Coupled sizing, shape and topology optimisation of bistable deployable structures

Arnouts, Liesbeth I.W.; Massart, Thierry J.; De Temmerman, Niels; Berke, Peter

Published in:
Journal of the International Association for Shell and Spatial Structures

DOI:
10.20898/j.iass.2020.009

Publication date:
2020

License:
Other

Document Version:
Proof

Link to publication

Citation for published version (APA):
Arnouts, L. I. W., Massart, T. J., De Temmerman, N., & Berke, P. (2020). Coupled sizing, shape and topology optimisation of bistable deployable structures. *Journal of the International Association for Shell and Spatial Structures*, *61*(4), 264-274. https://doi.org/10.20898/j.iass.2020.009

COUPLED SIZING, SHAPE AND TOPOLOGY OPTIMISATION OF BISTABLE DEPLOYABLE STRUCTURES

Liesbeth I.W. ARNOUTS[1,2], Thierry J. MASSART[1], Niels DE TEMMERMAN[2] and Péter Z. BERKE[1]

[1] BATir Department, Université libre de Bruxelles (ULB), Avenue Franklin Roosevelt 50, 1050 Brussels, Belgium,
larnouts@ulb.ac.be, thmassar@ulb.ac.be, pberke@ulb.ac.be
[2] VUB Architectural Engineering, Vrije Universiteit Brussel (VUB), Pleinlaan 2, 1050 Brussels, Belgium,
Niels.De.Temmerman@vub.be

Editor's Note: The first author of this paper is one of the five winners of the 2020 Hangai Prize, awarded for outstanding papers that are submitted for presentation and publication at the annual IASS Symposium by younger members of the Association (under 30 years old). It is published here with permission of the editors of the proceedings of the IASS Symposium 2020/21 "Inspiring the Next Generation", that will be held in August 2021 in Guildford, UK.

DOI: Digital Object Identifier to be provided by Editor when assigned upon publication

ABSTRACT

Bistable scissor structures, consisting of beams connected by hinges, are transportable and can be transformed from a compact to a deployed configuration. Geometric incompatibilities can be introduced during transformation to obtain a bistable structural response which enforces some instantaneous structural stability in the deployed state. The design of bistable scissor structures requires assessing both the non-linear transformation behaviour, as well as the service state, since a proper structural design has to provide stiffness in the deployed state as well as flexibility during transformation. These contradicting requirements were formulated previously in Arnouts et al. [1] as a multi-objective shape and sizing optimisation (SSO). The originality of this contribution is the elaboration of a design methodology coupling a novel topology optimisation (TO) to SSO and demonstrating its performance for the design of a bistable deployable wall. In this novel step, the number of bistable deployable modules (BDM) of the structure is optimised at low computational cost by finding the location of BDM, yielding mixed structures composed of BDM and non-bistable modules (NBDM) of lower weight and complexity than structures entirely built from BDM. TO is incorporated and assessed in the design methodology prior or subsequent to the SSO step. It is shown that the mixed structures combining BDM and NBDM resulting from the new coupled TO-SSO approach outperform pure BDM based structures.

Keywords: *structural design, non-linear computational mechanics, transformable structures, scissor structures, bistability, snap-through, multi-objective optimisation, shape and sizing optimisation, topology optimisation*

1. INTRODUCTION

Bistable scissor structures consist of scissor-like elements (SLE's), which are beams connected by hinges. They are transportable, reusable and can rapidly be transformed from a compact closed configuration offering a huge volume expansion (Fig. 1). These *self-locking* scissor structures avoid the need for external manipulation to ensure stability in the deployed configuration. Scissor structures can have a *bistable* structural response which is caused by the bending of some specific members associated with intended geometric incompatibilities during transformation. The structural response is characterized by a controlled *snap-through* behaviour that 'locks' the structure and provides instantaneously some structural stability in the deployed configuration.

Because of the transformable bistable nature, the design of bistable scissor structures requires assessing both the non-linear transformation behaviour as well as the service state in the deployed configuration (Arnouts *et al.* [2]). A proper structural design has to provide sufficient stiffness in the deployed state, and flexibility during transformation to limit the force required for (un)folding. These requirements are contradicting. Due to this complex structural behaviour, which prevents the formulation of any straightforward design methodology, existing applications of bistable scissor structures are rare.

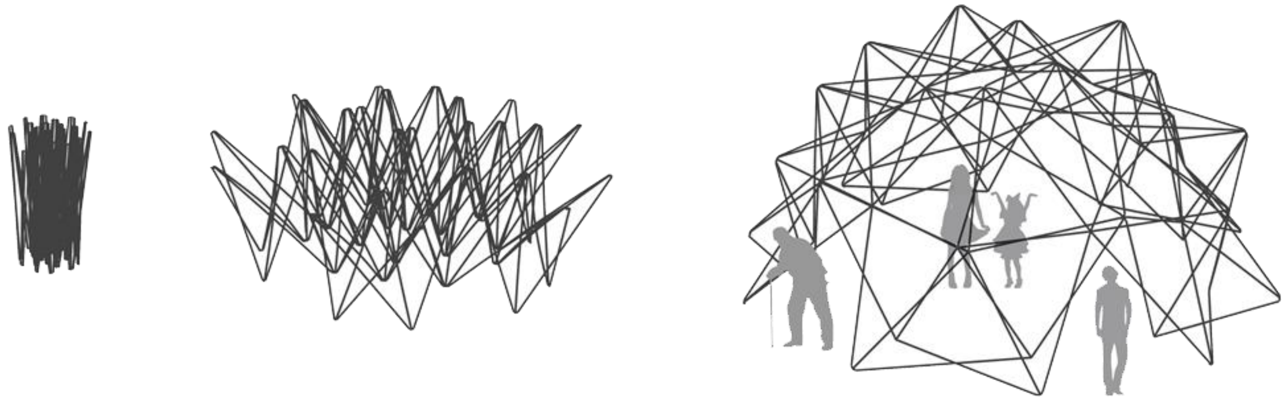


Figure 1: *The compact folded state (left), an intermediate state (middle) and the deployed state (right) of a large-scale bistable scissor structure.*

Optimisation methods have been used successfully in the past by several researchers in the field of mechanism-type of scissor structures (i.e. without snap-through), among whom You [3], Kaveh *et al.* [4], Thrall *et al.* [5], Alegria Mira *et al.* [6], Koumar *et al.* [7] and Salar *et al.* [8]. The optimisation of bistable scissor structures was first attempted by Gantes *et al.* [9]. The requirement of a low force during transformation and the opposing high stiffness requirement in the deployed state were formulated previously in Arnouts *et al.* [1] as a multi-objective non-linear shape and sizing optimisation problem (SSO) with the beam cross-sections (sizing optimisation) and a shape parameter (shape optimisation) as design variables, taking into account stress based, deflection and buckling constraints.

