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Research Article

Belt tension measurement and monitoring of load securing straps by using resistive stitch-based strain sensors

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Abstract: This paper focusses on the evaluation of stitch-based strain sensors suitability for the belt tension measuring and monitoring of load securing straps in road freight transportation. Formerly developed stitch-based strain sensor applications were embroidered on a commercial load securing strep, compliant with established industrial standards for load security in the Federal Republic of Germany. The applications were tested in lashing experiments, simulating the securing of a dummy load in road freight transportation. The experiment results showed that they are capable of measuring and monitoring applied amounts of belt tension with a computable change in stitch-resistance. However, cyclic belt tensioning causes strain wear on the stitched applications, resulting in resistance and sensitivity drift.

Keywords: smart textiles; strain sensor; lashing strap; load security

I. INTRODUCTION

The proper utilization of narrow fabric load securing straps is essential for an effective cargo security concept in modern road freight transportation. Not properly secured load has been proven to be a high-risk factor in road traffic, causing fatal road accidents. [1]

In recent years various research and development projects have successfully implemented stitch-based textile resistive strain sensors in various substrates, especially in medicine and healthcare applications. [2 - 3] However, the use of stitch-based strain sensors to monitor the belt tension applied to road freight transportation load securing straps has not been researched in depth so far.

In a past conducted research work, two stitch-based strain sensor applications were successfully developed to measure and monitor the strain induced elongation of different woven narrow fabric lashing straps. The stitch-based sensors enabled the strain measurement with the achieved level of strain sensitivity, depending mostly on the individual fabric's deformation characteristics. However, the stitched narrow fabrics weak recovery characteristics have been found to be a crucial limiting factor for the developed stitch-based strain sensors recovery abilities. [4]

Woven load securing lashing straps must provide good fabric recovery properties to be certified as safe for road transportation in the Federal Republic of Germany. With this main limiting factor expectedly less significant, strain measurement and monitoring may be an interesting use case for the former developed stitch-based strain sensors to possibly enhance road freight load security in future applications.

II. BACKGROUND

Load securing straps are woven narrow fabrics with attached fastening elements like metal hooks, ratchets, or rings. The straps are fastened and tensioned by an operator during the load securing procedure. During transportation a vehicle accelerating, braking, maneuvering or vibrating conducts dynamic acceleration force to the transported load. If the conducted acceleration force is great enough to exceed the loads grip on the ground, it may topple, fall over, hop, or move uncontrolled otherwise, causing damages to the load or even road traffic accidents. The load tensioned securing straps compensate the transport vehicles acceleration by exerting tensile force to the load. During load securing the necessary amount of belt tension [daN] must be calculated concerning a loads individual mass, size, and shape. In the Federal Republic of Germany, the established industrial standards *VDI 2700* and *DIN EN 12195-1:2021* describe proper calculation and documentation methods and means of securing procedures. [5 - 7] Those standards serve as benchmarks in legal jurisdiction to assess the correctness of load securing in the possible event of a legal claim, should transport damages to the load or a road traffic accident occur. [8]

Woven load securing straps for road freight transportation must meet the proscribed manufacturing and safety requirements of the standard *DIN EN 12195-2:2000* to be compliant with *VDI 2700* and *DIN EN 12195-1:2021*. A standard compliant load securing strap must be labelled with its maximum *Lashing Capacity (LC)*. The maximum *Lashing Capacity (LC)* is a safety limit for the maximum belt tension to be applied to a securing strap during normal use. The safety requirements for woven load securing straps proscribe that a strap tensioned to its labelled *Lashing Capacity (LC)* shall not elongate more than up to ε=7% in the direction of pull and shall show no permanent elongation or damages afterwards. This leads to compliant load securing straps being expected to show good fabric recovery abilities and resistance against permanent deformation at a level of applied belt tension below the labelled *Lashing Capacity (LC)*. [9] *VDI 2700* strongly recommends to methodically measure and monitor securing straps belt tension during the ongoing transport to ensure the maintenance of the straps proper tensioning over long transport periods. [10] For measuring and monitoring securing straps belt tension, various analogue and digital measurement tools are commercially available. However, a full textile stitch-based strain sensor application integrated direct into a securing strap does not by now.

Stitching techniques like sewing and embroidery are some of the oldest procedures to join and functionalize textile fabrics. A stitch is built by penetrating needle guiding a sewing thread thru a textile fabric. Modern CNC embroidery machines offer smart textile product developers a broad freedom in the design of aesthetic and functional stitched patterns. Textile products can be functionalized during various stages of manufacturing, enabling the stitch- based functionalization of pre-finished textile products like load securing straps. A *stitch* is commonly classified by established standards like *ISO 4915:1991*, concerning its loop formation and its geometrical properties like stitch length, width, and depth. [11 - 13]

A stitch made from one or multiple conductive yarns has a specific electrical resistance [Ω] in relaxed condition. Conductive yarns are mostly spun from myriads of single conductive staple fibres or filaments. A conductive piece of yarn can therefore be depicted not as an isotropic ideal conductor, but more as a conductive network of an infinitesimal high number of series and parallel circuiting single conductors, physically entangled with one another. In general, a piece of conductive yarns absolute electrical resistance [Ω] increases with its physical length. For a stitch, this means that its absolute resistance per meter is likely to increase dependent on the total length amount of stitched conductive yarn. The adjustment of stitch properties influencing the final length amount of stitched yarn therefore greatly influences a stitch's absolute electrical resistance. [14 - 18]

Depending on a stitches property like its width and density, sections of conductive yarn may touch or overlap at the substrates surface. Those physical contact points cause the stitched conductive yarn sections to short-circuit when not proper isolated. While a stitch's overall absolute resistance is likely to increases with an increasing total length amount of stitched conductive yarn, a high concentration of short-circuiting contact points has been found to reduce it. A Stitch is therefore best depicted as a complex conductive network whose overall electrical resistance [Ω] in relaxed state is an equilibrium of the factors of yarn length to the concentration of short-circuiting yarn contact areas.

