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Innovative Reclamation and Design: A Lightweight Structure from Reclaimed Golf Clubs

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Abstract
This paper presents an exploratory study of sustainable architecture through designing, optimizing, and constructing a structure utilizing reclaimed golf clubs. Highlighting the increasing adoption of resource-driven design, this research underscores the importance of integrating reclaimed materials into architectural design and fabrication. It sets a precedent for environmental responsibility within the architecture, engineering, and construction industries. The primary strategies discussed include material reuse, repurposing, and optimizing material use through computational design and digital fabrication. Central to the research is the creative utilization of reclaimed golf clubs, which vary in size and are employed without alteration to preserve the integrity of each piece. This method emphasizes the innovative potential of non-traditional building components. Another crucial aspect of this project is its contribution to reducing the construction industry's carbon footprint. By repurposing high-performance sports equipment, the study demonstrates how the lifespan of such materials can be significantly extended, enhancing sustainability and resource efficiency. The paper details the challenges in designing a joinery system that accommodates the unique properties of reclaimed golf clubs. The connection system developed for this project is vital, allowing for the assembly of the clubs without permanent modifications like welding or riveting. A proof-of-the-concept prototype of the system is designed, fabricated, and discussed in this paper, highlighting the complexities and uncertainties of working with reclaimed materials and showcasing the innovative solutions necessary for their successful architectural integration for promoting a shift towards more sustainable and responsible design methodologies.

Keywords: resource-driven design, design for reuse, form finding, optimization, lightweight innovative structures.

1. Introduction
The pursuit for sustainable habitats, innovative living spaces, and unique spatial experiences is becoming increasingly critical in our rapidly evolving world. As global warming intensifies and our population grows, the depletion of natural resources and the accumulation of landfill waste present formidable challenges. The construction industry, a significant contributor to resource depletion, greenhouse gas emissions, and waste generation, is at the forefront of this environmental impact. Addressing the sustainability of building structures has thus become an increasingly pressing concern. The imperative that drives this research is to explore alternative approaches to address these pressing issues.

Materials are fundamental to architecture, shaping our environments and defining our spaces. However, due to environmental concerns, the traditional approach to material usage is no longer viable. The construction industry contributes significantly to waste, with debris from building activities and the disposal of architectural components at the end of their life cycle accumulating in landfills. By reevaluating how we use materials, we can reduce the waste generated during construction and find new uses for materials at the end of their life cycle.

Recycling or reusing materials from other industries after their end of life is a promising strategy that has gained interest in experimental architecture over the past 25 years (Diarte et al. [1]). This approach promotes environmentally compatible structures and circular construction practices, utilizing reclaimed materials and developing new bio-based materials (Ghazvinian et al. [2]). However, the direct reuse of materials has challenges due to uncertainties in repurposing and the need to redefining design and fabrication approaches. These factors increase complexity and require a resource-driven approach.

This paper outlines research that originated from a second-year undergraduate architecture course aimed at covering construction materials. The course initially covered traditional materials like concrete, steel, and timber before focusing on unconventional materials, highlighting their potential for future design and construction. In the final project of the course, students formed groups to investigate a range of materials, both conventional and unconventional. They were tasked with designing various architectural elements, urban furniture, and experimental structures without constraints on material selection, fostering innovative approaches to rethinking materials and structures for future design.

The project highlighted in this paper and the pavilion showcased in the Working Group 21 competition at the 2024 IASS Symposium originated from this exploratory process. The concept began with the idea of repurposing golf clubs, which are commonly used sports equipment in the US and often discarded in landfills at the end of their lifecycle. Golf clubs have the structural strength necessary for architectural reuse. The research started with collecting discarded golf clubs from a local golf course, assessing their limitations and affordances, and developing a connection method. The aim was to design a spatial form that could be constructed using the golf clubs and the connection system developed through this research.

