Novel component for smart sustainable. Building Envelopes

gianluca.rodono@unict.it
angelo.monte@unict.it
vincenzo.sapienza@unict.it

Gianluca Rodonò, Angelo Monteleone, Vincenzo Sapienza,
Department of Civil Engineering and Architecture, University of Catania, Italy

Abstract. Contemporary approaches to the topic of the responsiveness of architectural components tend to simplify the moving parts as much as possible, avoiding the use of complex mechanisms. KREO is a component for lightweight responsive envelopes made with a composite material with elastic matrix and a textile reinforcement. The composite is pre-folded and it is possible to fold and unfold it without hinges through its elastic mechanism. The component is also capable of producing energy for its handling system through an integrated high efficiency photovoltaic system. Furthermore, its pre-folded geometry ensures its strength. This research involves the construction of a prototype of this energy self-sufficient kinetic component and the definition of its production process.

Keywords: Composite material; Smart envelope; Foldable surface; Kinetic structure; Building integrated photovoltaics.

KREO, the innovative component

In recent times, the increasingly complex and diversified demands of social living require the availability of flexible, lightweight, and reusable service equipment. Think, for example, of the needs arising from climate emergencies, cultural events, first aid for migrants and, above all, the protection of cultural heritage.

The field of study focuses on smart building components, i.e., capable of mitigating the exposure to risks of different kinds by extemporaneously assessing the probability that certain phenomena occur, through their own "sensory system", and in reaction to this they are able to reduce the vulnerability of the areas of action by changing their spatial configurations.

The research referred to in this article focuses on adaptive kinetic building elements, through the use of tessellated geometries originating from the ancient art of origami. The aim is to obtain an architectural component capable of modifying its morphology, adapting to the users' needs (Fig. 1). Hence the choice of the acronym KREO (Kinetic Responsive Envelope by Origami) as the title of the research project and its main output.

The study was directed towards the use of a material similar to a sheet of paper, so that it can be folded according to a pre-established pattern. An additional strength "by shape" is given by folding (Salvadori and Heller, 1963), but the fold lines are also a preferential guide for handling the material through elastic deformation. In particular, tests on the base material were concentrated on composites, which are made with several constituents to guarantee an increase in performance, compared to the individual material, by combining their properties. They generally consist of a matrix, i.e., a homogeneous continuous phase, and a reinforcement, i.e., a phase dispersed in various ways within the matrix.

In testing, the use of a thermoplastic material allows to shape the composite as a result of the type of cross-linking of its structures. In fact, unlike thermosets that, once produced, degrade when heated, the thermoplastic material allows a two-stage process. In the first stage, the composite is produced and in the second one it is hot molded to give a specific folding pattern. The idea of a two-stage production is closely linked to the need not to create a shape defined in advance, but to make it customisable for each individual project, for different components and different kinematics.

The elastomeric properties of the matrix aim, instead, to create a material that, in the wake of the most recent research, can exploit its elastic deformation to ensure the kinematic motion of the component.

Preliminary analyses have made it possible to verify the performance of the material as the matrix and reinforcement layers vary. In those that were found to be more suitable, flexible monocrystalline silicon photovoltaic cells were inserted to guarantee the possibility of using the component, suitably wired with a storage system, in off-grid conditions.

Responsive systems and energy self-sufficiency

Kinematics and Responsiveness

The terminology used to indicate architectures equipped with kinematic components is quite varied and is generally linked to the numerous researches in this field. These have given rise to a proliferation of definitions, whose fields of application often have limits that are not well defined and in any case are made flexible by the continuous evolution of the technique. This is a field that over the last century has experienced the transition from manually controlled mechanical systems to smart materials that interact directly with the environment, so even the terminology tends to follow technological progress to inform about the evolutions taking place.

Among the definitions with a broader meaning there is Kinetic Architecture defined as « the set of those buildings and/or parts of buildings with variable mobility, location, and/or geometry» (Fox, 2002).

The relationship between architecture and kinematics already existed in Roman times in the *velaria*, i.e., solar shading systems for amphitheatres, such as the Colosseum. They were made by reusing naval techniques with a complex system of cables that supported and unfolded the covering fabrics.

In the first decades of the 20th century, the advent of the Modern Movement and technical evolutions allowed designers to experiment with solutions in which buildings could alter their configuration. Just think of Walter Gropius' 1927 project for the Total Theatre by Erwin Piscator or the Villa Girasole designed by Angelo Invernizzi and built in 1929.