When mechanical strain is applied to a stitched fabric, its deformation causes the stitches conductive network to shift. The resistance of a stitches conductive network changes due to its rearrangement, caused by the substrate fabrics elongation. Overlapping and cross sectioning yarn areas may separate from another and cross sectioning areas may shift in contact size and localisation. The short-circuiting contact areas eventually open, turning the conductive networks equilibrium to alter and the stitch's absolute resistance to increase or to decrease. (**Fig. 1**)

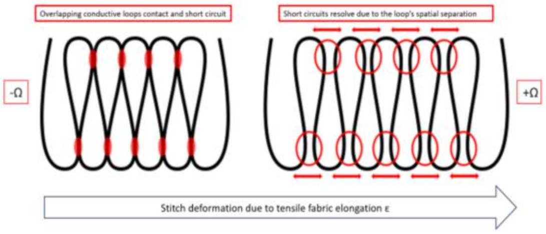

Figure 1. *Schematic representation of short-circuits resolving due to physical yarn separation*

The fabrics and stitches deformation may induce mechanical stress to the stitched conductive yarn as well, causing single spun conductive fibres to break or their conductive surface coatings to crack. A damaged conductive yarn may experience a drift in its resistive characteristics, therefore causing the whole stitch's conductive network to alter. [19 - 25]

A measurable resistance change of a stitch-based strain sensor can be used to calculate the stitched fabrics elongation. The calculation method uses the sensors strain sensing gauge factor. The gauge factor K is a proportional factor depicting the sensors grade of resistance change in comparison to its elongation. (Eq. (1) – (3))

$$K = \frac{\frac{\Delta R}{R0}}{\frac{\Delta l}{l}} \tag{1}$$

$$\frac{\Delta R}{R0} = \frac{k \cdot \Delta l}{l} = k \cdot \varepsilon \tag{2}$$

$$\varepsilon = \frac{\Delta l}{l} = \frac{\frac{\Delta R}{R0}}{k} \tag{3}$$

where K = gauge factor; R0 = Resistivity [Ω]; l = length [mm]; ε = elongation [%].

The gauge factor is widely established in the use of commercial strain gauges and has been used in various past research to indicate a stitch-based strain sensors general level of strain sensitivity. Other important factors are a strain sensors linearity and especially its recoverability. [22, 26 - 28] A past conducted experiment suggested that a stitched yarns orientation angle in the applied strain force direction directly influences the strain sensors overall resistance and sensitivity drifting characteristics, due to the total amount of conducted mechanical stress likely being dependent on the yarn orientation. Therefore, it’s important to consider that a stitch-based strain sensors sensing characteristics are the result of three main aspects interacting with one another. Those being the stitches conductive network shifting under deformation as well as the yarns drifting behaviour and the stitched substrates fabric deformation properties. [4]

III. PROBE PREPARATION

A commercial *DIN EN 12195-2* compliant cargo load securing strap was chosen as a substrate for testing the stitch-based strain sensor applications. (**Fig. 2**) The chosen securing strap is named *Ratschenzurrgurt 1000daN Orange* in this report, after its original product name given by the supplier *(Lasi24 GmbH, Rostock (GER)).* The strap consisted of two narrow fabrics, connected with a supplied metal ratchet for belt tensioning and fixation. The belts technical specifications are given in **Table 1**. The stitch properties are given in **Table 2** and illustrated in **Fig. 3** – **Fig. 7**. All probes were embroidered with loose ends for contacting with a multimeter for resistance measurement.

Table 1. *Technical specification Ratschenzurrgurt 1000daN Orange*

Belt pieces	2 pieces (1* loose end and 1* fixed end)
Total belt length	4000mm
Fixed end length	500mm
Loose end length	3500mm
Belt thickness	35mm
Belt width	2mm
Fixation belt-attachment	Metal hooks
Belt fastener	Metal ratchet
Maximum Lashing capacity LC	1000daN
Elongation at Maximum Lashing capacity LC	<7%
Fibre Material	100% PES

The Load securing straps were embroidered with two versions of an *ISO 4915:1991* 304-ZigZag lockstitch using a *ZSK JCZA* computer-controlled embroidery machine *(ZSK Stickmaschinen GmbH, Krefeld (GER)).* Both applications dimensions are illustrated in **Fig. 3**. Both stitches were developed in a research work prior [4]

Table 2*. Stitch properties*

Stitch Version	***Stitch density***	***Stitch width***	***Stitch depth***
ZigZag_V2_Axial	11 Stitches /10mm	5 mm	0.9 mm
ZigZag_Double_V2	8 Stitches /10mm	0.8 mm	1.2 mm

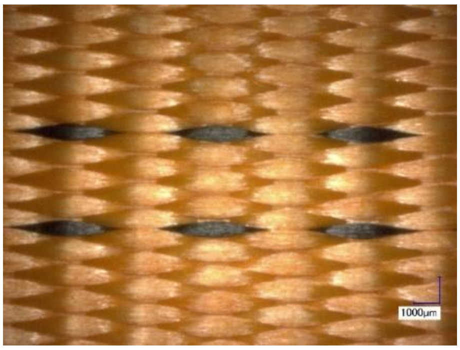

Figure 2. *Narrow fabric surface image “Ratschen-zurrgurt 1000daN Orange”*

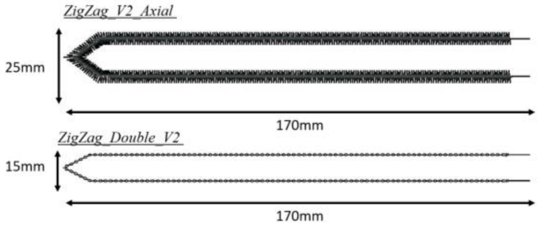

***Figure 3**. Stitch-dimensions*

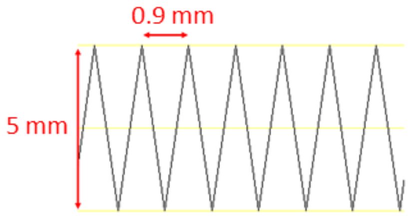

***Figure 4.** Stitch properties ZigZag_V2_Axial*

***Figure 5.** Microscope image ZigZag_V2_Axial*

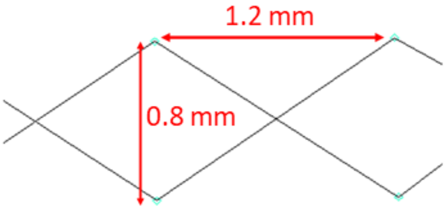

***Figure 6.** Stitch properties ZigZag_Double_V2*

***Figure 7.** Microscope Image ZigZag_Double_V2*

The chosen silver-plated yarn *Amann Silver-tech+150 (Amann&Söhne GmbH & Co.KG, Bönningheim (GER))* was successfully used to manufacture stitch-based strain sensors for measuring and monitoring lashing straps belt tension in a previous study. [4] The stitch version of *ZigZag_V2_Axial* was embroidered using only a conductive upper thread and the non-conductive yarn *Amann ISA Tex 80* as a lower thread. In the version of *ZigZag_Double_V2* the upper thread and the lower thread consisted of the conductive yarn *Amann Silver-tech+150.* (**Table 3**)

