Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

MUSCLE: a new open-source Grasshopper plug-in for the interactive design of tensegrity structures

Jonas FERON[a], Basile PAYEN[a], João ALMEIDA[a], Pierre LATTEUR[a]*

* Institute of Mechanics, Materials and Civil Engineering, UCLouvain
Place du levant 1/L5.05.01, Louvain-la-Neuve 1348, Belgium
pierre.latteur@uclouvain.be

[a] Institute of Mechanics, Materials and Civil Engineering, UCLouvain, Belgium

Abstract

This paper introduces 'MUSCLE', a new open-source plug-in for Rhino-Grasshopper, devoted to the design, analysis, and optimisation of tensegrity and tension-based structures. MUSCLE offers various types of structural analysis, including 1) Non-linear static analysis under external loading or prestressing, 2) Form-finding and deployment through dynamic relaxation, and 3) Computation of mechanisms, self-stress modes, and natural vibration modes. The structural results provided by MUSCLE, such as internal forces, displacements, and natural frequencies, align closely with benchmark experimental measurements obtained from large-scale tensegrity prototypes built by the authors. Additionally, MUSCLE features a user-friendly interface that allows users to visualise calculation outcomes instantly and adjust structural parameters, thereby fostering creativity in the design process. Engineered for fast and complex non-linear computations, MUSCLE serves as an efficient optimisation tool when coupled with Galapagos, enabling users to maximise structural stiffness or minimise material consumption.

Keywords: computational design, form-finding, dynamic relaxation, SVD, Grasshopper, Rhino3D, Kangaroo, Karamba, Galapagos

1. Introduction

The Architecture, Engineering, and Construction (AEC) industry is currently undergoing a revolution driven by the increasing adoption of computational design [1]. Computational design combines parameters and algorithms to easily explore the design space. After breaking down their logic into manageable steps (i.e. into an algorithm), designers can receive immediate feedback regarding certain variations of the structural parameters (such as topology, shape, elements' size, or materials). This allows for the optimisation of arbitrary objectives (such as self-weight, cost, or embodied carbon) within constraints that ensure the design's adequacy, reliability, and sustainability [2], [3], [4], [5].

To both automatically update the structure's geometry and the structural analysis, strong connections are required between the CAD (Computer-Aided Design) and the structural analysis software. In this context, the visual programming language Grasshopper offers appealing solutions to designers as it runs within the CAD environment Rhino3D [6]. In addition to powerful and abundant native geometrical functions represented as input-output components, Grasshopper (GH) allows for the development of custom plug-ins that may for instance perform the structural analysis (see Figure 1).

Karamba3D [7] is a well-known GH plug-in developed by C. Preisinger for the structural analysis of various structural types such as frames, trusses, or shells. Karamba3D is an intuitive and powerful tool that allows for clear visualisation of the structural results. Nevertheless, Karamba3D may lack suitability for tensegrity and tension-based structures which can be prestressed mechanisms [8], [9].

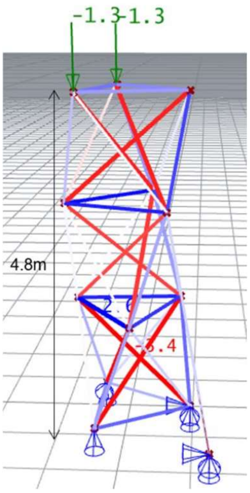

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Figure 1: Project intuitively designed by UCLouvain students with MUSCLE, a) Forces in a tensegrity tower computed by MUSCLE and visualised in Rhino3D, and b) Construction of the project.

Tensegrity structures, renowned for their architectural appeal, have captivated the scientific community for over 70 years, finding applications in robotics, aerospace, and more [10] due to their deployability and adaptability to external stimuli. They have also inspired various civil engineering applications like footbridges, towers, or domes [11]. Despite this, the number of built tensegrity structures remains limited in the AEC industry. Potential explanations are their lack of stiffness, their excessive self-weight, their lack of robustness, their construction complexity, the challenges related to their prestressing [12], which result in a lack of trust from the structural designers. Furthermore, there are few comprehensive tools for their design and analysis, which is addressed in this article.

K2Engineering [13] is an open-source GH plug-in suitable for the analysis of tensegrity structures. It relies on the GH native component Kangaroo2 to perform the Dynamic Relaxation (DR), a well-known form-finding and analysis method [14], [15], [16]. This implies that the DR implementation used for the structural analysis is not open-source and may suffer from slow convergence. In addition to this plug-in, other software exists outside Grasshopper to deal with tensegrity structures analysis. The software *ToyGL* [17] and *PushMePullMe* [18] can simulate the real-time physics and analyse tensegrity structures, while *MOTES* can perform dynamic analysis [19]. It is noteworthy that some robotics software like the *NASA Tensegrity Robot Toolkit* or *NTRT* [20], were made to model deployable and intelligent structures. However, some of these codes lack full open-access, parametric and optimisation capabilities, user-friendliness, or suitability for the AEC industry.

