Finite element analysis of the mechanical stresses on the core structure of electronically functional yarns

M.N. Nashed, *A.M. Shahidi*, *T. Hughes-Riley**, *T. Dias*
Nottingham Trent University, Advanced Textiles Research Group, Nottingham School of Art & Design, Bonington Building, Dryden Street, Nottingham NG1 4GG, UK
*Correspondence to: theodore.hughesriley@ntu.ac.uk

Introduction

Electronic yarns (E-yarns) are a type of E-Textile where the electronics are embedded within the yarn structure (as shown in Figure 1), resulting in a yarn with normal textile properties [1; 2]. This is achieved by soldering copper wires onto a small electronic component(s), encapsulating the electronic component within a UV curable resin, and covering the component with fibres. The resin micro-pod protects both the component and the solder joints and increases the reliability in post-processing. This work used Finite Element Analysis (FEA) to evaluate the mechanical stresses at the soldered joints of the core structure of the E-yarn (soldered component) under axial loading before and after the encapsulation of the component. The results of this analysis were then compared to tensile test results of the core structure of the E-yarn. The model was subsequently used to understand and optimize key micro-pod parameters.

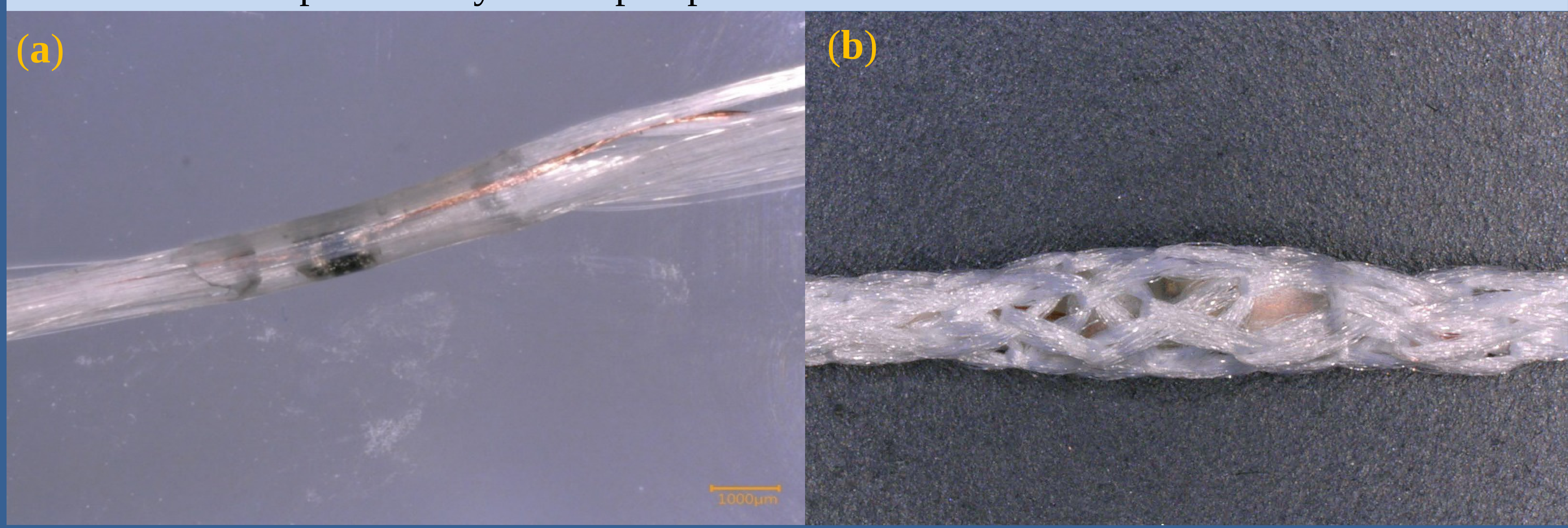

Figure 1: (a) The core structure of the E-Yarn consists of the soldered component surrounded by polyester yarns. (b) Final E-yarn covered by a knitted sleeve.

