# Life-Cycle of Structures and Infrastructure Systems

Editors
Fabio Biondini and Dan M. Frangopol

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# LIFE-CYCLE OF STRUCTURES AND INFRASTRUCTURE SYSTEMS

**Life-Cycle of Structures and Infrastructure Systems** collects the lectures and papers presented at IALCCE 2023 - The Eighth International Symposium on Life-Cycle Civil Engineering held at Politecnico di Milano, Milan, Italy, 2-6 July, 2023. This Open Access Book contains the full papers of 514 contributions, including the Fazlur R. Khan Plenary Lecture, nine Keynote Lectures, and 504 technical papers from 45 countries.

The papers cover recent advances and cutting-edge research in the field of life-cycle civil engineering, including emerging concepts and innovative applications related to life-cycle design, assessment, inspection, monitoring, repair, maintenance, rehabilitation, and management of structures and infrastructure systems under uncertainty. Major topics covered include life-cycle safety, reliability, risk, resilience and sustainability, life-cycle damaging processes, life-cycle design and assessment, life-cycle inspection and monitoring, life-cycle maintenance and management, life-cycle performance of special structures, life-cycle cost of structures and infrastructure systems, and life-cycle-oriented computational tools, among others.

This Open Access Book provides both an up-to-date overview of the field of life-cycle civil engineering and significant contributions to the process of making more rational decisions to mitigate the life-cycle risk and improve the life-cycle reliability, resilience, and sustainability of structures and infrastructure systems exposed to multiple natural and human-made hazards in a changing climate. It will serve as a valuable reference to all concerned with life-cycle of civil engineering systems, including students, researchers, practitioners, consultants, contractors, decision makers, and representatives of managing bodies and public authorities from all branches of civil engineering.

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# Life-Cycle of Structures and Infrastructure Systems

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# Reuse of fibrous tectonics as the secondary structure of the facade system

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ABSTRACT: Fibrous structures are structures that are made of fiber-reinforced polymer (FRP) composites. Their excellent mechanical properties, in addition to their low densities, can result in a lightweight structure. However, there are some obstacles that prevent them from being used more widely: high material and manufacturing costs, end of life (EoL), plus optimizing their design and fabrication procedures to be used on a building scale, like they have been used efficiently in the aerospace and automobile industries. The current recycling process for FRP can cause a huge loss in mechanical properties and be costly. The goal of this study is to reuse the entire continuous fiber-reinforced polymer composite with minimal loss in mechanical properties, so the current use of thermosets has to be changed to thermoplastic. The secondary structure of a façade system is intended to replace existing bulk structural systems and scale up the FRP composite to the building scale.

## 1 INTRODUCTION

### 1.1 *History of FRPs in industry*

Owens Corning was the first to introduce glass fiber in 1935, kicking off the fiber-reinforced polymer (FRP) industry. Following World War II, the burgeoning petrochemical industry made available glass fiber embedded in polymeric resins; as a result, high-strength, high-stiffness structural fibers were combined with low-cost, light-weight, environmentally resistant polymers to create a composite with better mechanical properties and durability than the constituents alone (Bakis et al., 2002). Moreover, due to the demands of World War II, the FRP industry transitioned from research to manufacturing. Bill Tritt prototyped and tested a totally composite body car built of glass fiber-reinforced polymer composite (GRP) in the 1940s. In the 1950s, manufacturing innovation continued with the developments of pultrusion, vacuum bag molding, and large-scale filament winding. Later, fibers with higher stiffness, strength, and density, such as boron, aramid, and carbon, were used for high-performance applications in space exploration, aerospace, and air travel, as well as the defense industry (Bakis et al., 2002). High-performance fibers were initially too expensive to be employed in other applications; as a result, work began in the 1970s to reduce the cost of high-performance fibers (Bakis et al., 2002). As the cost reduced and the defensive market waned, the use of FRP as a new material in the renewal of infrastructure increased at the end of the 1980s and the beginning of the 1990s. Furthermore, lots of funding opportunities were devoted to industries and governments around the world (Bakis et al., 2002). Figure 1. represents a summary of the history of fiber-reinforced polymers in industry.