2. Background

The environmental impact of the building industry is a pressing concern. Reusing or repurposing materials from construction or other industries post their lifecycle is a promising strategy that avoids sourcing new materials, reduces waste, and requires less energy than manufacturing new components (Brütting et al. [3]). Design for deconstruction (DfD) strategies involving prefabricated modular assemblies and reversible connections enable the reuse of durable building elements. These strategies can potentially decrease life cycle energy and environmental impacts by 60-70% (Eckelman et al. [4]).

However, the direct reuse of materials remains relatively unexplored due to uncertainties associated with repurposing materials. While reusing structural components offers substantial environmental benefits, it introduces unique design challenges. The synthesis of structures must conform to the availability, mechanical properties, and geometric constraints of the reclaimed elements, inverting the conventional design process (Brütting et al. [5]). This strategy requires a complete redefinition of design and fabrication approaches, necessitating a resource-driven approach to navigate predetermined properties and the complexities of uncertain geometry.

2.1. State-of-the-art

Researchers have developed computational tools and optimization formulations to facilitate the design of load-bearing systems from reused components while minimizing embodied environmental impacts (Brütting et al. [6]). Digital design tools incorporating matching algorithms have been proposed to optimize the use of reclaimed building elements, reduce design time, and promote the adoption of circular design strategies. These tools suggest the optimal assignment of available elements for a desired configuration, considering user-defined constraints and optimization criteria (Tomczak et al. [7]).

Existing research has investigated the design of reticular structures using a combination of reclaimed and new elements, achieving more than 50% lower environmental impact than structures constructed entirely from recycled steel (Brütting et al. [5]). Optimization techniques have been developed to synthesize multiple structures from a single stock of elements, creating optimal "kits-of-parts" that minimize waste (Brütting et al. [8]). These methods have shown significant potential for reductions in embodied energy, up to 70% less than optimized designs using new materials (Brütting et al. [6]). Studies have investigated the application of these techniques across various structural typologies, such as trusses (Brütting et al. [9]), frames (Brütting et al. [10]), and reciprocal structures (Parigi [11]).

In addition to technical challenges, implementing material reuse in architectural design faces environmental, social, and infrastructural barriers. Despite these obstacles, successful case studies have demonstrated the reuse of construction waste materials such as concrete, brick, wood, metal, plastic, and glass in buildings (Kozminska [12]). Researchers have also developed prototypes of "design with reuse" guides to assist architects in considering reclaimed materials and integrating circular design solutions into their projects **(**Kawa et al. [13]**)**. Furthermore, legislation that mandates reuse and recycling thresholds for new projects has been identified as a potential driver for enhancing circularity in the built environment and encouraging innovation in resource recovery from construction and demolition waste **(**Ghaffar et al. [14]**)**. The widespread adoption of circular design practices requires a collaborative effort involving academic researchers, designers, and policymakers **(**Kawa et al. [13]**)**.

The potential for reusing non-standard, reclaimed elements in the streamlined production of standardized building components has also been demonstrated **(**Parigi [11]**)**. These efforts represent an initial step in understanding and supporting the design of load-bearing systems from reused elements, in line with circular economy principles.

A notable case study illustrating the use of this strategy is designing and constructing a 36m^2 grid shell (Figure 1) made from 210 reclaimed skis **(**Colabella et al. [15]**)**. This innovative approach achieves rigidity by bending an initially flat grid of skis, virtually eliminating waste production. The study addresses unique challenges such as sporadic material supply, categorizing variable mechanical properties, altering material behavior, and uncertainties in structural modeling. The findings suggest that reclaimed skis can perform comparably to conventional timber in designing elastic grid shells while significantly reducing environmental impact metrics like non-renewable energy demand and global warming potential compared to a hypothetical timber grid shell.

Building on this previous study, (Haskell et al. [16]) introduced a process for generating elastic geodesic grid shells with anisotropic cross-sections like those found in skis. Their methodology allows for flattening arbitrary geodesic grids for initial ground assembly before lifting them into the final shell shape, which minimizes bending moments in the formed and near-flat configurations. This innovative geometric relaxation algorithm improves prefabrication, transportation, and construction efficiency while validating the mechanical behavior of the grid shell.