The above was for structures made of square bistable deployable modules (BDM) only (Fig. 2 top). BDM are naturally more complex than classical non-bistable deployable modules (NBDM) (Fig. 2 bottom). The hubs of structures consisting of BDM connect up to 8 beams, while the hubs of structures consisting of NBDM connect up to 4 beams. More material is needed for BDM since there are more members in the module, leading to a higher weight of up to 0.292 kg for one BDM (for the modules described in this contribution) compared to 0.182 kg for one NBDM. A lower weight reduces the cost of the structure but is also beneficial in many applications, for resource efficiency and for transportability. Hence it would be interesting to find a way to keep the advantages of the bistable behaviour of BDM while reducing the complexity, weight and cost of the overall structure by combining BDM and NBDM, thereby obtaining a mixed structure.

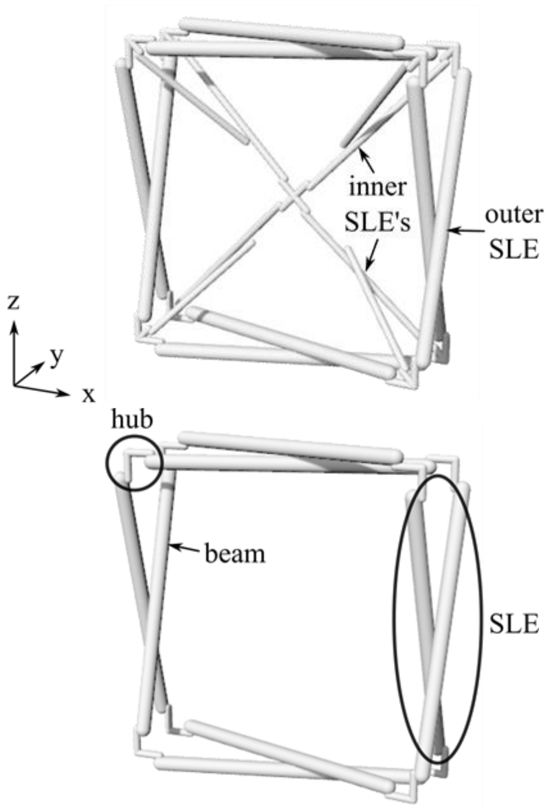


Figure 2: *A bistable deployable module - BDM (top) and a non-bistable deployable module - NBDM (bottom).*

The originality of this contribution is the elaboration of a design methodology coupling a novel topology optimisation (TO) and SSO and demonstrating its performance for the design of a bistable deployable wall. In the novel TO step, the number of BDM of the structure is optimised at low computational cost by finding the optimal location of BDM, yielding mixed structures composed of BDM and NBDM. It is shown that the mixed structures combining BDM and NBDM resulting from the new coupled TO-SSO approach outperform pure BDM based structures.

Moreover, using TO is shown to impact the force required for transformation as well, allowing for designs with a lower transformation load which is an important requirement to obtain feasible applications. TO is incorporated and assessed in the design methodology prior or subsequent to the SSO step and the different sequences of SSO and TO are critically compared.

2. PROBLEM STATEMENT

The novel design optimisation will be assessed on the realistic example of a bistable deployable wall which could be used for mobile barriers for imposing physical distancing (COVID-19 requirement), privacy, branding, screen projection, exhibitions, or artistic work. The curved wall with a thickness T of 0.1 m and of external envelope of 2x2.1x0.3 m in the service state is an assembly of 5x5 modules (Fig. 3). The outer SLE's of each module (on the edges of the BDM or NBDM) remain straight during transformation, while the inner SLE's (on the diagonals of the BDM) bend due to geometric incompatibilities. The material used for the beams is ASA (Acrylonitrile Styrene Acrylate) with E=2.05 GPa, ν=0.4, ρ=1070 kg/m³ and σ_y=44.2 MPa. The hubs are envisioned to be 3D printed from plastic, which will make the structure lightweight (transportable) and easy to transform.

During transformation, the bottom points of the structure are fixed in the vertical direction while the upper points are subjected to a vertical displacement, as can be seen on Fig. 4. In the deployed configuration (service state), the bottom points of the structure are fixed in the vertical direction z (the structure is standing on the ground). Gravity is applied (total structural weight of maximum 5.5 kg) and a banner (plastic layer) on two sides of the structure is modelled by vertical forces on the upper points which correspond to the weight of a banner, 4.3 kg, in PVC (0.510 kg/m²).

