1. INTRODUCTION

Starting from the Nineties, the necessity of individuating Cultural Heritage at risk of damage or fall and the opportunity of programming possible interventions, led to the realization of the Carta del Rischio (Risk Map), a data bank system addressed to catalogue and measure all aspects which contribute to determine risks [1]. As known, risks are determined by two factors: vulnerability and hazard. This second one, which represents the probability that a risk occurs, is not controllable by human actions. So, the mitigation techniques are addressed to reduce the propensity to damage, so as to reduce vulnerability.

In the specific case of archaeological heritage, there is a higher level of risk: it is due to the characters of incompleteness and fragmentation, that cause a reduction of the performance of its components and a major exposition to the
weather. So, the mentioned Carta del Rischio has a special section related to the presence of a covering structure [2]. In this section the constructive efficiency of the cover is evaluated (protection from sunshine, rain, hailstorm and so on) together with its formal relationship with the landscape and the archaeological heritage.

In view of these experiences, the aim of the research is to project a protection element for archaeological heritage. Rather than current, our design has an additional performance: responsivity. This is the ability of something to change its performances, on users’ requirements.

Our project is called KREO (Kinetic Responsive Envelope by Origami); its main idea is to reduce risks. It can evaluate the possibility for an event to occur, thanks to its sensorial grid; through it, KREO can change its spatial configuration so reducing risks.

2. STATE OF ART

The typological analysis on architectures with kinetic components is a critical step, that could direct the work. In particular, we have decided to start from the first approach to this topic, done by Frei Otto and his research group at the ILEK in Stuttgart. Our contribution consists in updating this catalogation, by taking into account the most recent cases. “Fold” is classified as one of the types of possible movements (such as rolling, sliding, rotation, …) which allows the building components or the entire building to change configuration. The construction system, which allows the bending movement, can be obtained in two different ways: with membranes or with rigid elements. In the first case, the flexible surface is made with light materials, usually supported by space lattice structures with hinges that allow movement [3]. A further typological classification, useful to our studies, divides the structures of the last years on the base of the needs that architectures with kinematic components try to meet.

Among them, the most frequent are the following: resistance against intrusion with building envelope protection systems, flexibility and adaptability of spaces, control of solar gain and lighting, noise control and sound insulation. This research aims at cataloguing the projects of the last years by following these two typological classifications for possible future developments of this issue. As shown in Figure 1, the folding is the most used type of movement due to its expressive potentiality and its propensity to movement. For this reason, our research has been focused on folding surfaces. In the last years, folding surfaces are widely used in engineering and architectural field thanks to the performances that they are capable to exhibit.
<table>
<thead>
<tr>
<th>Requirement category</th>
<th>Type of movement</th>
<th>Sliding</th>
<th>Folding</th>
<th>Rolling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Requirement</td>
<td>Parallel</td>
<td>Central</td>
<td>Circular</td>
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<tr>
<td>Security</td>
<td>Intrusion resistance</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
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<tr>
<td>Usability</td>
<td>Flexibility (space adaptability)</td>
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<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
</tr>
<tr>
<td>Comfort</td>
<td>Solar radiation/lighting control</td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td><img src="image19" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>Noise control/soundproofing/absorption</td>
<td><img src="image25" alt="Image" /></td>
<td><img src="image26" alt="Image" /></td>
<td><img src="image27" alt="Image" /></td>
</tr>
</tbody>
</table>

1. DRMM, SLIDING HOUSE, SUFFOLK, 2009.
2. PINO ZOPPINI, PISCINA ALLA SCIORBA, GENOVA, 1993.
3. BAD GLEICHENBERG, DOME STADIUM, FUKUOKA, 1996.
This characteristic is related to the mechanical properties of corrugated structures (folded surfaces without kinetic properties). By folding a surface, it is possible to produce a stiffening in the direction of the bend. In fact, a folded surface is capable of covering a much larger space than a flat surface, made with the same material. The additional resistance is called “form-resistance”. This property is useful in many applications to optimize the use of base materials. The result is an articulated form, the charm of which consists in the complexity of the tessellated geometry, together with the evidence of stress distribution.

Folding properties, and the consequent kinetic properties, of these surfaces give them a high degree of transformability, while maintaining adequate mechanical performances in all possible configurations. Given the complexity, experiments on these issues often interact with various engineering sectors when coordinating issues related to materials, mechanical behaviour, architectural composition and building production.

Furthermore, the use of lightweight innovative materials, such as wood, glass, metal sheet and last generation plastic, improves the aesthetical-morphological appearance of corrugated surfaces, by guaranteeing extreme lightness to the overall structure. These features make foldable surfaces an excellent tool in types of work that show these needs, such as environmental emergencies, overall structure. These features make foldable surfaces an excellent tool in types of work that show these needs, such as environmental emergencies, overall structure. These features make foldable surfaces an excellent tool in types of work that show these needs, such as environmental emergencies, overall structure. These features make foldable surfaces an excellent tool in types of work that show these needs, such as environmental emergencies, overall structure.

