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Structural optimisation of a bistable deployable scissor module

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Abstract
Bistable deployable scissor structures can be designed to be transportable and can easily be transformed between two stable states, the compact and the deployed state, offering a huge volume expansion. In the deployed state they instantaneously reach structural stability as a consequence of an intended snap-through behaviour during transformation, generated by designed geometric incompatibilities. The design of such structures is ideally based on the duality of taking into account both their nonlinear transformation phase, as well as their service state in the deployed configuration, with opposing requirements. During transformation the peak force – and snap-through magnitude – needs to be minimized to obtain an easily transformable structure, while in the deployed state the stiffness of the structure should be high enough to allow sustaining gravity loads – requiring a high snap-through magnitude. In this contribution the computational design based on these opposing trends is formulated as a multi-objective optimisation approach. The feasibility of the proposed computational optimisation approach is demonstrated on the example of a bistable module.

Keywords: structural engineering, non-linear computational mechanics, deployable structures, scissor structures, bistable structures, multi-objective optimisation

1. Introduction
Scissor structures consist of beams connected by hinges. They can be designed to be transportable and can easily be transformed between two stable states, the compact and the deployed state, resulting in a huge volume expansion. In the deployed configuration they instantaneously offer some structural stability as a consequence of an intended snap-through behaviour during transformation, generated by designed geometric incompatibilities. The transformation of bistable scissor structures, first studied computationally by Gantes [1], is highly non-linear due to the large displacements and rotations and their bistable nature. Hence, such scissor structures should ideally be based upon the duality of taking into account both their nonlinear transformation phase as well as their service state in the deployed configuration, with opposing requirements. During transformation the peak force – and snap-through magnitude – needs to be minimized to obtain an easily transformable structure, while in the deployed state, the stiffness of the structure should be high enough to allow sustaining gravity loads – which can be showed to require a high snap-through magnitude. Because of this complex structural behaviour, the formulation of any simplified rigorous and automated design methodology is hindered, and consequently existing applications of the bistable scissor concept are rare in civil engineering.

In the past, several researchers in the field of mechanism-type scissor structures (without snap-through, otherwise called foldable) have successfully used optimisation methods [2-6]. All of these efforts were aimed at optimizing the deployed configuration through linear structural analyses. The optimisation of bistable scissor structures, taking into account geometric non-linearities during transformation, was attempted by Gantes [7] by using genetic algorithms to minimise the weight, by varying the cross-sectional dimensions and material properties using penalty functions for the stress and displacement constraints, leading to a single optimal design. The proposed approach resulting in a single optimal design didn't allow the designer to make choices based on preferences related for instance to the desired aesthetics or morphologic parameters of the structure.

In this contribution, the computational design based on a multi-objective optimisation approach is proposed as design concept and its feasibility is demonstrated using an example of a single bistable module. The objectives are the minimisation of the peak force during transformation, as well as of the deflection in the deployed state of a bistable module as a function of the geometry and the cross-sections of the beams. The originality of this contribution is the proposal of a multi-objective optimisation concept for bistable scissor structures, obtaining a Pareto front with several optimal solutions based on the transformation as well as on the structural response in the deployed configuration.

2. Optimisation problem statement

2.1. Geometry and structural response

The considered structure is a square flat polygonal bistable deployable scissor module of 0.7x0.7 m and a height of 23 cm (Fig. 1). During transformation, the inner beams of the module bend elastically while the outer elements remain straight. The lower corner points are considered to be fixed in the vertical direction, while the upper corner points are subjected to a horizontal load in the diagonal direction, as shown in Fig. 1.