***Table 3.** Yarn properties*

Yarn	***Fiber material***	***Titer [dtex]***	***Yarn resistivity [Ω/m]***
SIlver-Tech+150	100% PA	220	<300
ISA Tex 80	100% PES	180	-

IV. TESTING METHOD

To judge the developed strain sensors usability for load securing applications it was decided to design experiments as close to a reality as possible. For testing the stitched applications capability to measure and monitor the applied belt tension, a cyclic tensioning experiment and a long-term lashing testing experiment were conducted. Both experiments were inspired by common use cases of load securing straps in road freight transportation.

Two dummy loads, consisting of 7 wooden *EN 13698* compliant load carrier palettes (LxWxH = 1200mm x 800mm x 140mm) were stapled onto one another. The total size of the two dummy loads was LxWxH = 1200mm x 800mm x 850mm. The dummy loads were exposed to climatization 20°C/65% rel. humidity for 24 hours in an accessible climate chamber together with the stitched load securing straps. After climatizing, the stitched load securing straps were used to lash 6 of the palettes onto the lowest seventh palette. (**Fig. 8**) The probes stitch applications were positioned free-floating approximately in the middle above the dummy loads' length. The straps were orientated in the same direction while lashing so the stitch applications pointed in the same direction. Edge protectors made of cardboard were put between the lashing straps and the upper palettes edge to protect the straps from abrasion. (**Fig. 9**)

***Figure 8**. Lashed dummy load*

Figure 9. *Positioned strain sensor applications*

Figure 10. *Measurement of the probes electrical resistance (left) and belt tension (right)*

For fastening the strap's attached metal hooks were hooked into the lowest wooden palette. The securing straps were tensioned using the attached metal ratchets. For measuring the belt-tension the belt tension measuring tool TENMET 500 *(GWS®-Schlobohm, Zeven (GER))* was used. The conductive stitches electrical resistance [Ω] was measured with a *DMM6500 6 ½ Multimeter (Keithley Instruments Inc., Cleveland (USA)).* (**Fig. 10**)

The cyclic tensioning experiment was designed to simulate the multiple use of a functionalized load securing straps lashing down the dummy loads multiple times. The stitched lashing straps were successively tensioned from 0daN to 100daN and to 200daN without loosening in between. The cycle was repeated 5 times in total. The stitch applications electrical resistance [Ω] was measured before tensioning as well as 30 seconds after reaching 100daN and 200daN. At each cycles end the straps were loosened by opening the tensioning metal ratchets. Between every tensioning cycle the 10 minutes were waited to give the woven lashing strap enough time for relaxation. Before and after every conducted tensioning cycle the stitch applications length was measured using a steel measurement ruler. This was conducted to detect a possible permanent stitch elongation. In each cycle the probes strain sensitivity measured by calculating the strain gauge factor.

The described testing method didn't allow a precise measurement of the narrow fabric elongation [ε] during the belt tensioning procedure. For reference unstitched probes of the used load securing strap were tested for their tensile strength according to *DIN EN ISO 13934-1* with a *Zwick Allroundline Z100* tensile testing machine, a *50kN Xforce K* loading cell and a VideoXtens elongation transducer *(ZwickRoell GmbH & Co. KG, Ulm (GER))*. The tensile testing procedure was conducted using a *50kN roller specimen holder Type 8564 (ZwickRoell GmbH & Co. KG, Ulm (GER)).* For measurement data gathering the program *TextXpert 3* was used. The tensile testing procedure was conducted by *ZwickRoell GmbH & Co.KG.*

For reference testing 3 unstitched probes of the strap *Ratschenzurrgurt 1000daN Orange* were tested until rupture. From the gathered data the straps average elongation [ε%] was calculated at 100daN and 200daN applied tension force. The averaged elongation percentages were used for reference to calculate the probes strain gauge factors as an indicator for the strain sensitivity.

The long-term lashing experiment was designed to simulate a load being lashed down for a long transport duration. The dummy loads were lashed down with 200daN applied belt tension. The lashed loads were left unmoved in the climate chamber under constant 20°C/65% rel. humidity climate exposure for 48 hours in total. The stitches electrical resistivity was measured after 12 hours, 24 hours, 36 hours and after 48 hours alongside the belt tension. With this procedure the stitched applications ability to monitor the straps applied belt tension and possible belt tension loosening overtime were tested. All stitched applications lengths were measured before both experiments and 24 hours after completion in a 20°C/65% rel. humidity-controlled climate environment. For the length measurement a steel ruler was used. (**Fig. 11**)

Figure 11. *manual application length measurement*

It is important to note, that both experiments were conducted inside of a climate chamber and in a stable climate environment 20°C/65% rel. humidity to minimalize climate fluctuations for the duration of this research work.

V. RESULTS

In this section the cyclic tensioning and the long-term lashing experiment's results are presented. The cyclic tensioning experiment's results show that both stitch applications enable the measurement of the applied levels of belt tension by a distinctive change in electrical resistance [Ω].

The reference tensile tests of the unstitched securing straps resulted in an averaged elongation of ε=0,57% at 100daN and ε=0,84% at 200daN applied tensile force. This elongation values were used to calculate the probes gauge factors during cyclic tensioning. In the first cycle the probes based on *ZigZag_Double_V2* show an averaged gauge factor of 5,3 at 100daN and 8,71 at 200daN belt tension. The probes based on *ZigZag_V2_Axial* had an averaged gauge factor of 5,32 at 100daN and 7,25 at 200daN belt tension. (**Fig. 12** – **Fig. 13**)

The probes of both stitches experience a cyclic electrical resistance drift and a cyclic sensitivity drift. The measured electrical resistance at 0daN, 100daN, and 200daN belt tension increases after each conducted tensioning cycle. (**Fig. 14** – **Fig.15**) The relative resistance drift related to the first cycle is shown in **Fig. 16** and **Fig. 17**. The *ZigZag_Double_V2* probes relative resistance drift is slightly higher than ZigZag_V2_Axial and both the absolute and relative drift curves indicate a comparatively more volatile resistance drifting behaviour. However, both applications show a largely similar positive electrical resistance curve progression.

