Shape-Shifting End-Effectors: A Scaled Origami Approach to Reconfigurable Grippers for Limp Textile Automation

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Abstract. Presently, manual operations are required for the material handling of flexible components such as woven textiles. The flexible nature of these fabrics allows them to bend and conform to varying curvatures (i.e., mould surfaces). This compliance coupled with a fabric's surface texture and variability in geometry, creates automation challenges related to reliable handling. To support automation efforts of flexible composite materials, pick and place operations that combine strategic flexibility for these textiles need to be developed, which is the goal of this research. This paper builds on previous work by demonstrating a larger-scale, reconfigurable origami gripper that self-collapses for textile pick-and-place tasks on non-planar mould surfaces. Material extrusion-based additive manufacturing (ME AM) is employed to build and test gripper iterations. These promising results indicate that research should continue related to origami-based automation solutions.

Keywords: Compliant Gripper, Reconfigurable, Origami, Flexible Material Pick and Place, Rapid Prototyping

1   INTRODUCTION

Polymer composites are lightweight materials that offer superior stiffness and strength. However, currently there are no comprehensive, efficient, rapid, semi-automatic or automatic solutions for handling limp composite textiles (or other similar materials). Manual operations (layups) are required for the material handling of flexible components such as fabrics and woven textiles. This manufacturing strategy is labor-intensive, presents safety issues, and creates process bottlenecks [9, 19]. Draping, a manual technique for positioning textile patterns onto a mould for composite manufacturing, depends on fabric properties like in-plane shear, bending stiffness, and structural stability, as well as the mould's geometric features [2, 5]. Some of these fabric properties (i.e. bending stiffness) can be determined through the cantilever bending principle where a sample of

fabric is slid along a flat surface until the fabric bends under its own mass over the edge of the surface (Fig. 1 (a)) [3].

Fig. 1 (b) illustrates the use of Abaqus Dynamic Explicit to model the fabric behavior observed in the experimental setup shown in Fig. 1 (a), chosen due to the complex, nonlinear deformation of the material geometry [3]. A finite element (FE) model can be used to predict how a material will perform in real-world conditions, reducing the need for extensive physical testing.

However, this work focuses more on the variability of limp material properties rather than advancing the finite element model as the drape behavior of fabrics can vary significantly depending on their structural characteristics. Fabrics made from heavy, coarse yarns with dense construction drape poorly, while those with long floats and filament yarns with little twist drape much better (Fig. 1). Considering this, fabrics that drape better tend to be more delicate and more prone to surface creasing or wrinkling than materials that drape poorly.
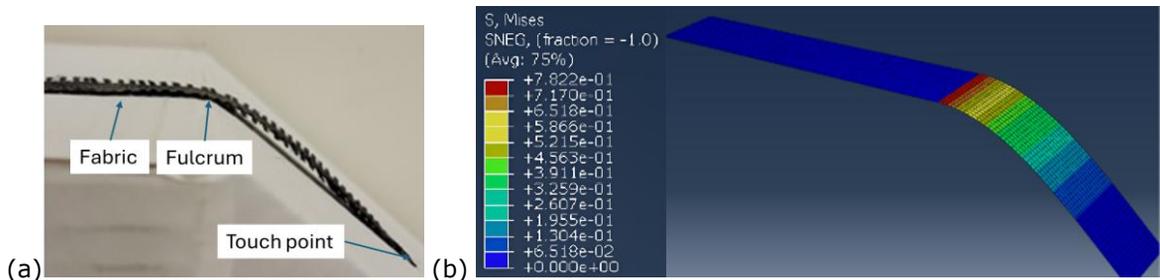

Figure 1: (a) Using the cantilever model to determine carbon fiber draping characteristics, and (b) a simulation model of the fabric [3].

The flexible nature of these textiles allows them to bend and conform to varying curvatures (i.e., mould surfaces). This compliance, coupled with a fabric's surface texture, construction, and variability in geometry (i.e., shape, size, presence of cut-outs and slits), creates automation challenges related to reliable handling without inherent damage to the material. Prior research activities have focused on characterizing carbon fiber material draping and wrinkling characteristics, developing a calibrated simulation model [1] for identifying wrinkling for different placement strategies and simple concave or convex surfaces, and a framework for expanding simulation scenarios for different fabric types and weaves. However, rectangle specimens were considered. Incorporating branches and slits in the design (Fig. 2), is common, and increases the complexity of the simulation and automation challenges.
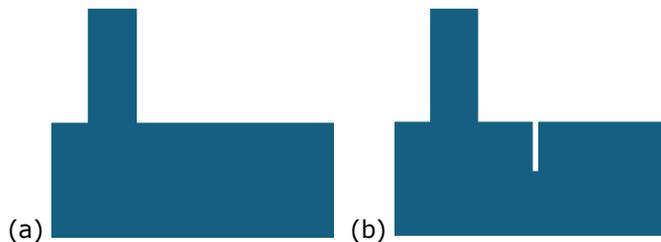

Figure 2: (a) Layup fabric design with a branch, (b) with a branch and a slit.

Unfortunately, the significant mass reduction potential associated with polymer composite fiber-based components is offset by high labor intensity and the associated long 'pick and place (draping)' cycle times due to the flexible nature of the fabric, and shape complexity of the fabric design and/or

the mould surface. These repetitive handling tasks often involve awkward postures, leading to work-related musculoskeletal disorders, resulting in increased absences, productivity loss, and higher healthcare expenses [19].

Automation should be employed when the tasks are repetitive, risky, and remote. Production cycle times in automotive production facilities are approximately 65 jobs/hour, and many assembly components could be required per vehicle, scaling the production quantities. Consequently, we need an automation solution, but automation is typically introduced for rigid components. Therefore, it is required to transform the flexible materials into a rigid structure without introducing damage (i.e., using a 'needle' gripper to pick up the material).

The pick and place activity can be divided into three stages: pick -> transfer -> place. A solution needs to be developed that 'grips' the fabric for the picking element, is rigid during the transfer, and provides compliance to adapt to a mould's surface for the placing element. The goal of this research is to develop a reconfigurable, self-collapsing origami gripper for textile pick and place onto non-planar mould surfaces, thereby addressing the need for a low-complexity automation solution that is easily adaptable to various fabrics, simple to install, and minimizes material damage or residue. For the proof of concept, material extrusion based additive manufacturing (ME AM) strategies are leveraged to build and test gripper iterations. In the next section, material handling approaches and the Miura fold origami are discussed.

2 LITERATURE REVIEW

2.1 Material Handling Solutions for Flexible Fabrics

To handle non-rigid parts, principles such as force closure, form closure, and material bonding are employed. Techniques include mechanical grasping, ingressive grasping (like needle grippers and Velcro systems), and adhesion grasping (using suction cups, electromagnetic or electrostatic forces, air jets, or cryogenic principles). Each technique has specific advantages and limitations depending on the material and shape of the object [7]. These handling methods encounter diverse challenges, ranging from fabric damage, high costs, and excessive energy consumption to inflexibility and complexity. Soft robots, with pliable bodies that mimic biological systems, provide deformable structures and muscle-like actuation for enhanced flexibility. These grippers are particularly effective in handling fragile or deformable objects by conforming to object contours, securely holding complex geometries with uneven surfaces and varying sizes and ensuring safe and efficient handling while minimizing the risk of damage [17, 20, 11, 12]. However, soft robotics solutions documented in the literature primarily rely on either tendon-driven or pneumatic mechanisms, showcasing limitations in adaptability and controllability during operation. Therefore, another approach is required. To overcome the limitations of current textile handling methods, this research explores the use of the Miura-Ori fold, a traditional origami technique.