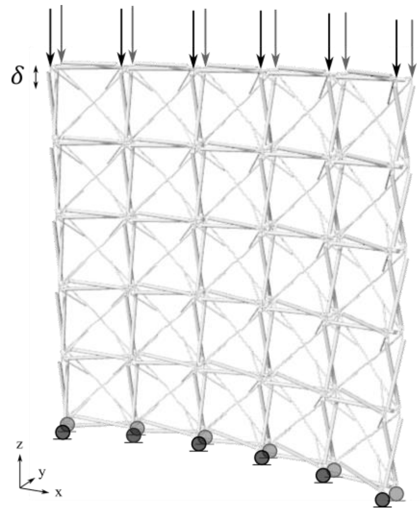


Figure 4: *Boundary conditions and applied loads.*

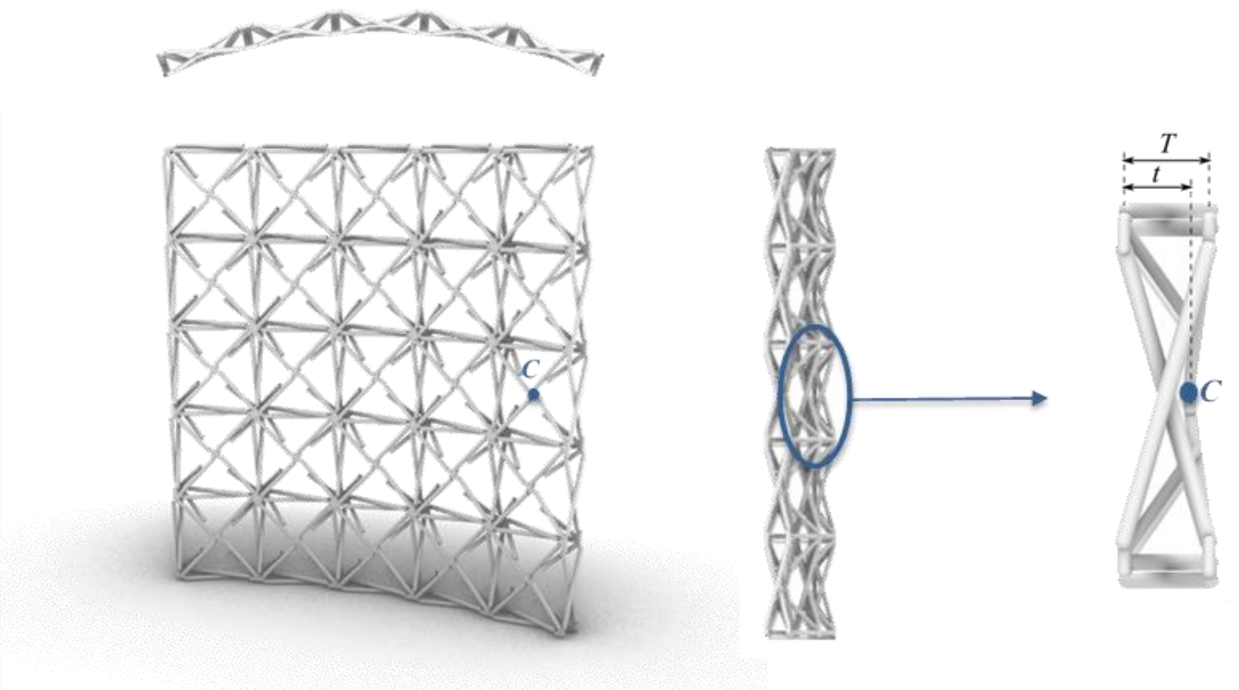


Figure 3: *A perspective (bottom left), top (top left) and side (middle) view of a bistable deployable wall and a side view of one module (right).*

In the FE model, which is described in detail in Arnouts *et al.* [10], structural members are modelled by Timoshenko beam elements and the connector type 'hinge' is used to model the joints in Abaqus. Friction is not considered for the sake of simplicity and computational efficiency. A spacing is incorporated between the beam elements, since in reality the two beams in an SLE do not lie in the same plane. This spacing promotes the out-of-plane buckling of the inner SLE's for large height-to-width cross sectional ratios. Finite size hubs (i.e. connections of several beams) are described by stiff grids of small beam elements. To solve the snap-through problem, the modified Riks solution strategy is used.

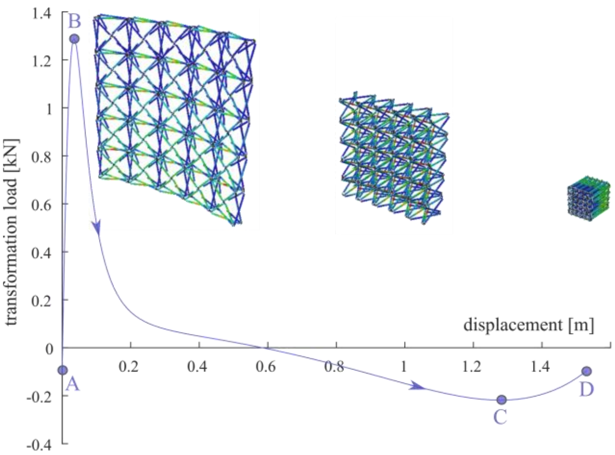


Figure 5: *A folding transformation curve.*

The load-displacement curve of a bistable scissor structure is similar to Fig. 5, showing the folding of the structure. It has been verified that the snap-through process is reversible i.e. the structure exhibits the same structural response during folding and unfolding. The load is the sum of the applied vertical transformation forces $\sum_{p=1}^{n_{forces}} F_{p,i}$ (with n_{forces} the number of forces) and the displacement is the vertical displacement of an upper edge point downwards. Point A corresponds to the initial deployed configuration. An increasing force is required to fold the structure from A to B, followed by a snap-through from B to C. Point D is the final folded configuration.

3. OPTIMISATION METHODOLOGY

First, in Section 3.1, the shape and sizing optimisation approach (SSO), which was introduced in a previous work for structures consisting of BDM, is explained. Second, in Section 3.2, the topology optimisation approach (TO), which is a main novel contribution of this work, is introduced allowing for consideration of mixed structures with BDM and NBDM. The optimisation approaches explained in this Section are used in Section 4 to optimise the bistable deployable wall introduced in Section 2.

3.1. Shape and sizing optimisation methodology (SSO)

The multi-objective shape and sizing optimisation previously proposed in Arnouts *et al.* [1], in which the requirement of a low force during transformation and the opposing high stiffness requirement in the deployed state were taken into account, is employed here for structures consisting of only BDM and for mixed structures consisting of both BDM and NBDM.

The horizontal position t of the centre points (shown by C in Fig. 3) and the cross sectional dimensions are target variables to optimise, while the hub size is a dependent variable taking cross section sizes and beam spacing into account to allow sound beam connection to the hub (Arnouts *et al.* [1]). Hollow circular cross sections of 1 mm wall thickness were chosen to obtain a lightweight structure. In total, three continuous design variables are defined:

1. the outer diameter d_i of the inner SLE's,
2. the outer diameter d_o of the outer SLE's,
3. a geometrical parameter being the horizontal position of the centre point in the module t relative to the thickness of the wall T.

