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研究課題名（和文）The role of cracks on the out-of-plane rotations, plasticity and fracture in kirigami structures

研究課題名（英文）The role of cracks on the out-of-plane rotations, plasticity and fracture in kirigami structures

研究代表者

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研究成果の概要（和文）：切り紙の変形様式によって、伸縮許容量がどのように変化するのかを理解するために、切り紙の構造のき裂進展の数値シミュレーションを実施した。シミュレーションにより、切り紙構造物のout-of-plane変形がbulging cracksと呼ばれる現象の結果であることを突き止めた。この結果は、修正された非線形Foppl-Von Karmanプレート理論を開発することでもたらされたものである。さらに、得られた知見は、アメリカVirginia Commonwealth Universityとの共同研究において、フォトリソグラフィ技術を用いた多機能シルク切り紙の製造に応用することに成功した。

研究成果の学術的意義や社会的意義
切り紙の力学についての研究は発展途上であり、特にその変形様式によって、伸縮許容量がどのように変化するのかを理解することが大きな課題。本研究では、数値シミュレーションにより伸縮許容量を適切に見積もることが出来た。これらの成果は査読付き論文2編にて発表し、学術的に評価を受けた。また、得られた知見の応用範囲は広くその対象は伸縮可能な電子機器、エネルギー貯蔵装置、ヒーター、マイクロ波吸収服などのデバイスなど多岐に渡り、アメリカとの国際共同研究における製造技術開発にも貢献した。

研究成果の概要（英文）：With my simulations, I clarified that the out-of-plane rotations could not emerge naturally as a consequence of the introduction of the cuts. Instead, they represent a mechanical instability that can be obtained only with a buckling analysis. Another achievement was the implementation of a large rotation plate theory.
This theory led me to obtain unforeseen results in folding of plates, which are akin more to origami structures. Folds in a sheet can be seen as discontinuities in the rotations, just like cracks are discontinuities in the displacements. This idea brought me to publish two papers in this field and opening up a new line of research. Finally, a significant accomplishment was the actual use of my computational and theoretical results in a real application. My collaborators manufactured multifunctional silk kirigami. My model guided and supported the experimental findings, provided insights into the deformation and fracture, including the presence of self-shielding cuts.

研究分野：Mechanics of Materials

キーワード：kirigami　meshless　large deformations　large rotations　plates　analytical solutions

１．研究開始当初の背景

Kirigami (切り紙 from the Japanese kiru = to cut, kami = paper) is the ancient Japanese art of paper sculptures, and it consists of cutting a thin sheet of paper and then stretching it.

Back in 2017, little was known about the mechanics of these kirigami metamaterials, particularly in how their mechanical deformation could increase the maximum stretch they experience.

In the past years, the idea of kirigami found many applications as devices for stretchable electronics, stretchable energy storage devices, stretchable heaters, stretchable microwave absorption clothes and many others. Recent studies produced kirigami batteries and power generators (made with a base of polypropylene) that do not lose capacitance and power output even when loaded to thousands of cycles of 100% uniaxial strain.

２．研究の目的

Experimental studies carried out by my group (Figure 1) showed that with polypropylene it is possible to reach an even higher strain than 100%. In fact, we were able to obtain strains