2.2 Miura-fold Origami

The Miura-Ori, also known as the Miura map-fold, is a traditional origami fold based on a tessellation of slanted parallelograms. It is used to fold large flat geometries into smaller surface areas and can be refolded back to its collapsed shape, demonstrating a form of 'shape-memory' origami (Fig. 3) [16]. Its folds consist of a series of mountain and valley creases, which are fundamental in origami. A valley fold dips downward, resembling the shape of a 'V', while a mountain fold rises upward, like the peak of an 'A'. These two types of creases work together to form the three-dimensional structure of the Miura–Ori. In Fig. 3 (a) and (b), valley folds are indicated in red, while mountain folds are shown in blue.
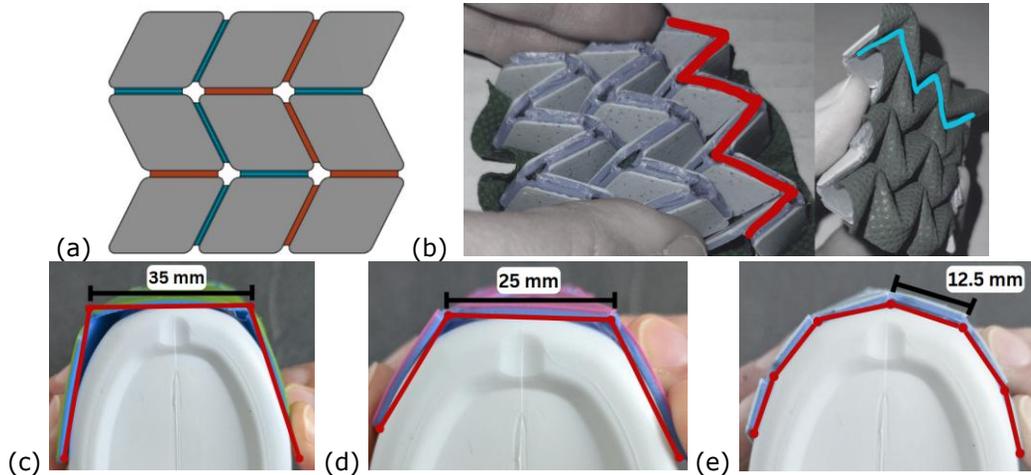
Figure 3: (a) Flat Miura-Ori CAD model (b) folded 3D printed Miura-Ori gripper (c) example of Miura-Ori's shape adaptivity along curved surface (out- of plane bending) with 35mm, 25 mm, and 12.5 mm panel sizes, shown by segmented red line.

The kinematics are characterized as "in-plane" and "out-of-plane", where the geometry has motion following the folds of the origami, and motion via twisting and bending, respectively (Fig. 4) [18]. The red arrows in Fig. 3 (a) (left and right) indicate the collapsing motion of the Miura-Ori fold, while the green arrows indicate its expansion, illustrating its folding behavior. The white curved arrow in Fig. 3 (b) (left) demonstrates the fold's ability to bend along a radius, showcasing its out-of-plane geometry. Fig. 3 (b) (right) highlights the twisting deformation of the Miura-Ori, indicating its capacity to conform to a non-flat, non-planar surface.
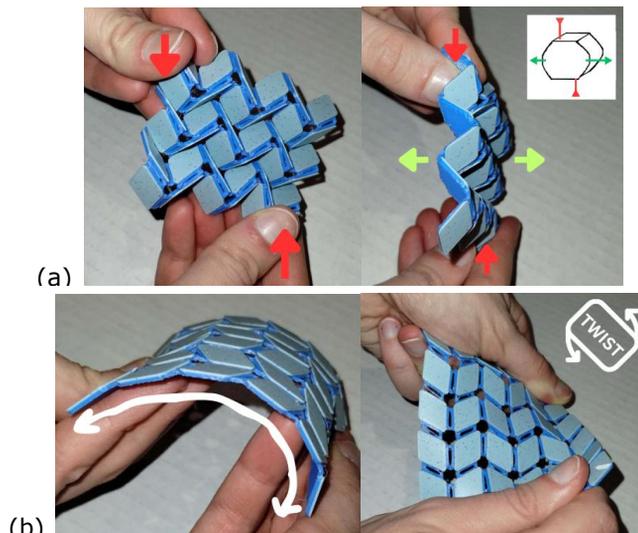

Figure 4: (a) In-plane kinematics of Miura-Ori fold (collapsing via peak and valley folds) where red arrows indicate collapse and green arrows indicate expansion of the origami and (b) out-of-plane kinematics of Miura-Ori gripper, showing bending (left) and twisting (right) capabilities, adapted from [15].

The Miura-Ori tessellation was specifically selected for this study due to the unique mechanical properties that make it well-suited for fabric handling applications. Its geometry allows a large, flat sheet of limp material to be compactly folded into a smaller, more rigid structure. This transformation facilitates easier manipulation and transport of fabrics within an automated workflow. Moreover, the Miura-Ori pattern exhibits a form of mechanical 'shape memory,' allowing it to repeatedly collapse and expand along predefined crease lines without requiring complex actuation mechanisms at each hinge point. This reconfigurability makes the Miura-Ori a strong candidate for adaptive, reusable gripper systems in soft materials handling. Building on this, the Miura-Ori can conform to curved surfaces as a result of its complex kinematics, illustrated in Fig. 4 [4]. Its folding behavior is inherently tied to its geometry—specifically, the number of parallelograms, the spacing between them, and the fold thickness. Preliminary work has illustrated the potential of this solution [19]; however, these efforts have focused primarily on small-scale designs. The concepts must be scaled up to determine the feasibility for larger and more complex fabric shapes. This study begins to address that gap by investigating the performance and adaptability of a larger-scale Miura-Ori gripper design.

2.3   Existing Origami-Inspired Grippers

Origami-inspired designs have seen growing interest in robotics due to their compactness, customizable kinematics, and reconfigurable nature. Numerous grippers have been developed using different traditional fold patterns (e.g., magic-ball, water bomb, Yoshimura, Kresling etc.), with many focusing on pick-and-place operations for rigid or semi-rigid objects (Tab. 1). Prominent examples include pincer, finger or claw style grippers that fold in on themselves to grasp an object through pinch/linear or cable-driven actuation [22, 6]. Other gripper concepts begin with flat tessellated patterns—such as those based on triangulated or parallelogram geometries—which are then folded into cylindrical or conical forms and actuated via pneumatic or hydraulic pressure [13]. Fabrication techniques for these systems vary widely, including laser-cutting of flexible films, mould-based casting methods, and Additive Manufacturing (AM) approaches such as multi-material deposition or direct 3D printing onto fabric [15, 22, 13, 6, 14].

Among the tessellations studied, the Miura-Ori fold has garnered attention for its ability to compact and expand predictably. Several studies have leveraged this fold to create artificial muscles, typically by enclosing the origami structure in a fluid-tight skin that enables controlled actuation via internal pressure [14]. While Miura-Ori has been explored for grippers, these implementations largely focus on rigid-body interaction and symmetric collapsible structures.

In contrast, this work advances the field by adapting the Miura-Ori tessellation for the handling of limp, flexible textiles—an area with relatively limited exploration in the origami robotics literature. Rather than functioning as a rotationally symmetric or claw-based gripper, the design proposed in this work leverages the in-plane collapse of the Miura-Ori tessellation to contain and transport limp bodies such as textile sheets. This approach is structurally and functionally distinct from the pincer and artificial-muscle models. Tab. 1 provides a comparative summary illustrating the differences in geometry, actuation method, target materials, and novelty between this work and selected origami-based grippers in the literature.

Reference	Origami Style/ Tesselation	Gripper Style	For Handling Flexible Bodies?	Publication Year
[14]	Miura-Ori	Artificial muscle with fluid-tight skin	No	2017
[13]	Magic-ball	Rotational symmetric pincer with air-tight skin	No	2019
[15]	Kresling, Miura-Ori, Yoshimura	Cylindrical gripper	No	2023

	Yoshimura	Rotational symmetric pincer	No	2023
[6]				
[22]	Kresling	3 finger style pincer	No	2025
This Research	Miura-Ori	Flat/ in-plane collapse	Yes	2025

Table 1: Summary of existing origami-Inspired gripper designs.

3   MATERIALS AND METHODOLOGY

A three-step experimental methodology: (1) Design -> (2) Fabricate -> (3) Test, was taken for this research including three main parts: a fabric sample for pick and place tests (Part A), a non-planar mould surface (Part B) and a customized Miura Ori gripper (Part C) for the selected fabric sample and mould surface. It is important to note that although various Miura-Ori gripper variants are presented in this work (Fig. 13), the smaller tessellations originate from a previous study [19]. The methodology outlined here focuses on a large-scale gripper and more complex material handling configuration. While the smaller tessellations are not the primary focus, they are revisited in this study for specific analyses – including compression ratio and life cycle testing – to further evaluate the feasibility of the larger-scale configuration.