Mechanical Analysis

The mechanical loads transferred into the solder joints due to axial loading would result in shear stresses and bending moments that would result in the debonding of the solder pads of the component as shown in Figure 2. The single-lap joint structure was used for assessing the shear strength of adhesives [3-5]. Stress distribution in the single-lap joint can be obtained using FEA.

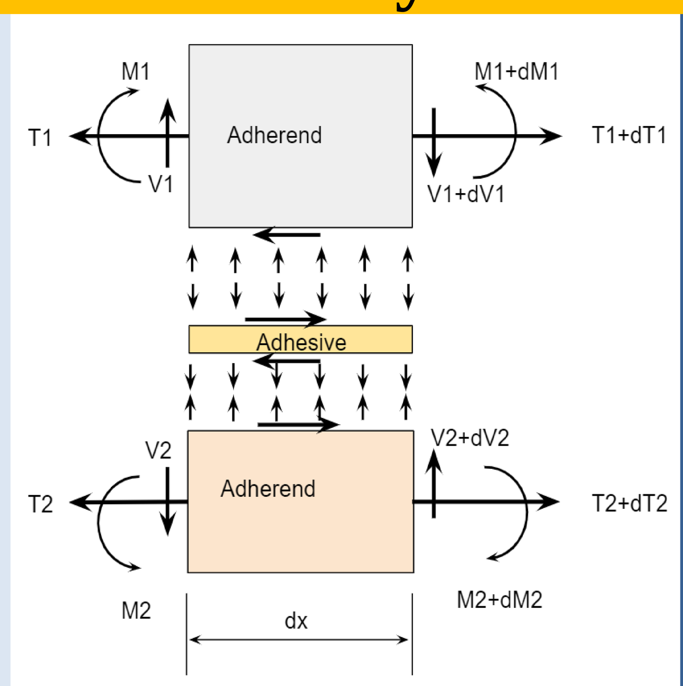

Figure 2: Stress distribution between the adherend and the adhesive layer in single-lap joints, and the resulting shear and bending stresses due to axial force .

Model assumption

The following assumption were implemented to simplify the 3D model:

- The thickness of the soldering joints were negligible compared to the size of the component and the wire.
- The copper wire is uniform, and the physical properties of both the electronic component and the wire are homogenous.
- The load applied in the modelling is axial to the copper wire and boundaries restrict the deformation in other direction .
- The contact between the copper wire and the resin is fixed and would not de-bond due to axial forces applied on the structure.
- The axial displacement of the fibre can be assumed to be independent of the radius of the fibre, and is identical to the axial displacement of the matrix.

Tensile test results

Tensile results were obtained using Zwick Z2.5 Tensile tester (Zwick Roell Group, Ulm, Germany) to evaluate the physical properties of the core structure before and after the encapsulation. The tests were conducted on soldered LEDs (50 mm copper wire length, test speed 200mm/min). Results showed a failure of the soldered LEDs at 3 N (Figure 3a). After encapsulation, the breaking force required was 0.5 N higher (Figure 3b). Failure after encapsulation was due to breakage of the copper wire under axial loading.