### 1.2 *History of FRPs in architecture and construction*

Fiber-reinforced polymers have been used in architecture since the second half of the twentieth century (Dambrosio et al., 2020). After World War II, a large portion of the polymer output was made available for non-military uses. In 1955, the Radome, an enclosure for a radar station, was mounted in Washington according to Richard Buckminster Fuller's geodesic dome idea (Knippers et al., 2012). This enclosure had to be a free metal structure, which led to the first assemblies made entirely of synthetic materials. Buckminster Fuller continued to work on polymer geodesic domes, building the "Fly's Eye Dome" in 1970. The Monsanto Chemical

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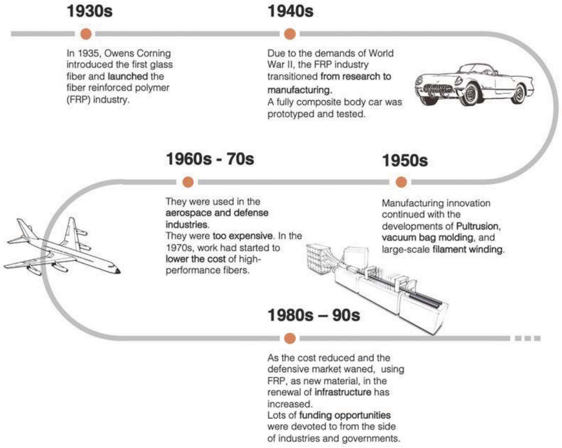
Company approached MIT in 1954 with the concept of building an entirely polymer-based dwelling. A year later, MIT published “Plastics in Housing,” a study that outlined how the house of the future would look (Knippers et al., 2012). The main motivations for adopting polymers in construction were flexibility for changing families, ease of relocation for increased mobility, and cost-effective housing for the developing middle class. All of these features were to be exhibited in a project that could be easily assembled and modified to fit varied plan layouts and local conditions (Knippers et al., 2012).

Fiber-reinforced polymer structural forms are one of the most common uses in the building and structural industries. The pultrusion method was utilized to create the structural shapes of the fiber-reinforced polymer. Via the pultrusion technique, the fiber-reinforced polymer has been employed in structural, non-structural, and electrical applications. Before the 1970s, the development of small-sized commodities for non-structural and electrical purposes was the main focus (Bakis et al., 2002). Since the 1970s, pultruded structural shapes have been used for primary load-bearing systems. The use of pultruded structural shapes of fiber-reinforced polymer in the design and construction of pedestrian bridges, such as the long cable-stayed Aberfeldy Footbridge in Scotland, is also evident (Bakis et al., 2002).



In 1935, Owens Corning introduced the first glass fiber and **launched** the fiber reinforced polymer (FRP) industry.

Due to the demands of World War II, the FRP industry transitioned **from research to manufacturing.** A fully composite body car was prototyped and tested.

They were used in the **aerospace and defense industries.** They were **too expensive**. In the 1970s, work had started to **lower the cost** of high-performance fibers.

Manufacturing innovation continued with the developments of **Pultrusion**, **vacuum bag molding**, and large-scale **filament winding**.

As the cost reduced and the defensive market waned, using FRP, as new material, in the renewal of **infrastructure** has increased. Lots of **funding opportunities** were devoted to from the side of industries and governments.

Figure 1. History of FRPs.

## 2 MATERIAL INVESTIGATION

### 2.1 *Fiber-reinforced polymer composite (FRP)*

FRP composites are high-strength, lightweight, with great fatigue resistance, a high elastic modulus, and low thermal expansion and corrosion resistance (Liu et al., 2015). Besides, they can be ductile (depending on the type of matrix), but they are anisotropic materials (Waimer et al., 2013), which means they present different behaviors in different directions. Since an FRP composite contains a reinforcement (fiber, 60%) embedded in a matrix (polymer, 40%) (Figure 2.) (Liu et al., 2015; Bhargava, 2004), it primarily exhibits the mechanical properties of the fiber in the fiber direction, i.e., relatively high strength and modulus. On the other hand, it exhibits the mechanical properties of the polymer and resin in the direction perpendicular to the fiber axis, i.e., relatively low strength and modulus (Liu et al., 2015).

The matrix of FRP can be a thermoplastic, elastomer, or thermoset. Because of its high mechanical strength, epoxy, a thermoset polymer, is often employed as the matrix material in fiber-reinforced polymer composites (Boon et al., 2021). Although making a thermosetting composite is a simple operation, the long curing cycle of thermosets will increase the manufacturing cost (Boon et al., 2021). On the other hand, fiber-reinforced thermoplastic polymer composites take substantially less time to make because of their fast consolidation cycles; they also offer higher toughness, a longer shelf life, are easier to repair, and can be recycled

(Arhant et al., 2019). The high melt viscosity of thermoplastics can cause non-homogenous impregnation of reinforcement during the infusion process (the process of producing FRTP). The melt flow index must be considered when using thermoplastic polymers. According to the standards ASTM D1238 and ISO 1133, it is defined as a measure of the resistance to flow (viscosity) of the polymer melt at a given temperature under a given force for a predetermined period of time. It has a direct relationship with the flow of thermoplastic and an indirect relationship with viscosity. A thermoplastic epoxy resin (TP-EP) that combines the benefits of thermoset and thermoplastic resins was recently created (Nishida et al., 2018).