This article presents MUSCLE, a comprehensive tool for the parametric design, analysis, and optimisation of tensegrity structures, developed as a Grasshopper plug-in at the UCLouvain. It is the result of extensive research from 2015 to 2023, including a PhD [11] and multiple master's theses. MUSCLE offers various types of analysis methods, including linear or non-linear static analysis, form-finding and deployment through dynamic relaxation, computation of mechanisms, self-stress modes, and natural vibration modes. MUSCLE combines parametric and algorithmic thinking with robust and efficient finite element methods. The GH native component Galapagos allows for the optimisation of the structural parameters to find the most material consumption efficient structure. This is only possible thanks to the fast computation time of the analysis methods optimised in Python3. The GH plug-in is fully open-source and developed externally in C# and Python3 to make the most of each language. The parametric capacity of MUSCLE coupled with its user-friendly interface and efficient non-linear analysis allows to design of all kinds of tensegrity and truss-like structures without any programming skills. The tower shown in Figure 1 was for instance designed and built by engineering students and analysed with MUSCLE. Finally, MUSCLE results were compared to experimental measurements obtained by the authors with the highest accuracy on an aluminium model of the simplest 3D tensegrity structure [21], [22]. All these aspects are developed in section 2, while a practical example of MUSCLE on a 15 metres span bamboo tensegrity footbridge is discussed in section 3.

2. MUSCLE overview

2.1. Initial geometry generation through parametric design

MUSCLE was developed in the Rhino-Grasshopper environment due to several advantages that explain its widespan acceptance in the AEC industry:

- Grasshopper provides an intuitive interface with graphical elements, eliminating the need for users to have programming language skills. Visual components can be placed and interconnected within Grasshopper's canvas, making it simple to use and program. Each of these components serves a specific function converting the inputs into outputs.
- Grasshopper provides parametric tools such as native slider components, allowing the users to quickly modify parameters, study geometric variations in structures, and easily adjust the inputs.
- Rhino's windows enable the real-time display of structural configurations given the Grasshopper instructions. Conversely, geometries may also be sketched directly in the Rhino3D's environment which may serve as input parameters in Grasshopper.

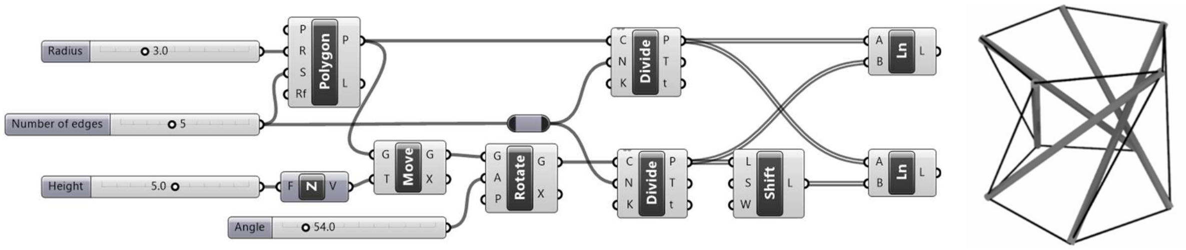

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Figure 2: Parametric definition of prismatic tensegrity modules, a) Definition of parameters and geometrical generative algorithm using native Grasshopper components, and b) Associated geometry visualised in Rhino3D.

With Grasshopper native components, users can parametrically generate all kinds of geometries. If some functions are missing, users may develop them using C#, Python2 or VBA scripts directly in Grasshopper, and outside Grasshopper through C# or VBA code. MUSCLE is a package of Grasshopper components that bring structural analysis functionalities which have been developed in C# outside Grasshopper while communicating with Python3 to perform fast structural computations. MUSCLE input is the initial geometry drawn as in Figures 2, 3 and 4 using native Grasshopper components.

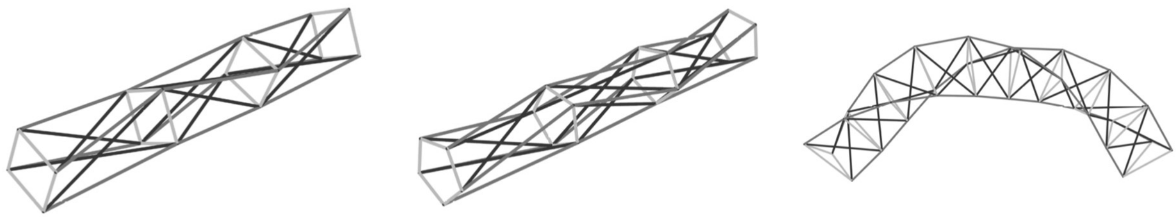

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Figure 3: Unidimensional assemblies of prismatic tensegrity modules with variation of, a) reference structure, b) reference polygon, and c) along a defined curve.