The sensitivity drifting behaviour deviates more significantly between both stitch applications than the observed electrical resistance drift. The *ZigZag_V2_Axial* based Probes display a strong gauge factor drop after the first conducted cycle. Between the following cycles the level of sensitivity remains then on a reasonable stable plateau. However, ZigZag_Double_V2 shows a much more volatile sensitivity drifting behaviour.

During the long-term lashing experiment all stitched securing belts display a continued belt tension loosening. The straps belt tension loosening is accompanied by a decline of both stich applications electrical resistance. While the probes belt tension curve progresses in a similar regressive pattern, the electrical resistance curve progression pattern diverges. (**Fig. 18 – Fig. 19**)

The probes based on ZigZag_V2_Axial exhibit a regressive electrical resistance curve progression during the experiment. The curves correspond well with the belt tension loosening curve progression. ZigZag_Double_V2 however shows an electrical resistance curve progression less regressive and less corresponding to the belt tension loosening.

The conducted length measurements before and after both experiments indicate no clearly measurable permanent stitch deformation. However, all probes show a permanently increased electrical resistance in relaxed state. (**Table 4** – **Table 7**)

Table 4. *ZigZag_Double_V2 – Cyclic tensioning experiment*

Probe	***A***	***B***	***C***	***D***	***E***
Δ l	0	0	0	0	0
Ωl_0	45.56	43.8	44.9	46.9	50.23
Ωl_1	46.91	45.91	50.8	54.12	56.07
ΔΩ	1.35	2.11	5.9	7.22	5.84
ΔΩ [%]	+2.95%	+4.82%	+13.14%	+15.39%	+11.63%

Table 5*. Cyclic ZigZag_V2_Axial - Cyclic tensioning experiment*

Probe	***A***	***B***	***C***	***D***	***E***
Δ l	0	0	0	0	0
Ω0	2088	2157	2113	2024	2029
Ω1	2159	2264	2248	2107	2111
ΔΩ	71	107	135	83	82
ΔΩ (rel.)	+3.40%	+4.96%	+6.39%	+4.10%	+4.04%

Table 6. *ZigZag_Double_V2 – long-term lashing experiment*

Probe	***A***	***B***	***C***	***D***	***E***
Δ l	0	0	0	0	0
Ω0	47.39	49.03	51.65	43.71	48,12
Ω1	48.11	49.86	52.04	44.23	48.57
ΔΩ	0.72	0.83	0.39	0.52	0.45
ΔΩ (rel.)	+1.52%	+1.69%	+0.76%	+1.19%	+0.94%

Table 7*. ZigZag_V2_Axial - long-term lashing experiment*

Probe	***A***	***B***	***C***	***D***	***E***
Δ l	0	0	0	0	0
Ω0	2063	2119	2071	2099	2104
Ω1	2079	2141	2108	2107	2121
ΔΩ	16	22	37	8	17
ΔΩ (rel.)	+0.78%	+1.04%	+1.79%	+0.38%	+0.81%

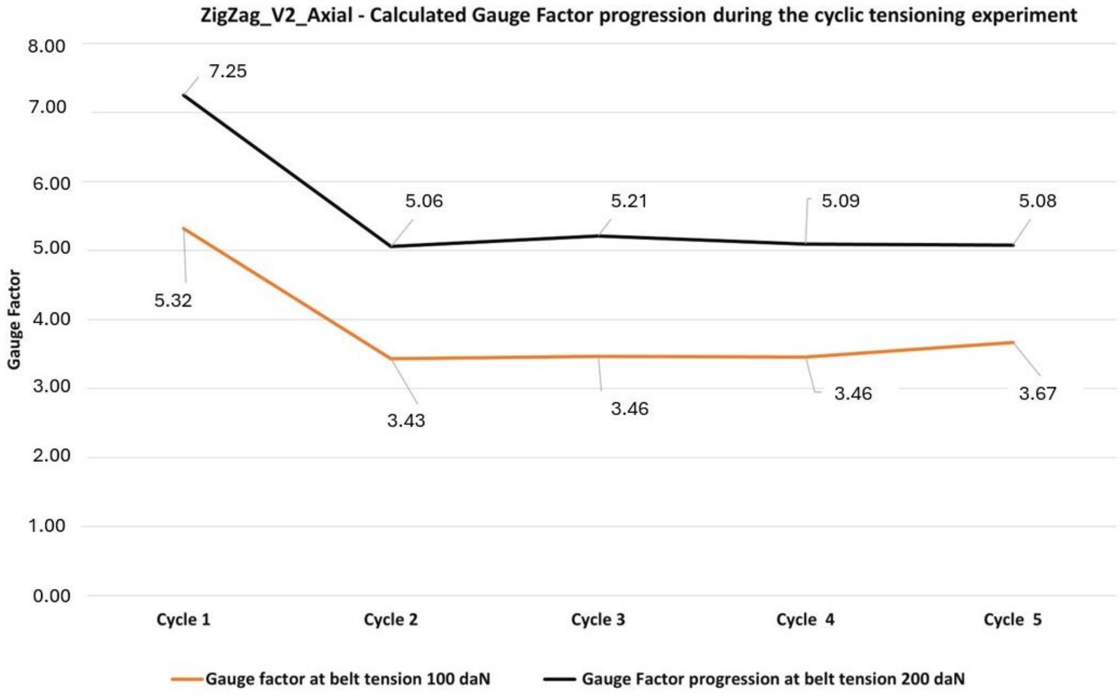

Figure 12. *Calculated Gauge Factor progression during the cyclic tensioning experiment – ZigZag_V2_Axial*