The lower and upper bound for the outer diameter of the cross sections are chosen to be 0.3 and 2 cm, corresponding to available profiles on the market. The lower and upper limits for t/T are chosen in a way that the centre point cannot be located outside of the volume envelope of a module defined by its 8 corners i.e. t/T is set between 0 and 1. The value of t/T influences the bending of the inner SLE's and hence the snap-through behaviour.

The two *objectives* of the structural optimisation are to minimize the maximum load required for transformation and to minimize simultaneously the maximum vertical displacement of the structure in the deployed configuration (referred to as δ on Fig. 4) under the applied loads (gravity and a banner on both sides of the structure), subject to the following *constraints*:

1. the maximum von Mises stress during deployment and in the service state must be below the yield stress σ_y of the material,
2. the vertical displacement in the service state is chosen to be lower than $L/100$ (Koumar *et al.* [7]) with L the maximum spatial dimension of the structure i.e. 2 m,
3. buckling of the beams must be avoided in the service state, which is verified using an analytical criterion following Eurocode 9 (Arnouts *et al.* [2]).

The applied force F_p, the von Mises stress $\sigma_{vonMises}$ and the generalized stresses N (normal force) and M (bending moments) are sampled at each increment δ of the non-linear FE simulations for each set of design variables in the SSO using the NSGA-II genetic algorithm by Deb *et al.* [11].

3.2. Topology optimisation methodology (TO)

The main novelty of this work is the topology optimization explained in this section. In this TO step the number of BDM of the structure is optimised at low computational cost by finding the location of BDM, yielding mixed structures composed of BDM and NBDM that outperform structures consisting of only BDM in complexity, weight, cost and transformation load. Inner SLE's (diagonal elements) responsible for the self-locking in a BDM are removed selectively. This results in a mechanism-type of module referred to as a non-bistable module, NBDM, i.e. an NBDM does not oppose to transformation and it does not contribute to the service state stability either. In general, the more BDM are present in a structure, the more pronounced the structural snap-through effect will be, and the stiffer the structure becomes in its service state (reduced deformation in the service state and a higher peak load of transformation). Note that switching BDM to NBDM is beneficial in the sense that it reduces the mass of the structure and its complexity (and cost) as well as the peak transformation load. Choosing which BDM to replace by NBDM is not straightforward and a computational discrete topology optimisation approach is proposed here for this purpose.

Binary variables are used to assign a value zero (NBDM, inner SLE's absent) or one (BDM, inner SLE's present) to each module in the structure. Similar to the shape and sizing optimisation method, a multi-objective optimisation is carried out to minimize the peak load during transformation, as well as the maximum displacement in the service state, δ, based on coupling nonlinear FE simulations with the NSGA-II algorithm. As a result, several structures with a different distribution of BDM and NBDM are obtained as optimal (non-dominated) solutions.

For the bistable deployable curved wall studied here, there are 25 binary design variables corresponding to its 25 modules. However, since the boundary conditions and loads are plane symmetrical (Fig. 4 left), the design variables can be reduced to 15, forcing also the geometry of the structure to be symmetric and reducing the computational time. The structure has five rows on top of each other consisting of five modules each. Every row has three design variables i.e. one variable for the two edge modules, one variable for the centre module and one variable for the two modules between the edge and central modules. The NSGA-II algorithm is employed without constraints, these are chosen to be taken into account only in the shape and sizing optimisation step (Section 3.1) in this work.

4. COMPUTATIONAL OPTIMUM DESIGN OF BISTABLE DEPLOYABLE STRUCTURES

The optimisation approaches explained in Section 3 are used to optimise the bistable deployable curved wall introduced in Section 2. First, in Section 4.1, SSO is used to optimise the deployable wall consisting of only BDM. Second, in Section 4.2, TO is used to optimise the distribution of BDM and NBDM in the wall. Finally, the two optimisation approaches i.e. SSO and TO are coupled to obtain the best performing optimised solutions for mixed BDM-NBDM structures. The different sequencing of SSO and TO are critically compared and a computational design methodology is proposed for bistable deployable structures.

4.1. Shape and sizing optimisation (SSO) of a pure BDM built deployable wall

The Pareto front resulting from the SSO optimisation of the bistable foldable wall built purely from BDM is given in Fig. 6. The maximum displacement in the service state, δ, ranges between 0.7 and 2.1 mm and the transformation force between 59.8 N and 3.294 kN. The mass ranges between 3.3 and 5.2 kg. The lower δ, the higher the transformation force and mass while a higher δ corresponds to lower transformation force and mass.

The solution with the lowest transformation load (59.8 N), the lowest mass (3.3 kg) and the highest displacement δ (2.1 mm) approaches the lower limit for the diameter of the inner SLE's and the upper limit for the diameter of the outer SLE's and the geometrical parameter t/T. The solution with the highest transformation load (3.294 kN), highest mass (5.2 kg) and the lowest displacement δ (0.7 mm) approaches the upper limit for all the design variables. When looking at the Pareto set (Fig. 7), it is clear that the optimal structures have a diameter for their outer beams of 2 cm (i.e. the upper bound of the variable) and t/T close to 1 (i.e. the upper bound of the variable). The smaller the diameter of the inner beams, the lower the transformation force and the higher the deflection in the deployed state.