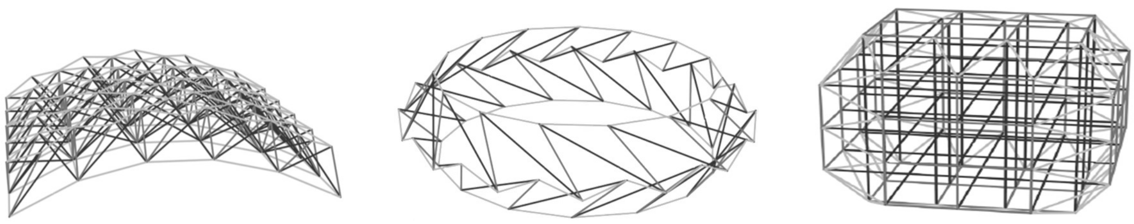

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Figure 4: Assemblies of tensegrity modules of various shapes along a) a plane, b) a ring and c) a volume.

The tensegrity geometries illustrated in Figures 2-4 are generated based on native Grasshopper components similar to Figure 2a. This Grasshopper script is provided with MUSCLE as a basis for tensegrity design. For instance, Figure 3a shows a unidimensional straight assembly tensegrity structure with some variations based on different parameters. Some other multi-dimensional assemblies are depicted in Figure 4. MUSCLE's users are, of course, invited to imagine and generate any truss and tensegrity geometry they wish. The interest of MUSCLE components is to ensure the feasibility and stability of the intended geometry.

2.2. Form-finding with dynamic relaxation

Once an initial geometry has been defined, nothing guarantees that it is in tensegrity, with compressed bars inside tensioned cables. For instance, the structure Figure 5a - with three struts, nine cables and 0° between the top and bottom horizontal triangles - is not feasible nor stable unless all cables are replaced by struts, which is a common truss structure that can be easily analysed by any classical structural analysis software.

Form-finding designates the search for the nodal coordinates ensuring the equilibrium of a given topology. In the case of Figure 5a, form-finding refers to the search of geometry ensuring that internal self-stress forces can exist without external loads and within the general constraint of all cables in tension. Several form-finding methods exist [15], [16] and usually involve non-linear techniques since large displacements occur through the process. The Force-Density Method (FDM) [23] is a very common form-finding method allowing it to be solved linearly. FDM takes the force densities (internal force divided by current length) as input and provides the nodal coordinates in equilibrium. Using FDM, designers are thus required to arbitrarily define the values of the force densities, which is the reason why the Dynamic Relaxation (DR) method is implemented in MUSCLE to solve the form-finding problem.

DR is a non-linear procedure taking as input the manufacturing (or free) lengths of the elements as well as possible external loads, and provides the nodal coordinates in equilibrium. DR can thus perform non-linear prestressing, non-linear loading and deployement analysis, which are all a kind of form-finding.

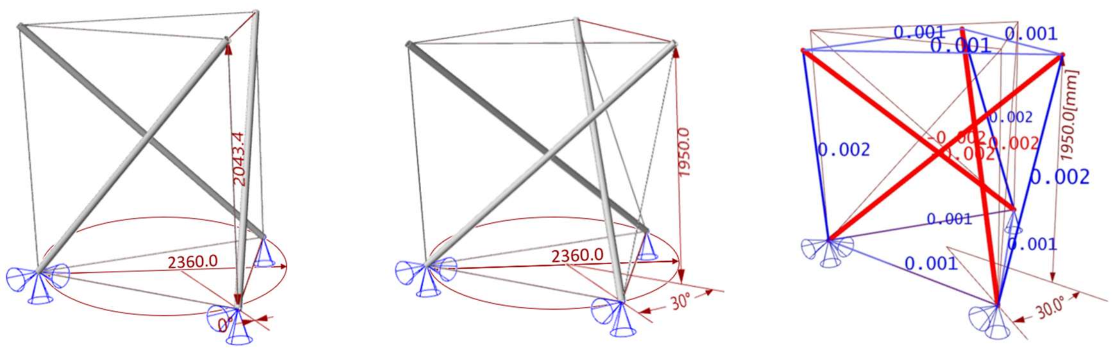

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Figure 5: Simplex form-finding without self-weight: a) unstable initial prismatic geometry with $\alpha = 0°$, b) form-finding through large lengthening of the 3 struts ($2890.1 \rightarrow 2999.8$mm), c) resulting stable geometry with internal force, red in compression and blue in tension.

