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Integration of Polymer Optical Fibers in Nonwoven Geotextiles for Continuous Strain Monitoring

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Abstract

Geotextiles are often used in large scale civil engineering projects, such as dams and embankments. Failure of these structures can lead to significant economic losses as well as mortal danger. Still, current monitoring solutions of such structures often rely on discontinuous, external systems and procedures, which are labor intensive and cannot be used at short notice in extreme load cases. Since geotextiles support large parts of the structures, the integration of a continuously operating sensor system in the geotextiles is an obvious solution. One such sensor system is based on polymer optical fibers (POF), which are used in various applications as strain sensors. In this paper, various methods are investigated to integrate polymer optical fibers into nonwoven geotextiles. The methods are examined for their suitability and behavior under load. The results show that adhesive and heat-based methods are most suitable to connect POF and nonwoven geotextiles, while a Velcro tape does not provide sufficient connection. For all methods, maximum strain is limited to values < 5% elongation.

Keywords: geotextile; structural health monitoring; polymer optical fibers; sensor integration

1. Introduction

Since their introduction into civil engineering in the last century [1], geotextiles have become increasingly popular and are commonly employed in large scale civil engineering projects today [2]. This makes geotextiles an obvious point of integration for sensors for structural health monitoring (SHM) in civil engineering structures [3]. According to Abedi et al. [4], three categories for the integration of sensors in geotextiles exist:

1. Integration of strain gauges;
2. Integration of fiber-optic-based sensors;
3. Self-sensing capabilities.

Of these categories, the direct integration of strain gauges into geotextiles is least common, since the integration is complex and most strain gauges are susceptible to damage during the installation process [4]. Self-sensing geotextiles are made from materials that inherently possesses some characteristics that reacts to outside stimuli and can be measured [4]. A common example of this are carbon fiber based textiles, which utilize the electric conductivity of the carbon fibers to detect strain or the presence of water [5,6]. The main advantage of self-sensing geotextiles is that the sensor is completely integrated into the geotextile. However, it is necessary that the self-sensing material also has the properties required by the main function of the geotextile (e.g., reinforcement or drainage), which is

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not always the case. Self-sensing geotextiles are also a relatively new field of research [4]. The most common method for the integration of sensors into geotextiles is the integration of fiber-optic-based sensors [4].

Fiber-optic-based sensors are employed for various measurements (e.g., strain [7], temperature [8], pH-value [9], etc. [10]) in various fields (e.g., composites [11], concrete structures [12], etc.). Several approaches to using fiber-optic-based sensors exist. In the simplest method, the intensity of the transmitted light in the fiber-optic sensor is measured and any changes are detected. This method only allows for an aggregated measurement of the change in intensity along the whole sensor fiber. More complex measurement methods, such as Bragg gratings or optical time-domain reflectometry (OTDR) allow for localized measurements [10]. Fiber-optic-based sensors are either made from glass fibers or polymer optical fibers (POFs) [13]. POFs have the advantage of lower costs and easier handling but suffer from higher transmission losses compared to glass fibers [14,15].

The integration of fiber-optic-based sensors into geotextiles has been investigated in several studies. For example, Liehr et al. used POF integrated into woven geotextiles for distributed strain measuring with OTDR [16]. Kuang et al. used a POF based sensor measuring light intensity to measure the localized strain in submerged geotextile tubes [17]. Xue et al. report on the use of a glass fiber based strain sensor using Bragg gratings employed in the subgrade of a high-speed railway [18]. These studies show that the use of fiber-optic-based sensors in geotextiles is possible. One central challenge noted in the studies is the integration of the fibers into the geotextile.

In this paper, we present the results of an experimental study on integrating polymer optical fibers into nonwoven geotextiles. Initially, the results of our investigation into possible integration methods are presented and the most promising integration methods are selected. A POF is then joined to a nonwoven geotextile using the selected methods. Two experiments are then performed on the integrated sensors: a peel test to determine the strength of the joint between sensor and geotextile and a tensile test of the geotextile, during which the change in attenuation of the POF is measured. Finally, the results are presented, discussed and the most suitable integration methods are selected.

2. Integration of POF Sensors into Nonwoven Geotextiles

The integration of sensors into a geotextile has several advantages compared to a separate installation of sensors into the monitored structure. The main advantages, according to Thiele et al. [19], are:

- Defined sensor placement;
- Area-wide monitoring;
- Simultaneous installation of geotextile and sensors;
- Simultaneous assurance of structure functionality and monitoring.

Sensor fibers can be integrated into geotextiles at different steps of the process chain, starting with the textile production, followed by textile finishing and finally during installation of the geotextile at the construction site. The main advantages and disadvantages of each possible integration step are given in Table 1. Since the installation during the textile finishing process is the most flexible option, allowing for various integration methods and free positioning of the sensor on the textile, the integration during textile finishing is focused on in this paper.

The requirements for any integration method for sensor fibers into geotextiles can be derived from previous projects [16–20]. First, the integration method must not damage the POF during installation and needs to protect the sensor fiber from damage during transport, installation and use. Second, the installation method needs to ensure a stable connection between the POF and the geotextile to ensure that any strain in the textile is

transferred to the sensor. And last, the integration process must be simple and inexpensive in installation and operation to ensure economic viability.

Table 1. Advantages and disadvantages of the integration of sensor fibers during textile production, textile finishing and geotextile installation.

Integration During	Textile Production	Textile Finishing	Geotextile Installation
Advantages	+ Full process integration reduces costs + Textile integration can protect sensor	+ Free positioning of sensor on textile + Wide selection of integration methods	+ Tailored positioning of sensors on site + Lowest risk of damage to sensors
Disadvantages	- Sensor position limited by production method - Limited selection of integration methods - Sensors need to withstand following production steps	- Sensors need to withstand transport and installation - Additional process step	- Labor intensive sensor installation - Limited selection of integration methods - Additional process step

Various methods for the integration of POF sensors into nonwoven geotextiles in a textile finishing process are available. These methods are categorized in the following paragraphs and in Figure 1 and the most promising approaches for further investigation in this paper are selected.