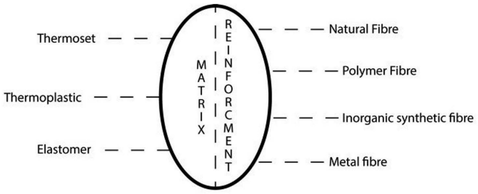


Figure 2. Reinforcement/Matrix in FRP composite.

## 2.2 *Market share of FRPs*

Fiber-reinforced polymer composites (FRP) have been in use since the 1930s, but they are now gaining popularity in the structure and construction industries (Bakis et al., 2002). FRPs are frequently used in place of metals in construction as well as in the military, energy, transportation, chemical, and electric power industries because of their high strength, light weight, and low maintenance requirements (Xue et al., 2022). Glass fiber-reinforced polymer composites (GFRP) and carbon fiber-reinforced polymer composites (CFRP) as two inorganic synthetic fibers are mostly common in different industries. In 2021, the global market for carbon fiber-reinforced plastic (CFRP), according to Statista, will be worth about 8.2 billion dollars. The size of the global market for carbon fiber-reinforced plastic is anticipated to reach approximately $13.1 billion in 2027. The market for carbon fiber (CF) is expanding at a fast rate of 10%–12% annually due to the growing use of CF in aerospace, wind turbine blades, and other industrial applications (Xue et al., 2022). Glass fibers (GFs) were in high demand globally in 2019 (5.26 million tons), and it is anticipated that they will continue to lead the composite materials market (Xue et al., 2022). This shows an increased use of these materials in the construction industry. An investigation shows that the market share distribution of fiber-reinforced polymers in the construction industry is about 26 percent (Zyjewski et al., 2017).

While carbon fiber-reinforced plastics (CFRPs) are primarily used in the aerospace, wind power, sporting goods, and automobile manufacturing industries, glass fiber-reinforced plastics (GFRPs) are more commonly used in construction, transportation, industrial applications, electronic products, and other fields (Xue et al., 2022).

## 2.3 *State of the art in recycling and reusing of FRPs*

The disposal and burning of FRP will no longer be permitted due to the new regulation (the "green deal") (Kang et al., 2021). Additionally, recycling has economic and energy advantages; for instance, recycling carbon fibers uses between 80% and 98% less energy than producing virgin fibers (Ghanbari et al., 2021). Consequently, recycling and reusing FRP have become more popular these days. However, due to the combination of two materials in FRP composite, recycling is a challenge (Rybicka et al., 2016). The thermosetting continuous FRP, which is considerably more prevalent than thermoplastic, can be recycled by thermal, chemical, and mechanical processes (Freeden et al., 2022). Thermal and chemical strategies are focusing on the separability of reinforcement and matrix to recover the fibers alone (Freeden et al., 2022). The mechanical strategy for recycling results in a loss of mechanical properties because the continuous FRP is shredded (Freeden et al., 2022). These techniques are extremely expensive, so they are routinely utilized for recovering carbon fiber, and mechanical recycling is mostly used for glass fiber-reinforced polymer (GFRP) composites (Rybicka et al., 2016). Thermal recycling strategy causes approximately 80%

of GFRP strength losses; however, this figure is only about 10% for carbon fiber-reinforced polymer composites (CFRP) (Pender et al., 2019).

There are a few examples and strategies for reusing the entire fiber and thermosetting matrix composite. Bus stops, benches, and children's playgrounds constructed from recycled wind turbine blades are a few isolated examples. The large amounts of End-of-Life (EoL) material cannot be recycled or reused using these methods (Freeden et al., 2022).

