A Methodology for Optimal Design and Simulation of Deployable Structures

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Abstract. Deployable structures with bars have been used in different technological fields since the beginning of the 20th century. It was as of 1930 when their use in construction became widespread, especially in roofs with large spans. The research group at San Pablo University in Madrid, along with Keene State College has developed a new type of deployable structure that minimizes the weight and maximizes the span. The structural efficiency is based on the fact that the tensioned elements of the modules are made of cables. In addition to contributing to the overall stiffness and strength of the structure, these cables are designed to guide the folding and unfolding process of the structure. In each module the tension cable is extended until it is connected to the midpoint of the compression bar, thus regulating its position and avoiding the possibility of unforeseen folding while the structure is fully deployed. This article shows a method to optimize the geometry and to test the static behavior of the structure.

1. Introduction

Deployable bridges have a broad market nowadays in rural areas, disaster management, and as a temporary alternative for damaged bridges [1]. These bridges can be easily removed and transported and provide the following advantages: flexibility in design, low self-weight, and low cost [2]. Deployable structures can be stored and transported in a compact folded configuration and then deployed into a load-bearing configuration [3]. These light, deployable structures are often prone to difficulties associated with fulfilling its function adequately when used as civil engineering structures [4, 5]. There is extensive research on methods to assess the behavior of deployable footbridges, focusing on the geometric constraints due to deployment and the influence of post-tensioning strategies [6, 7].

Structural optimization has not been used as a design tool until high-performance computing systems were made widely available [8, 9, 10]. An optimization method is needed during static and dynamic analysis to make deployable structures lighter and more reliable. Design optimization seeks the best values of design variables to achieve optimum behavior in terms of displacement and serviceability with minimum weight and material [11, 12].

The system presented in this article consists of a foldable, transportable, and deployable structure that allows the construction of temporary walkways, stages, and scaffolds, with a low-cost system and the possibility of being reused. The authors have patented a system that reduces the amount of material needed to fulfill the safety requirements in accordance to the span it covers. The system has been tested...
on a case study, a footbridge that covers a 40-meter span, and a basic module described in figure 1. The modules that make up the bridge use a scissor mechanism, which enables compactness and rapid deployment. Connections can be classified as nominally pinned when they are capable of transmitting axial and shear forces without creating a significant bending moment, as well as they can accept the resulting rotations under the design loads [13, 14]. Ideal pinned connections must accommodate rotations without adding bending moments, which can result in premature failure of the structure or parts of it. The real behavior of the joint is often underestimated in deployable structures at the design stage, despite its influence on the structural performance and deflection limits. At the first stage of the static analysis, connections can be considered as pinned, without creating a significant bending moment. However, the results of the idealized structure may be quite unrealistic compared to the response of the actual structure. The geometry of the joint adds eccentricity and, despite the ability of the bars to rotate about it, it can develop significant bending moments [15]. Finite element analysis (FEA) is a process of modeling complex problems by subdividing into an equivalent system of smaller and simpler parts [16]. FEA is complex and requires commercial software, but it can help designers understand internal efforts and displacements to save material and money without affecting the stiffness and resistance of the structure [17].

The first goal of this paper is to describe an analytical model to control the different stages of the deployment process. A basic module is analyzed and modified to solve singular points. The second goal is to describe a design optimization of the steel frame. After designing the different types of bars and cables for a standard situation, and having already checked the effect of post-tensioning on the global stiffness of the frame, it is time now to understand the impact of eccentricity on bending moments at the joints. The third section of this paper describes a FEA of the typical joint to implement a design optimization.

2. Analysis of the geometry and deployment process

In the prototype described in this section, the primary cables that provide stiffness and strength to the whole system are complemented by another set of secondary cables that guide the folding and unfolding process of the structure and avoid the possibility of unforeseen folding while the structure is fully deployed.

During the deployment phase, these secondary cables change their dimension. One of the challenges when it came to developing a real prototype, was to understand the variation in their length during the unfolding process. The analytical study of this variation, developed in previous papers, showed that they experienced phases of increase in its dimension combined with others of decrease [18, 19]. Figure 1 shows the geometry of the basic module and the detail of the scissor joint that allows maximum compactness.