Methods for joining polymer optical fibers to nonwoven geotextiles

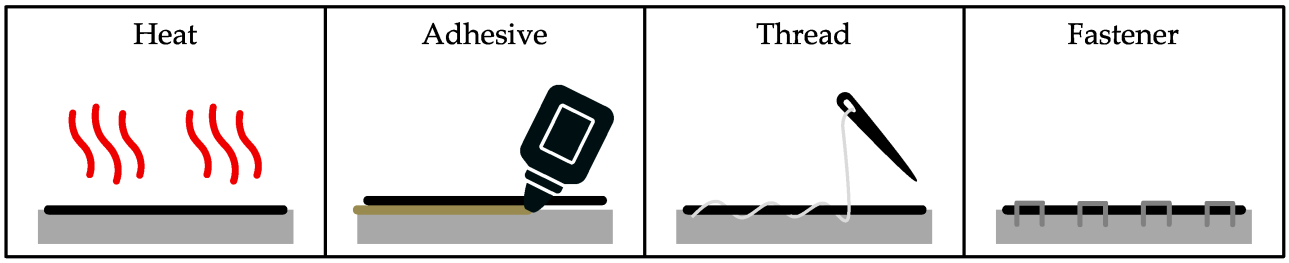

Figure 1. Four categories of methods to join POF (black) to nonwoven geotextiles (gray).

The first category of integration methods is the integration based on the application of heat. By melting a thermoplastic material, a connection between POF and nonwoven is formed. This method is best used with nonwovens made from thermoplastic materials, which can be melted to form the connection with the POF. The heat can be applied to a larger area of the nonwoven, e.g., by using heated rollers in the calendering process. Alternatively, the heat can be applied locally, welding the POF to the nonwoven. However, it is necessary to ensure that the temperature and pressure do not damage the POF during the connection process.

The second category of integration methods is adhesively bonding the POF to the nonwoven geotextile. Adhesive bonding is achieved by adding an adhesive material in between the POF and the nonwoven, either in a local application process or by completely coating the nonwoven or POF. Adhesives can be divided into chemically reacting adhesives (cold or warm curing) as well as hot melt and solvent based adhesives [21]. Critical parameters are temperature and pressure. Additionally, the chemical composition of the adhesive needs to be compatible with textile, POF and the soil after installation.

The third category of integration methods involves using a thread to join the POF to the nonwoven geotextile. The thread can be applied using different textile production

methods, such as sewing, knitting or embroidering. Critical parameters for these methods are the production parameters, which limit the diameter and placement of the POF.

The fourth and last category of integration methods involves the usage of additional materials to connect the POF and the nonwoven geotextile. Possible examples for this method are staples or the use of tape to form the connection. Critical parameters for this method are the application speed of the fastening material and the compatibility with the POF and the nonwoven.

In our paper, integration methods based on heat, adhesive and fasteners are investigated. Integration methods based on using threads to connect POF and nonwoven are excluded since they have already been investigated in prior studies [19,22].

3. Materials and Methods

The POF used in our experiments is a commercially available step index polymer optical fiber (SI-POF) called TC-1000 manufactured by Asahi Kasei K.K., Tokyo, Japan. The properties of the fiber according to the manufacturer are given in Table 2.

Table 2. Selected properties of the used POF according to the manufacturer.

Property	Value
Outer diameter	2.2 mm
Core diameter	1.0 mm
Core material	Poly(methyl methacrylate) (PMMA)
Cladding material	Fluorinated PMMA
Cable jacket material	Polyethylene (PE)
Attenuation	$\leq$0.15 dB/m
Breaking strength	$\geq$90 N
Elongation at break	$\geq$90%

Two nonwoven geotextiles are used in our experiments, both produced and provided by NAUE GmbH & Co. KG, Espelkamp-Fiestel, Germany. The nonwovens are commercially available under the trade name "Secutex" and are used in geotechnical applications for separation, filtration and protection. The properties of the nonwovens according to the manufacturer are given in Table 3. All specimens are cut from the nonwoven so that the machine direction is tested.

Table 3. Selected properties of the used nonwovens according to the manufacturer.

Property	Nonwoven 1 R401	Nonwoven 2 R1201
Fiber material	Polypropylene fibers, 90 mm long with 6.7 dtex	
Area weight	400 g/m^2	1200 g/m^2
Thickness	3.9 mm	8.2 mm
Maximum tensile force (md/cmd) [1]	30/32 kN/m	63/100 kN/m
Elongation at maximum tensile force (md/cmd) [1]	50/50%	60/45%

[1] md: machine direction; cmd: cross machine direction.

To enable an easy evaluation of the deformation of the POF during trials, the attenuation of the POF is determined using an attenuation meter made by DieMount GmbH, Wernigerode, Germany. The attenuation meter has an internal light source with a wavelength of 650 nm and can measure the attenuation between 0 dB and 45 dB. The attenuation meter is connected to one end of the POF and a reflector is placed on the other end of the POF, so that the light is reflected back to the meter and the attenuation is determined.

To ensure a flat surface of the ends of the POF for coupling with the attenuation meter and the reflector, the POF is cut using a POF-cutting tool also made by DieMount GmbH, Wernigerode, Germany. The tool consists of a sharp cutting edge embedded between two metal sheets with a defined opening for the POF, ensuring that the cut is flat and perpendicular to the fiber length. The reflector is fastened to the POF using a metal ferrule. However, the attenuation introduced at the contact areas between POF and attenuation meter as well as reflector is still significant (between 2.6 dB and 8.7 dB) and more importantly, not constant under de-coupling and re-coupling in our trials. Therefore, relative measurements are only valid if the attenuation meter and reflector remain coupled to the POF during the testing procedure.

