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Computational modelling of the transformation of bistable scissor structures with geometrical imperfections

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ABSTRACT

In many applications structures need to be easily moveable, or assembled at high speed on unprepared sites. For this purpose, preassembled deployable structures, which consist of beam elements connected by hinges, are highly effective. Intended geometric incompatibilities between the members are introduced for instantaneous structural stability after deployment. In such bistable scissor structures, these incompatibilities result in the bending of some specific members that are under compression with a controlled snap-through behaviour. The main goal of this contribution is to qualitatively and quantitatively discuss the behaviour of bistable scissor structures during deployment. To do this, a 3D nonlinear structural model is proposed to simulate the deployment, including explicitly geometrical imperfections in a stochastic approach. The originality of this contribution is (i) the implementation of gravity, (ii) the geometrical imperfections and (iii) the extension of the numerical model to complex deployable structures. Bounds on geometrical tolerances on several uncertain parameters (length of the beams, eccentricity of the pivot points, hinge misalignment and finite hinge stiffness) are proposed based on non-linear finite element simulations on a single module transformation. The computational tool is then applied to structures consisting of multiple modules and the influence of geometrical imperfections is characterized.

1. Introduction

In many civil engineering applications (emergency shelters, exhibition and recreational structures [1–4]) and aerospace applications (satellite antennas [5–7]), structures need to be compact, easily moveable, and deployed at high speed. Among the available solutions, preassembled scissor structures are transformable structures designed using the principle of the pantograph [8]. Also called a scissor-like element (SLE), its simplest unit consists of an assembly of two beams connected through a revolute joint [9] (Fig. 1). By connecting such SLE's at their endpoints, a grid structure is formed which can be transformed from a compact bundle of elements to a fully deployed configuration [10]. Because of a design and deployment process that is generally more straightforward, 'stress-free' scissor structures have been used preferentially in the past [11–13]. Assuming a perfect, ideally rigid 'wireframe' geometry, these structures are geometrically compatible before, during and after deployment; i.e. their beams remain straight and undeformed during the deployment [14]. By consequence, these mechanisms have the disadvantage that they need external manipulation to bear loads in the deployed configuration.

Another approach consists of the introduction of intended geometric incompatibilities between the members as a design strategy. This is achieved by choosing a kinematic design based on a rigid wireframe model that complies with the mathematical equations of geometric compatibility (straightness of the beams) in the folded and in the deployed configurations [15–21], while forcing the elastic deformation of specifically chosen elements during transformation. This class of scissor structures is referred to as *bistable*. They exhibit a snap-through phenomenon during deployment to instantaneously achieve a structural stability that can be sufficient for small loads (such as self-weight).

Zeigler was the first to theoretically identify the 'snap-through' phenomenon in deployable structures [22–27]. The design aiming for a limited range of geometric shapes resulted in the existence of bent elements in the deployed configuration. Zalewski and Krishnapillai improved his work and found polygonal modules that were geometrically compatible before and after deployment [28]. Based on this work, Logcher and Rosenfeld carried out experimental work on these structures [29,30]. In parallel, Gantes developed a geometric design approach and studied the structural response of structures that consist of assembled polygonal modules, using finite element models

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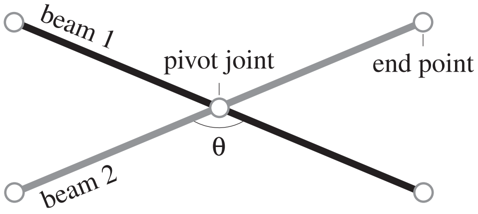


Fig. 1. Pantograph or scissor-like element (SLE).

[15–21,31,32].

Developing and analysing bistable scissor structures is a contemporary subject in civil engineering research. The works of Kawaguchi and Sato (deployable geodesic sphere [33,34]), Kim and Lee [35–37] and Roovers [38] are the most relevant works with respect to this contribution. Although some of these researchers are using the finite element method to perform structural analyses in the deployed state, modelling the complete transformation cycle of scissor structures is very scarce, since the underlying phenomena and modelling tools and concepts are complex.

In our best knowledge no civil engineering application of the bistable scissor structure concept exists today. Bistable scissor structures are classically designed as a rigid (i.e. undeformable) wireframe, referred to as pure kinematic design. The objective of this contribution is to qualitatively discuss the behaviour of bistable scissor structures during deployment, to get a deep understanding of their structural response. To do this, a 3D nonlinear finite element model is developed to simulate the deployment, for which similar models have already been proposed in the literature. The originality of this contribution is:

1. the investigation of the influence of gravity during deployment,
2. the implementation of geometrical imperfections and the investigation of their effect on the deployment behaviour,
3. the extension of the numerical model to complex deployable structures.