Using DR for the form-find of Figure 5a, the three struts can be lengthened until self-stress forces appear. After lengthening the struts, the angle reaches 30° (Figure 5b) which corresponds to the tensegrity simplex. The simplex is known to be self-stressable (Figure 5c), which means that any further struts lengthening will increase the self-stress forces and ensure tension in the cables as described next.

2.3. Singular Value Decomposition (SVD)

The SVD [8] can be performed within MUSCLE, and the results can be visualised as in Figure 6 to obtain insightful information regarding the behaviour of any structure. On the one hand, computing the self-stress modes (Figure 6b) allows to evaluate the prestress-ability of the structures resulting from sections 2.1 or 2.2. This may guide the designers when choosing the cable locations. Computing the mechanisms (Figure 6a) on the other hand shows if geometric non-linearities need to be considered under loading. This may help the designers to choose an appropriate structural analysis method.

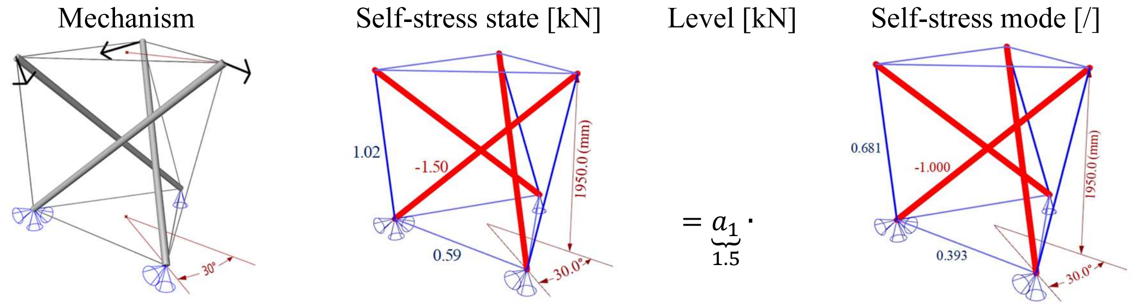

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Figure 6: Singular Value Decomposition results in, a) the inextensional modes (i.e. displacements without elongation), and b) the self-stress modes, which can be multiplied by arbitrary levels to obtain a self-stress state.

2.4. Linear prestressing

With MUSCLE, prestress forces can be introduced through two methods [12]:

2.4.1. Theoretical prestressing through arbitrary increases of self-stress levels $\{\boldsymbol{a}\}$

Figure 7 shows that after performing the SVD on any structure, a self-stress state can be obtained arbitrarily by choosing the values of the self-stress levels $\{\boldsymbol{a}\}$. This method remains theoretical since it assumes no geometrical distortion during the prestress implementation.

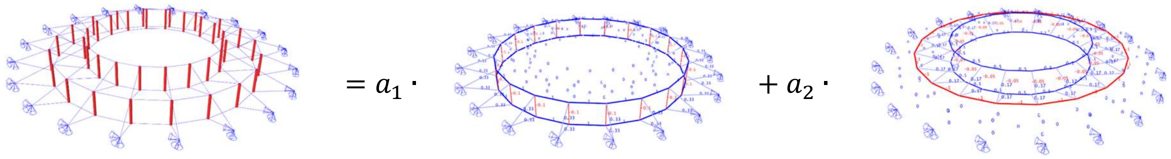

Figure 7: Self-stress state of a Geiger dome obtained by the addition of two self-stress modes multiplied by their arbitrary levels.

2.4.2. Practical prestress implementation through cables shortening and struts lengthening

In practice, self-stress forces co-exist inevitably with self-weight forces (except in outer space) which may activate the mechanism (Figure 8a) and influence the geometry of the structure. A comprehensive experimental campaign was performed at UCLouvain [21], [22] on an aluminium simplex (Figure 10a) with 8 mm diameter cables and 60 mm diameter struts with wall thickness 2 mm. Figure 8b and c show the influence of lengthening all the struts on the internal forces and the rotation angle of the top horizontal triangle. Measurements were compared with both the DR and the theoretical prestressing results obtained with MUSCLE. Other prestress implementation tests are described in [21], [22].