A complex 'W' shape fabric sample with an internal slit was chosen to represent the intricacies of textiles handled in industry (Fig. 2). A mould surface with a slight curvature was designed to simplify the tessellation complexity of the gripper and assess its ability to conform to non-planar geometries. Based on existing literature [4, 19], a tessellation pattern for the Miura-Ori fold was determined to create a structure capable of collapsing and conforming to the mould surface. The compliant gripper was fabricated using Material Extrusion-based Additive Manufacturing (ME AM) with X-920 Flex (Shore 89A durometer) [9] for living hinges and PLA for rigid panels. All samples were printed with a 0.2 mm layer height and a 0.4 mm bead width. The grippers were fabricated using a Prusa i3 MK3s+ system, while the mould surface was printed in PLA using a Bambu Lab X1C. Further details regarding the extruder temperature and flow rate used for the flexible material prints are provided in the Discussion section of this paper. Due to 3D printer constraints, the gripper was assembled from sub-modules. Manual pick and place tests were conducted, to validate the gripper's ability to pick the 'W' shaped fabric. Compression data, including open and closed diagonal distances, was collected to quantify the gripper's characteristics and support the design of a collapsing frame for future automated use. The textiles explored in this work are summarized in Fig. 6.
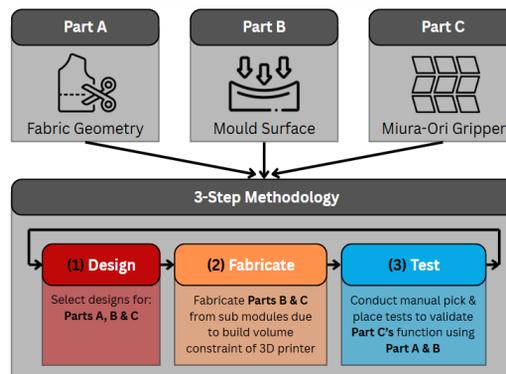

Figure 5: Summary of the three-step experimental methodology implemented in this research, organized into (a) Design, (b) Fabricate, and (c) Test phases.

The Design → Fabricate → Test methodology outlined in Fig. 5 establishes a framework for evaluating the handling of various textile types. In this study, synthetic, silk-like material (polyester micro weave) was used during validation due to its availability, ease of cutting, ability to retain its designed shape, and suitability for observing surface damage or wrinkling caused by its fragility. To assess the adaptability of the Miura-Ori gripper, future work will involve testing it with a broader set of textiles, as illustrated in Fig. 6. The evaluation criteria include the gripper's ability to lift and hold the fabric securely without slippage, critical surface damage, or excessive wrinkling. Future experiments will involve materials such as fiberglass cloth, carbon fiber, and leather.

Figure 6: Summary of explored and to be explored fabrics for pick and place via Miura-Ori solution.

3.1 Fabric and Mould Geometry

A "W" fabric geometry was chosen for testing, including an internal slit (Fig. 7 (d)). This experimental configuration was designed to represent the complexities of textiles being handled in industry as the fabric features slits and irregular boundaries, and the mould is curved. Convex and concave geometry is incorporated.

The 'S' shaped mould surface was designed to be built in segments due to printer build volume constraints (Fig. 7 (a) through (c)). The curvature was introduced to reduce the tessellation complexity of the gripper while still evaluating the Miura-Ori's ability to pick and place material on a non-flat surface. As observed in previous work, larger parallelogram panels are better for adapting to gradual "S" shape curvature, and smaller panels follow tighter curvature with less surface discontinuity [19]. For this reason, medium-sized panels (25 mm) were chosen for constructing the gripper—small parallelograms were unnecessary due to the slight mould curvature (12.5 mm), while larger ones (35 mm) would have been less effective at holding the fabric's irregular boundary, including the slit (Fig. 3 (c) through (e)). The mould was designed with rectangular cutouts to reduce material usage during fabrication while also serving as a grid for fabric placement or as an integration space for sensors in future work (Fig. 7).

3.2 Large-Scale Gripper Design and Fabrication

Fig. 13 presents a collection of Miura-Ori gripper variants labelled 'A' through 'I'. Grippers 'A' through 'H' were developed and analyzed in a previous study that investigated the effects of panel size, panel count, and hinge style (slotted, solid, channel, etc.) on gripper spring constant and collapsing force [15]. Building on this prior work, the current study introduces Gripper 'I', which employs the favorable channel hinge in a larger configuration to explore the scalability of the Miura-Ori design (Fig. 8, gripper 'I').
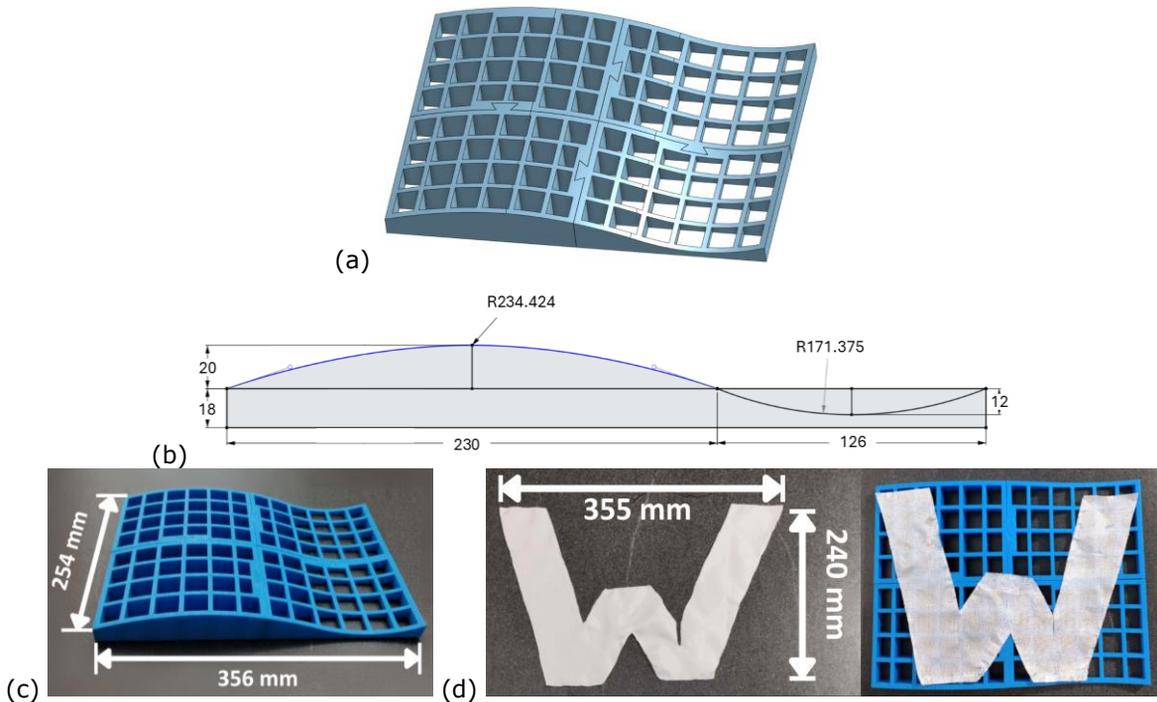
Figure 7: (a) Four-piece CAD model of the mould surface, featuring dovetail joining elements (b) side profile sketch used to generate the mould surface, highlighting key radius dimensions (in mm) that define the non-flat surface curvature (c) assembled mould and (d) dimensions of 'W' fabric with internal slit.

Due to the build plate space constraints of the 3D printing system, several gripper sub-modules needed to be assembled to fabricate gripper 'I' (Fig. 8 (a)). Submodules were designed in CAD, incorporating a "puzzle piece" geometry as the joining feature. After printing, a handheld 3D printer pen loaded with the same flexible filament (Sakata 3D X-920) was used to fuse the submodules. This resulted in a visible and rough seam on the underside of the gripper, which unexpectedly improved friction between the gripper and the fabric sheet (Fig. 8 (b)). However, this seam was inconsistent and difficult to control due to the manual assembly. For smaller-scale Miura-Ori grippers (i.e., 'A' through 'H'), a material change was programmed by print layer: after the flexible material layers forming the joints and hinges were printed, the printer paused to switch to PLA, ensuring that only the parallelogram sections were printed in the stiffer material (stiffer compared to Sakata 3D X-920).