The heat based joining of POF and nonwoven is performed by welding (locally melting the nonwoven and the jacket material of the POF and pressing both together). This is achieved by locally applying heat using a soldering iron while gently pressing the materials together manually. The joining speed is about 20 cm/min. Based on pre-trials, two temperature levels are selected for the heat based joining method: 200 °C and 220 °C. If lower temperatures are selected, the materials do not melt sufficiently quickly and the bond between POF and nonwoven is so weak it fails during handling. At higher temperatures, the core of the POF is damaged, as determined by large increases in attenuation (values > 10 dB after the joining).

For the adhesive based joining of POF and nonwoven, two different types of adhesive are used: a hot-melt adhesive and a two-component adhesive. Both adhesives used are commercially available products by the company Ruderer Klebetechnik GmbH, Zorneding, Germany. Selected properties of the adhesives according to the manufacturer are given in Table 4. For both adhesives, two variations for the application are investigated. In the first variation, the adhesive is applied as a line onto the nonwoven and the POF is manually pressed onto the adhesive during the processing time of the adhesive. In the second variation, the adhesive is applied onto the nonwoven in dots spaced about 2 cm apart, and the POF is the manually pressed onto the adhesive.

Table 4. Selected properties of the used adhesives according to the manufacturer (Ruderer Klebetechnik GmbH, Zorneding, Germany).

Property	technicoll® 9310	technicoll® 9410-1 A	technicoll® 9410-1 B
Type	Acrylate based hot-melt	Two-component	
		Methacrylate	Amine
Application temperature	180–200 °C	Room temperature	
Processing time	40 s	240 s	
Curing time	-	36 h	
Density	0.9 g/cm^3	1.0	
Viscosity	5000 mPas @ 180 °C	thixotropic	25,000 mPas

The fastener based joining of POF and nonwoven is performed by using a Velcro hook tape to fasten the POF to the nonwoven. The Velcro hook tape used is distributed by ELKUBEMA Vertriebs-GmbH, Hemdingen, Germany, and consists of a Polyamide (PA) 6 tape with Polyamide 6.6 monofilament-based hooks. The tape has a width of 20 mm and is manually pressed on top of the POF and onto the nonwoven, so that the hooks connect directly with the nonwoven.

To evaluate the strength of the connection between POF and nonwoven, peel tests following DIN EN ISO 11339 [23] are performed. For the peel tests, nonwovens and POF are cut to a length of 20 cm, with a width of 6 cm. The POF is integrated from one end of the nonwoven fabric with a length of 15 cm. The POF is joined so that it protrudes at the

ends of the joint in order to connect it to the attenuation meter after the sample has been prepared. According to the standard, the flexible parts of the sample are bent apart to a 90° angle and clamped in a tensile testing machine (type Z2.5 made by Zwick/Roell GmbH & Co. KG, Ulm, Germany). The textile and the POF are then continuously pulled apart at a constant separating speed of 100 mm/min. The force required to separate the bond is recorded by the force transducer over the peeling distance. The setup is shown in Figure 2.

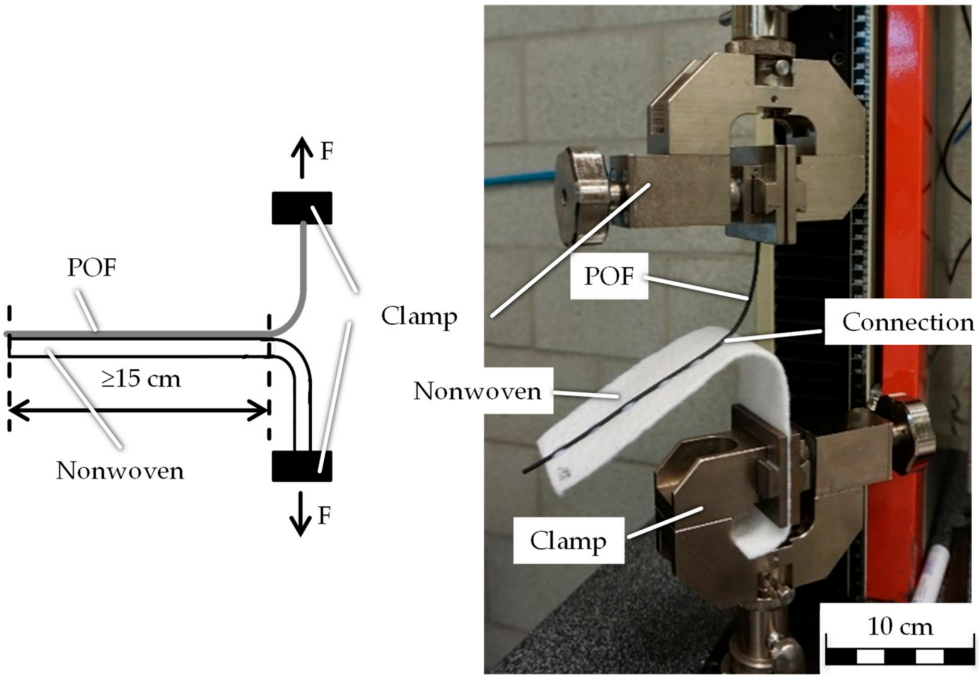

Figure 2. Test setup for the peel tests.

To evaluate whether the investigated joining methods are suitable to transfer the elongation from nonwoven to the POF, tensile tests with a simultaneous attenuation measurement are performed. As a baseline reference, the change in attenuation during elongation of a POF not connected to a nonwoven is tested. For that test, a tensile test following DIN EN ISO 2062 [24] is performed. To protect the POF during clamping, the clamping areas are embedded in epoxy resin. The POF is fixed in a tensile testing machine (type Z100 made by Zwick/Roell GmbH & Co. KG, Ulm, Germany). The POF is connected to the attenuation meter and defined elongations are approached with a speed of 50 mm/min. At these measurement points, the attenuation is determined using the attenuation meter. The setup is shown in Figure 3.