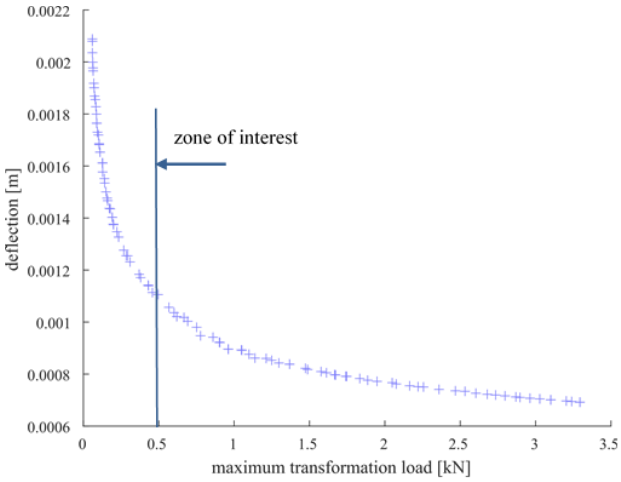


Figure 6: *Pareto front of the SSO of a foldable wall consisting of BDM.*

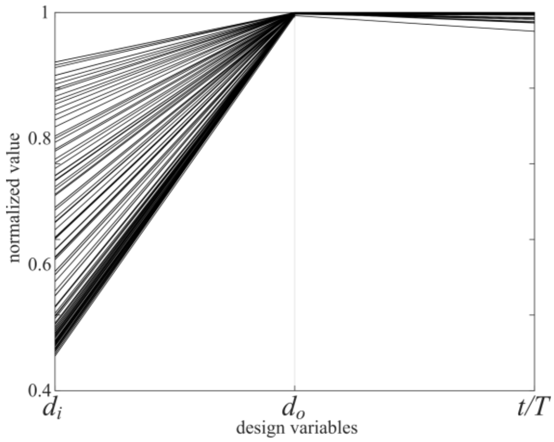


Figure 7: *Pareto set of the SSO of the pure BDM curved wall.*

In reality, all the solutions above 0.5 kN are unpractical and can be discarded, since a lightweight structure that is easy to transform (i.e. transformable by one person) is desired. 0.5 kN is taken as an extreme maximum. The objective of coupling the SSO with the TO in Section 4.3 is also to reduce the transformation load to obtain more feasible solutions, next to reducing the complexity, weight and cost of the structure.

4.2. Topology optimization (TO) of a bistable deployable wall

For the topology optimisation, both inner and outer SLE beam cross sections with a diameter of 2 cm were chosen and t/T was set to 1. The results of the TO (distribution of BDM and NBDM) were verified to be independent from this initial choice by varying these values and observing the same results for this structural example. For the fully BDM built structure, the maximum vertical displacement δ in the service state is 0.66 mm for this parameter set and the required transformation force is 4.1 kN (filled red circle on Fig. 8).

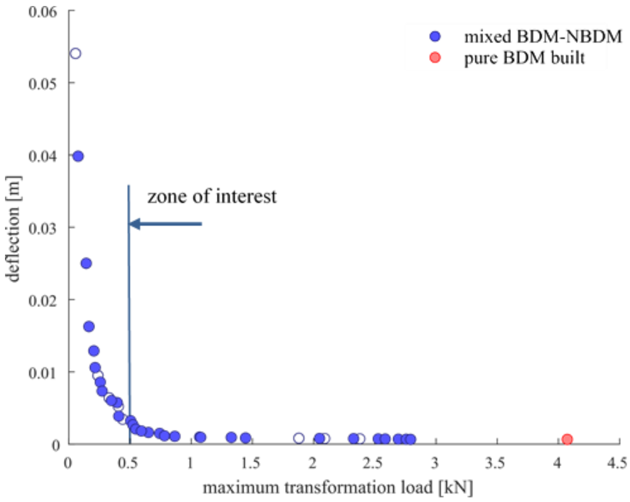


Figure 8: *Pareto front of TO of the curved wall.*

37 optimal configurations were obtained, however, some solutions were filtered out, denoted by unfilled circles on Fig. 8, because other solutions with a lower mass and the same transformation load and maximum vertical displacement δ existed, resulting in 29 non-dominated configurations (filled blue circles on Fig. 8). The transformation load ranges between 0.055 and 2.8 kN and the displacement δ between 0.65 and 54 mm, clearly outperforming the pure BDM built design. The displacement δ of 54 mm is higher than the constraint $L/100$ (Section 3.1) because the TO is unconstrained. The mass of the inner SLE's of the optimal solutions is reduced by 12 to 96%. The optimal configurations using this TO stage are shown in Fig. 9.

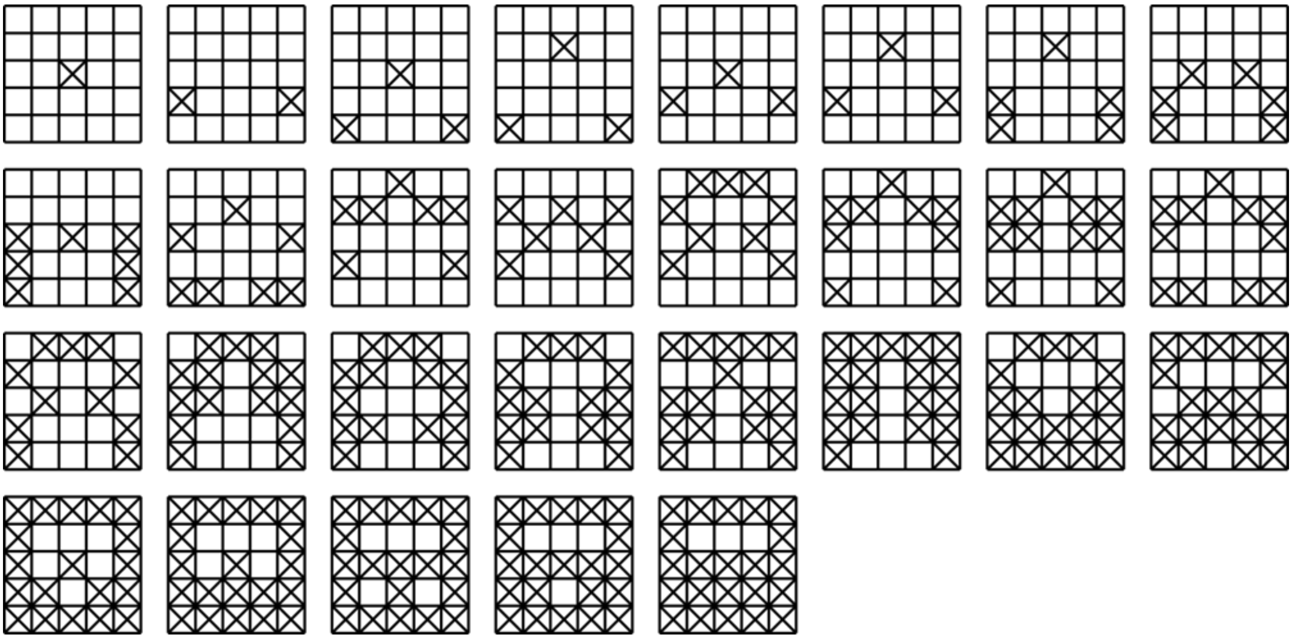


Figure 9: *The 29 optimal configurations from TO going from the structure with the highest displacement δ and lowest transformation load (top left) to the lowest displacement δ and highest transformation load (bottom right).*