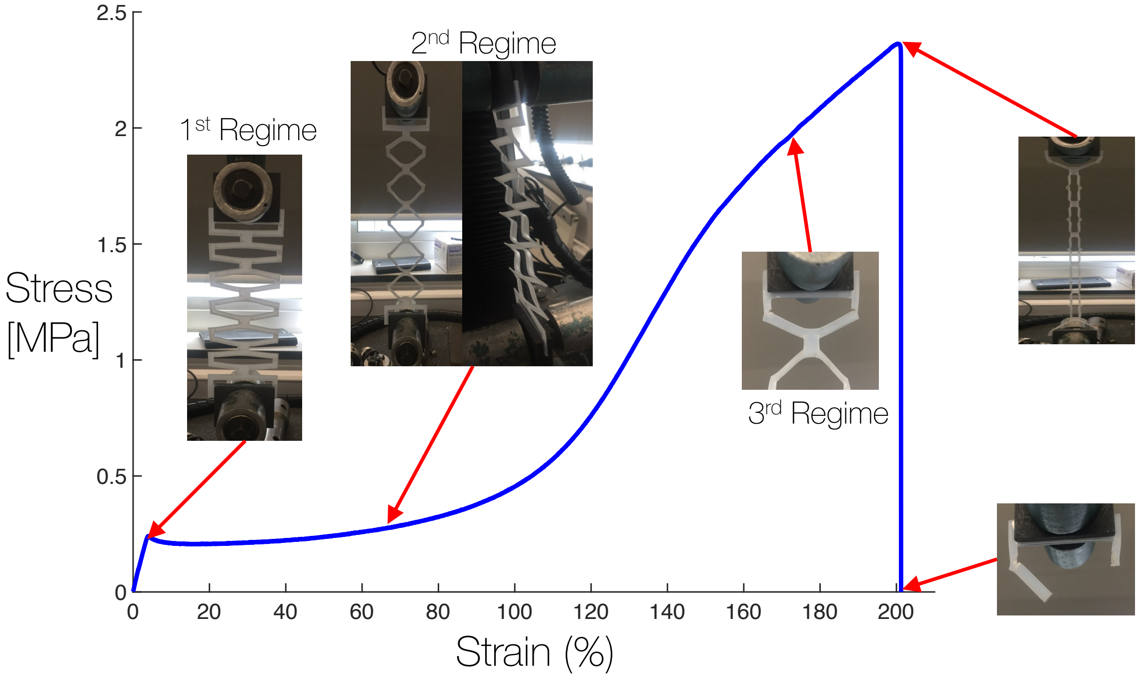


Figure 1: Experimental stress-strain curve of a kirigami structure under uni-axial tensile loading.

of around 200%.

The stress-strain curve of kirigami sheets consists of three regimes.

The first regime manifests in a linear elastic behaviour dominated by an in-plane bending that opens the kirigami cuts; the second regime consists in a quasi-linear behaviour dominated by the out-of-plane bending with rotation; finally, the third regime appears with strain hardening and highly localised deformation around the crack-tips, which ultimately leads to fracture. The transition between the first and the second regime occurs when the in-plane deformation energy equals the out-of-plane deformation energy. The transition between the second and the third depends on the competition between the out-of-plane rotation and plastic yielding. The final crack growth in the third regime depends on the fracture properties of the material, i.e. the length of the cracks, their positions, the strain energy release rate and the fracture energy.

Previous simulation results confirmed some known results from fracture mechanics: there exists an inverse relationship between strength and strain with the increase in the length of the cuts of the kirigami pattern. The shorter the length, the higher is the strength, but the lower is the maximum strain: the resulting fracture is brittle and unstable. Conversely, the higher the length, the higher is the maximum strain and the lower is the strength: the fracture, in this case, is ductile and stable.

What is less obvious is the role of the out-of-plane rotation on the transition between the regimes.

This project aimed at elucidating, through computer simulations with a software I developed, the role of the cracks (length and position) and the out-of-plane rotation on the overall failure of the kirigami sheet.

３．研究の方法

For the computer simulations, I used a software and a method I developed to treat crack propagation in materials. Despite several attempts at quantifying the role of the mechanics in kirigami structures, all the existing works in the literature neglected to show how cracks in kirigami propagate during the stretching and at which critical level of applied stretch. The absence of such results is due to the inability of conventional simulation techniques (like Finite Element Methods, FEM) in handling fracture problems. This project instead used a meshfree numerical method that allows crack propagation and interaction of multiple cracks without having to resort to a time-consuming re-meshing operation as in FEM.

To capture the appearance of out-of-plane rotations, I developed a modified non-linear Föppl-Von Karman plate theory. This theory accounts for large rotations and the full non-linear Green-Lagrange strain tensor. In particular, several nonlinear and coupling strains emerged: firstly, there is a transverse shear strain due to the rotations; secondly, a nonlinear term due to the large in-plane strains; thirdly, a coupling term between in-plane strains and rotations; finally, a coupling term between in-plane strains and large curvatures. There is also a nonlinear term for large curvatures, but this term scales with the square of the thickness of the plate, therefore it can be neglected for thin plates, as it is the case for kirigami sheets.