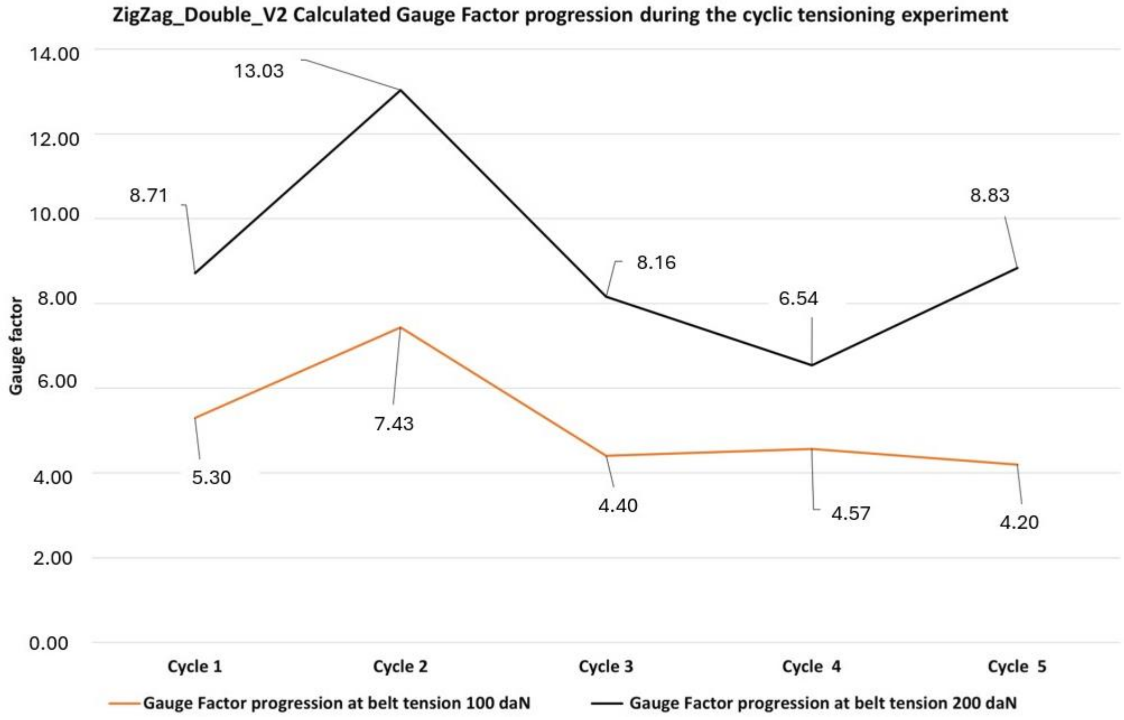

Figure 13. *Calculated Gauge Factor progression during the cyclic tensioning experiment – ZigZag_Double_V2*

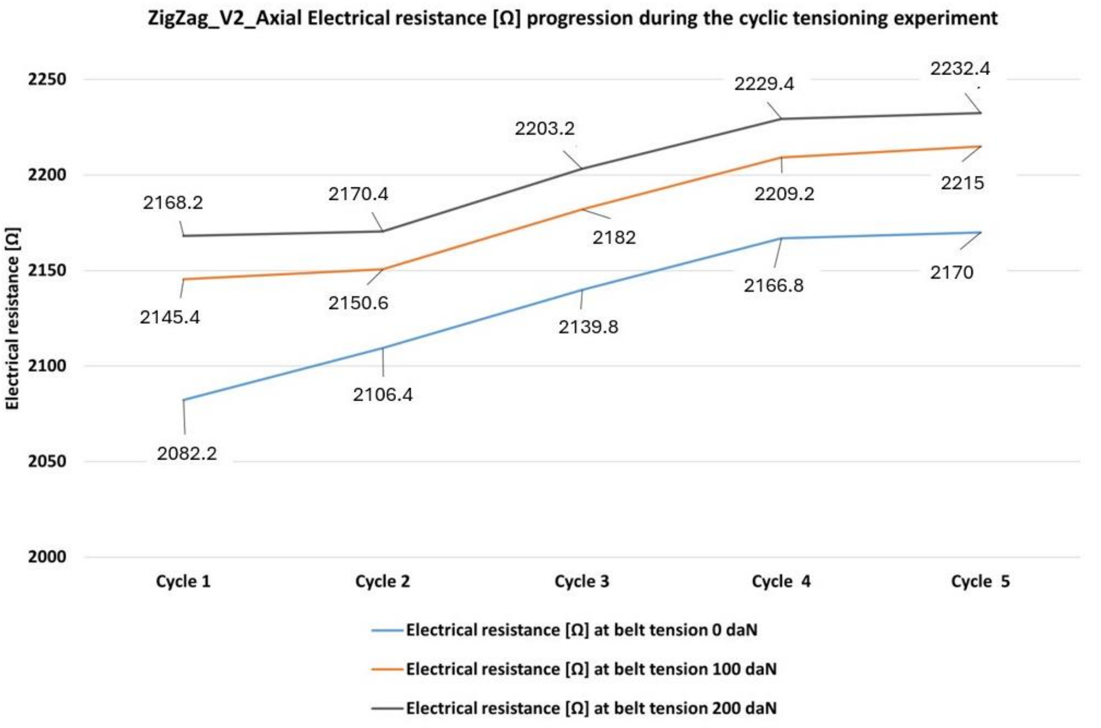

Figure 14. *Electrical resistance [Ω] progression during the cyclic tensioning experiment – ZigZag_V2_Axial*