Recently, two case studies for reusing and recycling FRP were investigated in the industry. The first is a reuse plan that was designed for the canopy of i-mesh at Expo Dubai. This canopy was designed by Werner Sobek Company and constructed by i-mesh Company by utilizing glass fiber reinforcement and a thermoplastic elastomer matrix. The system contains a set of patterns that are connected to each other and can be separated by certain lines. They plan to take away the canopy after the Expo exhibition and use it as the shading system for the courtyard of a middle-eastern country, which is suffering from the huge amount of light from the sun. Figure 3-Right presents the i-mesh canopy during Expo 2020 Dubai, and Figure 3-Left shows the reuse plan after the exhibition. This reuse potential, though only focusing on the reuse of the panels, can be useful for using the systems again; however, in this case, it is not possible to come back to the level of material filaments, so it can reduce the design potentiality because of these restrictions.

Figure. 3. I-mesh reuse plan.

Cygnet Texkimp's (cygnet-texkimp.com) waste recycling uses superheated steam to gently remove a range of polymers from filters and related production equipment, allowing raw material waste to be reused in your manufacturing process. Using a combination of superheated steam pressure swings or compression and decompression cycles, frozen polymer is removed from contaminated components and assemblies. The process takes place in a controlled environment contained within a custom-designed pressure vessel. The components are enclosed in a pressure vessel, and the pressure is rapidly decreased by opening the blowdown valves. Depending on the polymer type, temperatures above 250 °C will melt or soften the polymer, and a degree of hydrolysis will occur. When under pressure, the steam will penetrate fissures in the polymer, where it condenses as superheated water. On decompression, it boils, instantly cracking the polymer and carrying away broken particles along with the softened, degraded polymer fragments from the outer faces. The pressure swing cycle is then repeated at frequent intervals and controlled automatically with no detrimental effect on the integrity of the filter media or metal structure.

## 3 EXISTING GAPS AND RESEARCH AIMS

In the previous century, the consumption of building materials has increased dramatically, and the weight of the materials used for the structures is more than half that of the other systems involved. As a result, deconstruction wastes (Ng et al., 2015) and the use of virgin materials (Herrmann et al., 2018) have increased in the construction sector, and their fate cannot be landfill or burning.

The excellent mechanical properties of FRP, in addition to their low densities, can result in a lightweight structure as a result. However, there are some obstacles that prevent them from being used more widely: high material and manufacturing costs, end of life (EoL) in general, plus optimizing their design and fabrication procedures to be used on a building scale, like they have been used efficiently in the aerospace and automobile industries. Given the size of the market and the anticipated rise in waste generation over the coming years, it is critical that composite products are properly managed when they reach the end of their useful lives.

Besides, current research in the state of the art shows that these materials have been used primarily for temporary lightweight structures (primarily pavilions, shells, and membranes) in recent years. However, the IntCDC and ITKE at the University of Stuttgart presented a possible concept of having fibrous structures on a building scale at the Biennale di Venezia 2021 (Maison Fibre), but there is still a long way to go. Older case studies show the use of these materials at the building scale, but with design, structure, and fabrication processes that are mostly similar to the traditional procedures that have been used for other structural materials like steel (for example, pultruded structural shapes). However, FRP has its own specific mechanical properties and behavior that must be taken into account.

This paper aims to reuse the entire continuous fiber-reinforced polymer composite with minimal loss of mechanical properties, necessitating a switch from thermosets to thermoplastics. A secondary structure for the facade system is designed to take the place of current bulk structural systems and scale up the FRP composite to building scale.

## 4 RESEARCH METHODOLOGY

According to the standard BS 8887-2:2009, "reusing" is the operation by which a product is put back into use for the same purpose at its end-of-life. In order to reuse the material after the end-of-life of a system, its design must be disassembled and reversible to return to its original situation (Gorgolewski, 2017). In the case of fiber-reinforced polymer composites, disassembly is defined as the separation between the joints that connect the fibrous structure to the context, and reversibility can be defined as the ability to unwind and wind the spool of fiber-reinforced polymer composite without losing any mechanical or physical properties. "Reusing of Fibrous Tectonics" consists of three related but distinct fields: material, computational design, and digital fabrication. Its concept can be summarized in Figure 4.

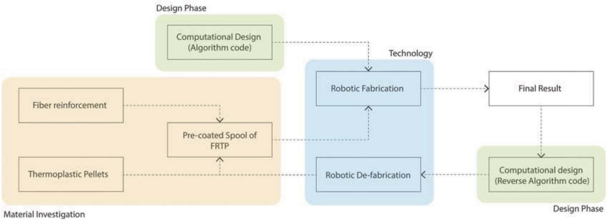


Figure 4. Research overview.