These pioneering studies exemplify how discarded materials can be reimagined for structural applications, potentially transforming construction industry practices. However, further research is needed on long-term performance, design parameter variations, scalability, and holistic environmental assessments of the material reuse strategies.

Figure 1: Nomad Pavilion: Grid shell structure fabricated with reclaimed ski, EPFL, Lausanne, Switzerland © 2017 EPFL Jan Brütting

2.2. Golf Clubs

The global golf club market, valued at USD 3.66 billion in 2019, is projected to grow at a compound annual growth rate (CAGR) of 2.5% from 2020 to 2027, driven by the increasing popularity of golf. Most revenue comes from leisure golf clubs, which account for 80.3% of the market share. North America leads the market, with 77.0% of golf facilities open to fee-paying golfers ([17]).

Golf clubs come in various types, including Drivers, Woods, Irons, Wedges, and Putters, with lengths ranging from approximately 85 to 115 centimeters (32 to 46 inches). In terms of materials, golf clubs are made from various materials, with stainless steel being particularly notable for its durability and wear resistance, making it a popular choice for irons and putters. Other materials include titanium, carbon steel, graphite, tungsten, aluminum, beryllium copper, and composite materials like carbon fiber, each chosen for its specific properties that enhance the performance. Golf clubs are eventually discarded when they reach the end of their useful life. Common reasons for discarding a golf club include a ripped or worn-down grip, a deformed or cracked shaft, a broken head, or a loose weight inside the shaft as shown in Figure 2.

Figure 2: Discarded golf clubs due to a) Grip damage, b) Deformed shaft, and 3) Broken head. [Image credit: Micah Regier]

The clubs utilized in this project were collected from a local golf course and encompass a variety of club types, such as pitching wedges and drivers. This diversity allows the pavilion to be adjustable, offering the ability to create different shapes and support the structure through the varying lengths of the clubs. The golf club's formation also provides a means of shifting and manipulating the structure's mass. The club head is the heaviest part of the club, while the handle is the lightest. This weight distribution enables reciprocity of the elements' orientation to adjust the distribution of weight throughout the pavilion and ensures stability within the structure once it is fully assembled.

3. Materials and Methods

After initial assessment of the resourced material, the golf clubs, an iterative framework of form-finding, optimization, and fabrication with multiple prototyping scales is defined. The following summarizes the workflow to design and fabricate the proof-of-the-concept prototype and pavilion.

3.1. Form-Finding

The form-finding process, for various scales of prototypes, starts with a circle as the initial geometry (Figure 3 – A). Three separate points are randomly selected on this circle, which serve as the center points of three corresponding circles (Figure 3 – A). These circles are constrained to maintain a safe distance from each other, with a specified threshold to prevent intersections. Subsequently, the portions of the three circles extending beyond the base circle are trimmed, retaining only the arcs within the base circle (Figure 3 – B). A control point is then defined between each arc and the central circle, allowing movement in the XY plane that controls the geometry of the arcs. The locations of the center points, the radii of three smaller circles, and the locations of the three control points are chosen as parameters to find the optimized form, explained in the following section.

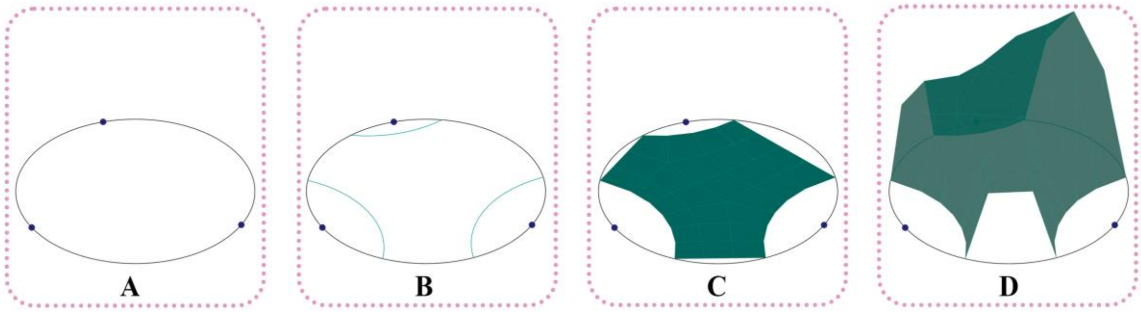

Figure 3: Form-finding process.