All the optimal structures are performing better than the full structure in terms of mass and transformation load, but only one solution is better in terms of both transformation load and vertical displacement (bottom right on Fig. 9 with a transformation load of 2,792 N and a displacement δ of 0.65 mm). The final choice of the structure is in the low transformation peak force range that could only be extended through the proposed topology optimisation approach (i.e. solutions with a lower peak load than the pure BDM built structure were found). Note, however, that it is not guaranteed that these optimised solutions will lead to feasible structures, since no stress, deflection or buckling constraints are taken into account in the TO approach. To increase the chances of finding feasible solutions, the extreme cases (i.e. the ones with a high displacement δ or a high peak transformation load) should not be used in the optimisation of bistable deployable structures.

4.3. Coupled shape, sizing and topology optimization of the deployable curved wall

To obtain better performing structures, the optimisation approaches are combined with the SSO preceding the TO (SSO→TO) or the SSO following the TO (TO→SSO). In this section both optimisation sequencing results are critically compared.

When the results of *prior shape and sizing optimisation* of a pure BDM built structure (i.e. for fixed SSO variables) are used for the topology optimisation (SSO→TO), new Pareto fronts are obtained, as shown in Fig. 10 for four randomly chosen non-dominated solutions (none of them performs better in terms of both transformation load and displacement δ). The red points are solutions that do not satisfy the constraints after removing the bistable elements as a result of TO.

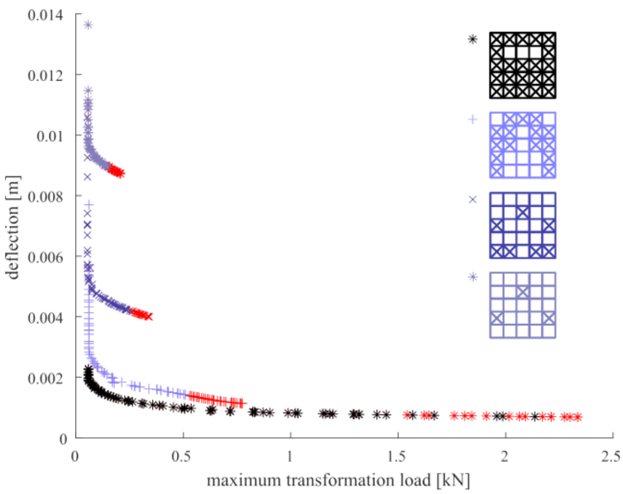


Figure 10: *Comparison of several Pareto fronts for different topologies for SSO→TO.*

Note that the SSO→TO sequence requires a final verification step in which solutions violating constraints are eliminated because TO is an unconstrained optimisation. Actually, for a given topology in the SSO→TO approach all solutions might be eliminated after verification of the compliance with the design constraints (only the initial SSO configuration for a pure BDM built structures is guaranteed to satisfy these). This is the case for the first three solutions (with one, two and three BDM) in Fig. 9.

The less BDM i.e. the more non-bistable modules, the lower the transformation load (for a slight increase in displacement δ in the service state), the lower the complexity of the structure and by consequence, the lower mass and cost. While the fully bistable structure has a transformation load ranging from 59.8 N to 3.294 kN and a mass ranging from 3.3 to 5.2 kg, for the structures on Fig. 10 the transformation load is further reduced to 53.6 N and the mass to 2.8 kg for the structure with the least BDM. While this decrease in transformation load is modest, and while there is a slight increase in the deflection in the service state, the complexity of the structure and its weight are reduced significantly.

When *starting from the topology optimisation* prior to the shape and sizing optimisation (TO→SSO), naturally, as a consequence of the optimisation sequencing, final optimum solutions satisfy the constraints. The main disadvantage of this sequencing is that for each different topology a costly constrained SSO is required.

Fig. 11 shows the comparison between the different optimisation sequences. TO→SSO outperforms SSO→TO. For cases in which the topology is similar to the purely BDM built design (i.e. only a few NBDM are incorporated), the difference between TO→SSO and SSO→TO is rather limited (Fig. 11 top) while in other cases the difference logically increases (Fig. 11 bottom).