For the tensile tests with POF connected to nonwovens, the tensile test is performed following DIN EN 29073 [25] part 3. The nonwovens are cut into strips with a width of 5 cm and a length of 30 cm. The POF is cut to a length of 22 cm and connected to the nonwoven, using the various methods described above, at a length of 10 cm in the middle of the nonwoven strips. The ends of the nonwoven are clamped into a tensile testing machine (type Z100 made by Zwick/Roell GmbH & Co. KG, Ulm, Germany) and the POF is connected to the attenuation meter. Again, defined elongations are approached (at a speed of 100 mm/min) and the attenuation of the POF is measured at those points. The setup is shown in Figure 3.

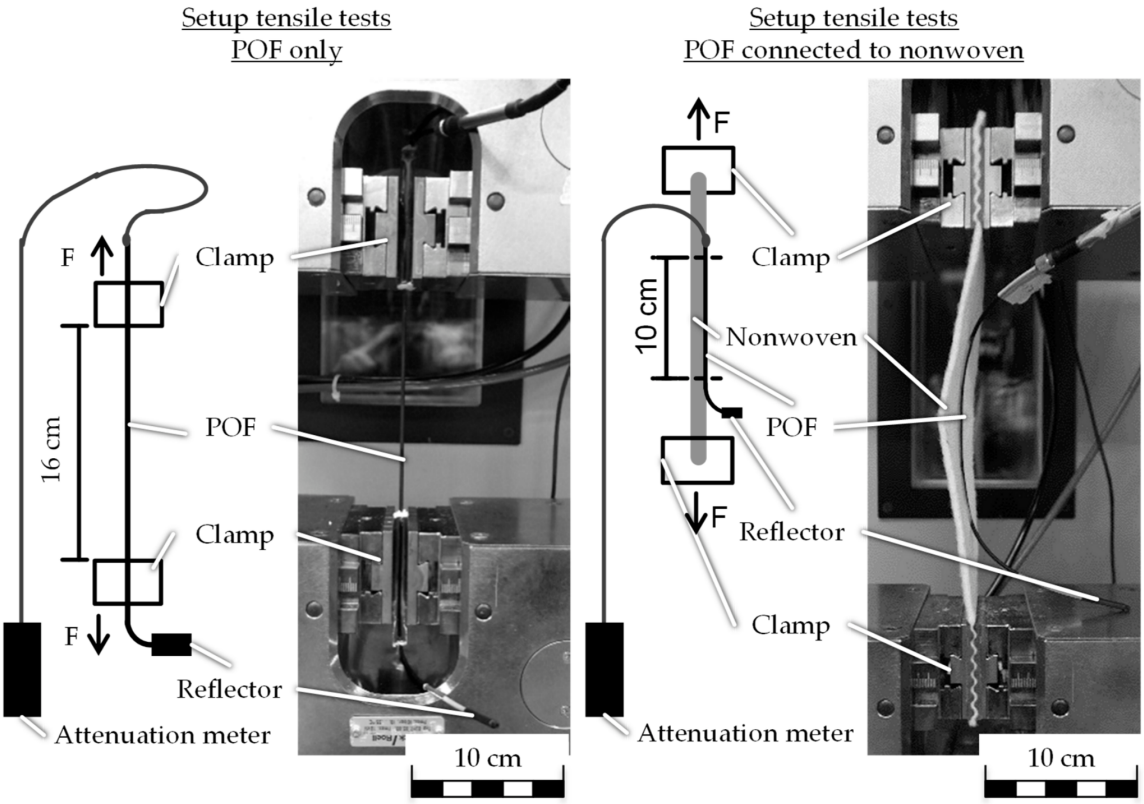

Figure 3. Test setups for the tensile tests.

4. Results and Discussion

In the following chapter, the readings of the attenuation measurements as well as the test results of the peel and tensile tests are presented and discussed.

4.1. Observations During POF Integration

During the installation of the POF on the nonwoven using the methods described above, several observations are made. First, for all methods, attenuation measurements are possible prior to and after integration into the nonwoven, with the variations in attenuation within the large variations in the pure POF under coupling and recoupling. Therefore, none of the installation methods significantly damage the POF. There is also no visible damage/change to the sheath of the POF for any specimen.

The adhesive based installations are more challenging than the welding or Velcro based methods, since the POF needs to be placed onto the nonwoven during the processing time of the adhesive and fixed in place until the adhesive is cured. For the hot-melt adhesive, the curing time is about 60 s, requiring a fast installation. For the two-component adhesive, the processing time is 4 min, while the curing time is 36 h. The long curing time can lead to loss of connection between POF and nonwoven if the connection is disturbed.

4.2. Peel Tests

The peel test determines the forces required to separate the bond between the POF and the nonwoven. According to DIN EN ISO 11339, the forces of the first 25 mm and the last 25 mm are not considered for the averaged forces of a specimen. Figure 4 shows a representative peeling force curve for each test series. Figure 5 shows the average peeling force for each series.

