Pliable structures with rigid couplings for parallel leaf-springs: A pliable timber torus pavilion

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Pliable structures with rigid couplings for parallel leaf-springs: a pliable timber torus pavilion

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Abstract

In the search for producing a low ecological footprint, a lightweight and high-performing technology, bending-active approach has been proposed to be appropriate for kinetic and transformable structures. While traditional deployable structures base their transformability on their hinges topology, pliable structures are based on the elastic deformation of elements. This paper will focus on the feasibility and serviceability of timber pliable bending-active structures by presenting two systems based on rigid couplings of coplanar flat planks. We discuss then their potential in simplifying manufacturing and assembling processes of kinetic systems by the enhancement of the elastic properties of the material, and efficient yet simple fabrication. This paper will present a topological classification of a variety of pliable structures based on rigid couplings. Furthermore it will discuss the implementation in architectural scale of one of the derived systems in a deployable fast-erected pavilion.
Keywords: bending-active, deployable structures, pliable structures, architecture, fast deployment, timber.

1 Introduction

Standard deployable structures base their transformability on hinged mechanisms where serviceability and affordability limits complex kinematics. Elastic kinetic or pliable structures base their transformation on the elastic deformation of their

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elements as defined in Lienhard *et al.* [1], rather than on the rotation of stiff members around distinct hinges. Such behaviour can be intuitively found by combining and coupling elastic elements, or can be easily implemented from flexible deployable systems found in nature. For the last three years, a research focus by the authors on lightweight structures and low technological systems led to the proliferation of serendipitous models performing elastic transformations, using bending-active suitable materials, such as thin plywood, and simple cuts or simple couplings hence highly eligible for architecture up-scaling. Illustrated in fig. 1, a classification of pliable structures typologies is suggested based on their structural performance and the nature of their joints.

Figure 1: View of the implemented timber pliable system.

In the graph, elastic based transformation systems are clearly separated from the well-studied rigid based transformation systems at the bottom. In the threshold are placed flexure mechanisms i.e. living hinges, which are based on a hybrid use of rigid elements and elastic joints with reversible deformation. The advantage of pliable structures is that the energy is stored along the deformed element, and not only in the flexure joint, hardly buildable in larger scale. Moreover, pliable structures can benefit from the pre-stressing of the elements providing more global stiffness and wider ranges of stability (Lienhard *et al.* [1]).

In our focus among the group of elastic based systems, we differentiate between their main structural request and the freedom nature of their joints. By the type of structural work the structures are going to perform primarily, we can differentiate in the vertical axis between simple bending and bending and torsion. This is normally dependent on the topology of the joints or the differential deformation between coupled pieces. By the nature of their joint we can differentiate in the horizontal axis between free and rigid joints, mainly represented by hinged or hingeless systems. Among hinged pliable systems, we can observe linear hinges i.e. curved folding, commonly found in nature, while punctual hinged pliable systems, are much rarer in nature yet very interesting. However, in this paper we are going to focus on the hingeless pliable systems, and more specifically on describing the basic performance of the systems derived from two simple couplings. The increase accessibility to numerical control machining and industrial plywood now renders the possibility of not only creating faceted rigid structures but highly controlled elastic shell structures. Based on this available technology, simple connectors or in-plane cuts are feasible rigid joints, here referred to as rigid couplings, between two bending elements here referred to as leaf-springs.