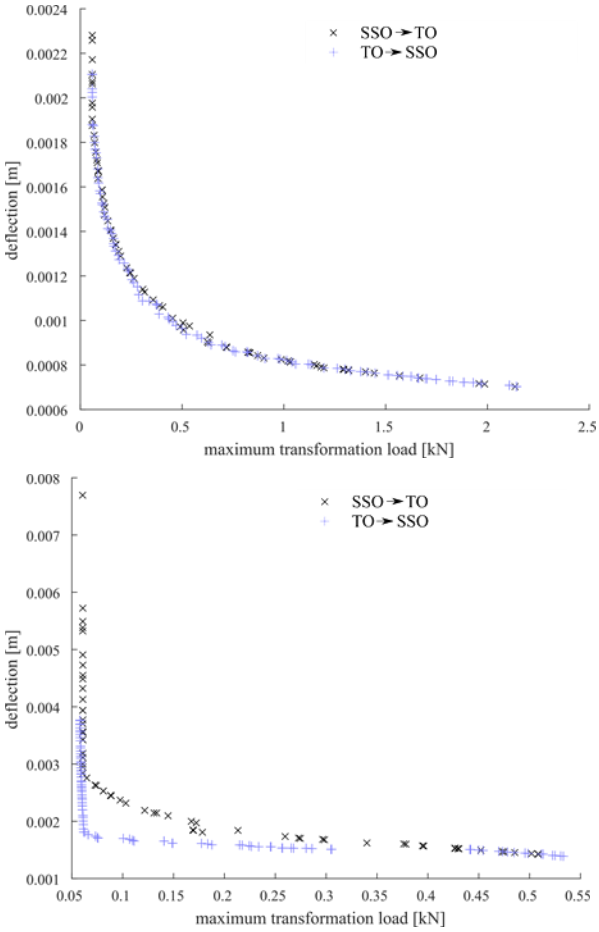
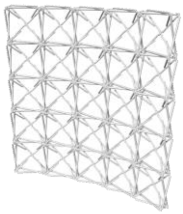
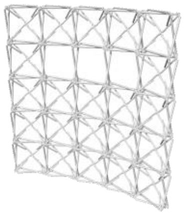
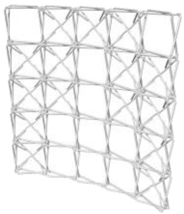
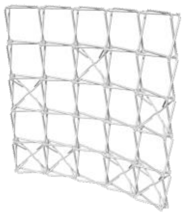
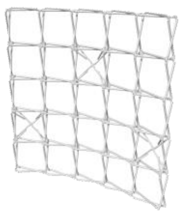


Figure 11: *Comparison of Pareto fronts of the same structure for different optimisation sequences.*

Table 1: *Comparison of several optimised solutions.*

deployed configuration									
# bistable modules	25	22		15		7		3	
optimisation approach	SSO	SSO →TO	TO →SSO	SSO →TO	TO →SSO	SSO →TO	TO →SSO	SSO →TO	TO →SSO
minimum mass [kg]	3.3	3.2	3.1	3.0	2.7	3.0	2.7	2.8	2.8
minimum transformation force [N]	60	59	58	60	58	54	52	57	57

The TO is computationally inexpensive and was shown to be independent from the initial set of design variables for the present example (Section 4.2). It is useful to obtain better performing (less complex and lighter) structures. The SSO is computationally expensive and only recommended in the final step to fine-tune the results.

Different solutions discussed before are compared in Table 1. The weight, the cost and the complexity of the structure is proportional to the amount of BDM i.e. decreasing the amount of bistable modules means also decreasing the weight, cost and complexity of the structure. By choosing a structure with less bistable modules, the transformation peak force can also be decreased. It is interesting to note that, contrary to the intuition of the less BDM the better, the structure with 7 BDM in Table 1 performs better than the structure with 3 BDM (2.7 kg and 52 N for the structure with 7 BDM compared to 2.8 kg and 57 N for the structure with 3 BDM) due to the complexity of the problem.

When the TO→SSO approach is used, the transformation load is slightly lower than when the SSO→TO approach is used. It is clear that performing the topology optimisation first and using a resulting optimised grid to do the shape and sizing optimisation subsequently (TO→SSO) is advisable. Note that when using this sequence (TO→SSO), there is still no guarantee for finding feasible solutions that satisfy the constraints once a topology is chosen. Therefore, it is again advisable to avoid the extreme topologies (i.e. the ones with a high displacement δ or a high peak transformation load) from Fig. 8.

The *proposed computational design methodology for bistable deployable structures* is given in Fig. 12. As input, the initial rigid wireframe model is used. Cross sections are chosen for the TO and a final grid (BDM-NBDM topology) is chosen by the designer for the subsequent SSO. When the SSO Pareto front is converged, the final structure can be chosen, i.e. and the final design with optimised grid (TO), cross sections and t/T (SSO) is obtained. This is a logical sequence of design decisions, since the choice of the topology would also be the first step in a conventional structural design.

