Piezoelectric Textile Facade for the energy supply of active sensor technology with regard to data management for circular economy in building construction

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Abstract. The high GWP potential of construction requires a holistic approach such as circular economy. Currently, common joining, construction and planning practices result in heterogeneous assemblies of different components that are difficult to deconstruct. Furthermore, there is currently little information and data on building components used and the climatic impacts on them. In this context and with the intention of recording long-term (circular) processes in construction, the Piezo-Klett basic research project (FFG no. 879459) funded by the Austrian Research Promotion Agency (FFG) deals with the energy supply of active sensor technology in construction by combining the hook and loop fastener with piezoelectric components. The aim is to open new perspectives on sustainable energy production systems by transforming buildings into energy carriers and generators, analogous to a "battery". To this purpose, the result presented in this conference paper is a description of the constructive structure (climatic impacts, construction, piezo technology) of a "Piezoelectric Textile Facade" as well as test results on piezo tapes. This opens new possibilities in the context of the application of hook-and-loop fasteners, the energy supply of active sensor technologies as well as in the field of data acquisition and data management.

Keywords: Facade system; concept development and tests; circular economy; construction technology; piezo technology

1. Introduction

Globally, the construction industry accounts for approx. 36% of final energy consumption, approx. 39% of energy-related CO2 emissions [1], for approx. 40% of resource consumption [2] and Europe-wide for approx. 36% of total waste generation [3]. In line with the Austrian climate and energy strategy and the European "Green Deal", the establishment of a circular economy is a suitable way of reducing these values. [4, 5, 6]
On the constructional level, recyclable buildings require a corresponding deconstructable design of the interfaces between short-lived and long-lived as well as materially heterogeneous components. Thus, non-destructive separation in the area of the primary structure (shell) to secondary structure (finish) to tertiary structures (technology) and subsequently the management of these connections, as well as ease of maintenance, accessibility and standardization [7]. Common joining, construction and planning practice results in components made of different material composites, which, depending on the joining method and design, can be reconstructed or rebuilt without destroying the parts to be joined, up to only with damage or destruction. [8] In practice, however, non-destructive replacement is seldom or never used to the full, even if the design allows it, because clean release, especially in the case of surface composites (e.g. gypsum board on stud frame), means considerable additional work and thus higher costs. Compared to conventional joining techniques, the hook-and-loop joint offers simple, clean and fast assembly processes, damage-free, repeatable and detachable connections and a uniformal system that can be applied to almost all structural elements from different suppliers [9, 10]. As a result, the joint meets the design requirements for recyclable buildings better than common joining methods and is accordingly the subject of various construction-related patents [11, 12, 13, 14].

In addition to constructional requirements, circular economy in the construction industry can only be established with corresponding knowledge about the built structure. Digitization makes it possible to analyze and process data with regards to circular economy in terms of predictive modeling or predictive maintenance, component replacement, recycling, and reuse on the basis of component data and climate data. At present, there is no information or standards on this subject at EU level or in Austria. [15, 16] Accordingly, the Viennese architecture firm BauKarussell must first create a detailed BIM model of the existing object within the scope of a deconstruction planning before the actual planning can begin. [17]

This could be different in the future, when deconstructing today's new buildings. As a result of the amendment to the EU Procurement Directives of the European Parliament in 2014, regarding a mandatory BIM planning, as well as a consequence of the ÖNORM 6241-2 (national Austrian standard), which deals with the definition of structures, exchange and collaboration in digital building models, BIM models are generated more and more often. [18, 19, 20] In the future, as a result of OpenBIM and the "6D model", a model for all life phases (management of the structure, building demolition, sustainability) also seems possible. [21, 22] While BIM models are theoretically well suited to generate building component data and apply them in the design and construction process, the issue of long-term information storage beyond the BIM model (in the context of the building's use and for sustainable deconstruction) remains unsolved or poorly addressed. Recognizing this fact, the project described here aims at a physical as well as digital interface between built and virtual model.

