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New opportunities for the conceptual design of material-efficient antifunicular structures

Nuevas posibilidades acerca del diseño conceptual de estructuras antifuniculares eficientes

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Abstract

Non-structural design criteria (e.g., usability, architectural needs, esthetics) may prohibit the selection of purely funicular or anti-funicular shapes. In response to this issue, this paper illustrates the possibility of achieving an axial-only behavior, even if the geometry departs from the ideally bending-free shape. This is achieved by adding forces through an external post-tensioning system, with a layout defined through graphic statics. The paper briefly illustrates examples of this approach and its implementation within a design-driven software where structural performance and geometric variation are embedded within an interactive and parametric working environment.

Keywords: Equilibrium; Funicular; Graphic statics; Conceptual design; Post-tensioning system

Resumen

Los criterios de diseño no estructurales (p. ej., funcionalidad, necesidades arquitectónicas o estética) pueden prohibir la selección de formas puramente funiculares o antifuniculares. En respuesta a este problema, este artículo ilustra la posibilidad de lograr un comportamiento axial solamente, aunque la geometría se aparte de la forma idealmente sin flexión. Esto se consigue mediante la adición de fuerzas a través de un sistema de postensado externo, con un diseño definido a través de estática gráfica. El artículo ilustra brevemente ejemplos de este enfoque y su implementación dentro de un software impulsado por el diseño, donde el rendimiento estructural y la variación geométrica están incrustados dentro de un entorno de trabajo interactivo y paramétrico.

Palabras clave: Equilibrio; Funicular; Estática gráfica; Diseño conceptual; Sistema de postensado

1. Introduction

1.1. Motivation

In the design of curved structures, the overall shape, usually decided in conceptual design, is a key contributor to the overall cost and structural efficiency. However, non-structural conditions, such as esthetics, functionality, and geotechnical issues, often prohibit selection of a structurally ideal funicular shape in which only axial forces are activated (the word funicular is independently used for only compression or tension curves). In contrast to a funicular shape, forces may not be able to act in pure tension or compression under self-weight, and bending moments inevitably arise, increasing the structural material required. While in form-finding problems, funicular curves are found from a given set of loads, this research explores the opposite problem: starting from a known geometry, and its related distribution of dead loads, how it is possible to find a system of external loads that, in combination with the existing loads, can convert the starting geometry into a funicular curve.

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Figure 1. Photo of the Pavilion of the Future (1992).

1.2. Historical background

This study applies the concept of funicularity to curves that are originally not funicular under dead loads, in order to take advantage of the material-efficiency due to a funicular behavior while also allowing for architectural and geometric flexibility. A classical design approach for non-funicular structures is based on the use of bending solutions, in which axial forces and bending coexist, or trusses. In contrast, this study rather explores the possibility of adding external loads on a two-dimensional curve for changing the internal forces distributions, and consequently for improving its structural behavior. An existing example of this concept is represented by the façade of the Pavilion of the Future (Figure 1) built in Seville for the Universal Exposition in 1992, designed by Peter Rice from Ove Arup & Partners [1]. The loadbearing structure of the façade, combining stone and steel, has a semi-circular shape which would require a thick arch size to contain the thrust-line within the thickness. The main design concept takes advantage of the gravity loads generated by roof beams to apply a set of radial equal forces onto the circular arch of the façade, forcing the thrust line to pass closer to the center of the arch.

1.3. Research significance

Inspired by this project, this work studies the possibility of achieving an axial-only behavior even if the geometry departs from the ideally funicular bending-free shape.

This paper presents a new design approach, based on graphic statics that shows how bending moments in a two-dimensional geometry can be eliminated by adding forces through an external post-tensioning system.

This results in bending-free structures that provide innovative answers to combined demands on versatility and material optimization. External post-tensioning systems can improve design performance significantly by converting arbitrary curves into geometries that better resist permanent loads with axial forces only; this design philosophy can be implemented to many structural typologies, empowering the designer to control the structural behavior of curved structures.

2. Methodology

2.1. Graphical construction

The theoretical framework is based on the technique of graphic statics, which relates structural geometry and internal forces through reciprocal polygons [2–5]. The concept of the funicular polygon for simply-connected structures (also known as Cremona or Cremona-Maxwell diagram) and force polygon was firstly introduced by Varignon [6], and later extended to analyze trusses and beams. It was the most employed design method until the end of the first third of the 20th century. The virtues of this method for form-finding structures have only been published recently [7–10]. The approach is graphical in the sense that forces are geometrically calculated from the force polygon.

The graphical construction to convert a non-funicular shape into a bending-free one is described in detail in other authors' papers [11–14]. Here, it is shortened in two main steps, and applied to a circular arch (Figure 2). It consists in:

- Step 1: Definition of the external point forces (blue continuous lines) to be applied to the structure to make it bending-free.
- Step 2: Definition of the post-tensioning system (orange dotted line) for generating the external point loads found in Step 1.

Continuous lines represent compressive elements and forces, respectively, in form and force diagrams; while dotted lines indicate tension elements and forces, respectively, in form and force diagrams.

The graphical procedure allows the identification of an equilibrated geometry where bending moments are eliminated in each polyline vertex, and only axial forces in the cross sections are obtained.

The process starts with a given a curve and its related loads. Yet, the problem is indeterminate: an infinite number of solutions exist to make the starting geometry bending-free. This indeterminacy, which is in-depth studied in the first author's thesis [11], conceptually corresponds to the fact that as infinite axial-only geometries match to a single loading distribution, an infinite sets

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