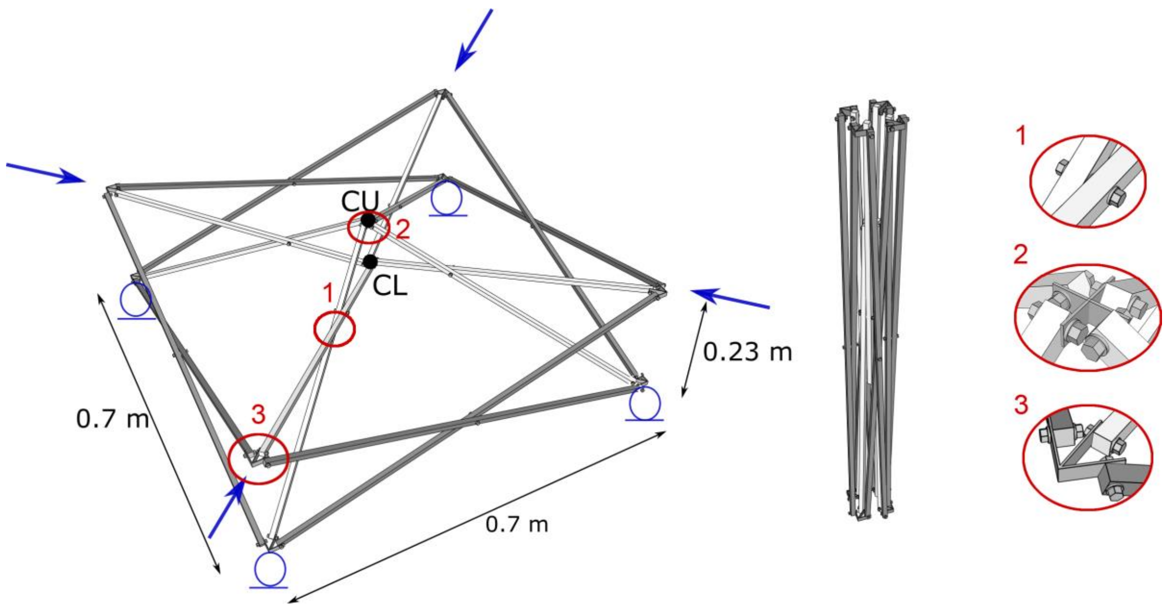

Figure 1: A square bistable scissor module in the deployed configuration with the applied loads and boundary conditions (left) and in the folded configuration (middle) and a detail of the different connections (right).

In general, the load displacement curve of bistable scissor structures is similar to Fig. 2. Point A corresponds to the initial deployed configuration. Due to geometric incompatibilities, an increasing force is required to fold the structure. The peak load is reached at point B, followed by a snap-through from B to D. The required load becomes negative (the applied load changes direction) from C to E, which implies that the structure would 'snap' dynamically to point E without a restraining force. After point D, the bent beams become straight again. Point E can be considered as the final folded configuration. To fold the structure further, an increasing load would be needed. When gravity is considered in the considered setup, the curve shifts upwards, which might result in a curve defined in the positive force range only (dashed line in Fig. 2). This would imply that the structure would unfold by itself from the folded to the deployed state due to its self-weight, a situation that should be avoided.

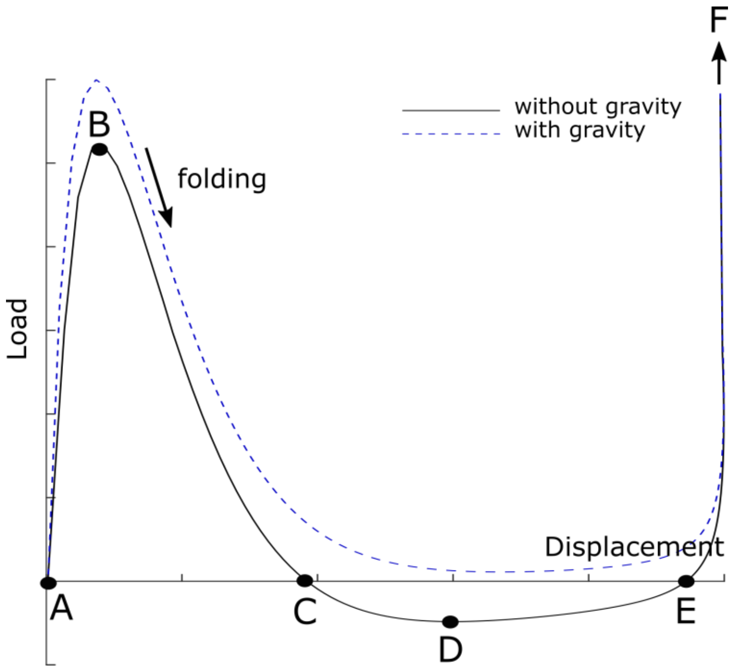

Figure 2: Schematic load-displacement curve of a bistable scissor structure with and without considering gravity.

The main design criteria to consider, define opposing trends in the non-linear problem: (1) point D must be negative to resist against spontaneous unfolding due to self-weight, (2) point B should be as low as possible to ensure an easy transformation, (3) the gradient between A and B should be as high as possible because it is related to the structural stiffness in the deployed state. It can be shown computationally that criterion (2) is opposed to (1)-(3), the former requirement striving for high stiffness, while the latter ones aim for low stiffness of the structural elements.