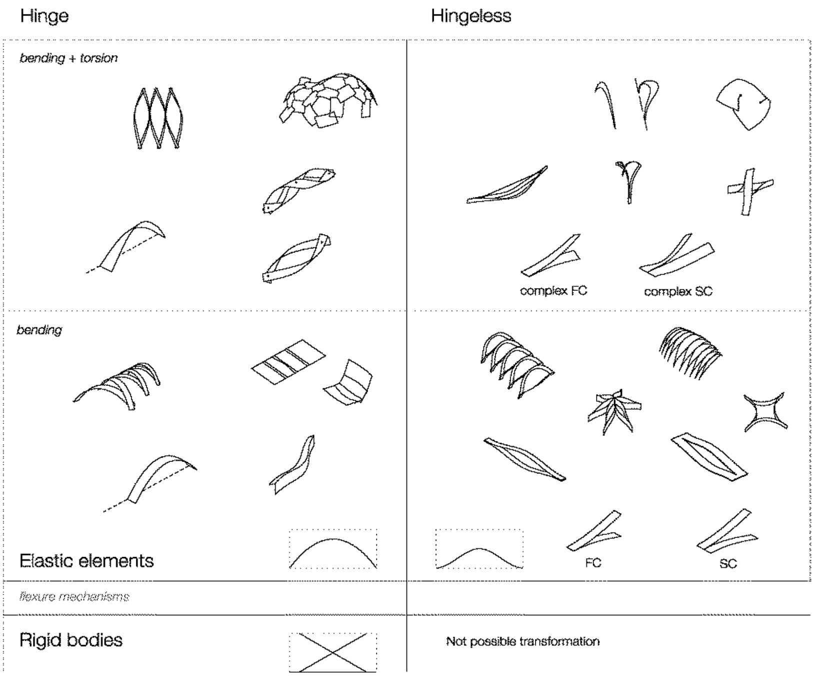

Figure 2: Typologies of hinged and hingeless pliable structures.

2 Rigid couplings of parallel leaf-springs

2.1 Leaf-spring bending element

As described by Brouwer *et al.* [3], a leaf-spring ideally constrains three degrees of freedom (DOFs) if it is flat. The three relatively stiff DOFs are the longitudinal elongation (x) and in-plane bending (z and ry) shown in fig. 3. The stiffness in twist (rx) and out-of-plane bending (y and rz) is relatively low. The leaf-spring assimilates a thin rectangular plank characterized by a main dimension, and where the width has no influence on the bending stress (Lienhard *et al.* [4]). The leaf-spring is rigidly coupled with a reflected one with opposite forces acting on it.

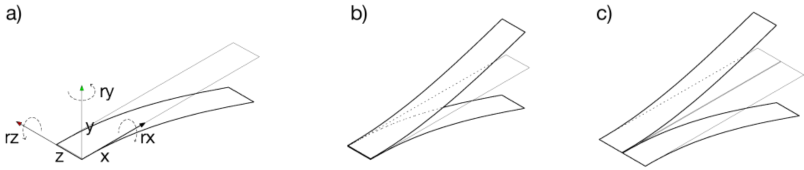

Figure 3: a) Leaf-spring, b) faced coupling, c) sided coupling.

2.2 Coupling topology

From a topological point of view we differentiate in fig. 3 two kind of parallel leaf-spring rigid couplings, based on the differences of their reflection.

Faced Coupling when leaf-springs are reflected in the leaf plane, and then sharing a rigid edge. *Sided Coupling* when leaf-springs are reflected perpendicular to the leaf plane, along the x axis, and sharing a vertex of rigid edge. There is an unlimited combination and gradients between these 2 models, and many more from varying angles in all planes, but we focus in connected parallel leaf-springs, by the ease of their fabrication as it will be discussed later.

2.3 Behaviour complexity

From a structural point of view both couplings are classified in fig. 4 as *simple* systems when distributed uniform loads are applied and *complex* systems whenever else. Deformation of both *simple* systems (a and b) are identical and will be simplified by assuming simple bending stresses and the proportionality of thickness and curvature (Lienhard *et al.* [4]). This will ease modelling and analysis. For architectural purposes this systems are especially interesting because transformability is independent to the cross sectional thickness thus all needed inertia can be provided without affecting deployability. Complex systems produce twists and complex stresses when not uniformly load and will require more precise analysis (Odhner and Dollar [5]). In these cases torsion will add a global stiffening effect.

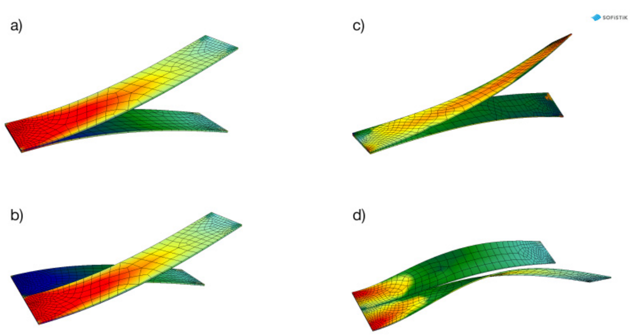

Figure 4: a), b) Simple systems and c), d) complex systems.