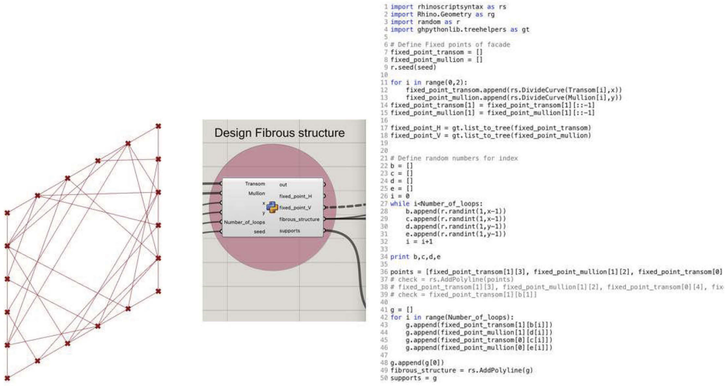
### 4.1 *Fiber-reinforced thermoplastic polymer composites (FRTPs)*

Although thermoset resins are more frequently used in fiber-reinforced polymer composites than thermoplastic resins, this study will use a thermoplastic resin. The pre-impregnated fiber-reinforced thermoplastic polymer composite (FRTP) is used in the research project, and an elastomer thermoplastic matrix has been used to feed the disassembly and reversibility, which are essential for the reusing process. The research project also makes use of the FRTP in the form of roving, which is a bundle of straight strands wound onto spools (Figure 5). However, the aim of this research is only to reuse the materials, but the use of thermoplastic matrix can bring about the possibility of recycling for future development. The unwinding and winding processes are made simpler by the composite's increased flexibility as a result of the use of elastomer thermoplastic resin. The FRTP spools have already been impregnated and manufactured in the factory. According to the mechanical properties of the FRTP, a design and optimization process is run to reach the final shape of the structure.

Figure 5. Spool of fiber-reinforced thermoplastic polymer composite.

### 4.2 *Form-finding process and fibrous pattern generation*

An integral component of this project, which investigated the material's reusability, was the form-finding procedure. In this study, the form-finding procedure was restricted to the generation of straightforward random patterns. For instance, no two consecutive points could be on the same side of the frame, and each loop had to have four points (mullion or transom). It is significant to note that no load was taken into account when finding the form. Because this is a lab-scale project, the paper's main emphasis is on reusability. The points were exported in order to be imported for the fabrication part after choosing the fibrous pattern. In Figure 6, the code used to generate the pattern in the Grasshopper can be seen.



```
import rhinoscriptsyntax as rs
import Rhino.Geometry as rg
import random as r
import ghpythonlib.treehelpers as gt

# Define Fixed points of facade
fixed_point_transom = []
fixed_point_mullion = []
r.seed(seed)

for i in range(0,2):
    fixed_point_transom.append(rs.DivideCurve(Transom[i],x))
    fixed_point_mullion.append(rs.DivideCurve(Mullion[i],y))
fixed_point_transom[1] = fixed_point_transom[1][::-1]
fixed_point_mullion[1] = fixed_point_mullion[1][::-1]

fixed_point_H = gt.list_to_tree(fixed_point_transom)
fixed_point_V = gt.list_to_tree(fixed_point_mullion)


# Define random numbers for index
b = []
c = []
d = []
e = []
i = 0
while i<Number_of_loops:
    b.append(r.randint(1,x-1))
    c.append(r.randint(1,x-1))
    d.append(r.randint(1,y-1))
    e.append(r.randint(1,y-1))
    i = i+1

print b,c,d,e

points = [fixed_point_transom[1][3], fixed_point_mullion[1][2], fixed_point_transom[0]
# check = rs.AddPolyline(points)
# fixed_point_transom[1][3], fixed_point_mullion[1][2], fixed_point_transom[0][4], fix
# check = fixed_point_transom[1][b[1]]

g = []
for i in range(Number_of_loops):
    g.append(fixed_point_transom[1][b[i]])
    g.append(fixed_point_mullion[1][d[i]])
    g.append(fixed_point_transom[0][c[i]])
    g.append(fixed_point_mullion[0][e[i]])

g.append(g[0])
fibrous_structure = rs.AddPolyline(g)
supports = g
```

Figure 6. Fibrous pattern generation through grasshopper.