2.2 Objectives and constraints

The objectives of the structural optimisation are to minimize the peak load required for the transformation and the deflection of the structure in the deployed configuration. The peak load is deduced from the load-displacement curve which is obtained from the computational analysis of the transformation phase. The deflection is obtained from a linear analysis of the deployed configuration under gravity loads. It is measured as the highest vertical deflection under self-weight.

The considered constraints are:

1. The maximum stress, both during transformation and in the deployed state, has to be below the material yield limit;
2. The maximum deflection in the deployed state has to be lower than the span of the structure divided by 100, according to [5];
3. The local buckling of each element has to be avoided (formula from Eurocode 9);
4. The minimum load during transformation has to be negative.

2.3 Design variables

To obtain a lightweight structure, hollow rectangular cross sections are chosen. The height of the upper centre point of the module (point CU on Fig. 1) and the cross-sectional dimensions are variables in the optimisation process, while the height of the lower centre point (point CL on Fig. 1) and the hub size (where the beams are connected) are dependent variables. The hub size (connections 2 and 3 in Fig. 1) changes according to the cross sections of the beams to allow their sound connection. In total, seven continuous design variables are defined (Table 1): the width, height and thickness of two groups of cross sections: the inner beams (which bend during transformation) and the outer beams (which remain straight). The seventh variable is a geometrical parameter being the height of the module in the centre (the height of the upper centre point) relative to the height between the lower and upper corners which is 23 cm. The lower centre point is constrained to be located above the lower corner points and it has to be below an upper limit chosen so that the structure can be folded using horizontal forces in the corner points. Aluminium (Young's modulus 70 GPa, Poisson's ration 0.35, density 2700 kg/m³, yield strength 200 MPa) is used for all of the beams.

Table 1: Upper and lower bounds for the design variables, considering 2 sets of cross sections.

	Lower limit	**Upper limit**
Cross-section width (x2)	0.01 m	0.05 m
Cross-section height (x2)	0.01 m	0.05 m
Cross-section thickness (x2)	0.002 m	0.005 m
h/H (height in the centre)	0.4	1.3

2.4 Mathematical formulation of the problem

To find optimal solutions that combine a low peak force during transformation with a low deflection in the deployed state, the following optimisation problem has to be solved:

$$\min_{x} f_i(x_p) \quad i = 1{,}2 \tag{1}$$

$$subject\ to: g_j(x_p) \leq 0 \quad j = 1, \dots, n$$

$$x_p \in X_p \quad p = 1, \dots, m$$

where x_p is the vector of design variables ($x_1 \dots x_7$) (Table 1), X_p the set of x_p, $f_i(x_p)$ the objective functions (peak load and maximum deflection) and $g_j(x_p)$ the (in)equality constraints. Neither $f_i(x_p)$ nor $g_j(x_p)$ are known, therefore they are sampled point-wise, running non-linear FE simulations for each set of variables. A genetic algorithm is used to solve computationally Eq. (1).

3. Optimisation methodology

3.1 Multi-objective evolutionary algorithm

Evolutionary algorithms are inspired by nature and use a series of iterations to obtain converging approximate solutions of the optimisation problem. These methods can result in several non-dominated optimal solutions (a Pareto front) from which the designer can choose the desired solution. NSGA-II is a popular method for multi-objective optimisation problems in civil engineering [5] and is the approach used in this work. An initial population N of 100 individuals is chosen randomly from which each individual is associated with a different design parameter set. An offspring population is created by applying the usual crossover (probability 0.9) and mutation (probability 0.1) operators by randomly picking parents from the parent population. The parent population P_t and its offspring population Q_t both have N members. The best N members are chosen from the combined population $R_t = P_t \cup Q_t$ which is sorted according to non-domination levels and the procedure is repeated until convergence is reached.

3.2 Geometric design

To define the geometry of the structure, the 3D modelling software Rhinoceros® and its parametric design plug-in Grasshopper® are used. As input parameters, the overall dimensions, the height of the centre points (CU and CL in Fig. 1), the spacing in between the beam midlines of each scissor (the two beams in a scissor-like element do not lie in the same plane, as can be seen in connection 1 in Fig. 1) and the hub size are used. As output, the wireframe design i.e. the beam lengths and the position of the nodes is obtained [8].