Climatic impacts on buildings or parts of buildings can already be measured by sensors during the utilization phase and transferred to databases. For this purpose, particularly active sensors are suitable, such as the product NETBEE of the company NET-Automation GmbH, which is applied and treated in this research, and was designed especially for the outdoor area, for the detection of environmental conditions. [23] This product can be combined with different sensors as a sensor interface. It allows measurements and transmissions outside the readout cycle and does not require additional use of readout devices and can react independently to limit or threshold exceedances (storm, hail). In addition, the product can be used as a local memory (e.g. for climate data, component data) and thus enables on-site readout for simplified urban mining, construction site controlling, installation instructions, warnings, "smart site", and much more. [24] However, the installation of such active sensors is costly due to the required cabling and complicated, especially in the case of retrofitted sensors; in addition, the service life is severely limited in the case of decentralized power supply by means of batteries. [25] To solve this problem, the project Piezo-Klett proposes an energy supply by using the piezoelectric effect. This effect is based on a shift in the center of gravity of the piezoelectric crystals in a material caused by length contraction (stretching or compression), which results in a measurable voltage deflection. This requires a dynamic load, which also causes a sufficiently high length contraction. [26] Examples of existing sensor products with piezoelectrics are the IoT Energy Harvesting module from Viezo, which uses vibrations from industrial machines to generate energy, [27] the DuroAct Patch.
Transducer from PIceramic, which is loaded on bending and can be used as an actuator, sensor or energy generator, [28] and the Piezo Ring and Piezo Tubes from Piezo Hannas, which are optimized for use in 3D printers or in a sonar. [29, 30] A particularly innovative approach to harnessing this effect is the "piezo textile" developed and reported by Lund. [31] In this research, bicomponent PVDF fibers with a conducting core were melt spun and then woven into a textile which could be used as the shoulder strap for a bag. A voltage equal to four µW could thus be generated and an LED powered during a brisk walk. [31] Compared to existing products on the market, this textile opens the use of different effects due to the possibility of being able to divert these into tensile load. Thus, as well as due to the potential for a combination with the textile hook-and-loop fastener, it offers exciting application opportunities, especially in the building industry.

In the context of constructional requirements in the building industry and necessary knowledge about the installed components, the basic research Piezo-Klett (FFG-no. 879459), funded by the Austrian Research Promotion Agency (FFG), deals with the combination of the (deconstructable) hook-and-loop fastener with the piezo textile [31] for the energy supply of active sensors in building construction for the measurement and storage of climate and component data. Buildings and building components are thus regarded as energy generators, in order to operate so-called energy harvesting and collect data directly at component interfaces as a result of occurring voltage and load changes caused by environmental effects (wind, sun, earth pressure, water pressure, temperature-related expansions). Of all building impacts, wind allows the highest possible impact frequency with comparably high loads at the same time. In the city of Graz (project site), the average normal speeds are between 2-5 m/s, [32] with an average maximum value (storm situations), according to ÖNORM EN 1991-1-4, of 20.4 [m/s],[33] On facades and roofs, high wind pressure, wind suction, but also rain impulses or thermal turbulence (temperature effects) are expected, whereby high impact frequencies can occur as a result of overlapping, [34] which are very suitable for the project objective. Accordingly, essential intermediate results of the project are presented in the following based on the concept "Piezoelectric Textile Facade". While the project deals with impact, construction technology, hook-and-loop fastener, piezoelectric technology, active sensor technology and related digitalization, this paper focuses on wind impacts, construction technology and piezoelectric technology.

2. Method
Due to the thematic breadth, the object of investigation was divided into several overlapping areas (wind impacts, construction technology, piezo technology). In these areas, as well as across all areas, a general literature research was carried out on the basis of heuristic methods, and concepts were empirically developed and experimentally investigated. The basic goal was not to develop a finished product, but to verify the project idea and to determine further potential for the construction industry.

2.1. Literature research
Research reports, papers, patents, product data sheets and technical books with a thematic reference were researched and analyzed regarding the research objective.

2.2. Concept development
Concept development forms the core of the project and was carried out in the field of construction technology using creativity techniques, construction methods, architectural and structural design techniques, and simulations.

2.3. Tests
To quantify the tensile strength, the internal resistance as well as the recoverable electrical energy as a function of load application, the piezo textile was investigated experimentally at the Laboratory for Structural Engineering (LKI). For this purpose, piezo textile tapes with electrically insulated steel jaws were clamped in a hydraulic testing machine. The tensile strength of the textile was determined by slowly increasing the load until breakage. The recoverable electrical stress, energy and efficiency were
tested by dynamic loading single and parallel connected tapes. Experiments with different clamping situations and variable load resistances in the electrical circuit also allowed estimation of the internal resistance of the textile in operation. Displacement measurement was performed directly via the testing machine, and force measurement was recorded using a 100 kN load cell with measurement class 1.

3. Piezoelectric Textile Facade

The "Piezoelectric Textile Facade" concept is based on the idea of attaching facade textiles to a facade and designing the textile in the respective attachment points, or the attachment itself, as a piezo textile. As a result of wind and rain, the facade textiles are exposed to strong vibration frequencies. This results in tensile stresses and strains in the edge areas and current due to the piezoelectric effect.