In the 1970s, studies on the mathematical relationships at the basis of origami geometries led to important applications in aerospace to obtain Deployable Surfaces to transport and deploy photovoltaic panels in satellites.

Such research had an architectural implication in Frei Otto's studies on Convertible Roofs, i.e., flexible roofing systems that allow buildings to adapt to different functions through mobility (Otto, 1972).

The innovations in the IT field of the early 1970s are also reflected in Nicholas Negroponte's theories on Responsive Architecture. This term refers to a type of architecture or construction that, incor-

ISSN online: 2239-0243 | © 2021 Firenze University Press | http://www.fupress.com/techne
DOI: 10.13128/techne-10699

01 | Simulation of an application of the KREO component as a protective shelter for archaeological sites

02 | (a) Flectofold prototype photo by Julian Lienhard; (b) Hylite® panel photo by 3AComposites and Curletto & Gambarotta

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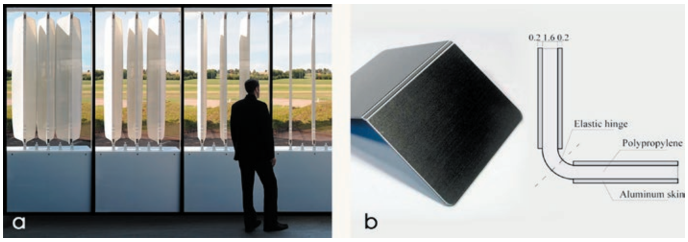

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porating intelligent and responsive technologies, has the ability to modify its shape to continuously reflect the environmental conditions surrounding it (Negroponte, 1975).
Experimentation continued throughout the twentieth century, with high tech solutions, such as those adopted by Santiago Calatrava in the St. Gallen Emergency Services Centre or by Jean Nouvel in the Arab World Institute, in Paris.
In more recent literature, the application of the principles of responsiveness to the architectural envelope is primarily investigated for the optimisation of the energy performance of a building. In this sense, Performative Skin (Turrin *et al.*, 2012), Adaptive Skins (Hasselaar, 2006), or Adaptive Building Shell (Loonen *et al.*, 2013) are mentioned as envelopes capable of adapting to changes in the context by altering the performance of the building.

The Simplification of Movements: Elastic Kinematics
The latest scientific research gives a new and decisive impetus to the subject by tending to limit as much as possible the use of mechanical systems to ensure the possibility of movement. This is essentially due to a need to simplify kinetic components, not so much in the implementation phase as in their management. In fact, even the most sophisticated mechanical systems require maintenance that involves the preparation of regular maintenance plans and activities. Often, due to negligence or financial needs, maintenance is not implemented, causing a premature performance degradation of the items. This has resulted in kinetic component applications remaining limited to projects with large budgets. An alternative solution is given by systems with elastic kinematics (Lienhard, 2014; Barozzi *et al.*, 2016). In these systems, materials capable of deformation, energy storage and return to their initial position when no longer under stress are used. Since there are no hinges, these systems require long-term maintenance cycles compared to previous systems and are, therefore, more economically sustainable. In the first implementations, this result was achieved by using composites formed with glass fibre reinforced polymers (GFRP) to make, for example, the Thematic Pavilion sunshade slats at the World Fair 2012 in Yeosu, or the Flectofin prototype at ITKE (Fig. 2a). Also made of composite material is the Hylite panel (Fig. 2b), consisting of a double layer of aluminium and a layer of polypropylene interposed, used in research on possible applications for Deployable Shelter (Curletto and Gambarotta, 2016).

Energy Self-Sufficiency: Building Integrated Photovoltaic Systems
In cases where the implementation system assumes the use of electricity, it could be produced on site, integrating power production systems into the kinetic component; this would ensure the potential self-sufficiency of the system.
Experiments to offer solutions for the integration of photovoltaic technology into building components were given a major boost with the introduction of flexible amorphous silicon cells in the 1990s. The first photovoltaic textile structure called "Under the sun" was built for the Cooper-Hewitt National Design Museum in New York in 1998 (Fig. 3a), consisting of a 9.7 m high envelope with flexible amorphous silicon solar cells encapsulated and laminated on shaped fabric panels (Orhon, 2016).
Among the solutions for the integration of photovoltaic systems in the building, the so-called BIPV (Building Integrated Photovoltaic) is the "textile solar system" developed for the prototype Soft House in Hamburg (Fig. 3b). Designed by Kennedy & Violich Architecture (Premier and Brustolon, 2014), the house is characterised by a dynamic façade with vertical banded solar shading (Fig. 3b). These are made of a semi-transparent and highly reflective PTFE fabric to which eight thin-film photovoltaic cells are overlapped.
The firm Carl Stahl Architektur GmbH for the central courtyard of the Peace and Security Building of the African Union Addis Ababa (Fig. 3c) (Orhon, 2016) designed a 25x20 metre photovoltaic sail with 445 blue transparent OPV (organic photovoltaics) modules, capable of shading and simultaneously providing sufficient electricity for the interior lighting of the building.