To simulate the crack propagation, I used a crack growth criterion I developed, based on the maximum strain energy release rate G for finite strain. Such criterion reconciles with the theory of configurational forces. The calculation of G was carried out through a domain-based J-integral, which required special attention due to the numerous non-linear coupled strains appearing in the Green-Lagrange strain tensor.

４．研究成果

With my simulations, I clarified that the out-of-plane deformation in a kirigami structure is the result of a phenomenon known as bulging cracks. I realised that, without incorporating buckling, the transition between first (in-plane deformation) and second (out-of-plane) regime could not be captured. Out-of-plane deformations, then, cannot emerge naturally as a consequence of the introduction of the cuts. Rather, they represent a mechanical instability that can be obtained only with a buckling analysis.

The implementation of a large rotation theory led me to obtain unforeseen results in folding of plates, which are akin more to *origami* structures, rather than *kirigami* sheets. In fact, folds in a sheet can be seen as discontinuities in the rotations, just like cracks are discontinuities in the displacements. This brought me to publish two papers in this field, and opening up a new line of research.

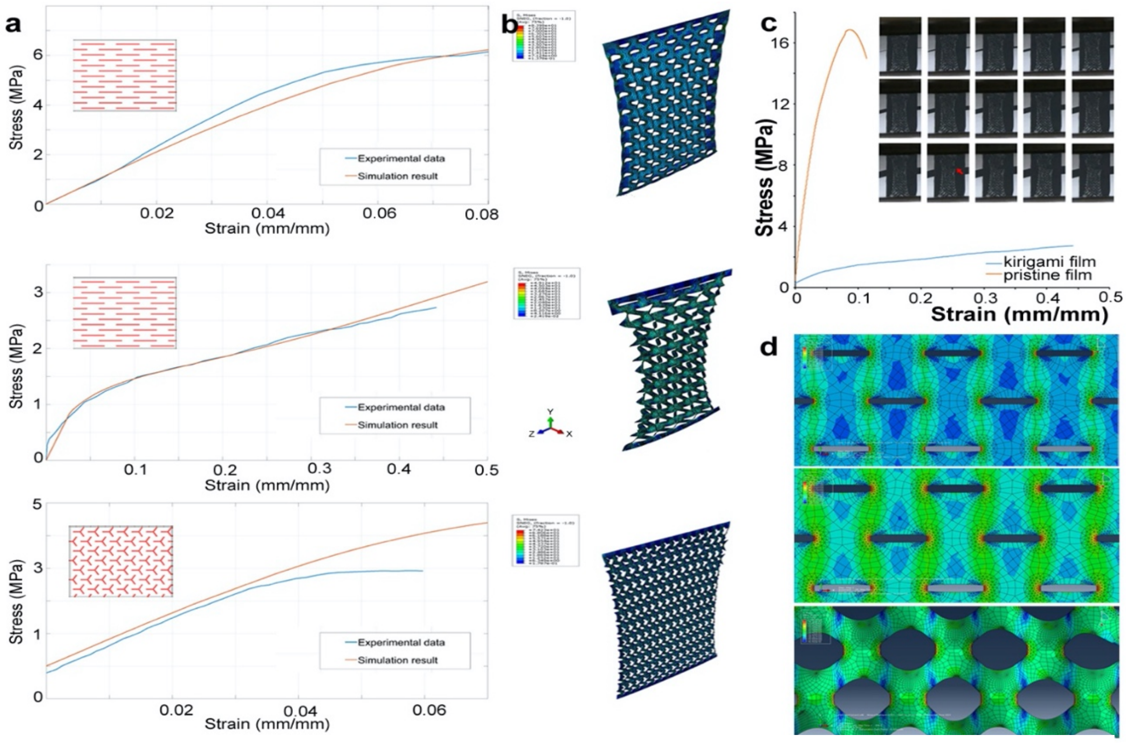
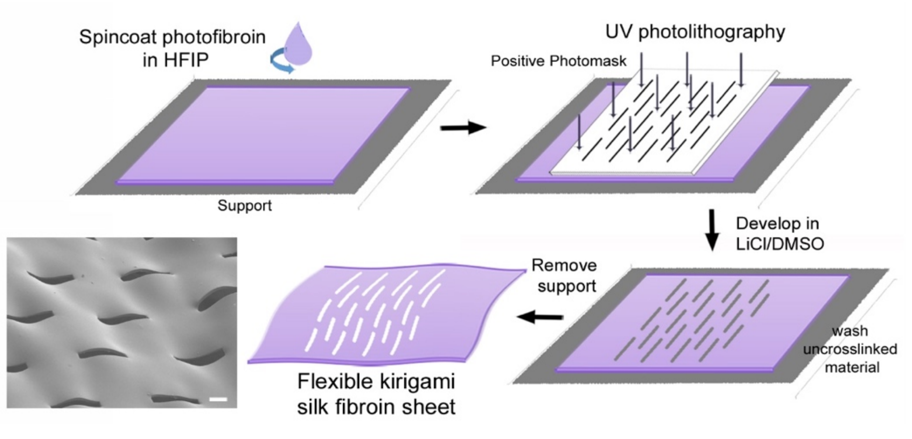