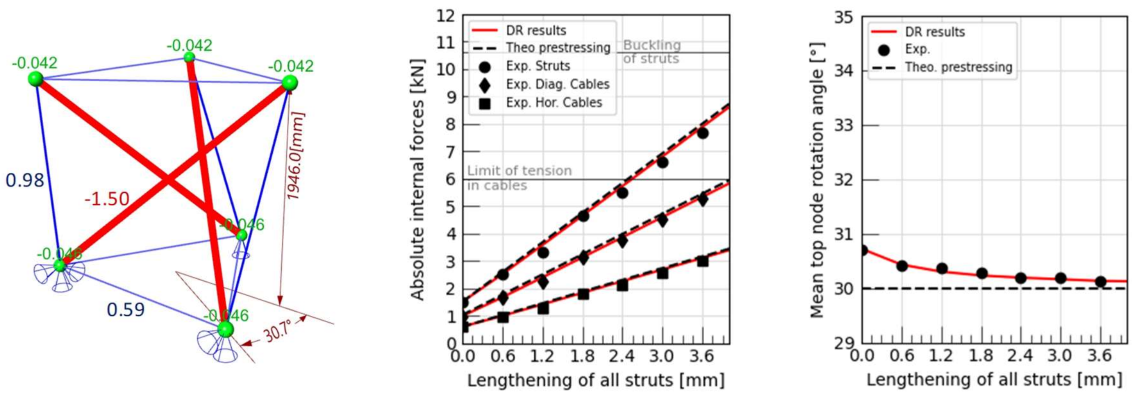

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Figure 8: Practical prestress implementation from a) initial self-stress state including self-weight (green sphere). The experimental measures obtained by lengthening the struts have been compared to the theoretical prestressing, and the DR results from MUSCLE in terms of b) the absolute internal forces, and c) rotation angle.

It must be noted that the increase of self-stress level resulting from lengthening the struts tends to reduce the angle towards 30°. This illustrates that self-stress forces increase the stiffness of the mechanism (Figure 6a) against the self-weight.

2.5. Non-linear prestressing

Consider that another cable is added in the simplex structure of Figure 6b which was already self-stressed by a level $a_1 = 1.5$ kN. The additional cable in Figure 9a has a free-length of 2556.7 mm and is equipped with a turnbuckle susceptible to alter it. Figure 9b shows that, initially, the force in the additional cable is null since it was just installed. Figure 9c shows the self-stress forces existing in the deformed shape after shortening the additional cable by 50 mm. It is noted that tensegrity simplex with additional cables can be stable for angles different than 30°. Figure 9 illustrates thus a non-linear prestressing phenomenon with large displacements and large free-length variation. Non-linear prestressing and form-finding are hence certainly synonyms. Finally, it may be noted that the simplex at 30° and the simplex with additional cable at 34.1° have both a single self-stress mode (as obtained by SVD) but with very different forces distributions. Also, the simplex with additional cable has no mechanism.

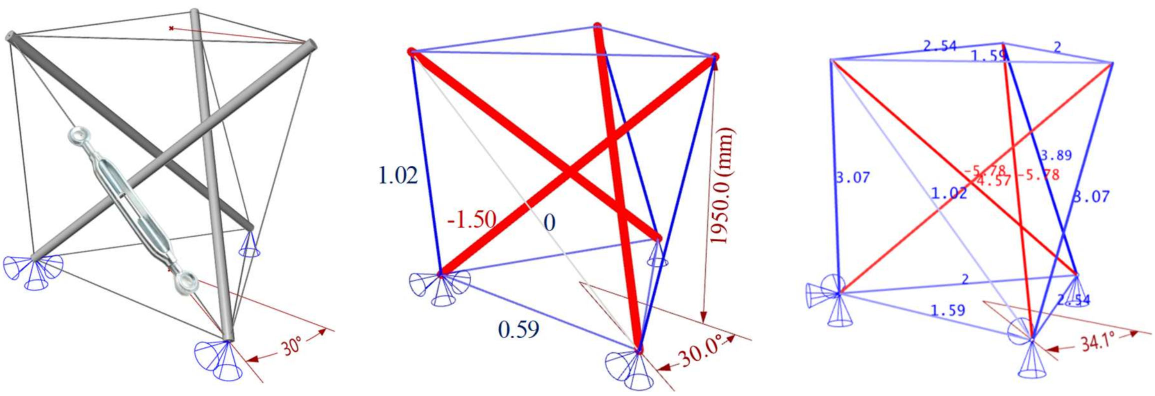

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Figure 9. Non-linear prestressing of a) a simplex with an additional cable, b) initial self-stress state before shortening, and c) resulting prestressed geometry after large displacement imposed by a 50 mm shortening.

2.6. Linear external loading through static modal analysis

The linear displacement and force methods of analysis have also been implemented in MUSCLE components. The static equilibrium and compatibility equations are solved by passing through the static modal spaces composed of the extensional, inextensional, and self-stress static modes obtained from the SVD. The reader is invited to refer to [9] for a comprehensive description of these methods. The authors intend to investigate the extension of this new modal paradigm to other structural analysis problems such as linear prestressing or non-linear loading for instance.