Method

The research aims at systematising the latest findings in the field of kinetic systems and integration of photovoltaics in the building items in order to obtain a component capable of producing the energy needed for movement.
The research method involves the definition of the energy self-sufficient kinetic component in composite material, the optimisation of the stratification of the base material and the production and folding process. The base material produced and the movement system designed were tested through the construction of a prototype, which validated the hypothetical process.
In the specific case of the research, it was decided to use a fibre fabric as reinforcement and a thermoplastic elastomer (TPE) as a matrix,

03 | a) Under the Sun Pavilion - Cooper-Hewitt National Design Museum New York 1998 (Orhon, 2016); b) Kennedy & Violich Architecture - Soft House, 2013 (http://www.kvarch.net.); c) Carl Stahl Architektur - Peace and Security Building of the African Union Addis Abeba, 2015 (Orhon, 2016)

04 | One of the samples and the stratification that passed the first test process

05 | Material sample with insertion of photovoltaic cells and its stratification

06 | Folding process of the composite with metal mould

a technology that is part of textile architecture (Maurin and Motro, 2013). This type of material preserves the characteristics of lightness and versatility typical of fabrics and adds to this impermeable features and resistance to deterioration from atmospheric agents.
The research methodology involved the creation of the first samples of the composite material of small dimensions handcrafted with a hot press, testing different fabric reinforcements (linen, carbon fibres and glass fibres) and two different matrices in thermoplastic elastomer, SEBS (styrene-ethylene-butylene-styrene) and EVA (ethylene vinyl acetate), and testing different possible stratifications.
Production parameters, which have been varied to optimise the material through the vacuum lamination process, are:

1. matrix-reinforcement ratio;
2. process duration;
3. temperature;
4. release agents.

For the first assessment, the samples were visually checked, then touch tested, and samples that passed these checks were further analysed with the cross-section method. Finally, the samples that passed these tests were subjected to a mechanical characterisation process with uniaxial tensile test according to UNI EN ISO 527-4 and UNI EN ISO 527-1 for the determination of the Young E modulus and the shear modulus G (Rodonò et al., 2019).
Once the most suitable parameters and stratigraphies were defined, the production process was industrialised by the company, producing larger samples (about 20x40 cm) (Fig. 4) using the vacuum production process in single Laminator SL-DM 231 made by PANAMAC S.r.l.
Once the laminator production process was validated, new samples of composite material with drowned photovoltaic cells were made in order to make the final component energy self-sufficient (Fig. 5). The choice of photovoltaic technology was oriented towards first generation silicon solar cells. In the component, the photovoltaic cells were positioned in correspondence with the panels and not with the folds; since the composite has a certain flexibility, they are in any case subjected to flexural stress. Therefore, high efficiency monocrystalline silicon solar cells with back-contact technology

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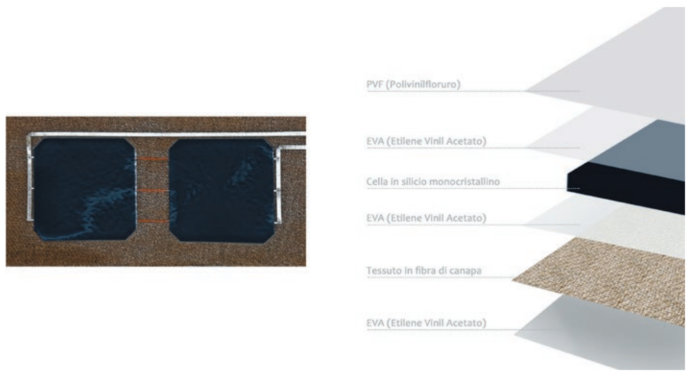