Figure 2: Photolithographic technique for kirigami manufacturing.

A major (and unexpected) accomplishment was the actual use of my computational and theoretical results in a real application.

My collaborators, Prof Yadavalli at Virginia Commonwealth University (USA) produced multifunctional silk kirigami using a photolithographic technique (Figure 2). These films are biodegradable and biofunctional made from silk. Also, these silk kirigami sheets are biocompatible, can serve as substrates for cell culture, and be proteolytically resorbed. The unique properties of silk kirigami suggest a host of applications as "green", functional biointerfaces, and flexible bioelectronics.

The kirigami films themselves are simultaneously extremely stretchable and robust thanks to self-shielding cuts and can be formed at various thicknesses ranging from thin (ca. µm) to thick (10s of microns), as well as degradable. My fracture mechanics model guided and supported the experimental findings, and provided insight into the modes of deformation and fracture, including the presence of self-shielding cuts and the influence of geometry (Figure 3).



This work resulted in a paper published in ACS Applied Material & Interfaces, a journal with Impact Factor 8.456.

Figure 3: Comparison between numerical simulations and experimental tensile tests.

As far as future prospects are concerned, the disruptive technologies of the future will originate, most likely, from a kirigami design.

The implications for the benefit of the public will be multiple. It is possible to design products that are simultaneously strong and stretchable, which can have repercussions in several markets.

From the financial perspective, the market size for stretchable electronics is "expected to grow at a rate of 121.3% between 2015 and 2023 and is projected to grow to $411.85 Million in 2023" (source: marketsandmarkets.com). According to Forbes, citing a market research from CSS Insight, "411 million smart wearable devices, worth a staggering

$34 billion, will be sold in 2020."

For example, wearable electronics can create significant opportunities for health-care technology companies and health-care providers, especially in Japan's ageing society. Imagine seniors that could wear clothing that continuously monitor their health and register all the vital stats with their smartphones thanks to the stretchable antennas. Stretchable heaters can provide direct skin application of heat for thermotherapy. Kirigami soft materials could provide non-invasive diagnostic devices, such as flexible probes for colonoscopy or auxetic stents, to expand occluded arteriosclerotic coronaries.

5．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　0件／うち国際共著　6件／うちオープンアクセス　5件）

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2．論文標題 Bone matrix development in steroid-induced osteoporosis is associated with a consistently reduced fibrillar stiffness linked to altered bone mineral quality	5．発行年 2018年
3．雑誌名 Acta Biomaterialia	6．最初と最後の頁 295～307
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.actbio.2018.05.053	査読の有無 無
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/polym10090988	査読の有無 無
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2．論文標題 Breaking the Nanoparticle Loading Dispersion Dichotomy in Polymer Nanocomposites with the Art of Croissant-Making	5．発行年 2018年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acsnano.8b02877	査読の有無 無
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3．雑誌名 Computational Mechanics	6．最初と最後の頁 1～19
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s00466-019-01671-w	査読の有無 無
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1．著者名 Ettore Barbieri	4．巻 6
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〔学会発表〕　計3件（うち招待講演　2件／うち国際学会　0件）

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考