In contrast, for the larger gripper 'I,' the same material change approach was used for its submodules, except at the joining sections, where separate PLA parallelograms had to be printed and attached post-assembly at the junctions where the submodules were fused. Initial attempts used hot glue and cyanoacrylate super glue, both which created a rigid bond between the PLA and X-920. However, after drying, the bond failed under flexing, causing the PLA parallelograms to detach around the edges (Fig. 8 (c)). A flexible adhesive is necessary to maintain a durable yet flexible bond between the two materials. To address submodule assembly and ME AM challenges, future work will explore an alternative fabrication method using a custom casting mould with rigid 3D-printed parallelogram inserts.
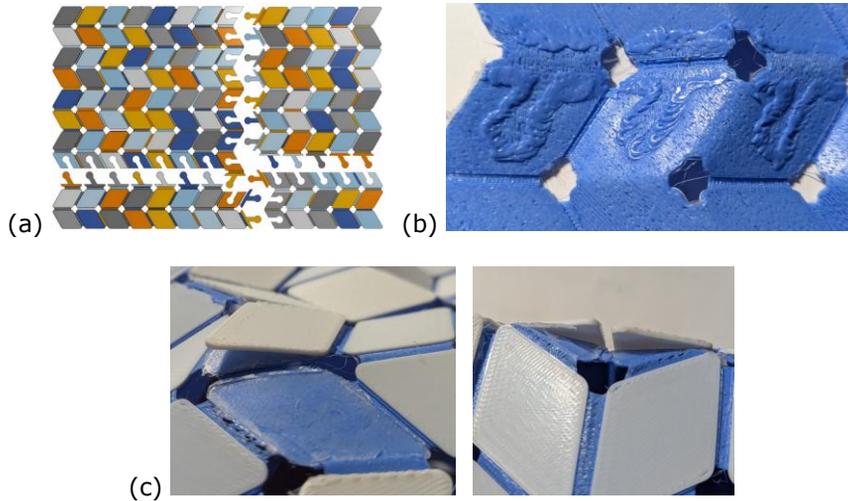
Figure 8: (a) CAD model of submodules for the large-scale Miura-Ori gripper 'I' (referenced in Table 1), highlighting (b) fused seams and (c) panel delamination issues.

3.3 Compression Data Collection

To quantify the gripper characteristics, compression data were collected as summarized in Tab. 2. The open and closed diagonal distances are defined in Fig. 9 (a) and (b), respectively. The closed distance was achieved by forcing the gripper into its collapsed state using a table vice. Equation 3.1 was used to calculate the compression ratio. Characterizing the flat and folded dimensions of the gripper defines the spatial limits that a retractable frame or structure must accommodate in order to secure the Miura-Ori for future use in automation systems (Fig. 15).

Given the range of gripper variants explored in both prior and current studies—varying in panel count and size, hinge thickness (gap distance), and hinge style—the compression ratio was measured to assess how these factors influence the gripper's ability to collapse compactly. This metric also provides valuable insight into how the Miura-Ori gripper can be dimensionally scaled for different applications or surface constraints. While the compression ratio can be derived from geometric design parameters, physical measurements were collected to account for potential deviations introduced by the ME AM process and the material properties of the selected filament, both of which can influence the gripper's actual collapsing nature.
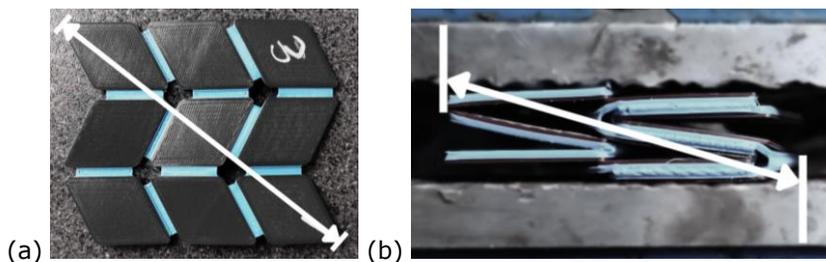

Figure 9: (a) open gripper distance and (b) compressed/closed gripper distance.

$$\text{Compression Ratio (CR)} = (\text{Open distance} - \text{Closed distance}) / \text{Open distance} \tag{3.1}$$

3.4 Relationship Between Collapsed Gripper Thickness, Textile, and Crease Points

An important measurement is the minimum vertical thickness of the gripper at its center point (Fig. 10). This value helps estimate the gripper's minimum thickness when holding a textile, offering valuable insights into the automation strategy and guiding the required frame dimensions for designing a mechanism to automate the Miura-Ori gripper. This vertical thickness is directly influenced by the number of collapsed parallelograms, their thickness, the number of gripper pinch points that grip the fabric, and the fabric's thickness, as shown in Equation 3.2. In this equation, the material thickness is doubled under the assumption that when a textile is "pinched," two layers of the textile are present at the pinch point. It is also under assumption that each crease/pinch point along the centerline of the gripper is holding onto fabric. If the fabric's geometry is highly irregular, this may vary, and variables related to the crease points can be adjusted to reflect the observed behavior in the gripper.
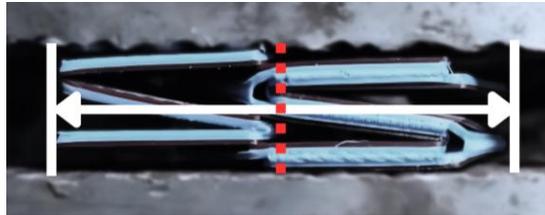

Figure 10: Length of collapsed gripper (white dimension) and vertical thickness/centerline (red dotted line).

$$\text{Min. vertical thickness (MVD)} = (x * \text{panel thickness}) + (2 * y * \text{material thickness})$$

$$(3.2)$$

where x = # of panels along collapsed gripper centerline and
y = # of creases that hold fabric along centerline