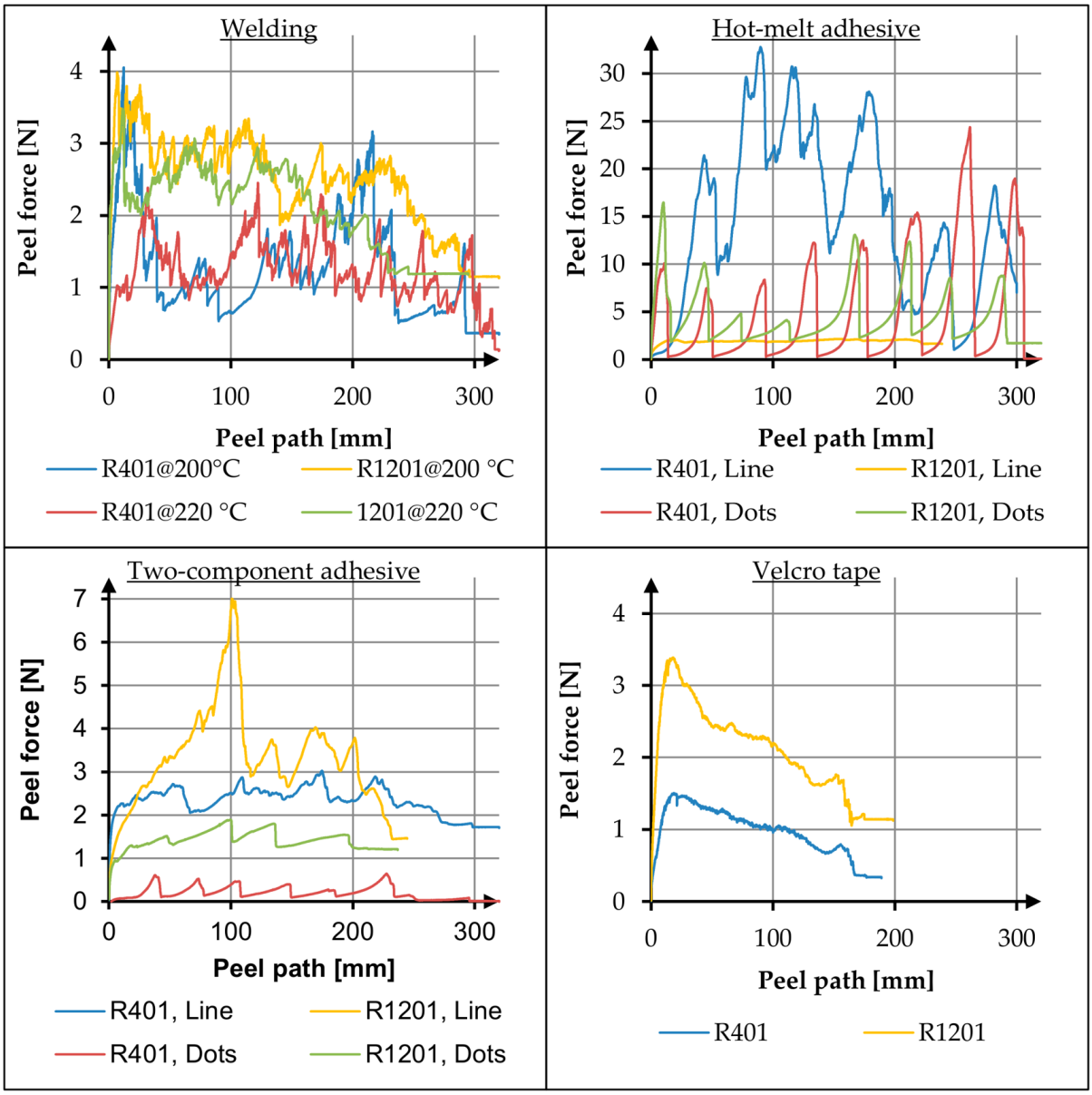

Figure 4. Representative peel force–peel path curves for each series.

As can be seen in Figure 4, the peel force–peel path curves for the welding series show a high variation in the peel force along the whole peel path, suggesting that the bond between POF and nonwoven is locally variable, but roughly constant on average along the fiber length.

For both adhesive series, the two application methods of the adhesive (line and dots) lead to very different peel force–peel path curves. While the line method leads to curves similar to the soldered series, the dot method leads to repeated increases in the peel force, followed by sharp drops. The sharp increases and drops in the dot method correspond to the peeling of each adhesive dot, while the area in between the dots has very limited peel force, since it is not connected to the nonwoven. For the series "Hot-melt adhesive, R1201, Line", the peel force is nearly constant and much lower than the series "Hot-melt adhesive, R401, Line". Closer inspection of the specimens reveals different failure modes: with the thicker nonwoven (R1201), there is an adhesive failure in which the POF is separated from the hot-melt adhesive, which remains glued to the nonwoven. For the thinner nonwoven (R401), there is a failure within the nonwoven itself, which is ripped apart with pieces remaining glued to the POF. This suggests that in the thicker nonwoven, with its higher

thermal mass, the hot-melt glue cools down faster, leading to a weaker adhesive connection between POF and nonwoven. This is supported by the failure modes of the dot method, where the dots naturally cool faster than the line due to a higher surface area and which both exhibit the adhesive failure in which the POF is peeled from the adhesive, which remains in the nonwoven. For the two-component adhesive, a cohesive failure is observed, in which some adhesive remains stuck to the POF while some remains within the nonwoven after peeling.