2.7. Non-linear external loading

Restarting from the initial self-stress state of Figure 8a, the simplex (without additional cable) is now subjected to external loading (Figure 10a). The numerical results obtained through DR are consistent with the experimental results, both in terms of internal forces (Figure 10b) and angle (Figure 10c). However, under the application of large external loads, a discrepancy of 11% is observed in the internal forces of the struts. This mismatch may be attributed to the bending of the struts in the prototype, which influences their free length and consequently, the distribution of prestress within the structure. For smaller loads not approaching the buckling resistance threshold, MUSCLE proves to be a reliable tool for analysing tensegrity structures.

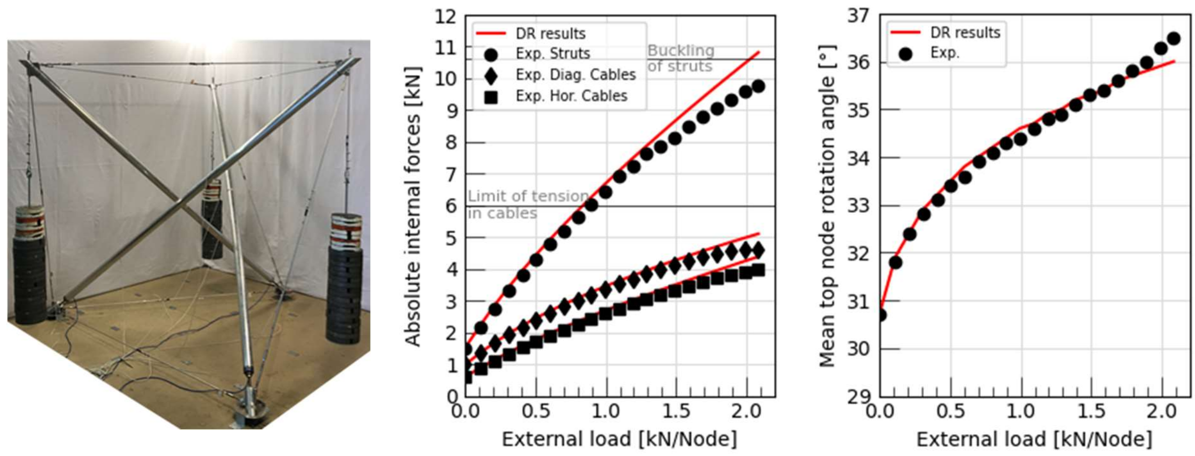

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Figure 10: Comparison of the numerical values from DR and the experimental values of a) a simplex under external loading, b) the absolute internal forces and c) the top nodes rotation angles regarding the external loads applied at each node.

2.8. Dynamic modal analysis

The dynamic modes and their frequency can also be calculated with MUSCLE components as shown in Figure 11. Figure 11c shows the comparison between numerical results and experimental measures obtained on the aluminium simplex using accelerometers placed on the top nodes.

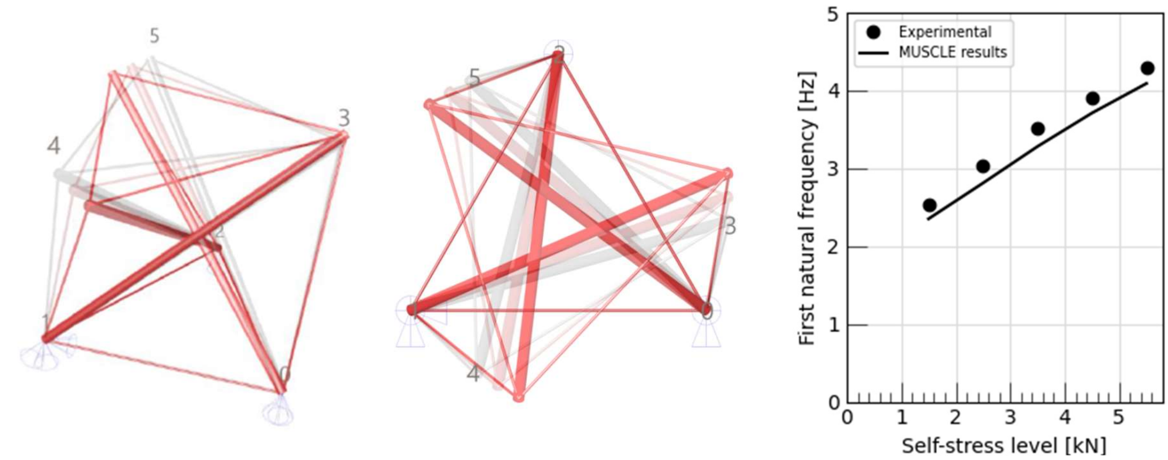

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Figure 11: First dynamic mode (computed with MUSCLE) of the simplex, with the faded shape being the initial geometry, a) perspective view, b) top view and c) the numerical values from MUSCLE and the experimental values of natural frequency varying with the self-stress level.