The next step involves defining the surface between the arcs and the lines connecting the endpoints of one arc to the starting points of the next arc (Figure 3 – C). This process results in a trimmed surface, which forms the basis of the quad mesh that is the input for initial form-finding. The number of segments in the mesh, representing the divisions of the quad mesh panels, is an essential consideration as it determines the number of mesh edges that correspond to the number of golf clubs in the fabrication phase of the project. The Kangaroo2 add-in is then used to find the initial form of the freeform structure with three unequal openings (Figure 3 – D).

3.2. Multi-Objective Optimization

The optimization process aims to achieve three objectives simultaneously: Equalizing the length of the load-bearing linear elements, which are the reclaimed golf clubs; Minimizing structural mass to make the structure lighter and use a smaller number of elements; And Minimizing displacement to ensure structural stability. The first criterion is to ensure the use of the resourced material, while the other criteria enable an optimization to identify a trade-off between them and generate the optimal freeform structure. The result encompasses determining the number and the precise location of elements and structural supports. The form generated by the form-finding process (Figure 3 – D) can be used as an input for structural analysis and the subsequent Multi-Objective Optimization (MOO). For structural analysis, the Karamba3D add-in is used to facilitate structural analysis simulations, incorporating the exact material properties of the golf clubs made of stainless steel and applying lateral and gravity loads to the structure.

The optimization uses the Wallacei X add-in within the Grasshopper environment, utilizing the NSGA-2 algorithm as the primary evolutionary algorithm and employing the K-means method as the clustering algorithm for multi-objective optimization. The Wallacei X approach enables the extraction of various acceptable and optimal constructible design orientations. The optimization process is limited to 5000 iterations, with a generation size of 100 and a generation count of 50, to prevent overfitting and ensure optimal results. Designers then select from the Pareto front solutions of the final ten generations. The decision was made to select the Pareto front solution from the 99th generation for the prototype case study fabrication to assembly, due to the numerical results of the optimization. Solution number 13, shown in figure 4, from this generation exhibited the least structural mass and displacement.

3.3. Connection system

Using reclaimed golf clubs as structural components necessitates designing and fabricating a specialized connection system that differs from traditional space frame joints. Welding and riveting were initially considered during the prototyping phase; however, given the goal of designing for reuse, these methods were deemed unsuitable, as they complicate disassembly and render the clubs unusable for future projects due to the time-consuming and costly process required to dismantle the structure.

In response, a connection system to keep the clubs intact and free from deformation has been designed, allowing for repeated use. This design constraint leads to exploring alternative connection methods and their impact on the project's end-of-life scenario. The design research includes maintaining the clubs at compound angles necessary for constructing a complex structure. The concept is inspired by universal joints used in automobile drivetrains.