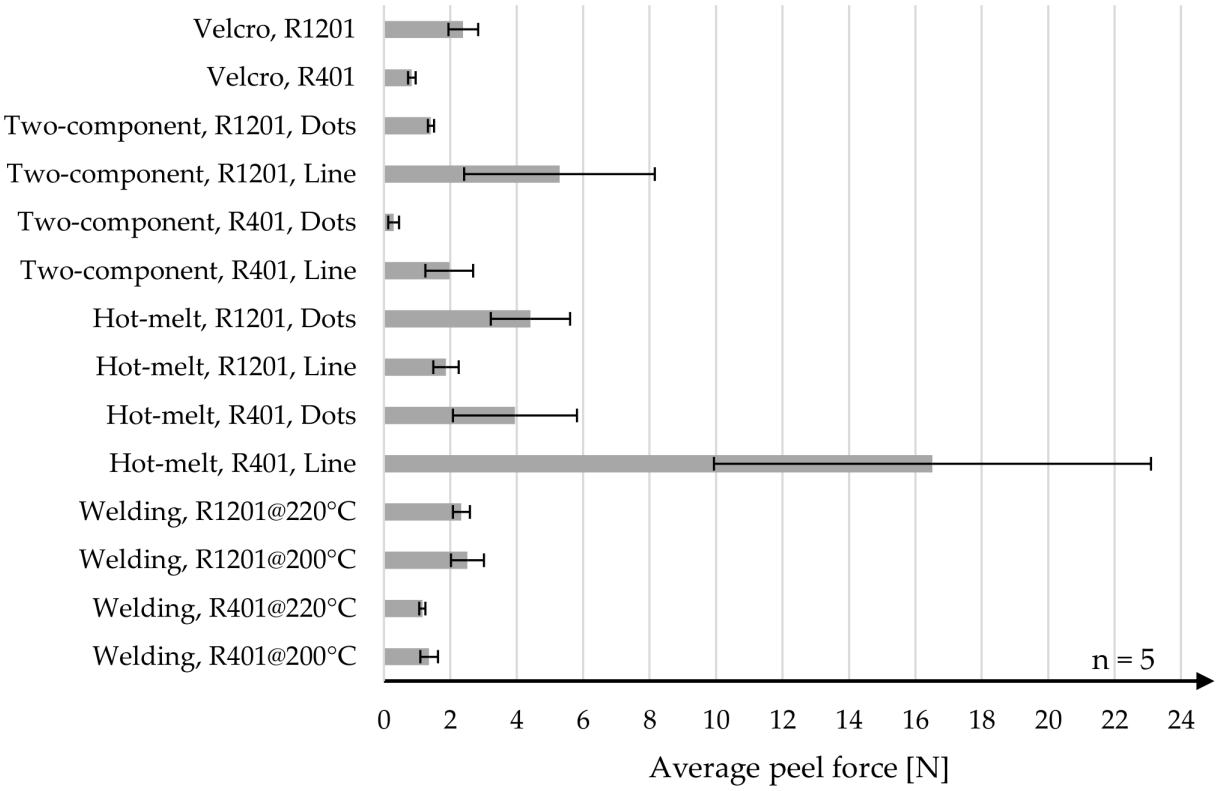

Figure 5. Average peel forces for each series (irrespective of failure mode). Error bars indicate standard deviation.

In the Velcro tape series, a sharp increase in the peel force in the beginning of the test is followed by a gradual, nearly linear decline of the peel force. This curve corresponds to the observed failure behavior, in which the POF is pulled from the inside of the Velcro tape without ripping the Velcro tape from the nonwoven. After the initial static friction is exceeded, the sliding friction is gradually reduced as more and more POF is pulled out from the Velcro/nonwoven connection.

As can be seen in Figure 5, the average peel forces vary greatly between the series. The greatest average peel forces are achieved using the adhesives method (16.5 N for the series "Hot-melt, R401, Line" and 5.3 N for the series "Two-component, R1201, Line"). Welding achieves lower values (1.2–2.5 N) similar to Velcro (0.84–2.39 N). In general, the values are higher for the thicker nonwoven (R1201), suggesting that more nonwoven material is beneficial to achieving a strong bond. For the adhesives, the values are generally higher if the adhesive is applied in a line compared to the dot method. This is easily explained by the fact that the line method leads to more adhesive being applied. The notable exception to these two observations is the series "Hot-melt, R1201, Line", which achieves lower average peel force of 1.9 N than both the series "Hot-melt, R401, Line" (16.5 N) and "Hot-melt, R1201, Dots" (4.4 N). As described above, the series "Hot-melt, R1201, Line" exhibits a failure of the adhesive bond between hot-melt adhesive and POF, most likely due to the

fact that the hot-melt adhesive cooled down rapidly after application onto the nonwoven, leading to failure of the connection with the POF. For the welding series, no significant difference between the investigated temperature values is found, although the higher temperature does lead to reduced standard deviation of the average peel force.

4.3. Tensile Tests

In the following, the results of the attenuation measurements on POF integrated onto nonwovens are presented. Since the nominal values for the attenuation differ for each POF due to local variations, especially in the contact areas with the attenuation meter and the reflector, relative values are used to enable a comparison across different specimens. The relative change in attenuation A_{rel} is calculated according to

$$A_{rel} = \frac{A_{measured} - A_{start}}{A_{start}} \quad (1)$$

with A_{start} being the attenuation of the specimen at the start of the test and $A_{measured}$ being the attenuation at each approached value of elongation.

In Figure 6, the change in attenuation over the elongation of the POF is shown for the reference measurements of the POF. The increase in attenuation is relatively linear up to elongation values of 50–60%. At higher elongations than 50–60%, the bond between POF and the epoxy resin used for load induction fails, leading to pull-out failure, which reduces the actual elongation of the POF and thereby the change in attenuation.