2.4 Plywood coupling fabrication

Manufacturing design of both couplings will bound the system expandability limits due to the stress concentrations. Despite the fact that plywood is a suitable material for actively-bent structures when the pre-stress is not playing a decisive role in the system's stiffness (Lienhard *et al.* [4] and Kotelnikova-Weiler *et al.* [6]) the non-compliance of fatigue control and creeping makes it apparently not recommended for elastic kinetic systems [6]. Nonetheless timber and in some degree plywood, is at the same time probably the most environmentally friendly and the most cost-effective material for actively-bent structures, hence its use may be endorsed but detailed analysis will be required for specific projects. The weakening of a material caused by cyclic loading or fatigue, depend on the internal stresses, and thus on the transformation ranges of the deformed elements in the pliable structures. Limiting the pliable structure long range of intermediate stable positions may be a solution, when pre-stressing is not decisive. In the other hand, creeping is far more complex, but at some degree reversible. The compelling variable is the cycling mode of the system. Pliable structures in specific deployability frequency can be understood as pseudo-static bending-active structure, and therefore, if pre-stress is no playing a major role in the integrity (Lienhard *et al.* [4]), creeping is of relatively little importance. These pseudo-static cycle modes can be either from very short cycles before the mechanism of creep occurs, or few long cycles, when the system is not committed to fast disassembling, and a shorter cycle of reshaping may occur if needed. Furthermore, the orthotropic and fibrous structure of plywood performs better than timber under wider variety of stress configurations and avoids crack propagation thus more resilient. FC can be very straightforward in monolithic manufacturing such in Odhner and Dollar [5], but especially difficult to build in single plywood sheet thickness, yet easy to fabricate with shear connectors in the overlap of two facing planks assimilated to leaf-springs. SC can be made from a monolithic sheet and a simple cut, but shear stress concentrations and crack propagation have to be avoided by enhancing the end of the cut. Hence SC may require numerically controlled machining for curved cuts or alternatively requiring for a rigid third element connector.

3 Kinetic systems with rigid couplings for parallel leaf-springs

The virtue of aggregative pliable systems derived from rigid couplings is their analogy to a spring, with a linear elastic behaviour performance and their ability to store mechanical energy when deployed within elastic range.

Pliable systems rely on the support and the tip boundary conditions to stay deployed, different deployment rail paths will add or reduce the DOFs of the structure. In curved path deployments, the supports of the structure need to fix in-plane displacements (4 DOF), counteracting the shift to a less energetic and straighter configuration. In this case, in linear path deployments, supports simply fix the opening direction (5 DOF). In the other hand, while in closed paths, all couplings have balanced counteracting deploying forces, in open paths, end points need to fix the pulling force. The aggregation of parallel planks with FC and SC couplings offers a wide range of possible structures, especially interesting in architecture because the transformability is independent to the cross-sectional width. Both systems accept virtually any shape that would connect pairs of parallel leaf-springs in a staggered pattern. Some are here presented categorized by the nature of their coupling.

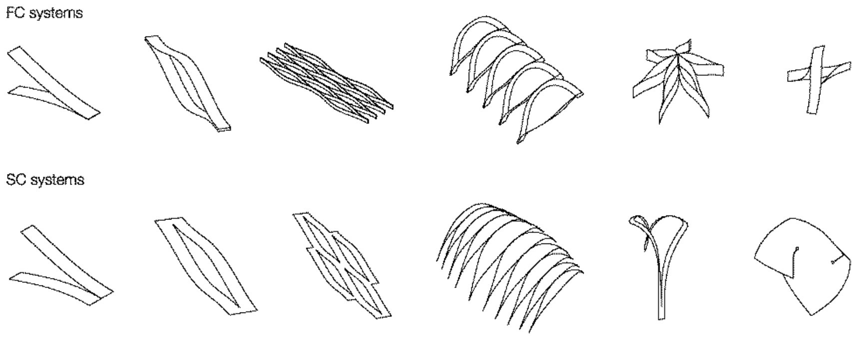

Figure 5: FC and SC native systems.