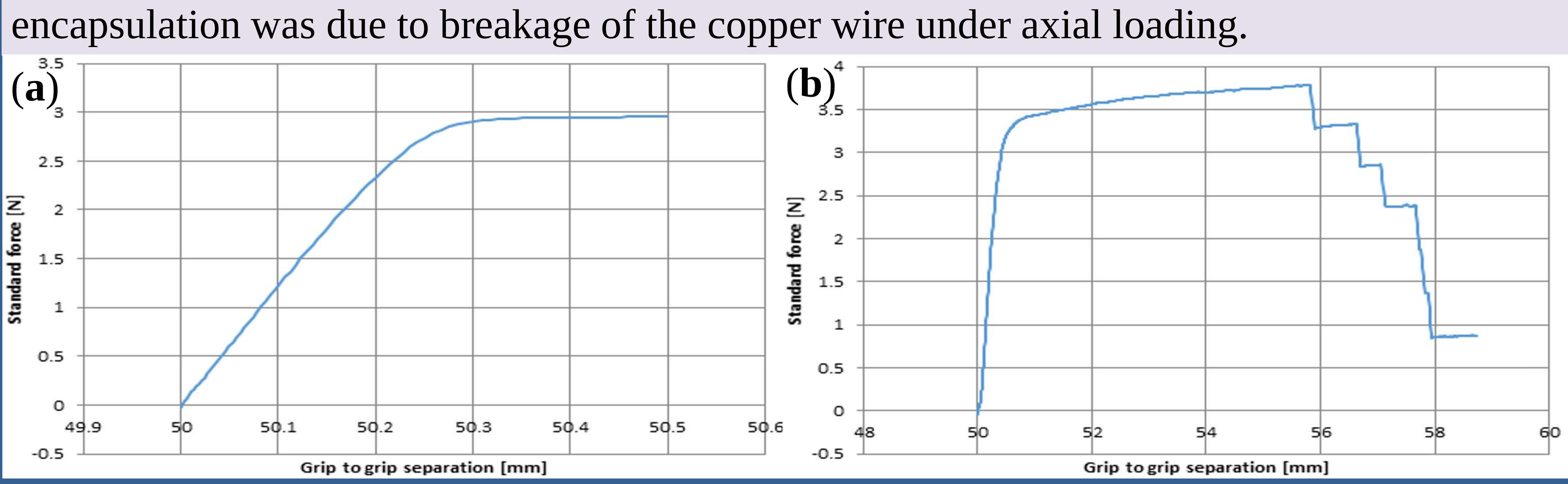

Figure 3: Tensile test of LEDs soldered to 50 mm of copper wire. (a) Un-encapsulated component. A soldered LED failed due to the debonding of the solder pads of the component. (b) The encapsulated LED failed at the interface between the copper wire and the micro-pod.

1. Hardy, D.A.; Rahemtulla, Z.; Satharasinghe, A.; Shahidi, A.; Oliveira, C.; Anastasopoulos, I.; Nashed, M.N.; Kgatuke, M.; Komolafe, A.; Torah, R.; Tudor, J.; Hughes-Riley, T.; Beeby, S.; Dias, T. Wash Testing of Electronic Yarn. Materials 2020, 13, 1228.
2. Satharasinghe, A., Hughes-Riley, T., & Dias, T. (2020). An investigation of a wash-durable solar energy harvesting textile. Progress in Photovoltaics: Research and Applications, 28(6), 578–592. https://doi.org/10.1002/pip.3229
3. Allman, D. J. (1977). A Theory for elastic stresses in adhesive bonded lap joints. The Quarterly Journal of Mechanics and Applied Mathematics, 30(4), 415–436. https://doi.org/10.1093/qjmam/30.4.415
4. Changt, D. 1, & Muki, R. (1974). Stress Distribuition in a Lap Joint Under Tension-Shear. In International Journal of Solids and Structures (Vol. 10). Pergamon Press. https://doi.org/10.1016/0020-7683(74)90055-9
5. Da Silva, L. F. M., das Neves, P. J. C., Adams, R. D., & Spelt, J. K. (2009). Analytical models of adhesively bonded joints-Part I: Literature survey. International Journal of Adhesion and Adhesives, 29, 319-33-. https://doi.org/10.1016/j.ijadhadh.2008.06.005

Finite Element Analysis of the 3D model

Adding the resin micro-pod to the single-lap joint structure (resulting from the soldering process) changed the distribution of stresses in the matrix. The 3D model shown in Figure 4a presents a component (0.5 × 0.5 × 1.0 mm) soldered onto a copper wire, and Figure 4b shows the same soldered component encapsulated in resin micro-pod. These dimensions were selected to represent a LED soldered onto a thin copper wire. The 3D model was then used for finite element static analysis using 'Ansys workbench 19' and 'Ansys workbench 2021R1' (Ansys, Inc, Canonsburg, Pennsylvania, USA). Static analysis was conducted to analyse the stress distribution in the single-lap joint of the electronic component soldered onto thin copper wires.

The analysis calculated the overall stresses at each element based on the von-mises criterion, shear stresses in the XZ (the plane parallel to the axis of the copper wire) direction, the highest stress in one of the principal directions at each element, and the highest shear stress at each element by plotting Mohr's circles at each element, using the principal stresses.