3.3 Structural analysis

Abaqus is used for the FE analysis of the non-linear transformation phase [9] as well as for the linear analysis of the deployed configuration under self-weight. 2-noded beam elements discretize the structural members and the connections are simulated with the Abaqus connector type 'hinge'. Four beam finite elements are used to model the semi-length of each beam, which was verified to be converged. The hubs are represented as a rigid grid of small beam elements.

3.4 Combination of different tools

To couple the structural analysis with the optimisation algorithm, a framework is used in which MatLab is combined with Grasshopper, Abaqus and Python (Fig. 3). First, the NSGA-II algorithm, written in MatLab, generates the initial population and sends the design variables for each individual to Grasshopper, in which the geometry is updated parametrically, and input files are written for Abaqus. Then, finite element computations are performed. The output of these FE analyses is accessed using a Python script and the constraints are calculated. The objectives and constraints are sent back to MatLab in which the optimisation algorithm evaluates the objective functions and creates a new population.

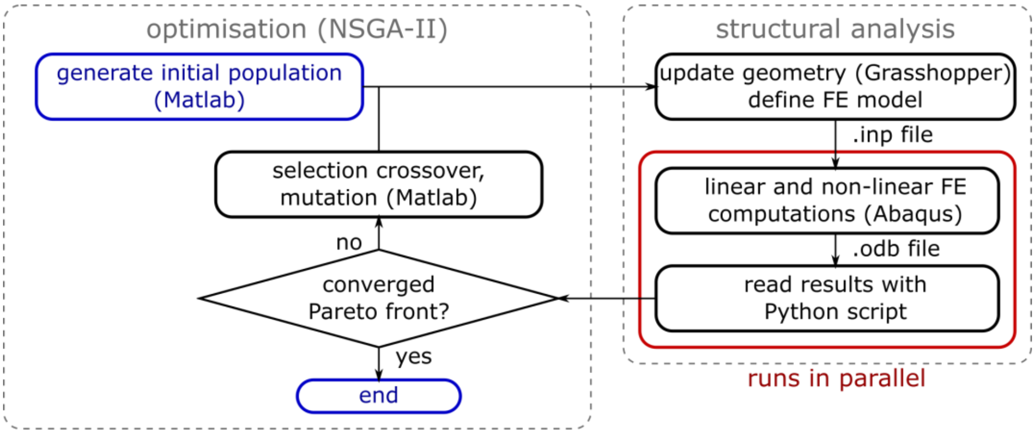

Figure 3: Flowchart of the computational approach.

4. Example of the optimisation of a single module

The evolution of the Pareto front throughout the optimisation process of a single bistable module is plotted in Fig. 4. After 5 generations, only a few structures are found that are a solution to the optimisation problem. This is due to the limiting constraints as well as the defined range for the design variables. Once a few solutions are found, the optimisation algorithm quickly finds other solutions by crossover and mutation. After 10 generations, already 20 solutions are part of the Pareto front. This number of solutions on the Pareto front increases throughout the generations until it reaches 100. In this example of the optimisation of a single module, it took 130 generations to obtain a converged Pareto front. The computational time for 130 generations, and thus for 1 linear and 1 non-linear FE simulation for 13,000 individuals, was around 16 hours using a personal laptop (2.9 GHz processor and 32 GB RAM).

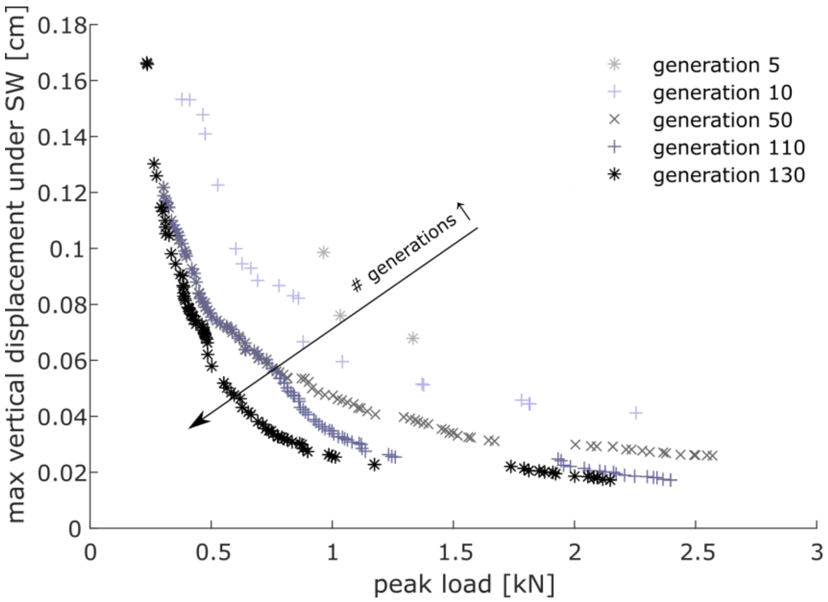

Figure 4: Evolution of the Pareto front throughout the optimisation process.