Depending on the design and area of application, the system can be used in new construction or in the renovation of existing buildings, as a structural component of the thermal envelope, or as an independent variant. In the form of a double façade, the system can, in addition to generating energy, also provide intermediate and useful spaces between the load-bearing plane (primary structure of the building) and the outer shell (membrane façade) from a typological point of view and serve as a weather protection and shading element.

3.1. Wind impacts

In principle, textiles have orthotropic, non-linear material properties. They have low extensional and flexural stiffnesses, which results in large strains even at low forces. [35] For the simulation of wind flows on buildings on the program Dlubal RWIND the maximum values (based on velocity of Graz 20.4 [m/s] [36]) were used. To simulate the velocity distribution as a function of height, the logarithmic distribution

\[ v_2(h_2) = v_1 \ln \left( \frac{h_2}{z_0} \right) / \ln \left( \frac{h_1}{z_0} \right), \]

with a reference height of 10m resulting from the design speed and a roughness length \( z_0 \) for the inner-city area, were selected. These generate a compressive force of up to 0.420 [kN/m²] on the wind-facing side. The wind pressure is distributed unevenly and shows the maximum value at the upper ends of the facade (see figure below). This shows the flow behavior in a building cluster at maximum values. However, the design velocity is rarely reached.
With the equation used from Bernoulli's energy theorem, \( q = \frac{1}{2} \rho v^2 \) at an average wind speed of 2 [m/s] and an average gust speed of 14.4 [m/s] and an average density of \( \rho = 1.25 \text{ [kg/m}^3\text{]} \) yields an average velocity pressure of 2.5 [N/m\(^2\)] and an average gust velocity pressure of 129.6 [N/m\(^2\)].

**Figure 3.** Velocity [m/s] (left) and pressure distribution [Pa] (right) at a building cluster at design wind speed [Institute of Architecture Technology (IAT), TU Graz]

In the following step, a modal analysis of a facade textile with corresponding material parameters (see Tab. 1) was carried out to estimate the natural frequencies of a "Piezoelectric Textile Facade". As this simulation showed based on three different material models, the targeted facade construction exhibits natural frequencies in the range of 2 to 10.9 [Hz] (see Tab. 2).

| Material model | Modulus of elasticity [N/mm\(^2\)] | Transverse contraction coefficient [-] | Shear modulus [N/mm\(^2\)] | M |
|----------------|----------------------------------|--------------------------------------|------------------------|---|
| Knitted material point | 3000 | 0.4 | - | 1 |
| Structure related | 650 | 0.1 | 90 | 2 |
| Fabric material point | 3000 | 0.4 | - | 1 |
| Structure related | 120 | 0.5 | 20 | 3 |

**Table 1.** Material parameters woven and knitted fabrics [Vohrer A 2012 Experimental analysis and simulation of the deformation of air-filled textile casings, Denkendorf]

| M | Natural angular frequency [rad/s] | Natural frequency [Hz] | Own period [s] |
|---|----------------------------------|------------------------|----------------|
| 1 | 68,485                           | 10.9                   | 0.092          |
| 2 | 29,364                           | 4.673                  | 0.214          |
| 3 | 14,495                           | 2.307                  | 0.433          |

**Table 2.** Results of the 3 material parameters [Institute of Architecture Technology (IAT), TU Graz]

**Figure 4.** Modal analysis model (top), 1st intrinsic form (bottom) [Institute of Architecture Technology (IAT), TU Graz]
In summary, it can be stated that wind forces probably generate the highest dynamically variable loads in building construction. Due to the low flexural and extensional stiffness as well as the bearing of the façade textiles, the excitation frequencies will exceed or at least reach the natural frequencies of the construction, which leads to a vibration of the textiles.

3.2. Construction technology

The structural components of the façade system are, in addition to the thermal building envelope (1), for example consisting of a shell in solid or skeleton construction with thermal insulation, the façade textiles (2) with piezo textile tapes (3), a corresponding substructure (4) and active sensors (5, 5.1). The substructure consists of point-positioned, cantilevered fastening anchors (4.1), which are connected to the building’s shell (primary structure) in an acoustically decoupled manner. T-shaped steel connectors (4.2) are screwed onto these anchors, to which in turn horizontal steel mold tubes (4.3) are attached by means of clamps. These serve on the one hand to guide the power cables (5.1) for supplying power to the sensors (5), and on the other hand to fasten the piezo textile tapes (3). For this purpose, pin joints (4.4) designed as hinges and thus capable of rotation are applied to the steel mold tubes (4.3) and the piezo textile tapes (3) are fastened to them in a force-fit in the form of a "piezoelectric hook-and-loop fastener" (3.1a) or by means of clamping strips (3.1b, 3.1c). As a result of the design of the pin joints (4.4) as a rotatable joint, actions acting on the textiles can be absorbed and the load in the piezo textile tapes is fevered with regard to the highest possible tensile load and longitudinal elongation and buckling at the clamping point is avoided. In addition, the electrical contact (inner and outer pole) of the piezo textile tapes (3) is made at the pin joints (4.4).