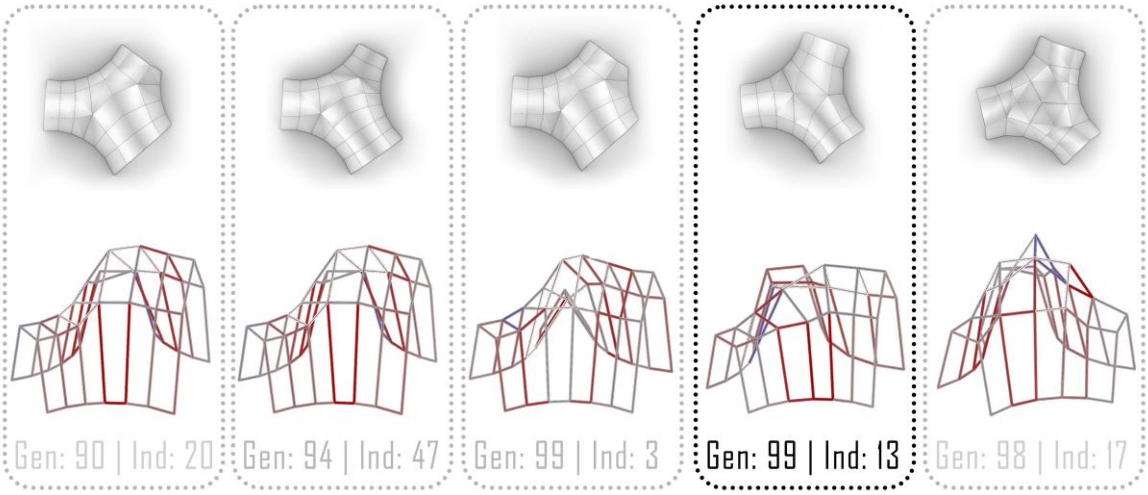

Figure 4: Pareto front solutions selected from the last 10 generations, highlighting five desired outcomes. The focus is on solution number 13 from the 99th generation, which exhibited the least structural mass and displacement.

To address these challenges, additive manufacturing and utilizing screws, washers, and nuts to fabricate a less material-intensive joint at a reduced cost is intended. The configuration of the golf clubs requires connections that accommodate intersecting elements while ensuring structural stability and flexibility. Figure 5 illustrates the development of the connection system.

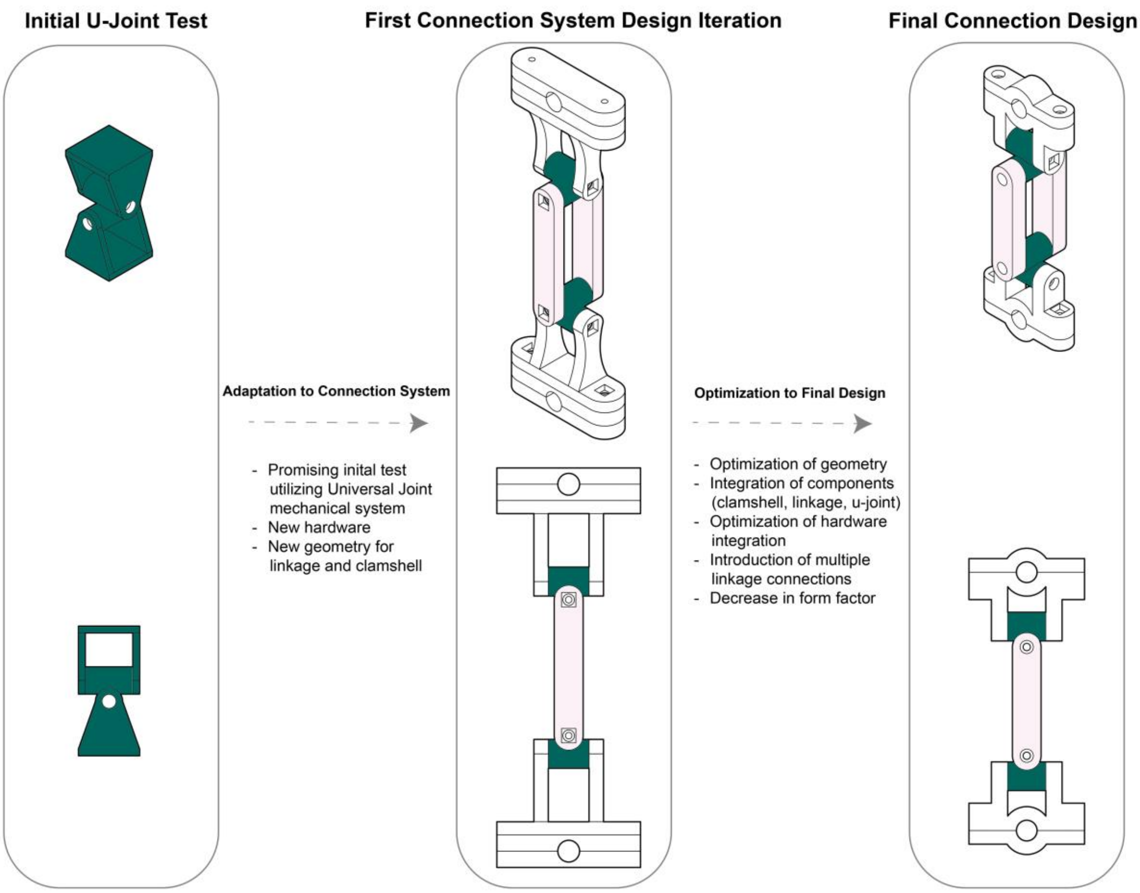

Figure 5: Development of the connection system.