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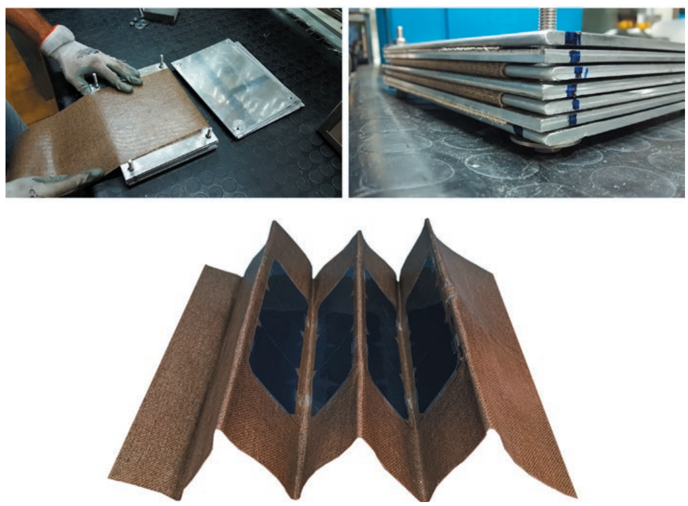

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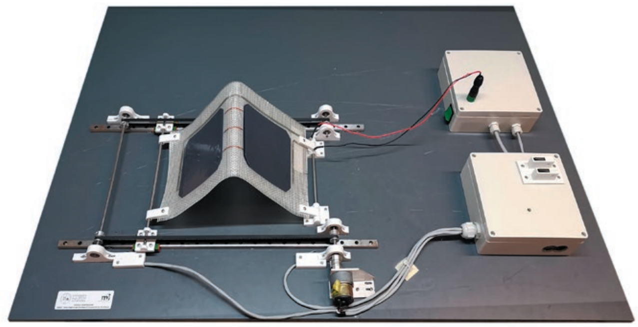
07 | The prototype made with fiberglass fabric reinforcement and monocrystalline silicon solar cells



were adopted and, in particular, SunPower Maxeon® cells measuring 125x125 mm.
In order to optimise the integration of photovoltaic cells into the composite, it was also decided to test the PVF (Polyvinyl fluoride), a thermosetting polymer used (under the name Tedlar) in the production of photovoltaic panels as a coating layer, since it is extremely waterproof and has excellent resistance to weathering and dirt, as well as to numerous chemicals.
For the folding process (Fig. 6) it was necessary to make a metal mould to be used in the press to give the composite the desired geometry, bringing the material to a temperature not exceeding 120°C in order not to recast the polymers contained.
The photovoltaic cells were connected in series using flexible copper braid tracks at the folding points, spaced at least 3 cm apart and connected to the poles through the adoption of rigid plated copper bus bars.

Results

The choice of the material to be used for reinforcement was oriented towards natural fabrics, in particular Biotex Flax fabric made of linen fibres, and glass fibre fabrics, while the other fibre fabrics resulted in poor cohesion between matrix and reinforcement.
The use of EVA as a matrix was defined during the industrialisation process for its easier commercial availability in large format thin sheets and better workability in the vacuum laminator.
The most performing stratigraphy consists of lower EVA layers and Biotex reinforcement fabric, interposition of the photovoltaic cells between two upper EVA layers, and final coverage, limited to the areas of the photovoltaic cells only, with PVF layers.
The results of mechanical characterisation tests show characteristics of the composite material comparable with those of the composite materials commonly used in textile architecture (Rodonò *et al.*, 2019).
In collaboration with Meridionale Impianti S.p.A., research project partner, a 1:1 scale prototype was developed (Fig. 7) aimed at simulating the operating cycles of the component. For the tests concerning charging and handling cycles of the system, the 20x40 cm simple bellows folding sample was equipped with two SunPower Gen I monocrystalline silicon photovoltaic cells and fiberglass reinforcement, and was connected to a Microelectronics ST SPV1040T battery charging circuit and a 3.7 V 2250 mAh 8.33 Wh lithium battery model 18650CA-1S-3J. A shield with Arduino Mega 2660 board was then made with an input reading for control buttons, limit switch and I2C sensing chip for monitoring voltage and charge/discharge current on the battery, load voltage and current (geared motor) and current of the two photovoltaic cells. The component kinematics was made with a mechanical system on 550 mm Mini MGN12H linear guides for 3D Printers, whose carriages are fixed to a pair of 852 mm long, closed-loop Tiptiper 2GT-6 belts for motion synchronisation, operated by four aluminium 20 teeth and 5 mm bore pulleys GT2 SIENOC, one of which is directly fixed to the shaft of a POLOLU-2205 150:1 Micro Metal gear motor LP 6V.
The prototype was tested with the use of a sunlight simulation lamp to check for proper functioning of the electrical connections after the rolling and folding processes. The voltage values were between 1.150 V and 1.155 V. These results are compatible with the sum of the voltage values from the data sheet of the individual cells, allowing the influence of the PVF coating layer adopted to be considered negligible.
Reading the data shows how the electricity produced is largely sufficient to power the handling system and how the need to deploy the layers in the optimal position for recharging can only be limited to a few hours of the day.
In design applications, the geometry of the tessellation, the number of photovoltaic cells, and their positioning on the tiles can be calibrated to the morphological needs of the project and its geographical location. On the other hand, the possibility of having variable inclinations allows to orient the layers in an optimal way at different latitudes.
The program code can also be implemented in order to provide for different settings, aiming at optimising the morphology of the component for battery recharging or orienting it to favour the thermal and/or lighting comfort of the areas concerned in relation to the accumulation state of the battery system.
To do this, the connection of a current sensor to the panel output and a tilt sensor on a single flap will make it possible to record the input values that the processing system will use to manage the correct opening of the component.