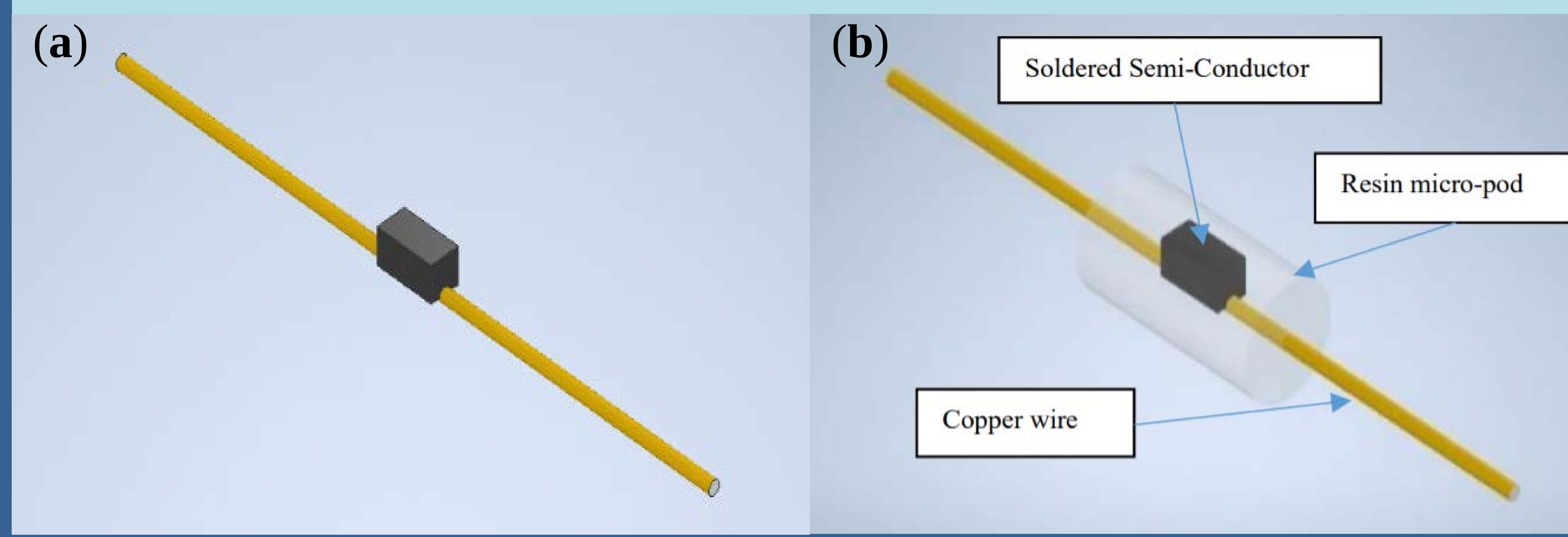

Figure 4: (a) The 3D model of the soldered components created in Autodesk Inventor. (b) The 3D model of the encapsulated component.

Stress distribution before and after the encapsulation process

The results off the analysis are shown in Figure 5, where a section was made in the core structure to show the distribution of stresses. The analysis shows the point of interest where the maximum equivalent and shear stresses are near the solder joints.

Results from the model showed that adding the resin reduced the maximum stress that the wire and soldered components were subjected to, as shown in Figure 5. Moreover, adding the resin would lead to a reduction in the equivalent stresses transferred to the solder joints by 6.85%, in comparison to the stresses before encapsulation, while the maximum shear stresses was similarly reduced by 6.7%. These results are in-line with the tensile tests that showed an increase in the total strength due to adding the resin micro-pod.