### 4.3 *Lab-scale robotic fabrication system for in-situ fabrication and de-fabrication*

The current use of industrial-type robots is primarily suitable for off-site and prefabrication of building components (Dörfler et al., 2019), which can increase the cost of transportation and the total cost in general. However, robotic technology in architecture brings greater freedom, the ability to fabricate intricate shapes and geometries (Dörfler et al., 2019), and improves the sustainability, efficiency, and productivity of building construction. The vertical-robotic system is inspired by the Polargraph drawing robot (http://www.polargraph.co.uk/), which includes three different yet connected subgroups. The material subgroups consist of spools of pre-impregnated fiber-reinforced elastomer polymer composite that are flexible enough to unwind and are used to fabricate the secondary structure of the façade system plus the tensioning system. The hardware subgroups, which included two motors, an electronics setup, and an Arduino, moved the end-effector (which is just responsible for fiber placement in this research) to wind the continuous fiber-reinforced thermoplastic polymer (FRTP) composite in the exact place according to the data that came from the design subgroups. The design subgroup is responsible for changing the data coming from the design and optimization process into data that can be read by hardware subgroups. Figure 6 presents the scheme of in-situ robotic fabrication on a façade.

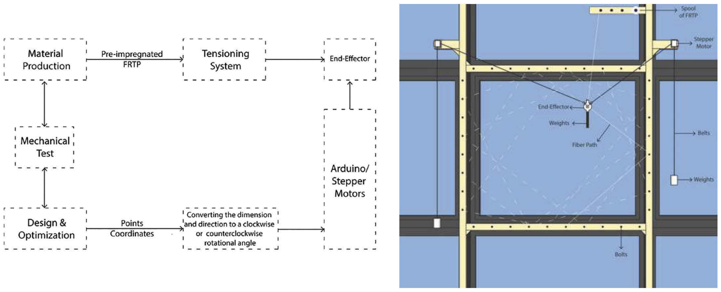


Figure 7. Robotics sub-groups.

During the form-finding process, each loop, which can be a rectangle, is considered a linear connection between four anchor points (two on the mullions and two on the transoms). The final solution of the form-finding process can be summarized in point coordinates, which represent the index of anchor points, respectively. These coordinates will be translated into angles that can be read by the Arduino and implemented by motors. The design subgroup considers any two points in a row as the direction of movement and changes the points' coordinates to the radius that is readable for the stepper motor. No load has been considered in the form-finding process. The difference between the fabrication process and the de-fabrication process is the order of anchor points. In fabrication, the order should be from the point with index 0 to the point with index -1, whereas in de-fabrication, the order should be reversed. Contrary to the de-fabrication process, which uses an additional servo motor to help wind the fiber-reinforced polymer composite back onto the spool, a tensioning system is utilized in the fabrication process since the fiber-reinforced polymer composite has to be pre-tensioned before the filament winding technique. Figure 8 shows the fabrication diagram of one loop of fibrous structure for the facade system. The result of this research has been prototyped at 1:1 scale in the laboratory as an internal secondary structural system for façade to test the reliability and functionality of the methodology exclusively for the fabrication and de-fabrication processes.

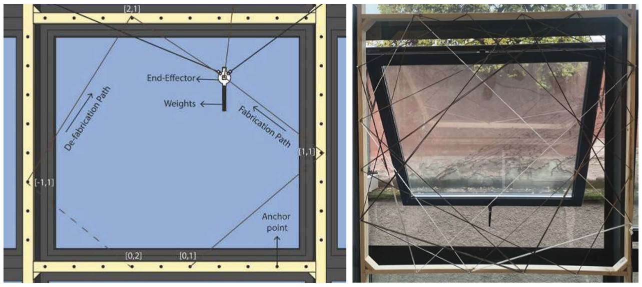


Figure 8. Fabrication diagram + final result - * [Index of point, Number of loop].

## 5 CONCLUSIONS

In order to overcome the difficulties and restrictions associated with using FRP composites in building-scale applications, this paper introduces a novel strategy that involves incorporating a design approach that emphasizes reusability, end-of-life, and environmental impact into the fabrication workflow of a fibrous structure for the secondary structure of a facade. In-situ fabrication is made possible by the suggested robotic system, opening up new avenues for the construction industry. This strategy may help to advance sustainability in the field of fibrous tectonics by using an elastomer thermoplastic matrix for the FRP composite. This study makes a contribution to the field by providing a fresh viewpoint on the use of FRP composites and outlining a potential fix for the environmental problems that currently prevent their use in large-scale construction projects.

This paper is part of a research project conducted at Politecnico di Milano's TextilesHUB laboratory with the collaboration of the i-mesh company, and it focuses primarily on the lab-scale prototyping.

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