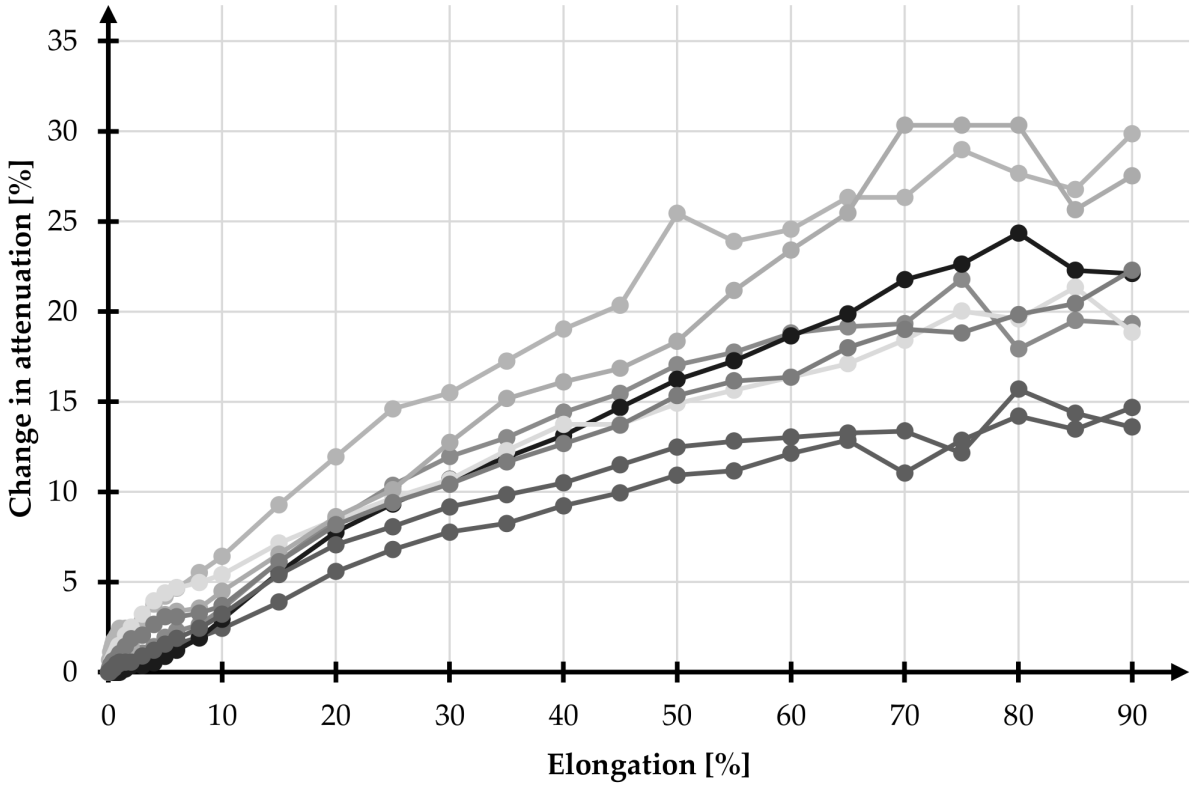

Figure 6. Changes in attenuation over the elongation of the reference POF.

In Figure 7, the changes in attenuation of the POF integrated onto the nonwovens using the investigated methods during the tensile tests of the nonwovens are shown. For reference, the average change in attenuation of the reference POF series is included in each graph. During the testing the bond between POF and nonwoven failed for all test series at higher elongations (>5%). Therefore, only the values up to 10% elongation are presented.

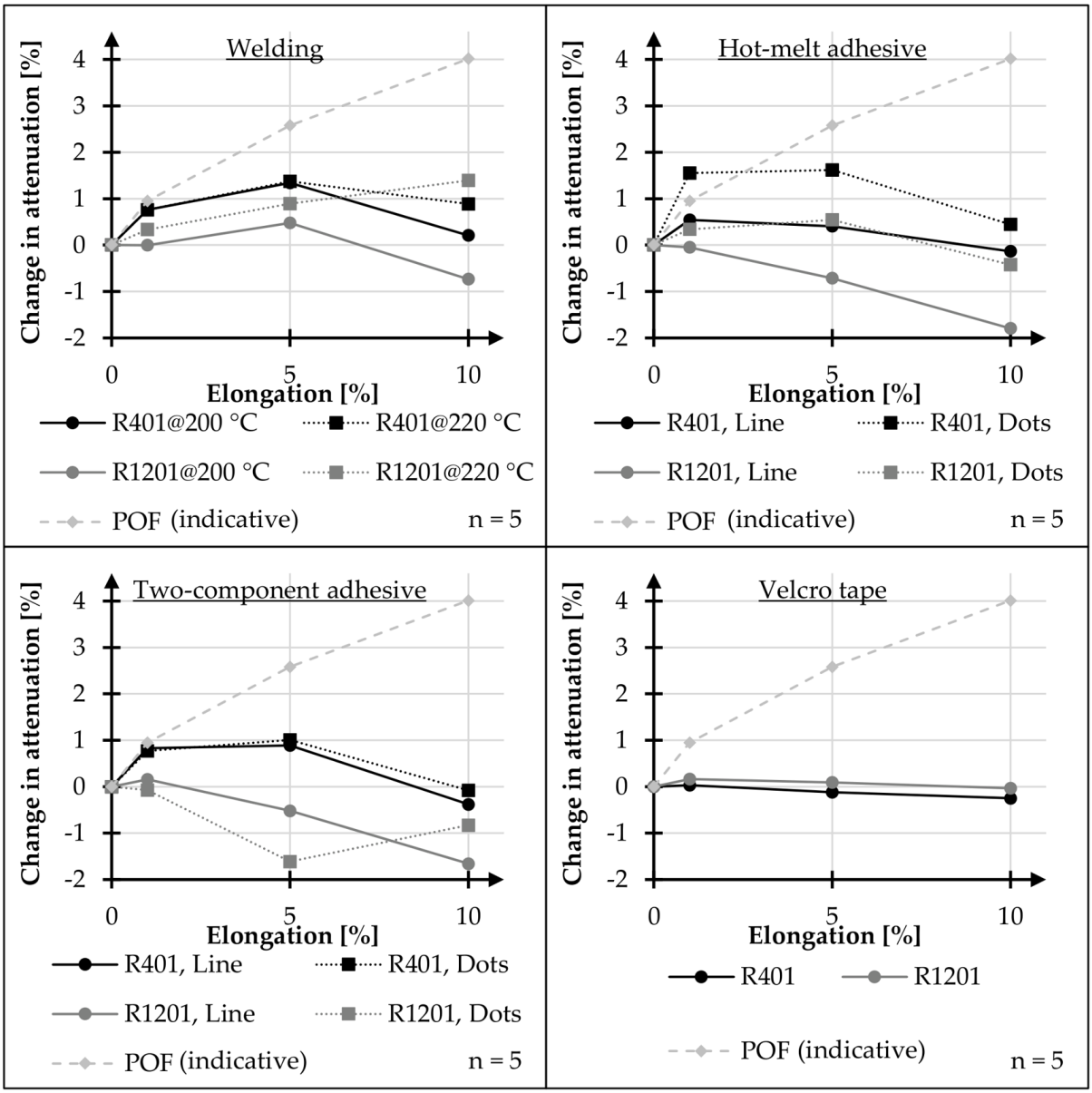

Figure 7. Changes in attenuation of the POF integrated onto the nonwovens during tensile tests of the nonwovens. The changes in attenuation of the reference POF is included in each graph for convenience.

For the welding series, the attenuation increases at low elongations (up to 5%), with a higher increase when using the thinner nonwoven (R401), suggesting a better match between the elongation of the thin nonwoven and the POF compared to the thick nonwoven and the POF. Additionally, the higher welding temperature leads to higher changes in attenuation, especially for the thicker nonwoven (R1201). This suggests that the higher temperature enables a better bond between nonwoven and POF, leading to better force induction.