Figure 5. “Piezoelectric Textile Facade”, facade view (left), detail front view (mid), detail section (right) [Institute of Architecture Technology (IAT), TU Graz]. Outer shell (new or existing building)
(1), facade textile (2), steel molded tube as intermediate piece (2.1), piezoelectric textile tapes (3), clamp or hook-and-loop fastening (3.1), loop design (3.2), substructure (4), fastening anchor (4.1), steel connector (4.2), steel molded tube (4.3), bolt joint (4.4), NetBEE module and sensor (5), cable routing (5.1)

As a building component, the facade textile (2) consists, for example, of polyester fabric with a plastic coating or glass fabric with a PTFE coating (Teflon). For connection to the piezo textile tapes (3), the textile is provided at two opposite ends with oval eyelets (3.2c), textile loops (3.2b), or with a hook/mushroom head surface (3.2a) capable of hooking. Through oval eyelets, the piezo textile tapes (3) can be guided directly, in the form of a loop. First, another steel mold tube (3.3b) is inserted into the facade textile loops as an intermediate element, around which the piezo textile tapes (3) are then guided as a loop. The design depends on the number of desired or required piezo tapes per facade textile, in relation to the structurally required distance between oval eyelets. In addition, it can be assumed that a loop radius that is too small can lead to increased wear and a shorter service life of the piezo textile tapes (3). If the textile is formed with a hook/mushroom head surface that is capable of hooking, then hook-and-loop piezo tapes can be directly connected to the textile by pressing them on. This eliminates the problem of the small loop radius, which can result in a longer service life for the tapes. In addition, easier installation and simple retrofitting or conversion of piezo tapes is possible. For example, if additional or differently positioned sensors are required.

Basically, one NETBEE sensor interface (5) per piezoelectric facade textile and potential sensors (5.1) on the interface or on the facade front are envisaged. This is mounted behind the facade textiles directly on the fastening anchor (4.1) with sleeves. As a result of the formation of fastening points around the building openings, in addition to externally mounted sensors, internally mounted sensors can also be supplied with energy.

The distance between the façade textile and the thermal building envelope or the structure behind it must be selected depending on the stretching properties of the textile and the necessary deformation for optimum energy generation, as well as the deformation of the substructure. This intermediate space is also a component of the planning parameters in connection with the façade construction.

3.3. Piezo technology

The piezo technology used are textile tapes, which were developed and used in the previous research project by Anja Lund mentioned in the introduction. For the present research, 3 cm wide and 1 mm thick tapes textile tapes of different lengths were custom made and supplied by RLSE (Research Institutes Sweden). The tapes were woven in industrial band weaving machines, using for this purpose, the researchers around Anja Lund and RLSE use a loom to produce threads that are spun from melt-spun piezoelectric microfibers as warp, and a conducting silver-plated yarn as weft into textile tapes. These piezoelectric fibers filaments in turn consist of a conductive core with a surrounded in the warp direction by β-phase poly(vinylidene-fluoride) (PVDF) sheath. The conducting yarn functions as and an outer electrode. Subsequently, the inner electrode is completely shielded from the outer electrode. For energy dissipation, the ends of the fibers of the inner pole are freed from the aforementioned coating and connected usingated with silver paste, which is reinforced by a and joined together by a copper foil which functions as a contact point. The counter pole consisting of the outer electrode can be tapped in this weave at any point of the textile. The piezoelectric tapes textile tapes generate several volts of power at the strains with less than one percent. [31]

These above-mentioned tapes are integrated into the facade system by means of forming a loop, hook-and-loop fastener, or clamps. Another possibility of integrating piezo components is to weave piezo fibers with the facade textile, in the attachment, or distributed over the entire textile according to the load progression (to transform any strain due to deformation into energy cycles).

In addition, six concepts were developed for combining hook-and-loop components with piezo elements. These concern the integration of piezo fibers in hook-and-loop elements (loop, mushroom
head, hook) or in the hook-and-loop component base. Since these concepts have a high potential with other concepts developed in the Piezo-Klett project and are thus subject of an ongoing invention disclosure to the Graz University of Technology, they cannot be published.

