

The project "rLightBioCom - New bio-based and sustainable Raw Materials enabling Circular Value Chains of High Performance Lightweight BioComposites". is funded by the Euro-pean Union within the Horizon Europe program, Project no.: No. 101091691.



UDC 687.3

JURGITA DOMSKIENE, INGA BREITMOZERE,
MEHEDI HASAN

Kaunas University of Technology, Faculty of Mechanical
Engineering and Design, Lithuania

IMPACT OF CYCLIC TENSILE DEFORMATION ON THE GEOMETRY AND SCANNING PERFORMANCE OF EMBROIDERED QR CODES IN KNITTED FABRICS

Purpose. To evaluate the distortion and readability of embroidered QR codes before and after cyclic tensile deformation using quantitative image analysis techniques.

Keywords: cyclic tensile deformation, QR code, shape distortion, structural stability.

Objectives. The integration of QR codes into textile products has gained relevance as the fashion and textile industries move toward sustainability, transparency, and digital product identification. Embroidered QR codes, while visually and functionally attractive for long-term use, face the risk to geometric distortion caused by the properties of the used fabric as the base and the mechanical stress experienced during intensive use.

Deformation caused by tensile forces in different directions of the fabric can alter the accuracy of the embroidered QR code due to the loss of lost precision of its structural elements that cause the readability faults of the QR code.

Since the correct configuration of key QR code patterns is essential for scanning [1, 2], evaluating how such distortions influence readability is crucial for practical applications. As traceability and circularity requirements expand with upcoming EU regulations to use Digital Product Passport for textile products, understanding these effects becomes

increasingly important for the successful integration of QR codes in textile garment labelling.

Methodology. Mechanical testing was conducted to estimate the durability of the embroidered QR codes, while image analysis was employed to assess their geometric distortion and readability. Interlock jersey fabric samples with 3 different-size embedded QR codes were treated mechanically using a cyclic tensile deformation procedure based on ISO 20932-1/2018 [3]. Elastic recovery and permanent deformations were assessed to determine the effects of multicycle stretching on the QR code. The geometric changes of the QR pattern were evaluated using *ImageJ* image analysis technique, while readability was assessed according to ISO 15415/2024 [4] under standardised conditions.

Research results. Cyclic tensile deformation testing revealed that permanent deformation in the wale direction for embroidered QR code samples was consistently 2 to 3 times greater than in the course direction. No clear correlation with QR code size was observed, although recovery after 30 minutes demonstrated a size dependency: 3 cm QR codes recovered the least, 4 cm codes showed partial recovery (approximately 20-30%) and 5 cm codes tended to recover more effectively (up to 40 %). Compared to fabric samples alone, the presence of embroidered QR codes significantly increased deformation and reduced recovery, suggesting that embroidery introduces structural stiffness and stress concentration, thus limiting the fabric's ability to regain its original shape.

Force–elongation analysis further supported these findings. Achieving 50% elongation in the wale direction required substantially higher forces across all QR code sizes compared to the course direction. In the wale direction, the required force is around 250 N across all QR code sizes, while in the course direction it ranges from 70 N to 180 N, depending on size. These observations are consistent with the trends observed in permanent deformation and elastic recovery, highlighting the combined effect of embroidery and mechanical direction on fabric behaviour.

Geometric distortion analysis indicated that 3 cm QR codes exhibited the highest percentages of mismatch (28.8% in the course direction; 42.8 % in the wale direction), 4 cm codes showed intermediate mismatch, and 5 cm codes had the 11.9 % mismatch in the course direction. Image analysis confirmed this pattern (Fig. 1), showing that mismatched areas were more pronounced in smaller codes and in wale-tensioned samples. QR codes under course tension generally retained a squarer shape and clearer alignment, while wale-tensioned samples displayed vertically stretched and irregular shapes, often affecting critical positioning and alignment markers essential for scanning.