![Figure 1](image_url)

**Figure 1.** Details of the basic module: a) elevation, b) connection between diagonal bars, c) folded position.
This case study focuses on a deployable footbridge with a 40-meter span. Figure 2 illustrates the different versions of the basic module that make the final footbridge.

![Folded beam](image)

**Figure 2.** Description of the modules and their position in the deployable bridge.

The next step is to define the final shape of the structure after the unfolding process. The deployment takes into account two goals: a) the continuity of the tensioned element along the column and the beam, and b) the possibility of unfolding and lifting the beam at the same time. The deployment process begins by placing the columns and the beam as independent entities, until a point in time when the overall length of these three elements in a semi-folded state matches the final length of the frame. It also happens that, in that precise moment, the beam is not lifted from the ground yet, which makes the use of auxiliary means unnecessary. The geometry of the constituting elements of the frame at that particular moment is illustrated in figure 3.
Equations (1-4) show the analytical expressions of the parameters when the beam and the column must be connected to each other.

\[ B_{beam} = 20 \left( 2 \sqrt{2} \sin \frac{\alpha'}{2} \right) \]  
\[ B_{column} = 3 \left( 2 \sqrt{2} \cos \frac{\alpha}{2} \right) \]  
\[ H_{column} = 5 \left( 2 \sqrt{2} \sin \frac{\alpha}{2} \right) \]  
\[ H_{beam} = 2 \sqrt{2} \cos \frac{\alpha'}{2} \left[ 1 - \left( \sqrt{2} \sin \left( \frac{\alpha'}{2} \right) \right)^2 \right] \]  

Where \( H_{column} \) and \( H_{beam} \) are the heights of the column and beam elements, \( B_{column} \) and \( B_{beam} \) are the lengths of the column and beam elements, \( \alpha \) is the opening angle at the scissor joint in the column, and \( \alpha' \) is the opening angle at the scissor joint in the beam, all of them at the precise moment when the whole system is assembled together.

Due to the scissor connection between diagonals, the bars are subjected not only to axial tension or compression forces but also to bending moments. Figure 4 shows the bending moments on the structure under vertical loads acting at the nodal points.
Once deployed, the bridge has two supports, and the condition that best represents the behavior of the beam is the simply supported case, where the supports have horizontal and vertical displacement constraints.

3. Analysis of the scissor joint

One of the challenges of the proposed deployable structure is to improve the compactness and lightness. The design of the scissor joint that allows all the bars to be contained on the same plane implies the appearance of eccentricities. The results of the static analysis of the system in which those slight changes in the geometry were taken into account made clear the need to study the scissor joint using a finite element analysis (FEA) solver to explore the local behavior of this element.

The model of the joint has been designed parametrically using Autodesk’s Fusion 360, which includes a connection to the Nastran FEA solver. The parametric design feature has fostered the optimization process, due to the automatic redefinition of the geometry by just changing the values of different parameters such as thickness values or fillet radiuses [20]. The FEA analysis was set up with the following layout: one scissor-joint and four bars attached to it (the way the bars are connected to the joint assures full transmittance of bending moment). The free ends of two of the bars are pinned, and the other two ends are restrained in a way that rotation is allowed, but any displacement perpendicular to the axis of the bar is not. Figure 5 illustrates the geometry and the loads taken into account to carry out the FE analysis.

The values of axial force that were obtained during the static analysis of the structure (see figure 6) made clear that dimensioning the joints exclusively with the highest ones would have been too conservative. Thus, two FE analyses were conducted to study the performance of the joint under two different conditions: on the one hand, being subjected to the most restrictive situation (-293.5 kN for load 1 and -62.88 for load 2); on the other hand, bearing different combinations of smaller axial loads, never higher than -105 kN. This process sheds light on the overall behavior of the joint and led to the final optimization procedure. The joints subjected to heavier loads need more material (they were tagged “heavy-duty joints”), whereas the rest could keep the same external appearance while using less material (“light joints”).