3.5 Assessing Qualitative Fabric Damage

The goal of an effective fabric-handling gripper is to minimize surface damage or creasing while manipulating the material. It is important to understand how fabric damage manifests given varied material construction, such as woven fabrics vs. fiber-based forms (e.g. faux leather being a plastic-coated fiber such as cotton or polyester). Fig. 11 qualitatively illustrates fabric conditions by comparing the material before and after creasing, pinching or physical manipulation, highlighting the differences observed across four different materials shown in Fig. 6.
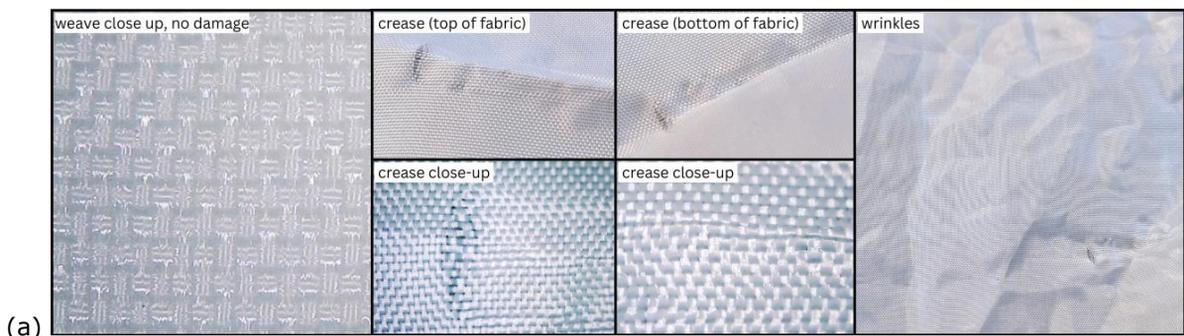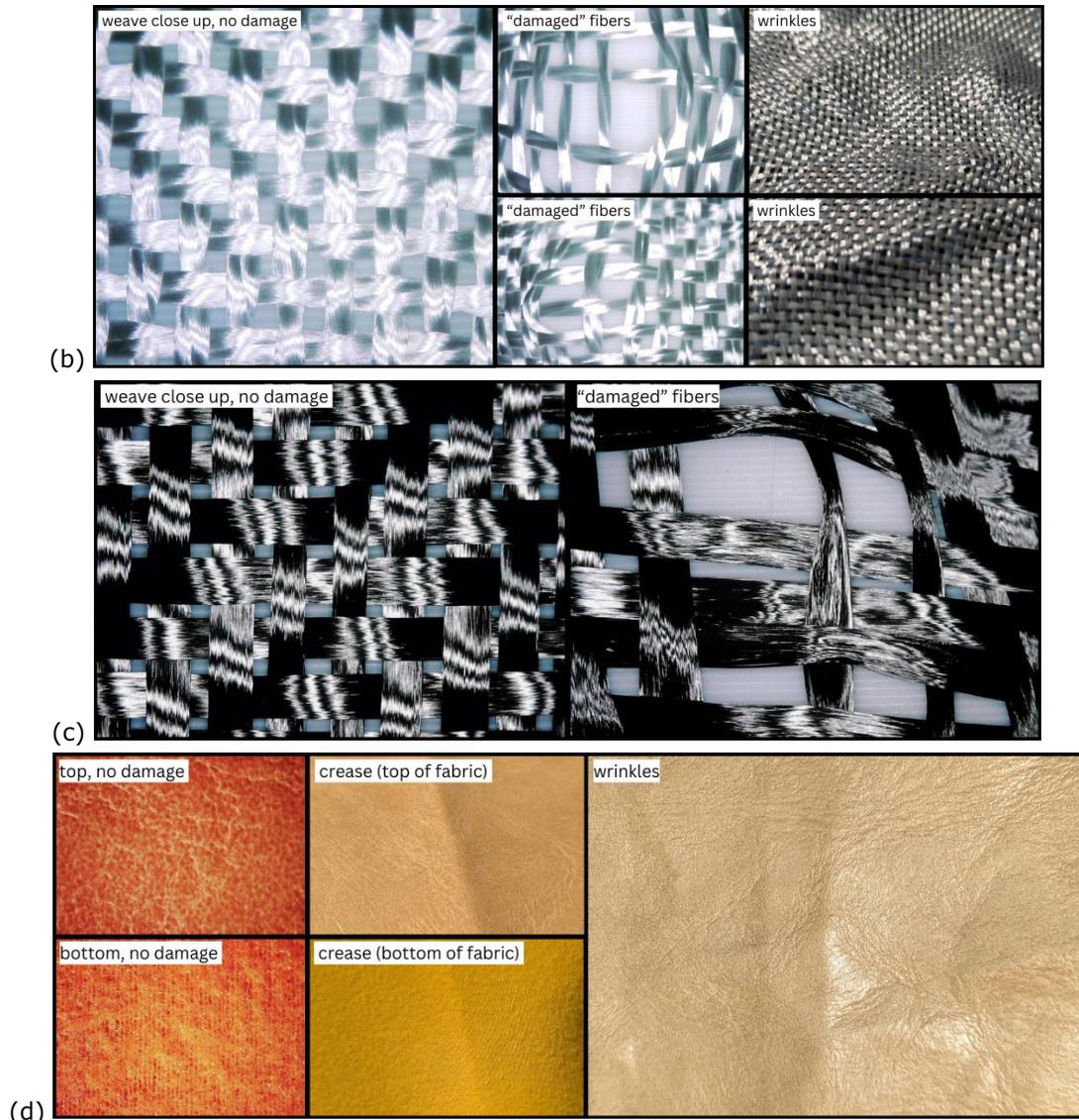

(a)

Figure 11: Insight into mechanical deformation and damage of (a) polyester micro weave (b) fiber glass cloth (c) carbon fiber (d) faux leather textiles.

3.6 Determining Minimum Fabric Radius Before Creasing Occurs

Some fabrics are more prone to marking or creasing depending on their construction. To assess this, a 3D-printed radius jig is used to fold the fabrics shown in Fig. 12, measuring their minimum fold radius. Any fold with a radius smaller than this threshold is assumed to cause a crease. This information is valuable when designing a Miura-Ori gripper for a specific material, as the minimum crease radius can help determine the optimal gap distance between parallelograms in the gripper's tessellation (i.e., the living hinge/joint width). This radius is especially important for composite woven materials, particularly those with thicker weaves like carbon fiber, which are stiffer and more prone to creasing. Wrinkles or folds in fiber weaves not only affect surface appearance but can also disrupt fiber orientation within the fabric, potentially compromising the strength of the final layup if

significant misalignment occurs. While this presents a notable challenge, it is not the primary focus of the proof-of-concept work discussed in this paper.
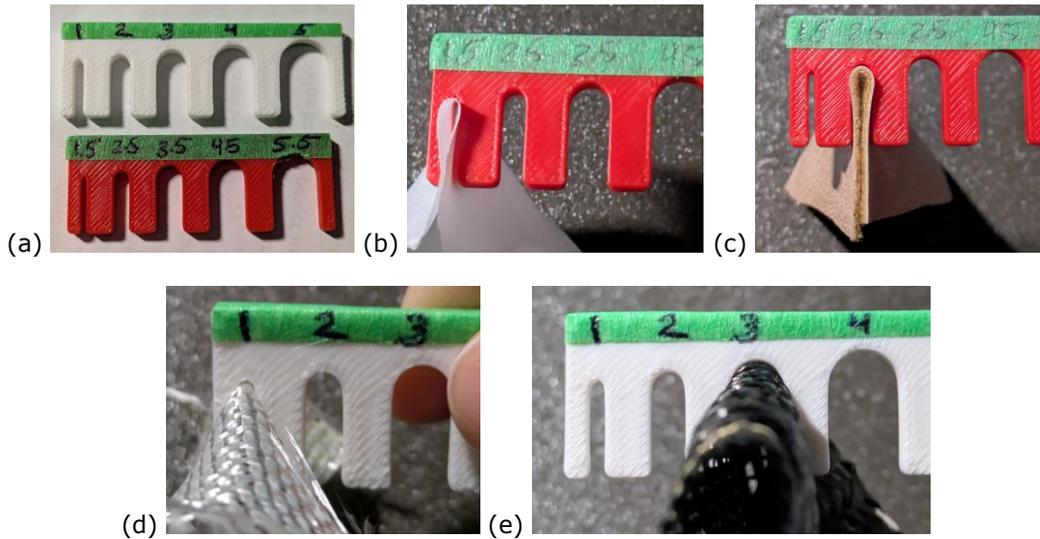

Figure 12: (a) 3D printed radius jig and testing procedure for (b) silk-like polyester microweave (c) faux leather (d) fiber-glass cloth and (e) carbon fiber.

3.7 Life Cycle Test

In automation applications, the durability and life span of a gripper is critical. A life cycle test was conducted to evaluate performance over repeated folding cycles – specifically 10, 100, and 500 iterations – where one iteration consisted of the gripper being fully folded or compressed and then fully flattened. The performance and lifespan of the Miura-Ori gripper in this study depend significantly on the durability of the flexible filament used in its fabrication, the slicer toolpath and print settings, and the thickness of the hinges connecting the parallelogram panels. All gripper variants in this study share the same hinge thickness, enabling the life cycle test to be conducted on a smaller variant while still allowing meaningful conclusions to be drawn for the larger-scale gripper.

In this work, the grippers were fabricated using a Sakata 3D X-920 copolymer blend with a Shore 89A durometer. An alternative material is explored in the Discussion of this work, Varioshore TPU by ColorFabb [21]. To evaluate material, longevity, the life cycle test was performed on two grippers of identical design – one printed with each material. This test aimed to assess how the selected material and manufacturing method influenced durability. It is important to note that the gripper's ability to pick and place fabric would remain unaffected unless mechanical failure occurred, such as a fully torn hinge.

4 RESULTS AND DISCUSSION

4.1 Compression Data Results and Gripper Force Capacity

Results of the collected compression data are shown in Tab. 2. Grippers 'A' through 'I' are labeled in Fig. 13. Both 'C' and 'F' have the same gap distances, number of panels, and size of panels, meaning results should be close to identical – and they are (red font, bolded text). The closed distance and compression ratio for grippers 'C' and 'F' show the data collection method to be repeatable, as both

show identical results. Interestingly, the compression ratio for all tested grippers was found to be between 0.44 and 0.46, except for gripper 'I' which is 0.49 (red, italicized font). This observed variation is believed to be attributed to gripper 'I' being a large tessellation made up of subsequent smaller prints that needed to be joined together, instead of being a homogenous print such as 'A' through 'H'. It is of interest to repeat the compression experiments for grippers 'A' through 'I' while holding the fabric to quantify the impact of material thickness on the gripper's compression ratio.
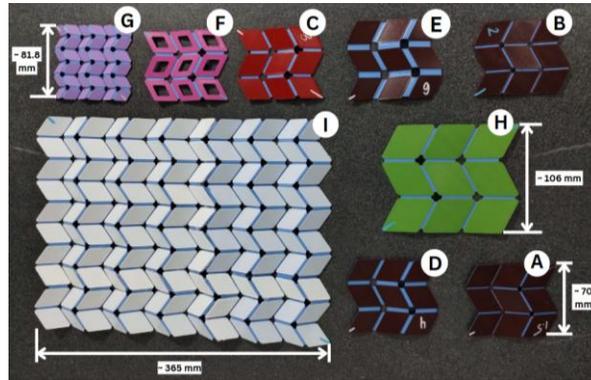

Figure 13: Select Miura-Ori gripper samples with varying panel sizes, gap distances, and panel count.