3. FOLDABLE SURFACES

The geometry of foldable surfaces comes from the Japanese Origami art, in which the structural element is the fold. This characteristic allows to generate a hinge for movement in a surface and, simultaneously, a stiffening along the direction of the fold. In particular, once fixed a XY reference system on the surface’s plane, it is possible to distinguish two types of folds: the mountain fold and the valley fold. Their difference depending on whether they tend to move, during their closing, either in the positive direction of the Z axis or in the negative one. A second fold [4], called reverse fold, is a further important Origami technique [5]. This is a cross-fold whit respect to the main fold. It determines an inversion of the bending type. A mountain fold that is crossed by a reverse fold becomes a valley fold and vice versa, a valley fold becomes a mountain fold. Unlike the first category of folds, that generates
an alternating of mountains and valleys on the surface, the reverse folds are always mountain folds or valley folds.

The fixed angle $\alpha$, that is an acute angle between the main fold and the reverse fold, the angle of deflection $\Phi$ and the angle of opening between the main folds $\delta$, determine the geometric relationship between the two categories of folds (fig.2). When $\Phi=180$ and $\delta=180$ the surface is lying on the floor, on the contrary it is fully closed when $\delta=0$ and $\Phi=180-2\alpha$ (5). There are three structural families of folding:

- dense, disordered tessellation (the plan may become deformed with endless configurations in the space);
- tessellation composed by polygons that are different among them (the surface reaches a specific configuration in accordance with the folds);
- division of the surface into groups of tiles that are identical among them (the surface assumes many possible configurations in the space).

The last case presents an infinity of possible configurations between two values: from the flat configuration to the configuration in which the shape cannot move because the vertices, or the edges, are touching.

This third type is certainly the most interesting one for architectural or engineering applications. In particular, Yoshimura tessellation and Miura Ori tessellation are the most studied in literature and the most used in practice. The Yoshimura pattern (or Diamond pattern) is characterized by a series of longitudinal folds, crossed by opposite reverse folds that generate a continuous inversion between the mountain and the valley folds. This kind of tessellation tends to close the surface on itself, by approaching the geometry of a cylinder. Depending on the distribution of reverse folds, the generated tiles can be triangular or quadrilateral. In the case of quadrilateral tiles there is a rectilinear preferential direction of the structure movement, from flat configuration to that in which all vertices are touching. On the contrary, the

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**Figure 2. Reverse fold [5].**

**Figure 3. Module of Miura Ori pattern[6].**
triangular tile pattern gives more degrees of movement to the surface along the rectilinear direction.

The Miura Ori pattern (or Herringbone Pattern) is also characterized by a repetition of longitudinal folds crossed by reverse folds; but in this case the latter ones are repeated in a concordant way. Generated tessellation wrinkles the surface, though it tends to maintain its flat configuration. The generated tiles are quadrilaterals and the movement imposed on a tassel univocally affects the entire surface (Fig. 3).

The mentioned geometric, kinetic complexity makes it necessary a control through simple, iterative methods that can be implemented through the Parametric Design, an expression that indicates the definition of three-dimensional models, by using an algorithm. This name derives from the central role of the input data, the parameters, through which you can create the link between geometry and building material [7] or environmental data. The result is a complex system where the particular and the general are continually in contact; at any time, you can get a fast reconfiguration of the pattern by adjusting the parameters explained in the algorithmic sequences.

4. THE CONCEPT OF KREO

KREO (Kinetic, Responsive Envelop by Origami) is the project of an advanced architectural component that has a high degree of kinematic motion, that is the ability to be folded back on itself.

From the constructive point of view, KREO consists of a thin sheet of composite
material, on which the mountain and valley folds are realized by following the adopted pattern. Then, this element is connected to a structure consisting of vertical supports, made of metal or wood, and horizontal elements, that are wires or steel bars. There are also other components such as the substructure elements and the manual or automated movement system.

There are two different versions. The first for the protection of archaeological excavation areas, in which lightness and mobility are required. Its structure is made of aluminium profiles and it is laid directly on the ground, regardless of specific foundation works, in fact it is ballasted. The covering surface can be stretched or closed manually, as necessary.

The second version is designed as a permanent protection for an archaeological site opened to visitors. In this case, KREO structure is fixed and it is made of welded, painted tubular steel elements. The foundation consists of prefabricated plinths and the movement of the cover surface is mechanized.