A parametric design approach is adopted to enable the production of modular connections that can interface with varying numbers of golf clubs, from two to six elements. These connections are produced using additive manufacturing techniques with polylactic acid (PLA) and polyethylene terephthalate glycol (PTGE) filaments. The connections include multiple components tailored to fit specific segments of the golf club's tapered cross-section (Figure 6- Left).

As the diameter of the shaft varies along the length of the club, the connection components feature three distinct circular profiles with large, medium, and small radii. These profiles are designed to securely interface with the club's tapered geometry at any given position. The individual connection components are then assembled using connector elements (Figure 6 – Right) that feature a corresponding number of linear components, enabling integration of the desired club configuration.

The parametric nature of the connection design provides the flexibility to adapt to various club orientations and intersection angles, facilitating the exploration of diverse structural forms. This approach sought to balance structural integrity with the geometric constraints of the reclaimed golf club elements, thereby enabling an efficient and sustainable structural system.

Although the materials used for fabricating the connections include elements that are challenging to recycle, the modular nature of the connection system allows for easy disassembly and reassembly. This capability extends the end-of-life duration of the modules across multiple projects.

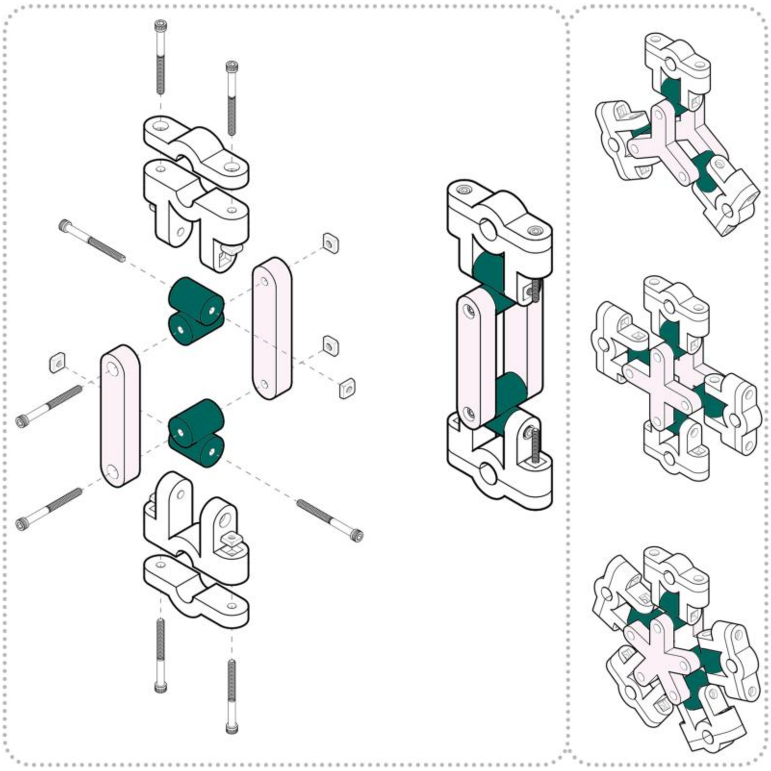

Figure 6: Connection system. Left: Exploded view of the connection system details.
Right: Adaptability of the connection system to the corresponding number of linear components.

4. Discussion and Conclusion

This paper discusses two pivotal strategies to address the building industry's environmental challenges: shifting material use through reuse and repurposing and optimizing the utilization of materials. This project embodies both strategies by showcasing the potential of reusing and repurposing materials. Among the five principles of environmental stewardship—refuse, reduce, reuse, repurpose, and recycle—this project emphasizes reuse and repurposes to counter the prevalent "throw-away" culture. This culture has normalized using single-use goods once and then discarding them, contributing significantly to environmental degradation.

