Exploration for a convenient shape-stress correction of a tensegrity girder

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Abstract

Tensegrities are interesting candidates for being intelligently adaptated according to changing environmental conditions because of their mechanical features, i.e. flexibility and stabilisation using self-stress of the system as a result of an interaction among tension and compression members. Aim of the mentioned adaptation, in terms of shape and stress modifications, is to meet system's service and ultimate state criteria. In the contribution is presented an exploration procedure which is able to effectively find a convenient shape as well as stress correction of selected tensegrity girder with respect to defined goals. Obtained calculated results are acceptable in a range of chosen search criteria.

Keywords: tensegrity system, tension, compression, active member, shape-stress correction, exploration

1. Introduction

Tensegrities, since their inception, are of the interest in a research sphere already for more than 60 years. Such systems comprise tension (cables, etc.) and compression load-bearing members (struts, etc.). All members are held together in a stable configuration by means of self-stress state, stemming from a convenient initial geometry and stress, see Ref. [7].

Adaptive tensegrity systems, in order to withstand changing load conditions of the surrounding environments, are able to be regulated by means of sensors, control computer and active members (actuators). With an evolution of information technology, machines and materials such structures indicate a potential in maybe each field of engineering, see Ref. [7].

The paper deals with a procedure for revealing of satisfactory shape-stress correction of a tensegrity girder regarding to defined criteria.

2. Design exploration for suitable active members' length corrections of a tensegrity girder

2.1. Properties of analysed numerical model

Tensegrity girder is composed of 5 four-strut tensegrity units. Each unit is of following theoretical sizes: (i) bottom base is of 2 × 2 m; (ii) top base is of 1.414 × 1.414 m; (iii) a height is of 1.5 m. Theoretical span of the girder is 10 m. Whole structure consists of 28 nodes, 56 cables and 20 active compression members (together 76 members). Three-dimensional model of the girder may be seen in Fig. 1.

In a case of materials, stainless austenitic steel 1.4401 was chosen for cables with a construction of 1 × 19. Young's modulus for cables is $130 \cdot 10^9$ Pa. Steel S235 was considered for active struts with its Young's modulus of $210 \cdot 10^9$ Pa. Cross-section of the active members was considered to be constant along their theoretical length of 2.693 m in the initial geometry.

Numerical model of the system was created in ANSYS 16.0 software. All members were modelled as truss finite elements. More precisely, LINK11 (linear actuators capable of length modifications) and LINK180 elements were considered for active members and for cables respectively, see Ref. [1].

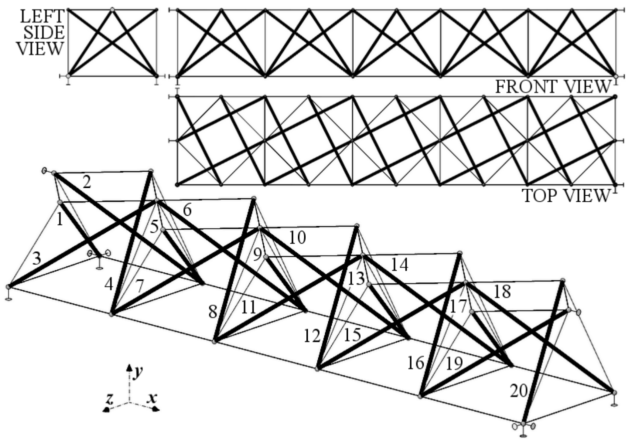

Figure 1: Plot of analysed tensegrity girder with numbered active members (thick members)

2.2. Short insight into employed procedure

For the purpose of finding a satisfactory shape-stress modification of examined tensegrity girder a design exploration (DE) procedure was used. DE is based on an assumption about system evolution during searching. However, without any proof about convergence, see Ref. [6].

Generally, the DE procedure is realised by optimisation algorithm generating inputs (design variables) for numerical simulations (approximative metamodel or direct computer simulations) which calculate outputs (state variables).

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Table 1: Optimal acquired length modifications of active members

Δl_1	Δl_2	Δl_3	Δl_4	Δl_5	Δl_6	Δl_7	Δl_8	Δl_9	Δl_{10}	Δl_{11}	Δl_{12}	Δl_{13}	Δl_{14}	Δl_{15}	Δl_{16}	Δl_{17}	Δl_{18}	Δl_{19}	Δl_{20}
(x10^{-3}) m																			
-	-8.5	9.0	10.0	8.5	-16.0	7.5	-	1.5	-	4.5	-	-4.5	8.0	-9.5	6.0	12.5	1.0	-4.0	-

Outputs are then checked according to defined objective functions and constraints, if any is present. If outputs are satisfactory the DE procedure is finished. Otherwise, new inputs are generated and the whole procedure continues. Success of finding a suitable solution to a DE is problem and goals' dependent and may uncover new facts about explored model, as well, see Ref. [6].