The final Pareto front is shown in Fig. 5. Three of the optimal solutions are shown i.e. the solution with the highest deflection (0.166 cm) and lowest peak load (0.234 kN), the solution with the lowest deflection (0.017 cm) and highest peak load (2.148 kN), and a solution in the middle of the Pareto front, i.e. a deflection of 0.023 cm and a peak load of 1.174 kN. By looking at these three solutions, it becomes clear how the design variables, i.e. the cross-sectional dimensions and the geometry, evolve on the Pareto front. The width of the cross section of the outer beams (the upper cross section on Fig. 5) is always as low as possible (1 cm), while the height of the outer beams is lower for low peak loads (1.59 cm) and higher for high peak loads (2.43 cm). The width and the height for the inner beams are as low as possible (around 1 cm) for all the solutions on the Pareto front and the height in the centre is for all the solutions approximately the same as the height in the corners.

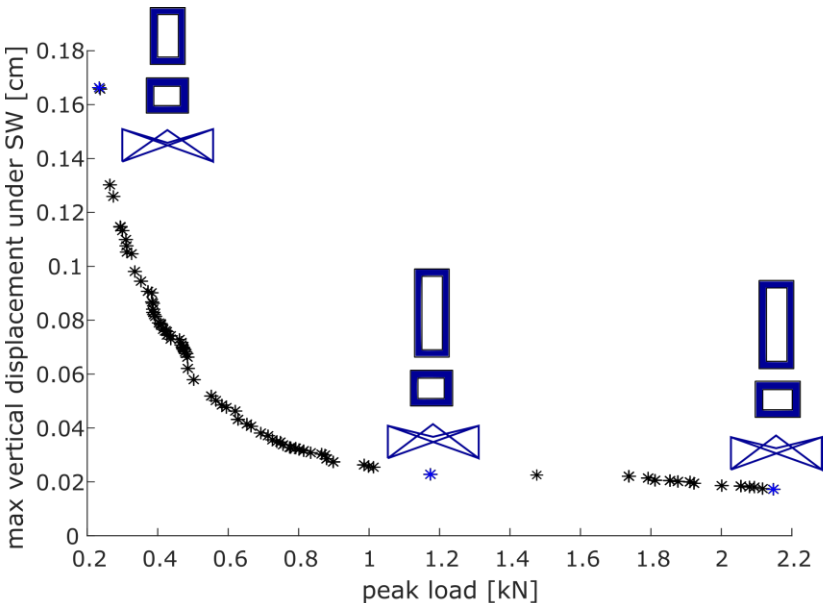

Figure 5: Pareto front and the design variables (from top to bottom: cross section of the outer beams, cross section of the inner beams and structural geometry) for three solutions.

In this example, the outer beams have the lowest width and thickness, while the inner beams have the lowest height possible (i.e. reaching their design bounds set in Table 1). A lower height for the inner beams corresponds to a decreased stiffness of the inner beams (which bend during transformation) against in-plane bending, leading to a decrease in the peak load. For the height of the upper centre point, values of around 1 are found for the parameter h/H, which corresponds to a height in the centre of the module which is approximately the same as the height in the corners of the module. The higher the upper centre point, the more pronounced the snap-through becomes, which increases the structural stiffness in the deployed state, but also leads to a higher peak load during transformation.

5. Conclusions and outlook

Bistable scissor structures should be lightweight, easy to deploy and provide enough stiffness in the deployed configuration to sustain their self-weight and potentially small external loads. To find acceptable compromises between these conflicting requirements, an optimisation methodology is proposed in which the peak force during deployment as well as the deflection in the deployed state are minimized, taking into account stress, deflection and buckling constraints. The proposed optimisation approach results in a Pareto front, i.e. several non-dominated solutions, illustrated in this contribution on the example of a single bistable module. This optimisation methodology was shown to be a feasible approach and can the basis of a rigorous design procedure, which will be developed in the future and validated on several real-life examples and shapes with real application potential such as domes and arches.

Acknowledgements

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