The first dynamic mode (Figure 11) follows the mechanism direction (Figure 6a). It is well known that the stiffness of the mechanism relies upon the geometric stiffness, i.e. upon the level of self-stress forces (Figure 6b). Hence, Figure 11 shows that the first fundamental frequency (associated with the mechanism) increases with the self-stress level. Figure 11 shows a satisfactory correlation between MUSCLE results based on the consistent mass matrix and the experimental measures. It must be noted that the next dynamic modes of the simplex tend to extend the elements which activate the material stiffness of the structure. It has been shown in [24], that the fundamental frequencies associated with extensional dynamic modes are not influenced by the level of self-stress, deciphering the fact that the geometrical stiffness is negligible compared to the material stiffness for such modes.

2.9. Optimisation via the GH native component Galapagos

As aforementioned, MUSCLE offers various efficient structural analysis components engineered to perform fast advanced computations. This is vital to rapidly explore the design space using tools such as Galapagos, a native GH component solving optimisation problems through an evolutionary algorithm, i.e. numerous intelligent trials and errors. Galapagos and MUSCLE can thus be combined as described in [5] to find the structure's parameters minimising for instance the weight, cost, or embodied carbon.

3. Prototype of a 15-meter footbridge designed and calculated with MUSCLE

A scaled prototype of the "Snake bridge" designed and optimised in [2], was built by the authors. Depicted in Figure 12, this 15 meter-span bamboo tensegrity structure, weighting 624 kg, consists of five simplex modules with steel cables and bamboo struts. This example is here used to demonstrate the application of MUSCLE during a real design process.

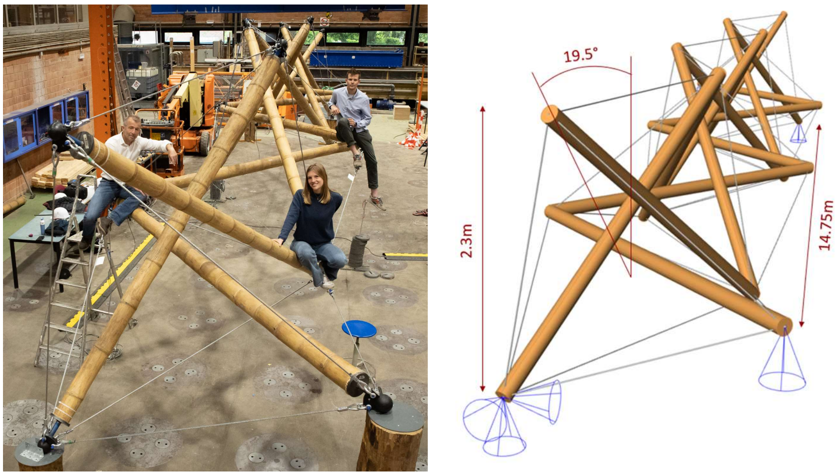

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Figure 12: a) 15-meter span bamboo tensegrity structure b) View in the Rhino3D windows.

Given a fixed span, all other parameters of the structure's geometry had to be optimised. MUSCLE, coupled with Galapagos, was used to determine the height, minimise the prestress, minimise the section of the bamboo struts and the cables. MUSCLE also allowed for the identification of the steps of the prestress, prediction of the deformed shape and determination of the internal forces in each element during the prestressing or external loading. A comprehensive Grasshopper script incorporating MUSCLE's components is depicted in Figure 13. The input parameters allow to create the geometry of the structure, which is then used to generate the finite element model. The model is stored in a "structure" object represented by a blue circle in the script. This object undergoes different loading phases (self-weigh, prestress, and external loads). These are computed using the DR, resulting in a modified geometry and its internal loads.