5. METHODOLOGY

Implementation and testing of the base composite material are carried out through laboratory experiments in collaboration with the Institute for Polymers, Composites and Biomaterials (IPCB) of CNR of Catania. This collaboration has helped to optimize a flexible, composite, pre-folded material achieved by using a matrix of TPE (Thermoplastic Elastomer) and a fabric reinforcement. The choice of a thermoplastic is linked to the type of cross-linking of the structures which, unlike the most common thermoset elastomers, allows malleability at high temperatures, so making it possible the subsequent folding step, on the base of a specific tessellation. The product has been obtained by thermoforming thin films in hot press, by alternating TPE and reinforcing fibres. Two versions of it have been optimized. The first one is with a hemp fabric, while the second version is with glass fibre.

As the matrix, we have chosen SEBS (Styrene-Ethylene-Butylene-Styrene), a TPE that has adequate resistance to weather, high toughness, good impact resistance and, finally, aptitude to be processed by thermoforming. We made about 25 samples, varying the production parameters (matrix-reinforcement ratio, thermoforming pressure, time of thermoforming, agents for the detachment from the press). The samples were subjected to various analyses: visual analysis, sensitive analysis and measures of the final thickness. Thanks to them it was possible to achieve the optimization of the ratio between the matrix and the reinforcement material. The final result was a good interface between matrix and reinforcement, the absence of air bubbles, constant thickness, minimization of the matrix with respect to the reinforcement.
The specimens that passed these first analyses were subjected to a mechanical characterization method that uses uniaxial tensile tests and follows the EN ISO 527-4 directives. The next step will be oriented to the development of the folding procedure. To get this purpose, we have already tested some handicraft procedures, starting from which, a protocol will be defined in relation with the industrial production process.

We will then go on with the parametric design of a virtual model, and finally with the construction of a physical prototype, to perform some mechanical, structural analysis.

### 6. INNOVATION OF THE PROPOSAL

KREO is an innovative and performing component. Its high flexibility makes it suitable to be used in wide range of situations, with various pragmatic implications. As said, the first hypothesis of application is the covering of archaeological areas, with two aims: to get higher preservation levels and to increase touristic fruition, thanks to better comfort conditions.

At present, protections of archaeological areas are made with several, various solutions. During the excavation and the study of finds, economic resources are not enough to provide a protective structure, almost always. Where it is possible, corrugated sheet with steel tubes is used, that is a very inflexible solution, without aesthetic form.

Firstly, the alternative offered by KREO shows a lower cost, thanks to the possibility to reuse it for a high number of cycles. But the expression “cost” can assume a wider meaning, if you take into account that the economic cost is only a part of the environmental cost. In this sense, the use of KREO is advantageous, if you consider that the utilized raw materials are potentially recyclable and also possibly recycled.

Another improvement is their easy transportability. In fact, while the common structures are fix, KREO can be easily moved, to follow the development of excavation. This ability is due not only to the low weight of its component, but also to the possibility of packaging the covering surface. In addition, the componibility of modules with small size, allows to cover large areas in a quick, flexible way. Obviously, in order to exploit this advantage, the design of the module must be addressed to facilitate assembly and disassembly, which don’t require skilled workers or specific tools.

Once archaeological areas are open to visitors, protection structures are

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**flessibile pre-piegabile realizzato utilizzando una matrice in TPE (TermoplasticElastomer) e un rinforzo in tessuto in fibre. La scelta di un termoplastico è legata al tipo di reticolazione delle sue strutture (TermoplasticElastomer), che, al contrario dei più comuni elastomeri termoindurenti, ne consente la modelabilità a caldo, rendendo possibile la successiva fase di piegatura secondo una specifica tassellazione. Il prodotto è stato realizzato tramite termoformatura mediante stampaggio in pressa a caldo di film sottili, alternando il TPE ai fogli di rinforzo. Sono state ottimizzate due versioni: nella prima è stato impiegato un tessuto in canapa; nella seconda invece è stata utilizzata la fibra di vetro. Come matrice la scelta è ricaduta sul SEBS (Stirene- Etilene-Butilene-Stirene), un TPE che possiede adeguata resistenza agli agenti atmosferici, elevata tenacità e buona resistenza agli urti ed infine facilità di lavorazione tramite termoformatura. Sono stati realizzati circa 25 campioni, variando i parametri di produzione (rapporto matrice-rinforzo, pressione di termoformatura, tempi di sottoposizione a termoformatura, agenti per il distacco dalla pressa). I campioni sono stati sottoposti ad analisi visiva, analisi al tatto e dalla misurazione dello spessore finale, per ottenere l’ottimizzazione della proporzione tra matrice e rinforzo (buona compenetrazione tra matrice e rinforzo, assenza di bolle d’aria, minimizzazione della matrice rispetto al rinforzo, spessori costanti). I provini che hanno superato queste prime analisi sono stati sottoposti ad un procedimento di caratterizzazione meccanica tramite prove di trazione monoassiale condotte seguendo le direttive delle norme EN ISO 527-4. Il successivo passaggio sarà orientato alla messa a punto della procedura di piegatura. A questo scopo sono state già condotte alcune prove con una procedura artigianaile; partendo da queste, verrà definito un prototipo in relazione al processo produttivo di tipo industriale. Si procederà quindi alla progettazione parametro di un modello virtuale ed infine alla costruzione di un prototipo fisico, per effettuare alcune analisi meccaniche e costruttive.**
often invasive compared with the heritage to preserve. Considering existent solutions [8], KREO shows a series of evident advantages, first of all, its kinematism linked with its geometrical pattern. In fact, the adopted pattern offers the possibility of folding and packaging the covering surface, when it is not useful, so reducing the visual disturbance of it. But folds, as (it has been) already said, together with kinematism, corrugate the surface. So you have an additional form resistance. Therefore, thanks to KREO, it is possible to improve the covered span, in comparison with a similar not corrugated material. So, it is possible to reduce the number or the dimension of the supports of the load bearing structure and minimize their impact.