3.4. Experimental laboratory tests
In a single test, the tensile strength of the piezo textile tape was first determined. A maximum longitudinal tensile force of 1.3 kN was measured over a 30 mm wide textile strip. The longitudinal tensile strength of the textile tape is 42 N/mm.

To determine the internal resistance RI of the piezo textile, tests with constant mechanical dynamic loading were used, each with 3 different load resistances RL of 100 kΩ, 1 MΩ and 2 MΩ. The higher the frequency in the test, the lower the determined internal resistance RI. At a test frequency of 1 Hz, an internal resistance of ~5 MΩ was determined, at 2 Hz ~3.9 MΩ and at 3 Hz only ~2.9 MΩ. Thus, the internal resistance decreases significantly as the frequency increases, but remains exceptionally high even at 3 Hz.

At the time of writing this conference paper, detailed evaluation of the recoverable electrical energy of the piezo textile tape, as a function of clamping length and frequency, is still ongoing. As previous results of preliminary tests show, alternating current is generated in the piezo textile under dynamic loads. The piezo-textile acts as a capacitive voltage source contrary to an inductive voltage source (such as an electric generator) and thus has an internal capacitance. Due to the alternating current, the internal capacitance of the textile is discharged, reversed, and charged again after each wavelength.

When the capacitance of a capacitor is reached, the current flow is blocked until the next polarity reversal occurs and the charge of the capacitor flows off again. This results in the high internal resistance at relatively low frequencies. Thus, the faster the process of charge reversal, the less the current flow is obstructed and the lower the resistance caused by the electrical capacitance. For the application, this means that the design should aim for the highest possible frequency. Another way to reduce the obstruction of the electric current flow by the electric capacitance would be to increase the electric capacitance. This is possible by reducing the distance between the capacitor plates (e.g., even thinner insulation on longitudinal fibers) or increasing the area of the plates (e.g., longer textile or larger-area elements). Since the fibers in the textile themselves have an ohmic resistance, this means that in long
elements occurs a higher resistance. The optimization of the element size is therefore dependent on the frequency of the application and the minimum capacity required to buffer the total AC current generated.

As determined so far, dynamic loading of two parallel connected tapes resulted in a calculated current of 6.951 [µA] and electrical power of 43.965 [µW] at an effective voltage of 4.88 [V] measured over 2 seconds. This would result in an electrical energy of 87.93 microjoules or 0.0000879 [Ws] and, calculated over 24 h, an energy production of 7.6 J [Ws]. With this result, it would be theoretically possible to perform 5 measurements in 24 h or one transmission in 20 days with the NETBEE module. Also noteworthy was the finding during preliminary testing that a wet piezo textile exhibited a factor of ~11.5 higher electrical output with comparable mechanical action within the same experimental setup.

4. Conclusion
The basic research Piezo-Klett (FFG-No. 879459) opens new approaches with the concept "Piezoelectric Textile Facade" in the context of the application of building textiles in combination with the deconstructable hook-and-loop fastener as well as about the existing energy supply of necessary active sensor technologies, as well as in the field for data acquisition and data management. Especially in the storage and tracking of long-term data decentralized and independent of cloud systems. In addition, potentials for facility management, for the optimization of environmental data and energy consumption, as well as decision support in the planning of future buildings will be opened up. [24] This is especially true regarding self-sufficient supply structures and, as a result, digital material parameters and their usage properties that are adapted to the life cycle of buildings.

In addition, new ways of looking at sustainable energy generation systems are being opened by exposing buildings to environmental conditions and thus passively turning them into energy carriers analogous to a "battery". The research team is aware that further research is needed in this regard to get closer to this vision. Furthermore, the investigation adds a technology claimed on train to the range of already existing piezo components. Accordingly, the potential in the application expands in the context of piezo sensor technology, which in the context of its stress on bending and pressure, now also becomes stress-able on tensile forces. Consequently, an attempt was made to convert the textile into a linear structure (rope) to be able to function as a traction rope. This results in a purely tensile loaded piezo component, which could function in numerous constructions as a primary (in composite) as well as secondary structure. Beyond the component parts, the "Piezo-Klett" research project, by combining it with sensor technologies, enables precise monitoring of environmental effects by detecting every vibration and surface change on a big scale and larger context (city quarters), especially wind, and thus opens possibilities for precise comparability of simulation and impact in a holistic way in structural engineering. Thus, the textile can be thought of as an "independent strain sensor", which measures and transmits energy only as information, whereby in combination with digitization, for example, conclusions can be drawn directly about the effects of wind on buildings.

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