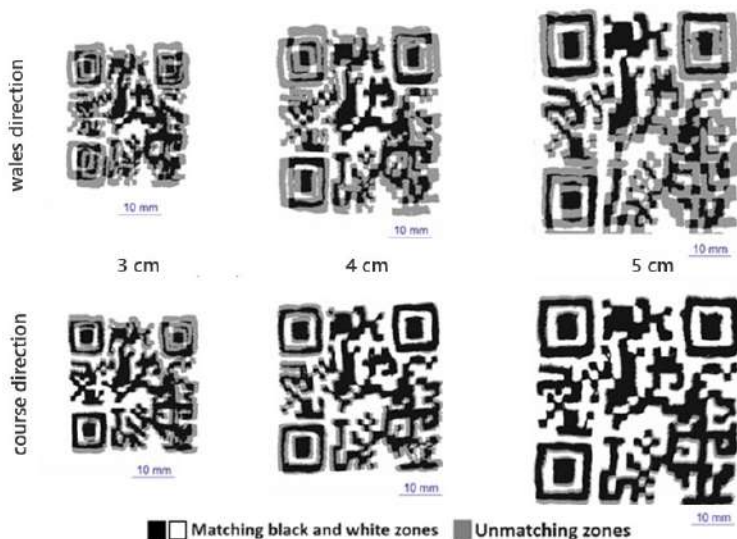


Fig. 1. Image analysis of QR distortion of embroidered specimens

Readability assessments further corroborate the effect of mechanical stress. Before deformation, 3 cm codes were completely unreadable, 4 cm codes were readable only for samples prepared in the wale direction (100 %) but unreadable - in the course direction (0 %), and 5 cm codes reached 80 % readability for samples prepared in the course direction. However, after cyclic tensile deformation, all QR codes became unreadable regardless of size of embroidered element or tension direction, confirming that repeated mechanical stress compromises the geometric integrity required for successful scanning.

Conclusions. This study, one of the first to investigate the distortion and durability of embroidered QR codes revealed that readability is strongly influenced by the precision of embroidered QR fine elements and structural properties of the knitted fabric. Due to thread overlaps formed during embroidery process and the anisotropic behaviour of knitted fabrics in the course and wale directions, geometric distortion of QR modules arises. This irregularity was clearly expressed in the readability results. Specimens with size of 3 cm QR codes showed significantly poorer performance compared to samples with 4 cm and 5 cm QR codes, which exhibited only partial readability also.

When subjected to cyclic tensile deformation, residual strain caused further geometric distortion, as quantified through image analysis. The mismatch values ranged from 12 to 29% in samples cut and stretched in the

course direction, and 39 to 43% in those cut stretched in the wale direction. As a result, post-deformation readability dropped to 0 % across all tested codes, regardless of size or orientation.

These findings underscore a critical constraint: the precision required for fine embroidered QR code elements limits their readability under repeated tensile deformation.

References

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UDC 687.3

EMILIJA MIELIAUSKAITE, DAIVA MIKUCIONIENE
 Faculty of Mechanical Engineering and Design, Kaunas
 University of technology, Studentu str. 56, Kaunas, Lithuania

FROM WASTE TO NEW DESIGN: CHALLENGES AND POSSIBILITIES

Purpose. *Raincoat development from recycled automobile tires and non-woven fabrics.*

Keywords: *Raincoat, end-of-life tires, circular economy, non-woven fabric.*

Objectives. Globally, approximately 1 billion end-of-life tires are generated annually, the majority of which end up in landfills. Automobile tires represent nearly 80% of global rubber waste due to the rapid growth of the automotive industry [1]. Within the framework of the “cradle-to-cradle” circular economy principle, this research proposes the design of a sustainable waterproof raincoat made from waste-derived materials. The idea has been expanded through entrepreneurial aspects in Eco-design Challenge [2]. This research idea suggests exploring hydrophobic fabric coating strategies, using devulcanized rubber granules for the film and non-woven fabrics as garment filing. This idea has several approaches for implementation, but to determine the most effective solution, prototypes from different coating films and non-woven fabric specimens need to be