Gripper (Fig. 13)	Gap Dist. (mm)	# of panels	Panel Size (mm)	Open Dist. (mm)	Closed Dist. (mm)	Compression Ratio
A	1.5	9.0	25.0	111.20	61.70	0.45
B	2.0	9.0	25.0	112.00	62.20	0.44
C	**3.0**	**9.0**	**25.0**	**115.00**	**63.30**	**0.45**
D	4.0	9.0	25.0	117.50	640.10	0.45
E	6.0	9.0	25.0	123.00	66.80	0.46
F	**3.0**	**9.0**	**25.0**	**115.00**	**63.30**	**0.45**
G	3.0	36.0	12.5	120.20	65.60	0.45
H	3.0	9.0	35.0	166.70	89.60	0.46
I	*3.0*	*130.0*	*25.0*	*438.15*	*225.43*	*0.49*

Table 2: Compression data of select Miura-Ori gripper samples (A-H) and prototype large tessellation (I), each gripper having a thickness of 1.5 mm.

To better evaluate the practical capabilities of the Miura-Ori gripper variants, preliminary experiments quantified the maximum gripping force via an equivalent mass required to collapse the gripper. It was found that 50 N of force could be applied in the collapse direction without visible damage to the gripper structures. Localized pressure pads will be applied within panels in future studies to determine the force profiles, and FE models will be created to explore this further. This is critical for understanding the structural limits of each gripper variant in practical applications.

4.2 Minimum Fabric Radius Before Creasing

Tab. 3 summarizes the collected data using the 3D printed jig for the materials highlighted in Fig. 6 and 12.

Material type	Material thickness (mm)	Min. radius before crease (mm)
Polyester microweave	0.1	0.5
Faux leather	1.0	2.5
Fiberglass cloth	0.2	1.0
Carbon fiber	0.4	3.0

Table 3: Minimum fabric radius before crease formation of four fabrics.

4.3 Material Pick and Place with Large Scale Miura-Ori

Fig. 14 shows the manual pick and place of the 'W' fabric sample using the large tessellation gripper 'I' onto the non-planar mould surface. The Miura-Ori fold successfully picks the silk-like sample. This was determined a successful test by the gripper's ability to lift the fabric with minimal surface pressure, fully accommodate the 'W' (irregular geometry and internal slit), and securely retain the fabric within its folds once collapsed. This was tested manually. As aforementioned, the testing jig needs to be designed and calibrated to quantify the gripping force. Testing has been done to quantify surface friction of select materials [5]. Friction and gripping testing solutions need to consider a system of contact points, and this is ongoing work.

The unique advantage of this Miura-Ori solution is its ability to transform the flexible and limp fabric into a rigid body as it collapses, thus enabling the rapid and slip-free manual transfer of the sample, which was subsequently flattened onto the mould surface without significant creasing or damage. Minor wrinkles in the fabric suggest that it was folded beyond its "minimum radius before creasing" threshold within the gripper. Although the gap distance in the larger Miura-Ori tessellation was 3 mm—greater than the measured crease radius of the tested material—excessive collapsing force in the gripper's fully closed state still caused minor creases and wrinkles. This issue is difficult to control in manual pick-and-place experiments. Automating the process will enable more precise force distribution and greater control, which is an ongoing area of development for this work. A pneumatic bladder can be employed to press the gripper onto the surface, minimizing the wrinkles. This solution has been successfully applied to composite carbon fiber [1]. This proof of concept can be readily automated and is scalable.
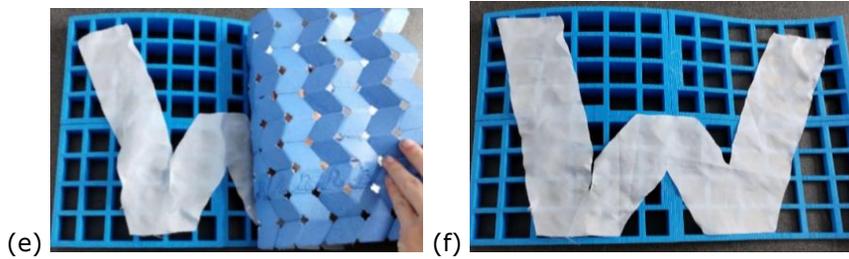

(a)

(b)

(c)

(d)
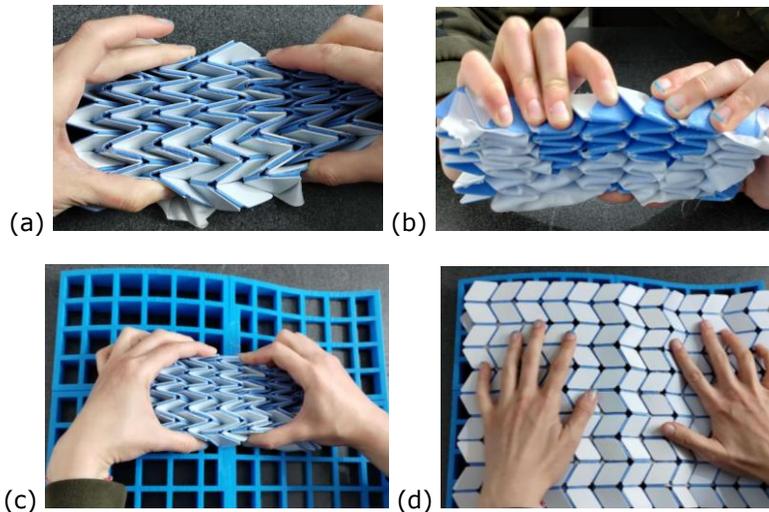
Figure 14: Manual pick and place testing including (a) pick, (b)(c) transfer, and (d)(e)(f) place.

4.4   Fabrication of a Support Frame for Automated Handling

With the appropriate frame, this solution can be automated (Fig. 15). As this gripper system is to be mounted onto a robot, minimizing the weight is a design constraint. Development is ongoing, with Fig. 16 showcasing an earlier frame variant attached to a cobot, picking different textiles using a smaller-scale Miura-Ori gripper. A robot may have a limited actuation range (Fig. 15). Therefore, a specialty frame (Fig. 16) or end effector configuration is required.
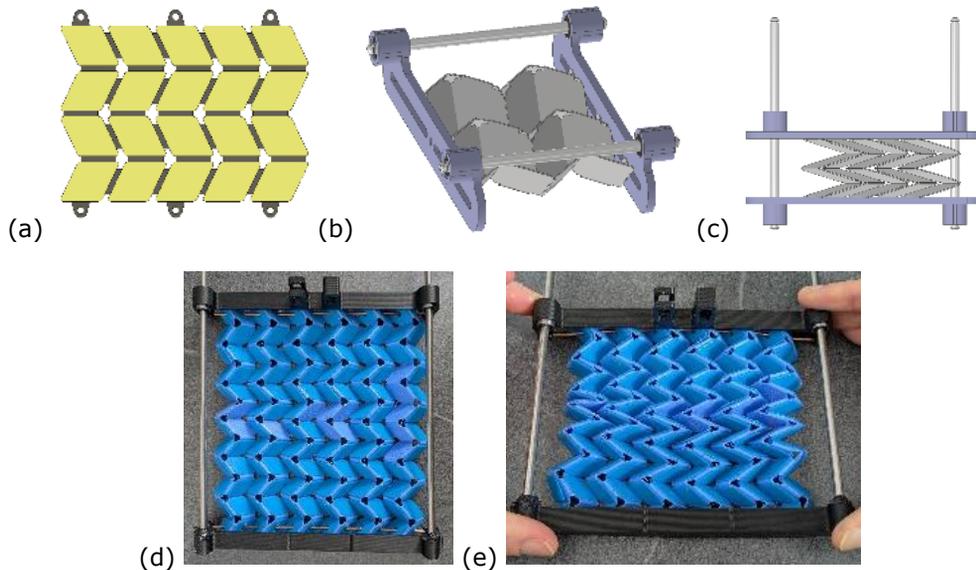

Figure 15: (a) CAD of sample gripper with frame connections (loops), (b) partially compressed frame and gripper (with the linear rod and bearing), (c) fabricated prototype uncompressed, and (e) partially compressed.