3.1 FC systems

Faced coupling systems benefit from the ease of assembling flat coplanar elements being the total compact thickness proportional to the number of leafs. The variation of the staggered coupling pattern among the element and the shape of the element offers a great variety i.e. honeycomb paper lanterns. The fact that deformation is independent to the cross-sectional width is especially advantageous in FC systems because deployed structure can adapt the area moment of inertia to the bending needs. In this case, the post-buckled shape is allowing thin and efficient cross sections.

3.2 SC systems

Sided coupling can be simply derived from simple cuts in a sheet, hence the system compacted thickness is the thickness of one leaf. This system is very common in plastically deployed sheets in the metal industry and associated with a type of flat kerfing technique for bending wood. The advantage of working with a 2D cutting pattern is the adaptability of the pattern, the cutting techniques and available materials. In a first term, the disadvantage is mainly the available elastic sheets sizes and the machinery sizes able to cut them and the limitations in directions of the cuts when using orthotropic materials. These problems appear when up-scaling the systems but third pieces or metallic plates can solve the rigid coupling, and hybridization of both FC and SC systems can solve size restrictions.

4 Faced coupling system implementation

4.1 An invitation for affordable deployability

CODA researchers were approached by ÚsBarcelona organizers to design a temporary structure for hosting events during an urban day festival in the city of Barcelona. The restrictions were a very limited budget, and very short time to assemble and disassemble. The research group, interested in the implementation of its research, found the necessary funding by finding a new client and a further use to the convertible structure.

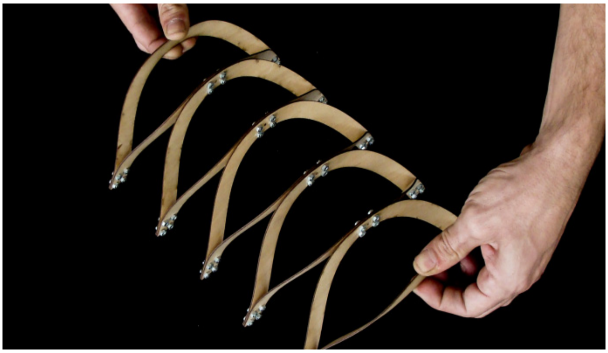

Figure 6: Prototype of a simple FC system.

4.2 Serendipity models

CODA design approach is based on the integration of actuating forces, material properties and manufacturing processes. During the last years, many small prototypes of several material systems have been emerging and revealing a wide diversity of elastic performance in a mainly behaviour based approach to active bending (Lienhard *et al.* [4]). It's only later, when building system and topology rules are derived that an integral approach is undertaken. For this special commission of building a temporary use and fast assembly urge, it was decided to develop further and combine the native FC simple pliable system.

4.3 Arched FC system development

The system is section-independent so the arch shape is used to shelter and to unload self-weight by form. It was furthermore decided to build a toroid by closing a curved circular deployment path. Closing a curved spring in itself solves the endpoints longitudinal reactions, whereas the contracting spring force creates a simple pulling force to the interior, normal to the circular trajectory easily materialized by free rotating flag-type ground fixings. Moreover, surveying the toroid and its sections is straightforward by very simple instructions and three parameters, defining centre, radius and string length. By ease of manufacturing, the rigid Faced Coupling is materialized with connectors that absorb axial stresses produced by the deploying process. Connectors are placed in a staggered pattern at the tip of the arches, and close to the arch center coupling alternating arches.

4.4 Numerical modelling

Non linear geometric analysis simulated using FE is performed to evaluate the self stiffening contribution to global structure stiffness. A single coupled arch is analyzed with the same boundary conditions as in the whole structure (radial symmetry). The deployability by elastic deformation consumes around 45% of the tensile strength of the coupled arch but stiffens it, as shown in fig. 7.

A single 1000 N load is applied at the connection to compare its behaviour with the same arch but not expanded. While the deployed coupled arch deflected about 12 cm and increased the stresses by 20%, the non deployed arch, buckled and failed. Pre-stressing the structure showed slightly better performance under external loads but global stiffness is mainly achieved by the geometrical configuration once deployed.