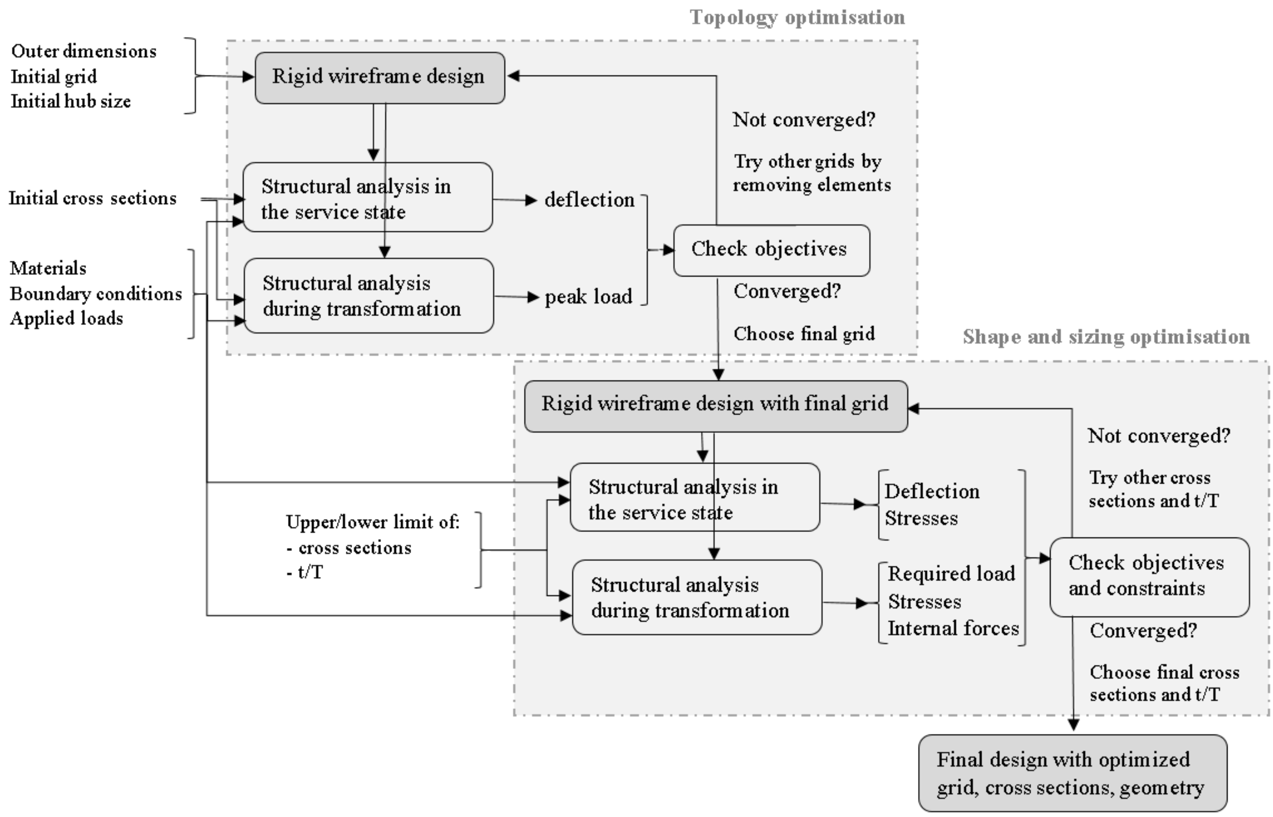


Figure 12: *Proposed computational design methodology for bistable deployable structures.*

5. CONCLUSIONS AND OUTLOOK

A novel design methodology combining TO (topology optimisation) and SSO (sizing and shape optimisation) was elaborated for bistable deployable structures. The example used to demonstrate the methodology was a deployable curved wall, supporting its own weight and the weight of a banner.

A novel TO step was incorporated in which the topology of the structure (distribution of BDM and NBDM in a mixed structure) was optimised at low computational cost. TO was sequenced before or after SSO and the issued results were critically assessed. It was shown that doing the topology optimisation as a first step leads to a more logical sequence of design refinements, and to better results. TO is computationally inexpensive, shown to be independent from the initial set of design variables and useful to obtain feasible, low cost, low weight and complexity topologies. SSO is computationally expensive and it is recommended to use the SSO as a final step for fine-tuning the results. Coupling TO and SSO results not only in solutions with a lower transformation load, but also a lower weight, a lower cost and a decreased complexity. A final computational design methodology was proposed with TO→SSO sequencing. This design methodology could be an important step towards increasing the application potential of bistable deployable scissor structures. As an outlook, the validity of the proposed design methodology could be verified for other structures as well.

ACKNOWLEDGMENTS

This work was supported by a Research Fellow (ASP – Aspirant) fellowship of the Fund for Scientific Research – FNRS (F.R.S.-FNRS) (Grant No. FC 23469).

REFERENCES

[1] L.I.W. Arnouts, T.J. Massart, N. De Temmerman and P.Z. Berke, "Multi-objective optimization of deployable bistable scissor structures", *Automation in Construction*, vol. 114, pp. 103154, 2020. DOI: 10.1016/j.autcon.2020.103154

[2] L.I.W. Arnouts, T.J. Massart, N. De Temmerman and P.Z. Berke, "Computational design of bistable deployable scissor structures: trends and challenges", *Journal of the International Association for Shell and Spatial Structures*, vol. 60, pp. 19-34, 2019. DOI: 10.20898/j.iass.2019.199.031

[3] Z. You, "Sensitivity analysis based on the force method for deployable cable-stiffened structures", *Engineering Optimization*, vol. 29(1-4), pp. 429-441, 1997. DOI: 10.1080/03052159708941006

[4] A. Kaveh A. and S. Shojaee, "Optimal design of scissor-link foldable structures using ant colony optimization algorihm", *Computer-Aided Civil and Infrastructure Engineering*, vol. 22, pp. 56-64, 2007. DOI: 10.1111/j.1467-8667.2006.00470.x

[5] A.P. Thrall, M. Zhu, J.K. Guest, I. Paya-Zaforteza and S. Adriaenssens, "Structural optimization of deploying structures composed of linkages", *Journal of Computing in Civil Engineering*, vol. 28(3), pp. 04014010-1-11, 2014. DOI: 10.1061/(ASCE)CP.1943-5487.0000272

[6] L. Alegria Mira, A.P. Thrall and N. De Temmerman, "The universal scissor component: optimization of a reconfigurable component for deployable scissor structures", *Engineering Optimization*, vol. 48(2), pp. 317-333, 2015. DOI: 10.1080/0305215X.2015.1011151

[7] A. Koumar, T. Tysmans, R. Filomeno Coelho and N. De Temmerman, "An automated structural optimisation methodology for scissor structures using a genetic algorithm", *Applied Computational Intelligence and Soft Computing*, vol. 2017, pp. 1-13, 2017. DOI: 10.1155/2017/6843574

[8] M. Salar, M.R. Ghasemi and B. Dizangian, "Practical optimization of deployable and scissor-like structures using a fast GA method", *Frontiers of Structural and Civil Engineering*, vol. 13(3), pp. 557-568, 2019. DOI: 10.1007/s11709-018-0497-z

[9] C.J. Gantes, P.G. Georgiou and V.K. Koumousis, "Optimum design of deployable structures using genetic algorithms", *Transactions on the Built Environment*, vol. 35, pp. 255-264, 1998. DOI: 10.2495/SM980231

[10] L.I.W. Arnouts, T.J. Massart, N. De Temmerman and P.Z. Berke, "Computational modelling of the transformation of bistable

scissor structures with geometrical imperfections", *Engineering Structures*, vol. 177, pp. 409-420, 2018. DOI: 10.1016/j.engstruct.2018.08.108

[11] K. Deb, S. Pratap, S. Agarwal and T. Meyarivan, "A fast and elitist multi-objective genetic algorithm: NSGA-II", *IEEE Transactions on Evolutionary Computation*, vol. 6, pp. 182-197, 2002. DOI: 10.1109/4235.996017

[12] Y. Tian, R. Cheng, X. Zhang and Y. Jin, "PlatEMO: a MATLAB platform for evolutionary multi-objective optimization", *IEEE Computational Intelligence Magazine*, vol. 12(4), pp. 73-87, 2017. DOI: 10.1109/MCI.2017.2742868