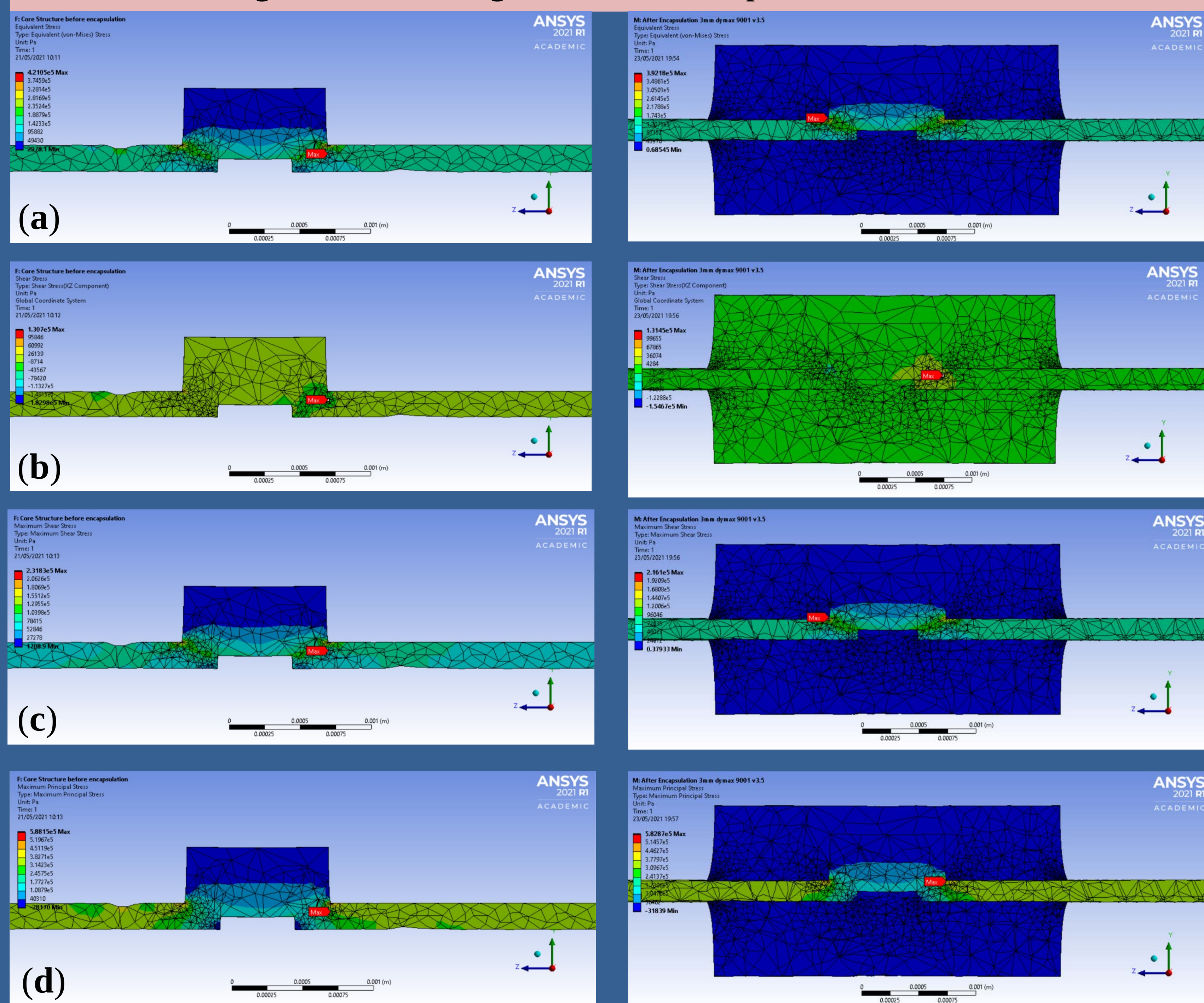

Figure 5: The finite element analysis for the core structure of the electronically functional yarn before (left) and after (right) the encapsulation. (a) Equivalent stresses. (b) Shear stresses in the direction of XZ. (c) Maximum shear stress. (d) Maximum principal stresses.

Acknowledgements: This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) grant EP/T001313/1 entitled *Production engineering research for the manufacture of novel electronically functional yarns (E-yarn) for multifunctional smart textiles* and EPSRC grant number EP/M015149/1 entitled *Novel manufacturing methods for functional electronic textiles*.

Nottingham Trent University

www.e-yarns.com

EPSRC