This project advocates repurposing frequently discarded items when they no longer suit their original intent. Repurposing, or upcycling, allows materials to serve multiple purposes beyond their intended lifespan, promoting a more sustainable workflow. Moreover, the project highlights the necessity of employing each material in the most efficient manner possible. A resource-driven design approach is vital when utilizing unconventional resources like reclaimed golf clubs. Using construction methods based on computational design and digital fabrication plays a crucial role in shaping future habitats. These techniques enhance structural efficiency and align well with a circular construction agenda when combined with sustainable materials. The customizable and affordable nature of these tools further supports sustainable practices. The project's form-finding and optimization processes, along with the parametric design of the connection system, enable the creation of three-dimensional structures that effectively utilize the chosen resource—in this case, golf clubs. Furthermore, a significant level of control was maintained during the form-finding stage to accommodate material limitations, with real-time feedback enabled by rapid computational processes and prototyping on various scales.

A half-scale prototype was constructed using the proposed method (Figure 7) as proof of concept. This prototype, exhibited in the First Friday Art Trail of Lubbock in May 2024, functions as a self-supporting structure under its weight. The connection system (Figure 7 – Right) was subjected to various stress tests involving different numbers of elements connected at varying angles, both acute and wide. This testing was conducted to evaluate the efficiency of the system under diverse scenarios.

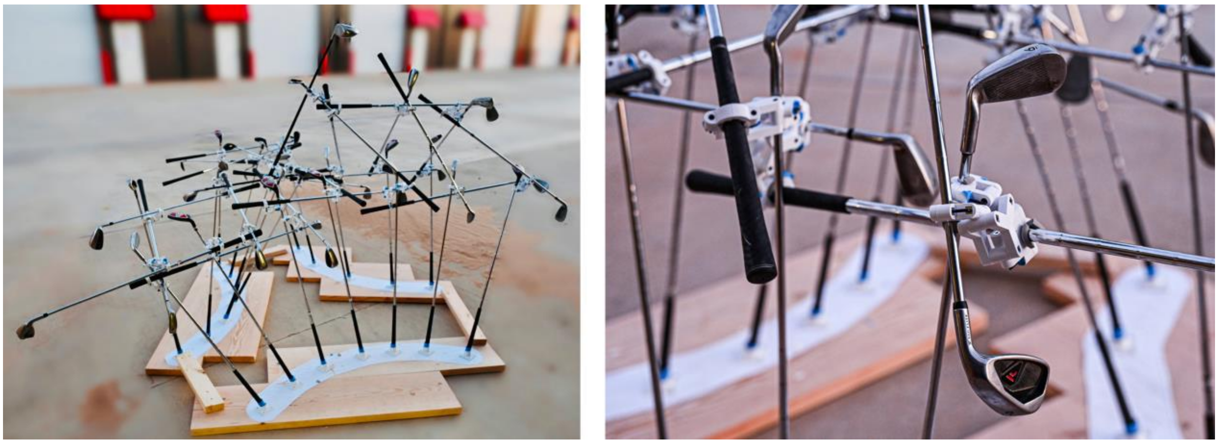

Figure 7: Left: Proof of the concept prototype. Right: Details of the connection components. [Image credit: Tahmures Ghiyasi]

This project aims to reduce waste, design for reuse, and decrease construction costs through a customized connection system. It presents an integrated framework for employing unconventional material—reclaimed golf clubs—in construction, enhancing the environmental aspects of architectural artifacts without significantly increasing costs or complexity of fabrication. The culmination of this project will be the fabrication of a large-scale pavilion, which is scheduled to be presented at the IASS Annual Symposium 2024 and the WG21 Advanced Manufacturing and Materials Expo. For a faster construction during the competition and the expo, a prefabricated connection system with similar workflow, but fixed angles is designed and fabricated, and silicone-made gaskets are added to the clamps.

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