4.5   Improvements for Gripper Fabrication via Additive Manufacturing

A major challenge in fabricating Miura-Ori grippers using a multi-material filament-based 3D printing process is the difficulty of bonding dissimilar materials, particularly in prints subjected to repeated flexing and use (Fig. 17 (a)). This issue arose from poor inter-layer adhesion between the two materials (PLA and X-920). Although the flexible material used in this study is a blend of PLA and a copolymer, delamination still occurred. To address this, process settings were adjusted, particularly by printing the first few interface layers of PLA directly on top of the flexible X-920 at 10°C higher than the typical printing temperature of 210°C to improve bonding. Despite these modifications,

delamination persisted, indicating an inherent incompatibility between the two materials. After fabricating the gripper samples for this study, a new material was identified and explored for further discussion. Varioshore TPU, developed by ColorFabb [21], is a foaming filament with variable shore hardness (55-92A), enabling users to control the density and hardness of a 3D print by adjusting temperature and flow rate during fabrication. The filament achieves Shore 55A at its maximum foamed state (around 250°C with 60-70% typical flow rate) and Shore 92A at its unfoamed state (between 190-200°C with typical flow rates) [21]. Using this material to fabricate a Miura-Ori gripper resolved the delamination issues, as the same filament could be used to create both the flexible and rigid regions of the gripper by varying the printing temperature. After repeated use, the rigid parallelogram panels of the Varioshore TPU gripper remained intact (Fig. 17 (b)). Future work includes exploring rapid tooling and overmoulding solutions.
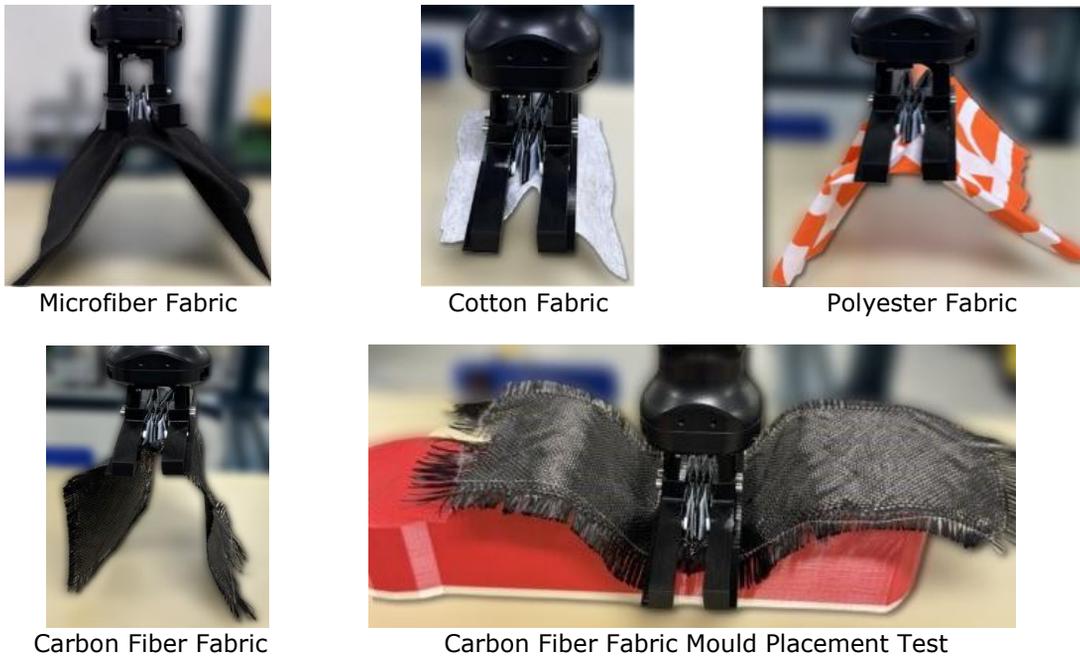

| Microfiber Fabric | Cotton Fabric | Polyester Fabric |

Carbon Fiber Fabric   Carbon Fiber Fabric Mould Placement Test

Figure 16: Fabrics being picked and placed into a concave mould using a collaborative robot and a small gripper, adapted from [1].
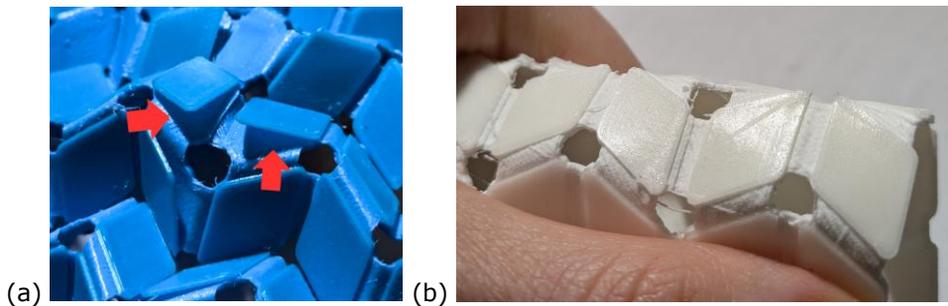

(a)   (b)

Figure 17: (a) Delamination of rigid PLA panels from X-920 flexible base of Miura-Ori gripper and (b) no evident delamination on gripper fabricated with Varioshore TPU filament.

Interestingly, the use of this new material also addressed an inherent issue in fabricating the gripper with material extrusion. With the original material, visible voids due to the toolpath were present in critical areas, such as the flexible joints/living hinges of the gripper (Fig. 18 (a) and (b)). Over repeated use, these voids became failure zones where the material began to separate. While increasing the flow rate during printing could help fill these gaps, it could also negatively impact the surface finish and material dimensions. The Varioshore TPU indirectly solved this void problem due to its expanding/foaming nature at high temperatures. In the test print shown in Fig. 18 (c) and (d), a temperature of 250°C was used for the flexible portion of the gripper (55A). This material will continue to be explored for this application.

New ME additive tool paths are being developed, and an appropriate post-processor is being developed to address this situation. The goal is to move the voids into non-stress regions, or to include local tool path variants (i.e., variable overlaps) to manage void issues. If an over-moulding approach is taken, this issue may be moot.
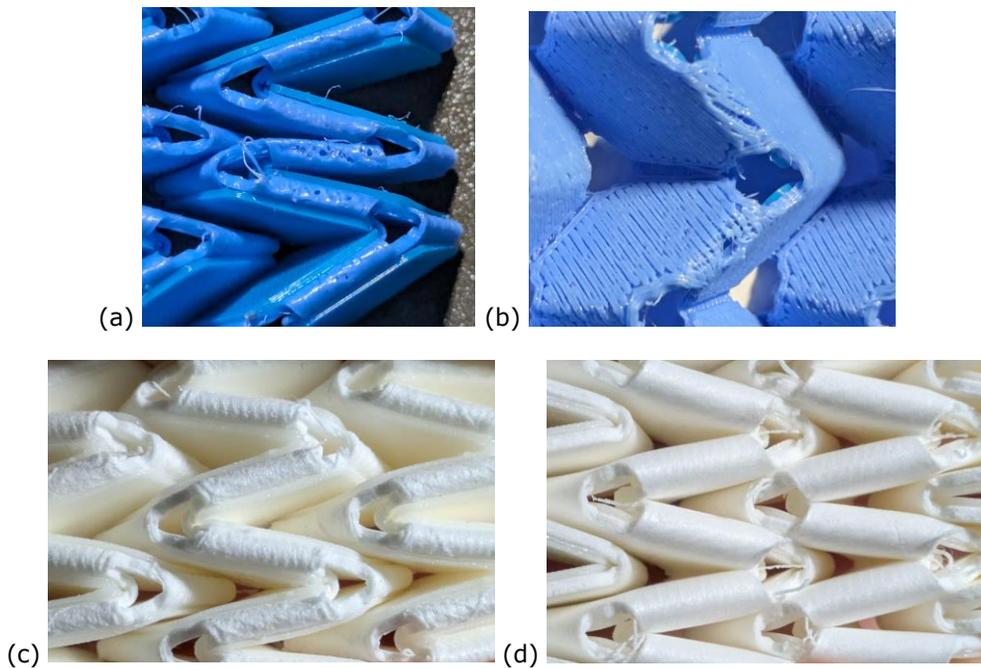

(a)   (b)   (c)   (d)

Figure 18: (a) Top and (b) bottom problem areas due to voids of the multi-material gripper made with PLA and X-920 (c) top and (d) bottom crease regions of the gripper made using Varioshore TPU.