Conclusions and impact

The use of folding composite materials makes a significant contribution to the implementation of adaptive architectural systems. Making such systems energy self-sufficient can help to significantly stimulate their use. Their application for roofs or envelopes gives a property of adaptability and versatility to spaces, aiming to improve their comfort and allowing different and customised uses.
KREO is made of a flexible composite with embedded monocrystalline photovoltaic cells. The production process gives it an origami pattern that allows it to be simply folded and unfolded. The matrix is in EVA while the reinforcement (with relative weave, transparency, weight, etc.) can be varied in relation to the performance it will have in the project it will be used for. The tests aimed at guaranteeing a high level of adaptability to KREO, also allowing to vary the

reinforcement and the number of layers in relation to the mechanical stresses to which it will be subjected during operation, since it is the reinforcement that gives the greatest contribution to the stiffness and mechanical resistance of the composites (Phol, 2010). The two-stage production process also allows the geometry to be customised according to the specific application.

For this reason it is expected to maintain these possibilities in large-scale industrial production with the production of the composite fabric in its flat configuration and only in the second phase configure the material with a specific folding pattern. In this way it will be possible to bring industrial production closer to handcrafted production, as increasingly requested by the market in the architectural sector today.

Limitations and future developments

The research presented is based on laboratory and prototype tests. By framing the component in a given application context, it will be necessary to make appropriate corrections to the process outlined, to make it competitive for large-scale production. At the same time, the theme of the relationship between the folding surface and the handling system – until now considered only marginally - will be addressed by identifying systems that provide for non-onerous maintenance cycles.

To this end, a pilot project will be carried out that will allow tests in real climatic conditions and tests with ordinary cycles of use, on the durability of the material, fatigue resistance of the folds, and resistance to exceptional stress (wind, hail, etc.). This experience will be carried out within the 'An Early Warning System for Cultural Heritage' project (http://www.ewas.eu/) in June in an area of the archaeological site of Megara Hyblea (Syracuse - Italy).

In addition to the project, the acquired information will be addressed on further possible future applications of the component for solar shading of existing and new buildings or for temporary roofing for events.

ACKNOWLEDGEMENTS

We would like to thank CNR-IPCB, based in Catania, for supporting the first laboratory tests. We would like to thank Mrs. Chiara Impellizzeri for her support in the initial phase of the research and Mrs. Noemi D'Amico for her support in the folding process.

INDICATION OF THE RESEARCH GROUP

The research was partly funded by the project PON ARS01_00926 EWAS - An Early Warning System for Cultural Heritage - PNR 2015-2020. The composite folding was carried out by NTEN S.p.A. The prototype was developed in partnership with Meridionale Impianti S.p.A.

CONTRIBUTION OF THE AUTHORS

Research programme, Vincenzo Sapienza; method for folding composite, Gianluca Rodonò; method for photovoltaic integration, Angelo Monteleone; analysis, data collection and editing, Gianluca Rodonò and Angelo Monteleone; revision, Gianluca Rodonò; validation and supervision, Vincenzo Sapienza.

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