![Figure 4. Bending moments in bars for the ULS check, including dead loads, live loads, and post-tensioning of the cable.](image)
To simplify the manufacture and assembly of the scissor structure, only those two different versions of the joint (heavy and light) have been considered. In both cases, the joint is made up by two equal pieces that can rotate independently around the shaft that connects them. In the heavy-duty version, the two rotating halves consist of two segments of 80.6 square hollow section tubes, connected to a solid core piece, all of it made of S355 steel.

The exterior envelope of the lighter version matches the heavier one (see figure 7). The core is carved, though, and the SHS profile is 4 mm thick instead, and the chosen material is S275 steel. This joint’s weight drops to 64.2 % of the heavy-duty design and can cover most of the loading situations in the structure.
Figure 7. Geometrical description and assembly of both versions of the joint

Figure 8 shows the performance of one of the halves of the heavy-duty joint under different loading conditions. In the lower right image, the joint is subjected to extreme loading conditions. The concentration of stress appears where a sudden change in the stiffness happens. An eccentricity in the transmission of the axial load in that bar eventually leads to bending on a plane perpendicular to the one on which the structure develops. Figure 10 clearly shows this effect, although when it affects the light joint instead.

Figure 8. Performance of one of the halves of the heavy-duty version of the joint under different loading conditions.
Additionally, figure 8 shows – on the image on the top left corner – that the heavy-duty joint would be unexploited if chosen as the only option for the whole structure, as the stress values that take place with loads under 100 kN are close to neglectable if compared to the previous case.

The light version of the joint required a more detailed process, exploiting the parametric capabilities of Fusion 360, as the widths of the different webs and stiffeners that were used to produce the carving in the solid core of the first, heavy-duty, joint had been defined parametrically.

In figure 9, the lower-left corner image represents the layout of the FE analysis of the assembled light joint. The rest of the pictures show the global performance of the joint in terms of Von Misses’ stress. The deformed shape has been exaggerated for clarity purposes.

![Figure 9](image)

**Figure 9.** Global modeling and behavior of the light version of the joint.

To understand the inner behavior of the carved version, figure 10 represents the performance of the light joint under the same conditions as in figure 9, but now the front half is removed. The lower-right corner image shows how stress increases dramatically in the webs that keep the same direction as the bars that are attached to the joint. Considering only the front view, it would seem that the increase in the stress is due to the alignment of the bars and the webs. However, a change in the point of view shows the actual origin of this behavior: the lower-left corner image illustrates the top view of the deformed shape of the joints. Lack of continuity in the bars produces eccentricity of loads, and that is why an increase of stress appears in those webs.

The results of the FE analysis of the light joint show how, once the axial load raises over 100 kN (lower-right corner image), the web elements are not able to bear the stress.
Figure 10. Performance of one of the halves of the light version of the joint under different loading conditions.

4. Conclusions
This paper has presented the geometric and structural features of a deployable system. Firstly, the geometry of the basic modules has been studied to achieve the minimum size and weight when the structure is folded. Secondly, the analysis of the deployment has been useful to identify the moment when the length of three elements in a semi-folded state matches the final length of the frame. The beam is not lifted from the ground yet, which makes the use of auxiliary means unnecessary. Finally, the results of the static analysis of the scissor joint, that allows all the bars to be contained on the same plane show the appearance of eccentricities. The FE analysis provides a more reliable prediction of structural behavior and shows that bending in the plane perpendicular to the structure could become a significant issue. The results of the parametric study prove that deflection on that perpendicular plane is what limits the usage of a light joint, as stress concentrates on areas where lack of continuity of the bars produce abrupt changes in the stiffness of the joint. The FE analysis enables the possibility of achieving more exceptional lightness by saving unnecessary material without sacrificing the even, uniform, and seamless appearance of systems that consist of a reduced number of different elements.

The deployable structure presented and detailed in this paper has confirmed to be very useful in many aspects: it has maximum compactness, guarantees the continuity of the tensioned element, and keeps the total length of the cable constant during deployment.

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