KREO’s kinematism is associated with its responsibility, i.e. the ability to change its form and adapt its efficiency to environmental conditions, such as rain, wind, sunshine, … In fact, the new pattern’s configuration changes the performance of the corrugated surface, according with the needs of the users. In general, KREO has a high level of sustainability. In the last years this concept, in the architecture field, has been addressed especially to energy saving. Vice versa, in this case, this expression assumes a wider meaning, if you consider the wide range of solutions and performances that KREO has.

7. STATE OF RESEARCH AND FUTURE DEVELOPMENTS

KREO started in the last part of 2014 and foresees the realization of a prototype in three years.

The first work package of this research was the analysis of the state of art. It allowed us to define the field of the research, that before was extended to the entire sector of kinematic architecture. Thanks to it, our attention was addressed to the typology to which the module belongs, that is a mobile membrane with a light load bearing structure, and the possible application field of it.

Successively, we proceeded with the design of the base material and its characterization. We obtained two composites with suitable performances; so, the technology to make the folds, will be experimented on both of them.

Next year, we will continue with the design of a case study. In particular, as already said, three different study cases will be assumed, to verify the use of KREO in the possible alternatives considered so far (realization of a provisional cover for an archaeological excavation area, final cover for a visitable archaeological area, covering of an archaeological area useful for theatre performances). In the plans we will have a particularly attention to the formal relation with the landscape, to the design of the load bearing structure
and to the possibility of moving and controlling the covering surface. In the third year of the research, we will realize a prototype in real scale. Thanks to an agreement with the Superintendence for Cultural Heritage, that is under definition, it will be possible to use KREO in their projects. At the same time, we are in contact with some companies which are potentially interested in producing and commercializing KREO in other sectors; they also could become sponsors and offer economic help to improve our project. At the end of the research, KREO will be patented and we will found a Spin-off.

8. CONCLUSION

Kinetic architectures form a set of the contemporary architecture with a large number of interesting aspects. Among them, the foldable architectures are the most promising subset; in fact, movement allows changes of configuration, so amplifying performances (flexibility, responsivity, lightweight, …). This type of constructions is particularly suitable to give an answer to the contemporary, complex, increasing needs of our society.

The project KREO, which is developing at DICAR of Catania, in collaboration with CNR of Catania, is addressed to realize a particular type of foldable surface. It will be used for the protection of archaeological heritage, to minimize the exposition to environmental risks and to facilitate safety fruition. At the moment, the preliminary work packages of the research have been realized in the laboratory of CNR. 

Figure 5. Characteristic parameters of the samples realized in the laboratory of CNR.

<table>
<thead>
<tr>
<th>MATRICE (G)</th>
<th>RINFORZO (G)</th>
<th>PRESSIONE (MPA)</th>
<th>SPESSORE (MM)</th>
<th>CARICO A ROTTURA (N/MM²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.35</td>
<td>6.30</td>
<td>0.5</td>
<td>0.98</td>
<td>20.12</td>
</tr>
<tr>
<td>5.60</td>
<td>3.38</td>
<td>5</td>
<td>0.58</td>
<td>98.52</td>
</tr>
</tbody>
</table>

completed, with the definition of the base material. The realization of various simulations of its use is programmed. The research will be concluded with the realization of a prototype.

9. ACKNOWLEDGEMENT

The work group is composed of the authors of this article, Giuseppe Recca (CNR of Catania) and Massimo Cuomo (DICAR of Catania).

10. REFERENCES


