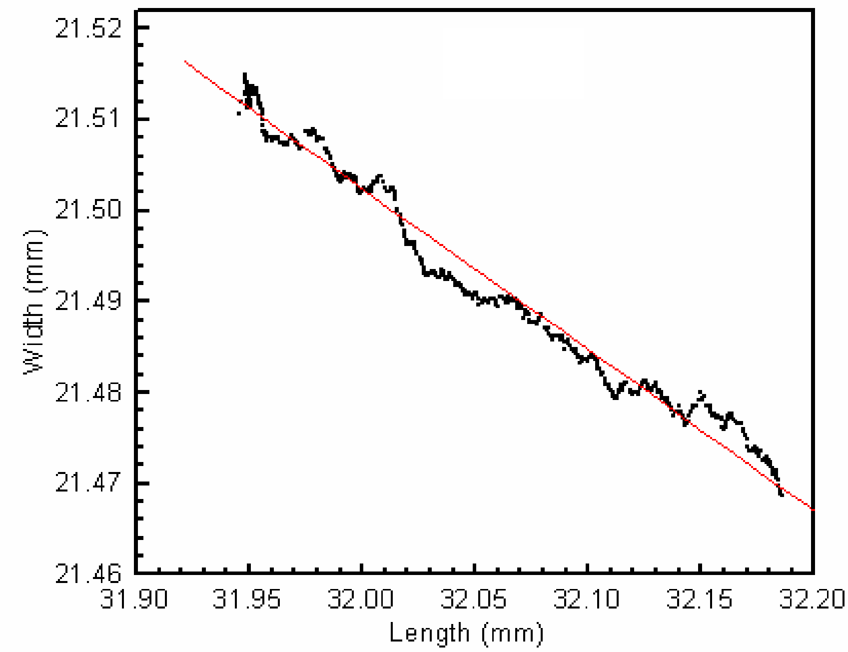


Figure 10.

Figure11

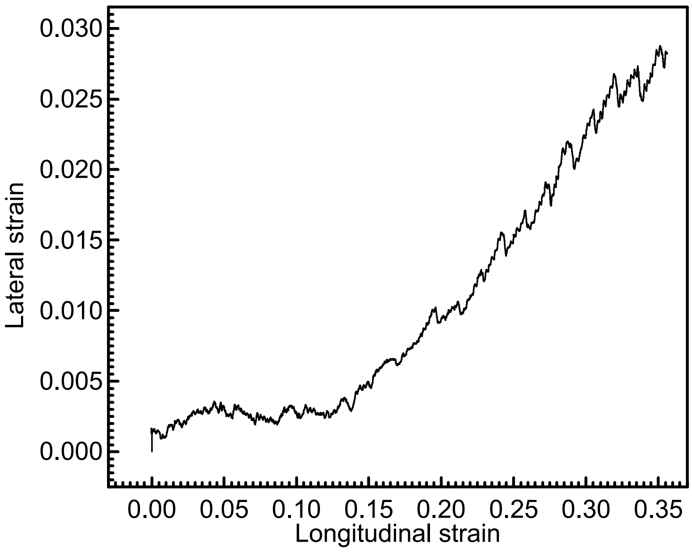


Figure 11.