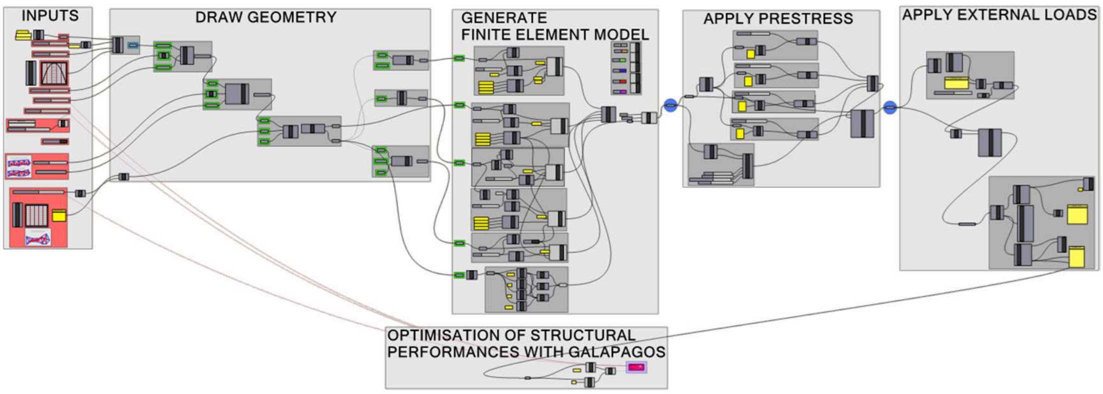

Figure 13: Full script for the structural analysis of the bamboo footbridge with MUSCLE.

The results, such as node positions and internal forces, can be exported or directly represented on the structure as depicted in Figure 14 under Rhino. Slider elements facilitate rapid modification of materials, cross-sections, prestress, or loads, which can be particularly useful during the design process. Any changes made are instantly visible on the Rhino window, providing real-time feedback.

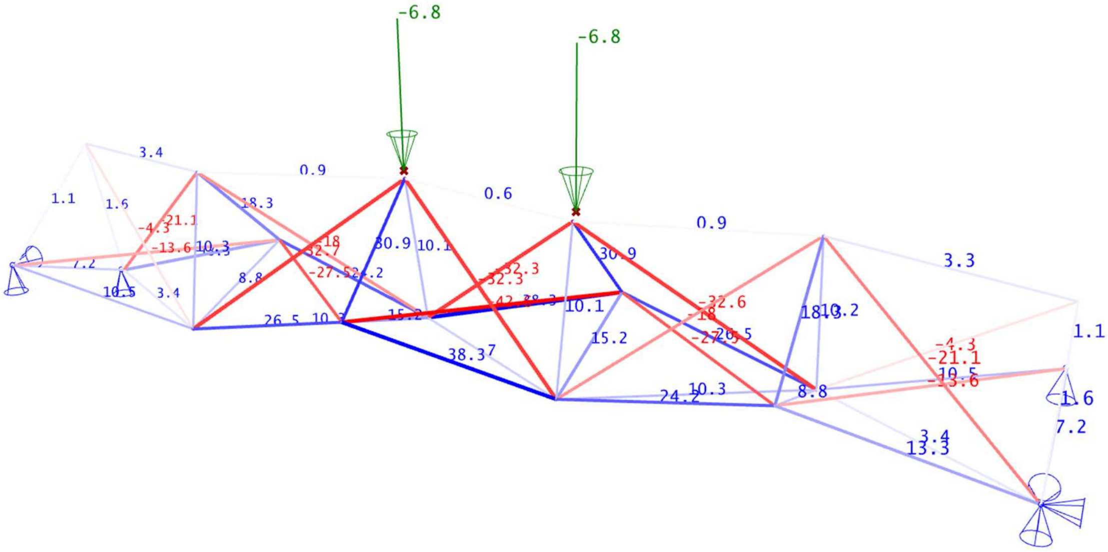

Figure 14: Internal forces [kN] in the bamboo footbridge via dynamic relaxation implemented in MUSCLE.

4. Conclusion

MUSCLE, a new tool for the intuitive and interactive design and analysis of tensegrity structures, is presented in this article. It is a plug-in to the Rhino-Grasshopper environment using computational design to help architects and engineers explore the relevance of tensegrity structures for construction projects. MUSCLE allows the designer to analyse each step of the construction of tensegrity structures. The Dynamic Relaxation method provides a correct shape of the structure and the internal forces. MUSCLE was validated with a real-scale experimental campaign on a 2 m high aluminium simplex, with a very good fit between the experimental and numerical values. This verification was followed by another experimental campaign on a 15 m span bamboo structure designed with MUSCLE. When coupled with Galapagos, the structural performances can be optimised within constraints of resistance and stability. The combination of MUSCLE and Galapagos is only possible thanks to the efficient implementation of all MUSCLE analysis methods. MUSCLE will soon be fully open-source on GitHub.

During testing, a difference was observed with the aluminium simplex under near-rupture loads, which could be due to the bending of the strut elements in the prototype. Further developments may thus investigate the use of Dynamic Relaxation with beam elements [25] rather than truss elements, to consider not only axial forces but also bending and shear.

Acknowledgements

The French Community of Belgium – FSR program for the financial support. Brussels Capital Region Innoviris for the financial support (Applied PhD 2019-2023). BESIX Engineering Department for the support of MUSCLE development. Many end master students from 2016 to 2023, in particular A. Flamant, A. Desmet, M. Caulier, N. Bouchat, T. Houriez and V. Labrouche.

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