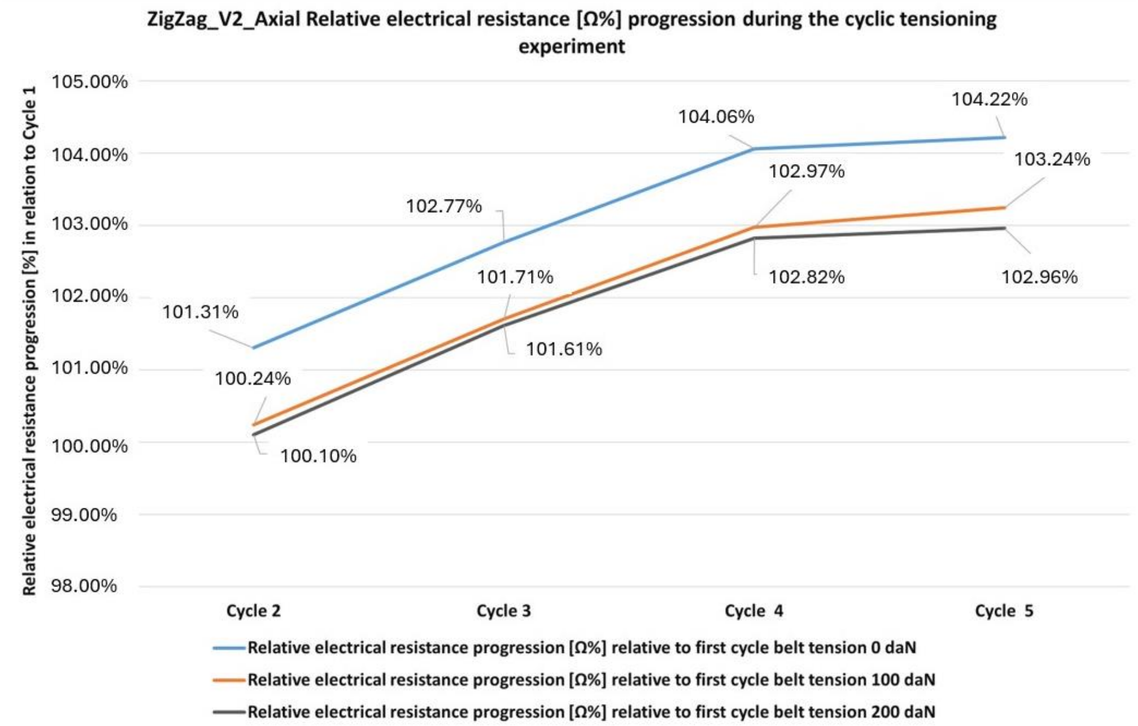

Figure 15 *Relative Electrical resistance [Ω%] progression during the cyclic tensioning experiment – ZigZag_V2_Axial*

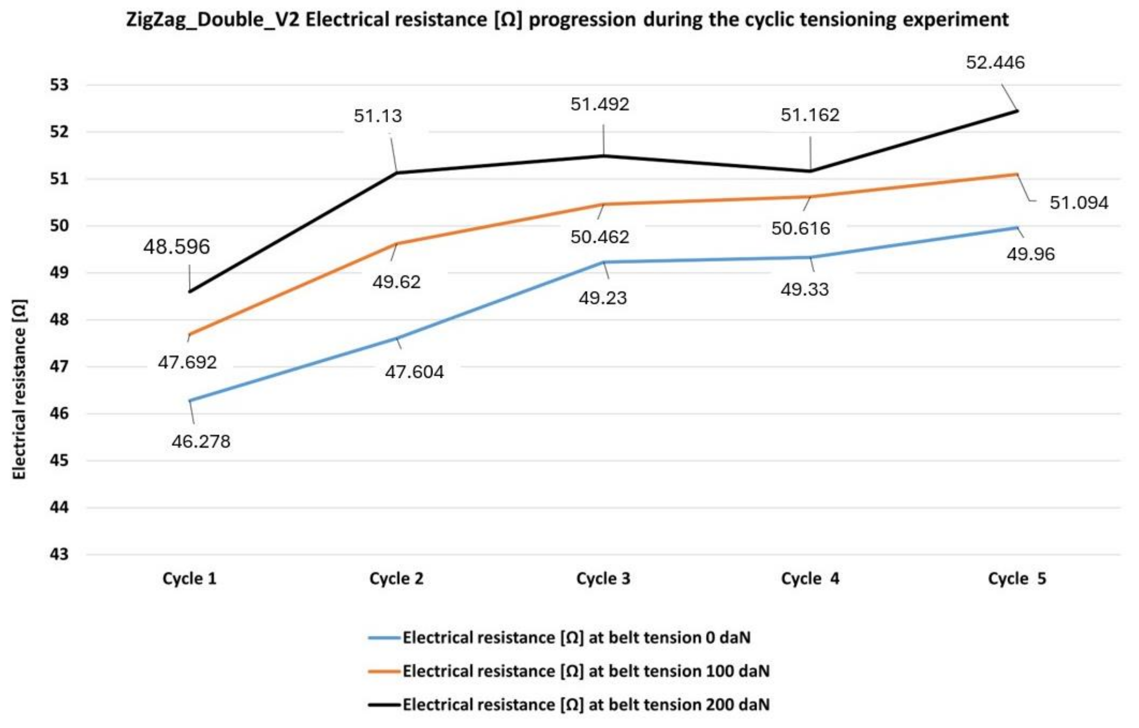

Figure 16. *Electrical resistance [Ω] progression during the cyclic tensioning experiment – ZigZag_Double_V2*

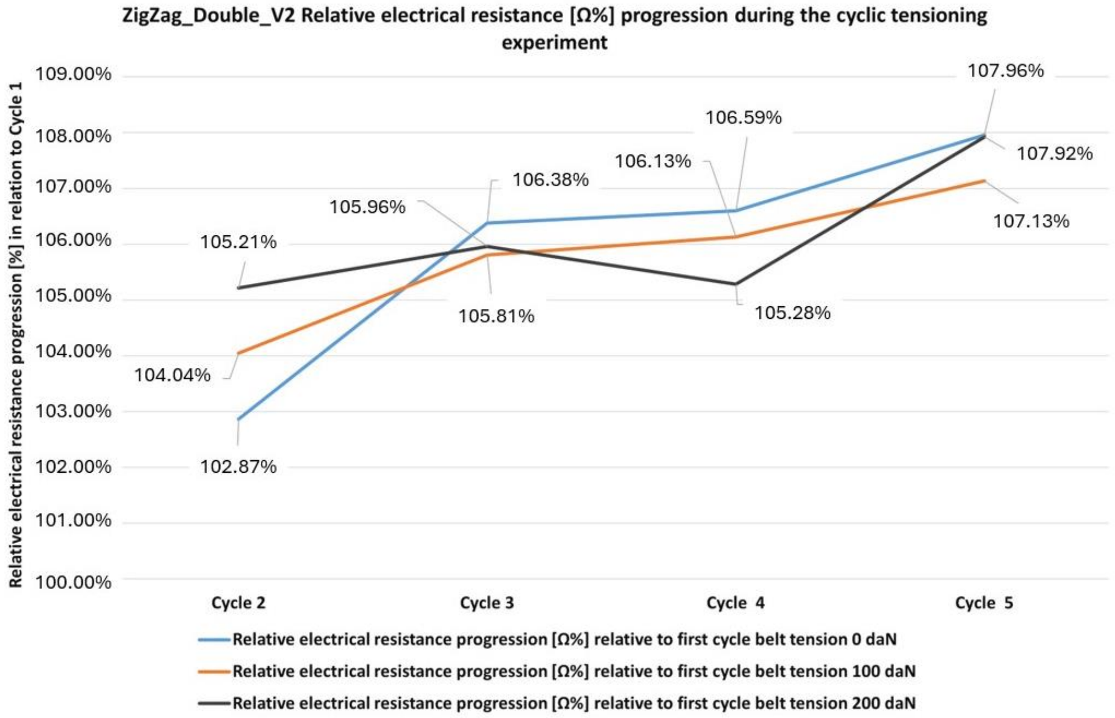

Figure 17. *Relative Electrical resistance [Ω%] progression during the cyclic tensioning experiment – ZigZag_V2_Axial*