Similarly, in both adhesive series, the series with the thinner nonwoven show greater changes in attenuation, while the thick nonwoven (R1201) shows only little change in attenuation at low elongations and a drop in the attenuation at higher elongations, most likely due to a failure of the connection between POF and nonwoven. In addition, for the hot-melt series, the dot application method leads to higher changes in attenuation. For the two-component adhesive, the differences between line and dots method are less pronounced, especially with the thinner nonwoven.

The Velcro tape method shows only very small changes in attenuation at any elongation, suggesting that no significant elongation is transferred from nonwoven to POF. This is in line with the results from the peel test.

In summary, the results from the tensile tests show that only welding, hot-melt adhesive with a dot-wise application, and two-component adhesive combined with the thin nonwoven (R401) show a correlation between the elongation of the nonwoven and the measured change in attenuation. For all methods, the connection between POF and nonwoven fails to transfer the elongation into attenuation changes at elongations >5%. Therefore, the investigated methods are only suitable for textiles which are to be used in applications with small elongations up to 5%. This is in line with the permitted strain in many geotextile applications, which is often is limited to 3–8% [26,27].

4.4. Comparative Evaluation of the Integration Methods

In Table 5, the investigated methods for joining the POF to the nonwoven geotextile are evaluated in three areas. The first is the processability, evaluating how easy the joining process between POF and nonwoven is. The second is peel strength, evaluating the strength of the connection between POF and nonwoven. The third is the transfer of elongation from nonwoven to POF.

Table 5. Comparative evaluation of integration methods.

Property	Welding	Hot-Melt Adhesive		Two-Component Adhesive		Velcro Tape
		Line	Dots	Line	Dots	
Processability	Very good	Good	Good	Moderate	Bad	Very good
Peel strength	Moderate	Very good	Good	Good	Bad	Moderate
Transfer of elongation (up to 5% elongation)	Very good	Moderate	Very good	Moderate	Moderate	Bad

The processability of both the welding and the Velcro tape method are very good, since both methods are easy to apply. Similarly, the hot melt adhesive has a good processability, with the only difficulty in the short process window (about 60 s) defined by the cooling hot-melt, which requires a fast joining of POF and nonwoven. The two-component adhesive has worse processability, since its relatively long curing time (36 h) slows down the process considerably. Especially in the dot method, the joining was sometimes unsuccessful due to relative motion between POF and nonwoven during the curing time.

For the peel strength, the hot-melt adhesive applied in a line provided the highest peel strength (see Figure 4), followed by the dot-wise application of the hot-melt and the line wise application of the two-component adhesive. Welding and Velcro tape provided similar peel strength, while the dot-wise application of the two-component adhesive provided the lowest peel strength.

For the transfer of the elongation from nonwoven to POF (up to 5% elongation), the welded samples and the hot-melt adhesive samples with a dot-wise application performed best. The line wise application of the hot-melt adhesive performed worse, especially for the thicker nonwoven R1201. The two-component adhesive performed well for the thin nonwoven, but failed for the thick nonwoven, resulting in a moderate evaluation. The Velcro tape failed to transfer the elongation.

Interestingly, there is no obvious connection between the performance in the peel test and the transfer of the elongation into the POF. The highest peel strength was achieved by the line wise application of the hot-melt adhesive, while the dot-wise application transferred the elongation better. Welding and Velcro tape achieved similar peel strength,

but performed completely differently in transferring elongation to the POF. This suggests that the perpendicular load induced during the peel test is not directly indicative of the ability of a joint to transfer elongation.

In summary, the welding method and the dot-wise hot-melt adhesive method performed best. The two-component adhesive method performed worse, but further investigations with different adhesive types (more flexible adhesives with faster curing times) are warranted. The Velcro method is not suited to transfer the loads from nonwoven to POF, since the friction bond is not sufficient. However, the Velcro tape is easy to apply and offers some protection to the POF against mechanical damage, so a combination of Velcro tape with the other methods might be beneficial.

5. Conclusions

In this experimental study, four methods to join a POF used for strain measuring to a geotextile nonwoven are investigated: welding, hot-melt adhesive, two-component adhesive, and Velcro tape. We investigated whether the connection of POF onto the nonwoven damages the POF by measuring the changes in attenuation, how strong the connection between POF and nonwoven is by performing peel tests and if the connected POF adequately measures the strain of the nonwoven in tensile tests. The main results of our investigation are:

- Damage free integration of the POF onto the nonwoven is possible with all investigated methods.
- Adhesives applied to the nonwoven as lines lead to the strongest connection between POF and nonwoven, with an average peel force of 16.5 N for the series "Hot-melt, R401, Line" and 5.3 N for the series "Two-component, R1201, Line". The lowest peel forces were observed for the dot-like application of a two-component adhesive (0.3 N) and the Velcro tape (0.84 N for series "Velcro, R401").
- During the tensile tests, elongation was transferred from nonwoven to POF only at low elongations (up to 5%). At higher elongations, the connection between POF and nonwoven failed to transfer the strain for all methods. For the Velcro tape method, no transfer of elongation to the POF was measured at all.
- Adhesive and soldiering methods are suitable to connect POF and nonwoven, as long as the expected elongation of the nonwoven during use is small.
- Further investigations into alternative, more flexible connection materials (e.g., flexible adhesives) that can transfer strain at higher elongations are necessary. In addition, we only investigated elongations induced in the fiber direction, but other load directions and also application patterns (e.g., sinusoidal waves) warrant investigation.
- One limitation of our study is the lack of investigation of the influence of the installation process in the soil on the properties of the POF integrated into the nonwoven. Another limitation is our focus on the short-term behavior of the POF and bond. Industrial applications of geotextiles often last years to decades, which makes investigations into the long-term behavior and the permanence of the reference state of the POF necessary.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fib14100115/s1.

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Abbreviations

The following abbreviations are used in this manuscript:

POF	Polymer optical fiber
SHM	Structural health monitoring
OTDR	Optical time-domain reflectometry
SI-POF	Step index polymer optical fiber
PMMA	Poly(methyl methacrylate)
PE	Polyethylene

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