Since the shape-stress correction of analysed system was investigated in the contribution, length corrections of active members were considered for inputs. Additionally, cross-sectional areas for load-bearing members using data in accordance with Ref. [3,5] and also initial pre-tension in cables were searched as inputs, as well. For DE's outputs were selected minimal/maximal nodal displacements and normal forces in members which were obtained by executing geometrically non-linear and physically linear static structural analyses. For such purpose was employed a finite element method and an incremental iterative Newton-Raphson procedure. Equilibrium of forces in such analyses may be derived from a basic formula seen in Ref. [2]

$$\mathbf{K_T} \cdot \mathbf{u} = \mathbf{F} \qquad (1)$$

where $\mathbf{K_T}$ is a tangent stiffness matrix, **u** is a vector of unknown nodal displacements, **F** is a vector of applied nodal loading forces (in global coordinates).

Examined tensegrity system was loaded firstly by its self-weight and subsequently by external static loading forces of $F_{x,y,z}$ = -2,000 N (according to orientation of global axes shown in Fig. 1). Afterwards, length corrections onto the active members were applied. Structural analyses were calculated using ANSYS 16.0, see Ref. [1] coupled with multi-objective hybrid and adaptive optimisation algorithm SHERPA employing a software HEEDS 2015.04.2, see Ref. [4].

Optimisation objectives in the contribution were elected as follows, minimisation of: (i) maximal nodal displacement in *x*, *y* and *z* direction separately; (ii) maximal difference among nodal displacements in *x*, *y* and *z* direction respectively; (iii) maximal length correction of the active members; (iv) maximal difference among length corrections of the active members; (v) number of the active members needed for actuation; (vi) maximal normal force in the cables; (vii) maximal normal force in the active members; (viii) maximal difference in the normal forces in each member between the last (self-weight, loading forces and active members' actuation) and the previous (self-weight and loading forces) load case; (ix) initial pre-tension force in the cables; (x) cross-sectional area of the cables; (xi) cross-sectional area of the active members; (xii) diameter of active members' cross-sections because the cross-sections in the DE procedure are represented by circular tubes with different diameters and wall thicknesses.

Defined constraints are for: (i) maintaining of all nodal displacements under 0.04 m which is 1/250 of the theoretical girder span (deflection limit for trusses) and keeping them above 0.035 m in order to force the DE procedure to stay near the upper limit; (ii) regulating of minimal/maximal normal forces to achieve tension in the cables and compression in the active members; (iii) keeping of maximal normal forces in all members below their resistance (tensile resistance of the cables and buckling resistance of the active members). Active members' length changes were bounded by -0.05 and 0.05 m, initial pre-stress was kept between values 1,000 and 100,000 N.

2.3. *Acquired results*

Optimal obtained length corrections Δl of the active members are highlighted in Tab. 1 (zero length corrections are marked by dashes). Defined objectives were calculated as follows, according to chapter 2.2. (before/after correction): (i) nodal displacement in *x*, *y* and *z* direction is -44.3/-38.0, -93.0/-39.3, -49.0/37.6 mm respectively; (ii) difference among nodal displacements in *x*, *y* and *z* direction is 85.7/75.0, 104.2/66.1, 92.4/74.4 mm respectively; (iii) length correction of the active members is -0.016 m; (iv) difference among length corrections of the active members is 0.0285 m; (v) number of the active members needed for actuation is 15; (vi) normal force in the cables is 127,891/168,498 N; (vii) normal force in the active members is -155,543/-232,321 N; (viii) difference in the normal forces in each member between the last and the previous load case is 76,778 N; (ix) initial pre-tension force in the cables is 95,000 N; (x) cross-sectional area of the cables is $288.9 \cdot 10^{-6}$ m^2 for nominal cross-sectional diameter of $22 \cdot 10^{-3}$ m, cables' tensile resistance is 280,000 N; (xi) cross-sectional area of the active members is $1{,}890 \cdot 10^{-6}$ m^2; (xii) diameter of active members' cross-sections is $76 \cdot 10^{-3}$ m. The 2 last objective functions refer to a cross-section Ø $76/9 \cdot 10^{-3}$ m. Active members' buckling resistance is 235,457 N.

3. Conclusions

The paper deals with a shape-stress correction of a chosen tensegrity girder. DE procedure, using a hybrid and adaptive multi-objective optimisation technique in combination with finite element method employed for structural analyses, was applied with the aim to find optimal active members' length corrections, cross-sectional areas and initial pre-tension. As a result, achieved was a remarkable shape-stress correction of the girder in accordance with all defined goals.

Results gained from DE procedures may be applicated in the case of adaptive tensegrity systems by means of which such systems can be trained and continuously controlled.

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