The focus of the paper is the structural response of bistable scissor structures during transformation. The coupling of the behaviour during deployment with the structural behaviour of bistable scissor structures in the deployed state is a relevant research question for future work.

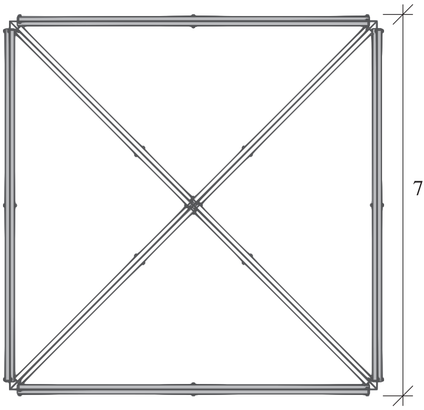
Starting from an initial simplified polygonal module, the computational model is refined in several stages (Section 2). The influence of the finite size of the hinges, gravity and geometrical imperfections is included using a probabilistic approach (Section 3). The computational tool is finally applied to realistic large structures consisting of multiple modules (Section 4). The conclusions and outlook are presented in Section 5.

2. Geometrically ideal single module

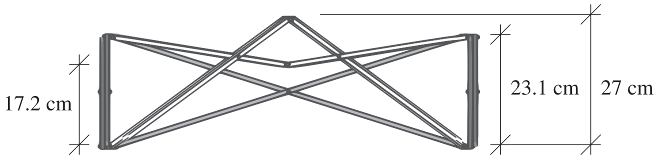
2.1. Geometry and materials

A square flat polygonal module is first investigated to ease the interpretation of the results of these complex structures and to uncouple effects of the assembly of several modules (treated in Section 4). The computational time of one module is 50 s, compared to 1.5 to 4 min for complex structures. The model cross sections, geometry and materials are similar to the one of Gantes [15].

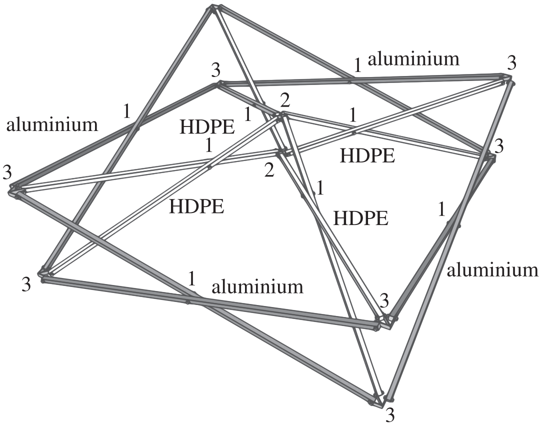
The dimensions of the deployed and folded module are given in Figs. 2 and 3, respectively. The other dimensions, angles between the beams and positions of the joints can be directly deduced from the given dimensions. Rectangular cross-sections of 9 by 9 mm are used with two different materials (Table 1) chosen to control the snap-through. The inner SLE's made in high-density polyethylene (HDPE) (on the diagonals of the square module) are geometrically incompatible during transformation, i.e. they are elastically bent, while the outer SLE's made of aluminium remain straight (Fig. 2).



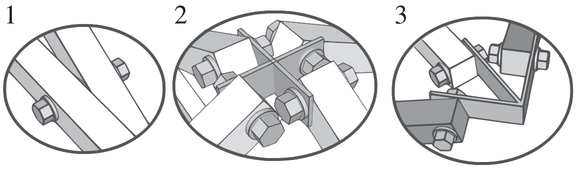
(**a**) top view



(**b**) side view



(**c**) 3D view with materials and connections



(**d**) different connections

Fig. 2. A single flat bistable module in the deployed configuration.

2.2. Computational model

In the FE model 2-node geometrically nonlinear Timoshenko beam elements in Lagrangian formulation are used for all of the structural members (as opposed to [15] using a combination of beam and truss elements). The semi-length of each structural beam of the outer SLE's is modelled by a single beam finite element, while the semi-length of each structural beam of the inner SLE's is modelled by four beam FE (verified to be a converged mesh).

Scissor structures have two types of connections (Fig. 2d):

(1) pivot joints that connect the beams in an SLE (1 in Fig. 2)