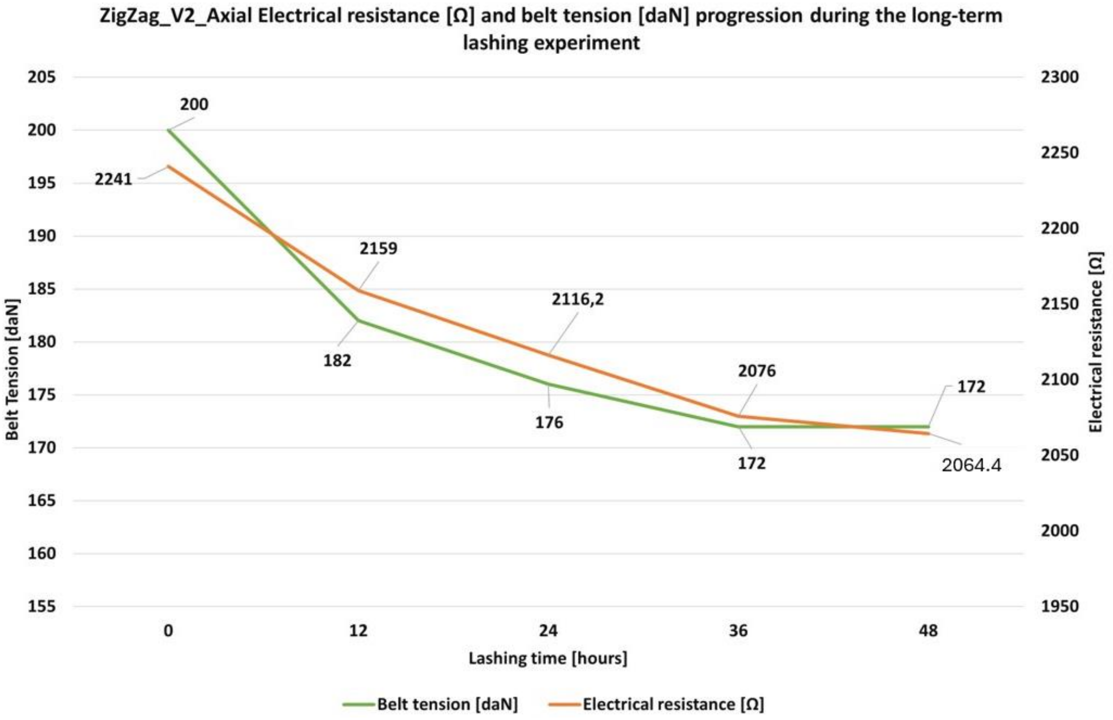

Figure 18. *Electrical resistance [Ω] and belt tension [daN] progression during the long-term lashing experiment – ZigZag_V2_Axial*

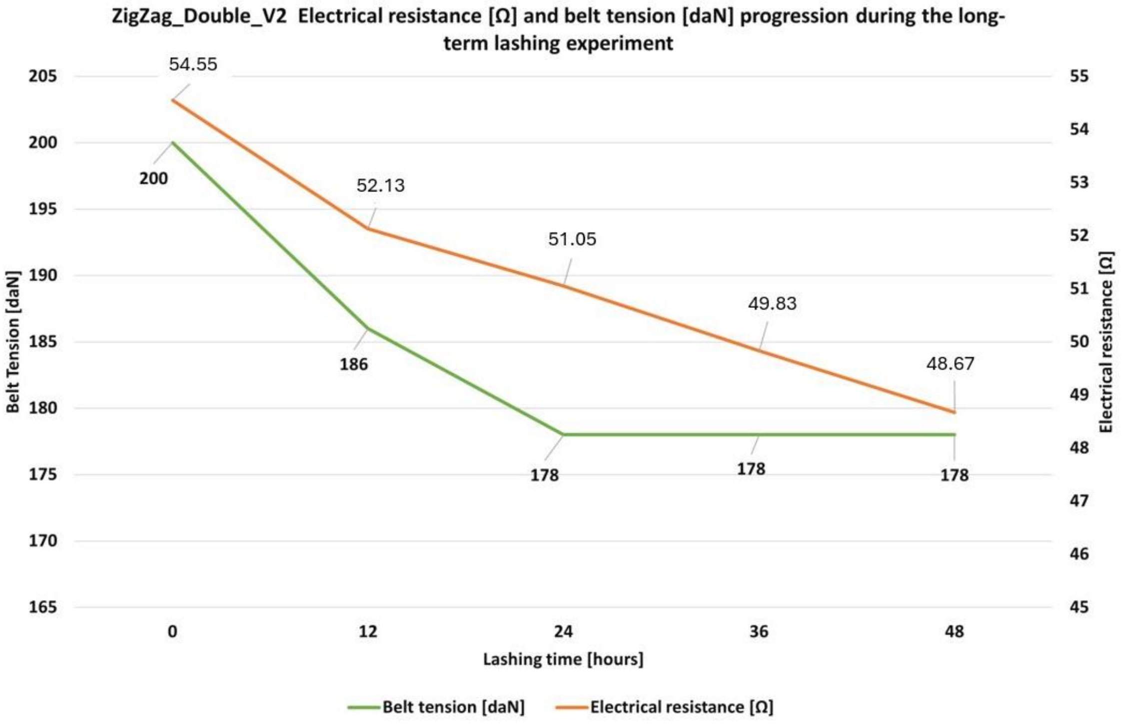

Figure 19. *Electrical resistance [Ω] and belt tension [daN] progression during the long-term lashing experiment – ZigZag_Double_V2*

VI. DISCUSSION

The conducted experiments results show that the developed Stitch applications *ZigZag_V2_Axial* and *ZigZag_Double_V2* both enable the measurement and monitoring of belt tension, applied to a standard compliant load securing strap. Both probes displayed clearly distinguishable changes in the electrical resistance corresponding to different levels of belt tension. The cyclic tensioning experiment showed that *ZigZag_Double_V2* provides a higher gauge factor compared to *ZigZag_V2_Axial* in every cycle and at every level of applied belt tension. However, in Comparison *ZigZag_Double_V2* displayed a higher and more volatile sensitivity and relative resistance drift. However, though *ZigZag_Double_V2* provides higher gauge factors, *ZigZag_V2_Axial* displays a less volatile cyclic sensitivity drift and therefore indicates better recovery properties in comparison.