4.6 Life Cycle Test Qualitative Results

A life cycle test was conducted to evaluate performance over 10, 100 and 500 folding cycles for two identical grippers, made from the same printer toolpath. One was fabricated as a multi-material print using the Sakata 3D X-920 copolymer for the hinges and PLA for the panels, while the other was printed entirely from Varioshore TPU, as detailed in the previous subsection. Fig. 19 presents qualitative observations and identifies failure propagation sites at each cycle milestone. The Varioshore TPU gripper demonstrated superior performance compared to the multi-material version. This improved durability is attributed to the foaming nature of the material, which expanded during extrusion and as a result filled the toolpath voids – locations where failure propagation was most evident in the multi-material gripper. Given these results, Varioshore TPU will be further implemented in future studies.
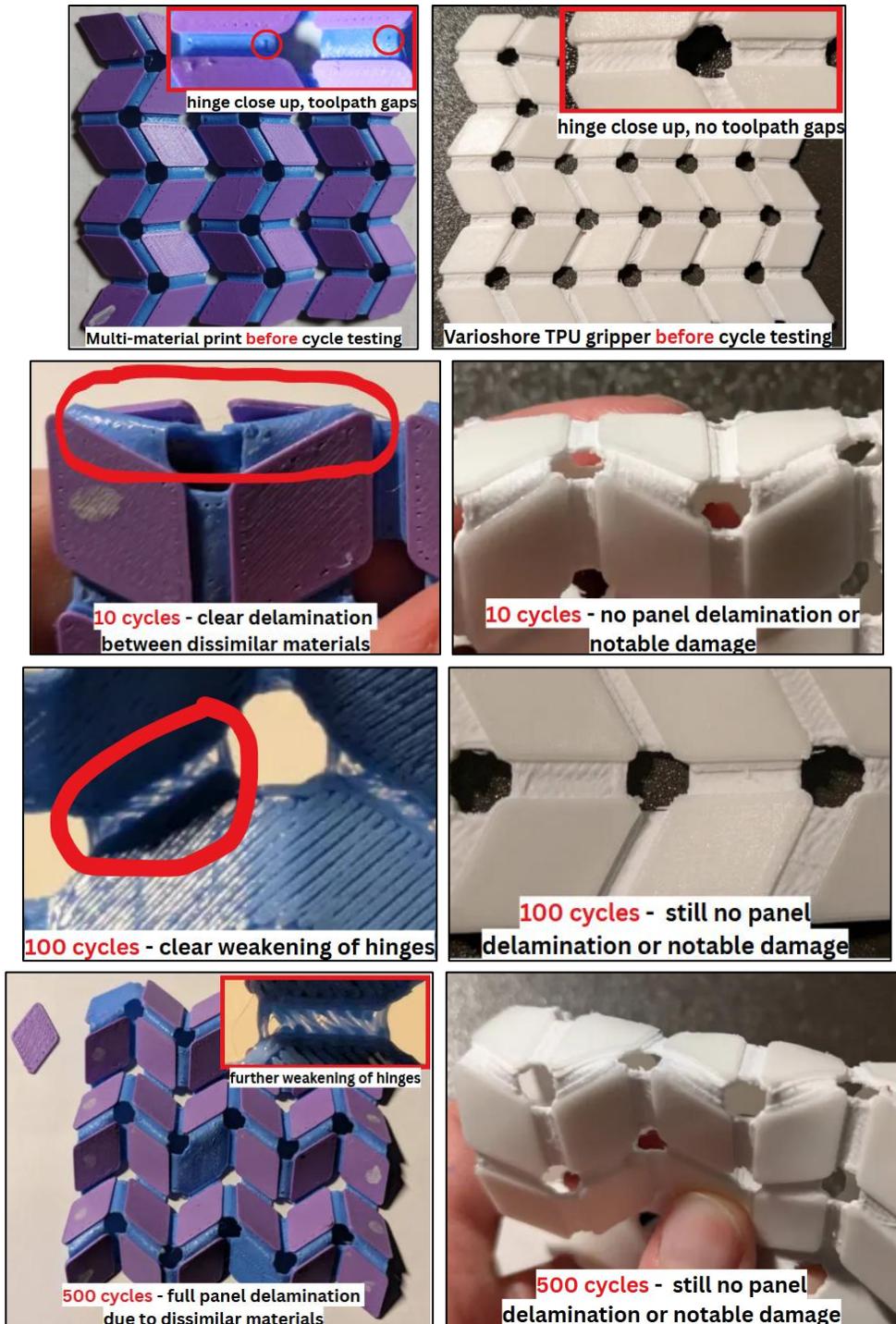
Figure 19: Qualitative results after 10, 100, and 500 folding cycles of multi-material Sakata 3D X-920 and PLA gripper (left) and Varioshore TPU gripper (right).

5 CONCLUSIONS

Innovative composite materials are being developed in tandem with new product ideas. However, introducing scalable and extendable high-volume production solutions for effective material handling is a roadblock. Automation solutions need to be established to produce large quantities of components efficiently and consistently to reduce per-unit costs. Employing needle grippers will damage the fibers, and vacuum (and related systems) are not energy efficient. Other approaches, such as using soft robotic grippers with multiple robotic arms, will allow for pick and place actions, but require more capital investment, controls to synchronize the motions, and there is the potential for significant wrinkling [5]. Another approach is needed. Contacting multiple surfaces with a controlled Miura-inspired fold enables limp fabrics to be picked up, collapsed into a 'rigid' structure, and unfolded and placed onto a curved surface, regardless of the fabric shape. This is a low-cost mechanical solution.

The specialty grippers presented in this work are designed as curve-compliant, self-collapsing end-effectors, making them particularly adept at handling such limp textile materials with complex shapes. This approach can be scaled up, and to automate this handling strategy, a collapsable frame needs to be incorporated. A sample frame that collapses the gripper in the X and Y directions is presented. Changing the tessellation patterns will allow for compliance for different mould geometries [4]. This preliminary research demonstrates strong potential and establishes a solid foundation for more detailed, rigorous studies that will refine and optimize this origami-inspired approach for limp fabric handling.

6 FUTURE WORK

To extend this work, future studies should include a detailed evaluation of the gripper's response time and gripping speed. These performance metrics can be more accurately studied once an automated actuation system is implemented, as the current study relied on manual operation to evaluate the gripper's ability to contain and hold fabric. Manual manipulation introduces variability, making it difficult to extract consistent response and gripping speed data. Although this work proposed an initial frame solution for containing the gripper, it served as a preliminary proof of concept and requires further development. Additionally, incorporating a finite element analysis (FEA) of the gripper's deformation behavior would significantly strengthen the theoretical framework of the Miura-Ori design. Such simulations would enable a more comprehensive understanding of the strain distribution, hinge mechanics, and out-of-plane deformations, and could validate experimental findings related to the spring constants and collapse forces obtained in previous work [19].

Another area of future work is in the development of a set of case studies involving non-planar mould surfaces with varying levels of geometric complexity to better evaluate the gripper's adaptability to diverse surface contours. While the S-shaped mould shown in Fig. 7 and 13 provides a reasonable starting point, it remains relatively regular compared to the more complex freeform surfaces encountered in real-world applications. Expanding testing to include more irregular surfaces commonly found in daily life and industrial settings would yield deeper insights into the gripper's practical versatility. Notably, the mould design in Fig. 7 includes rectangular cutouts that can serve as integration spaces for sensors and as a grid for fabric placement—features that can be leveraged in the design of future case study surfaces. These additions are useful for evaluating the accuracy and repeatability of future automated systems, as they provide fixed reference points for alignment.

Exploring alternative build materials or rapid tooling strategies, along with durability testing, is also necessary to assess long-term performance and application potential of the Miura-Ori gripper.

7 ACKNOWLEDGEMENTS

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