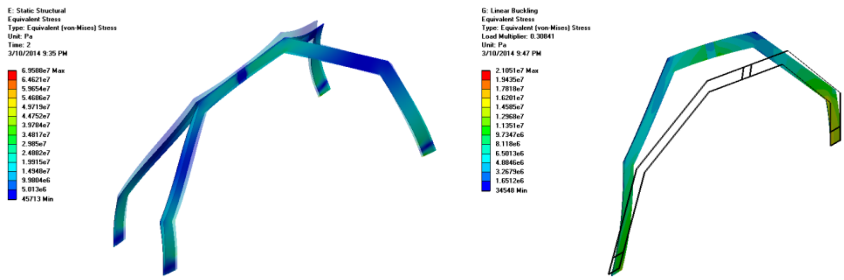

Figure 7: Pre-stressing effect.

5 Fabrication

5.1 Restrictions

The pliable structure had to be transportable because it was not possible to build it on site, and because it had to further travel to a new site for a further use. Hence the structure had to be prefabricated and meeting standard transportation sizes which were ultimately limiting the pavilion size. As discussed in 2.4, even though timber is not the most suitable material for kinetic structures, it was in that context the most affordable material for achieving a self-formation process. The kinetic performance is only needed in few cycles, and the creeping effect is not critically affecting the structure as the pre-stress is not crucial as seen previously. Pliability in this case is the most affordable strategy in terms of transport and assembling time.

In fact, spruce plywood was chosen as a more performative medium than timber and a cost-effective suitable material**.** Plywood standardized nature make the boards very easy to cut, bore and treat while being very accessible.

To simplify logistics and minimize the use of material the arch was redesigned to fit into one single plywood board, by being polygonized. Due to the asymmetrical surface shrinking nature of the torus shape, a half circular heptagonal arch was decided for performing an asymmetrical stiffness. An extra chamfer operation is performed into the arch conforming planks to ease angle assembling process, hence producing a small amount of cut-out being less than 5% of the total volume of timber. This could have been avoided by numerical boring of planks thus ensuring angle consistency.

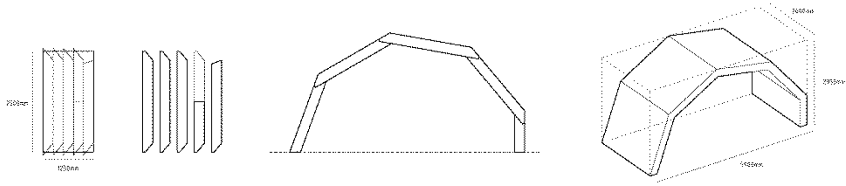

Figure 8: Fabrication constraints: board and transportation size.

5.2 Prefabrication process

The assembly of the structure consisted in the manual prefabrication of 56 identical arches. The boards were delivered already processed and cut in straight planks. At the school of architecture an exterior assembly line was improvised. Planks were bored with a template and waterproofed with elastic open pore treatment. Once dried, single arches were assembled and coupled in pairs, and finally packed to be transported.

5.3 Deploying process

Expanding. Even though the structure is able to deploy with very few amount of energy, the impact of the self weight produced excessive friction with the ground earthy nature to be fully deployed at once. Instead a progressive coupling assembly is adopted. Assembled pairs of arches are coupled to a placed arch in the top joint. Then the arch is deployed till reaching the next support where it is fixed. In other frictionless conditions i.e. ice ground or circular rails, FC system can perfectly be deployed at once with human-scale force.

Compacting. In a short cycle, the structure was behaving without experiencing any creeping. When compacting, supports were detached and the ground friction was enough to hold the leg supports, becoming a metastable system. Only a small amount of energy, counteracting the arch self weight to avoid the drag, was necessary to progressively fold every pair of arches. Only 4 persons were necessary to fold the whole structure in less than 20 minutes.

Figure 9: Packing and transport.

Figure 10: Drone image of final construction.

6 Conclusions

Parallel leaf-springs have demonstrated a high degree of feasibility, thus inducing the further research on exploiting these simple but versatile pliable structures.

We can understand the suitability of plywood for elastic kinetic structures in within specific use cycles and smaller opening ranges.

Architecture should provide more efficient technologies in a resources depletion context.

Active bending which has proved to be universal, affordable, efficient and easily feasible is enhanced by novel computation techniques and affordable elastic materials. This complex behaviours and efficient structures can be obtained with very simple models and universal fabrication techniques.

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