In the past conducted development work of the two stitch applications, a similar drifting behavior was found. The observed drifting behavior back then was suggested to be especially caused by the combination of the conductive yarns cyclic tensile wear, its orientation angle on the fabric surface and the tested narrow fabrics proneness for permanent elongation. [4]

The load securing strap used in this conducted work however shows good recovery properties with no permanent elongation measurable. With this factor considered expelled the observed resistance and sensitivity drift is very likely to be driven mainly by cyclic tensile wear to the conductive yarn. *ZigZag_V2_Axial* has a higher stitch length and width than *ZigZag_Double_V2*. This results in the single stitch sections laying in a lower angle and in a less direct orientation towards the tensile force direction during belt tensioning.

Due to the higher orientation, the conductive yarn is likely more exposed to mechanical stress, resulting in the spun silver-plated polyamide fibers experiencing more intense tensile wear. (**Fig. 20**) A fibers conductive surface coating cracking or loosing integrity otherwise due to mechanical wear is a commonly expected cause for conductive fibers electrical resistance permanently increasing and the strain sensitivity to alter is described by the so called *Crack Modell*. [19, 21] The myriads of single spun fibers *cracking* more severely due to *ZigZag_Double_V2*'s yarn higher tensile wear explains the increased and more volatile resistance and sensitivity drift compared to *ZigZag_V2_Axial*.

This suggests that both developed stitch-applications recoverability is limited by the used conductive yarns vulnerability to tensile wear, even in combination with a highly recoverable narrow fabric. Therefore, further modification of the stitch properties influencing the yarns orientation on the fabrics surface and the choose of yarn itself are expected to be key parameters for optimizing a stitch-based strain sensors recoverability in this special use case.

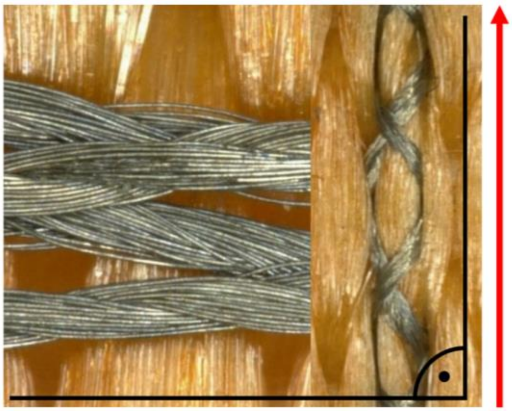

***Figure 20**. Yarn orientation in tensile force direction (left: ZigZag_V2_Axial; right: ZigZag_Double_V2)*

From the long-term lashing experiment results can be conducted, that *ZigZag_V2_Axial* enables a more precise monitoring of the securing straps losing belt tension. The loss of belt tension can be explained by the fabric progressively rearranging under static deformation to relief tension. The VDI 2700 mentions this behaviour as expectable for load securing straps and therefore strongly suggests ongoing belt tension monitoring over the transport time as a countermeasure. [10]

The measured resistance drop of both stitch applications is likely caused by the fabric's relaxation rearranging the stitches conductive network towards its former relaxed state as well. *ZigZag_V2_Axial's* resistance curve progression corresponds especially well with the securing straps behaviour in comparison to *ZigZag_Double_V2*. Due to the high stitch density and stitch width, *ZigZag_V2_Axial* has a high concentration of short-circuiting contacting yarn areas. When the fabric and the stitch rearrange towards their original relaxed state, former opened short-circuits may reconnect by yarn areas physically separated during fabric tensioning reconnect to one another. *ZigZag_V2_Axials* belt tension monitoring ability therefore likely benefits from the application's high concentration of short-circuiting yarn sections opening and reconnecting, in comparison to *ZigZag_Double_V2*.

The probes based on *ZigZag_V2_Axial* show a significantly higher absolute initial electrical resistance and higher absolute deltas in measured resistance [ΔΩ] both conducted experiments, compared to *ZigZag_Double_V2*. This is likely caused by *ZigZag_V2_Axial's* stitch properties (especially it's high stitch density and length) result in a bigger total length amount of conductive yarn being stitched onto the substrate.

VI. CONCLUSION

The results of this work suggest that both stitch-based strain sensors enable the belt tension measurement and long-term monitoring of a DIN EN 12195-2 compliant load securing strap. The conducted experiments were designed close to a practical load securing procedure to investigate the stitch-based strain sensors usability in this specific use case. From this viewpoint, *ZigZag_V2_Ax*ial is a promising candidate for future development attempts and iterations. *ZigZag_V2_Axial* in its current iteration is already capable to reproduce the fabric relaxation behavior of a load securing strap with a high degree of accuracy. The measured high absolute resistance deltas enable a precise distinction between different levels of belt tension. Both tested stitch-based strain sensor applications are vulnerable to cyclic resistance and sensitivity drift in their current iteration. This greatly limits the practical use in road freight transportation.

However, the conducted experiments result strongly suggest that the choose of conductive yarn and the yarns orientation influencing stitch properties are the main parameters for further optimization. Using a yarn less vulnerable for tensile wear and further adjustment of the stitch parameters could possibly greatly enhance the stitch-based strain sensors recovery properties in future iterations.

It's important to note that environmental interferences have been mostly left out for the experiments conducted in this research work. During road freight transport numerous interferences like a vehicle’s vibration, temperature changes or magnetic fields etc. can possibly greatly influence the stitch-based strain sensors behavior and require special kinds of insulation or shielding.

Those aspects must be considered and included in future experiments and research work. However, for better comparison of the results and especially due to limited technical possibilities concerning conducting the described experiments under controlled vibration, it was decided to exclude those factors from this conducted work.

Test equipment with a more precise measurement of belt tension and electrical resistance [Ω] must be used to further refine and to validate the observed sensor characteristics.

However, CNC-embroidery is a precise manufacturing technology with a high possible grade of automatization. A further developed and validated stitch-based strain sensor could become an interesting alternative for the cheap functionalization of load securing belts and to enhance road freight transportation security in the future.

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AUTHOR CONTRIBUTIONS

Norman Lesser: Conceptualization, Experiments, Theoretical analysis, Writing

Bernd Sadlowsky: Supervision and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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