The Journal of Open Source Software

TsgFEM: Tensegrity Finite Element Method

Shuo Ma [1], **Muhao Chen** [2¶], **and Robert E. Skelton** [2]

1 College of Civil Engineering, Zhejiang University of Technology, Hangzhou, Zhejiang, China **2** Department of Aerospace Engineering, Texas A&M University, College Station, Texas, USA ¶ Corresponding author

DOI: 10.21105/joss.03390

Software

- Review
- Repository
- Archive

Editor: Patrick Diehl

Reviewers:

- @HaoZeke
- @Kevin-Mattheus-Moerman
- @likask

Submitted: 09 June 2021
Published: 04 July 2022

Summary

The name of this software, TsgFEM, is suggested to be pronounced as Tenseg FEM. The purpose of this package is to facilitate the analysis of statics and dynamics of any tensegrity structures. The software allows one to perform topology design, statics, and dynamic FEM simulation of any tensegrity systems.

This software allows one to do the following studies but is not limited to the listed items.

Topology design:

1. Modeling any tensegrity structures by nodal coordinates and the node's connectivity information.
2. Specifying the constraints of nodal coordinates and grouping structure members and forcing them to have the same force densities.

Statics:

1. Conducting structure equilibrium configuration, pre-stress design, and stiffness studies.
2. Performing pre-stress and mechanism modes analysis.
3. Checking stiffness, stability, and robustness in terms of pre-stress, materials, and geometric information of the structure.
4. Conducting studies on form-finding of tensegrity systems.
5. Simulating the forced motion of structures.
6. Studying the feasibility of pseudo-static deployment trajectories.

Dynamics:

1. Rigid body dynamics with acceptable errors. This is achieved by setting relatively high stiffness for bars in the dynamics simulation.
2. FEM dynamics simulation with elastic or plastic deformations in the presence of various kinds of boundary conditions, such as fixing any nodes in any direction, applying static or dynamic external forces (i.e., gravitational force, some specified forces, or arbitrary seismic vibrations).
3. Modal analysis, including natural frequency and corresponding modes.
4. An interface towards structural control by a compact state-space form of a linear model.

The governing equations of the dynamics are derived based on the Lagrangian method with a nodal coordinate vector as the variable and given in an explicit form (Ma et al., 2022). The dynamics ordinary differential equation is solved by ode4 to simulate the dynamics of any complexity tensegrity structure. By neglecting the time derivatives terms, one can get the statics equations. The statics equation is solved by a modified Newton method to guarantee the result converges to a stable equilibrium configuration. The software allows solving for the minimum mass subject to buckling and yielding failures of structure members by optimizing the cross-sectional area in the strings and bars in the presence of any external forces (M. Chen & Skelton, 2020). The minimal mass problem is a constraint nonlinear optimization one in terms of the force densities in the structure members. The nonlinear optimization problem is solved by the Matlab function fmincon. We also provide a detailed user manual and strongly suggest beginners follow the descriptions step by step. TsgFEM provides a set of unit test and demonstration examples. The unit tests and accuracy discussion is given in the last section of the user manual.

Motivation and Introduction

Tensegrity is a coined word by Buckminister Fuller (Fuller, 1982) for the art form created by Ioganson (1921) and Snelson (1948) (Lalvani, 1996) to represent a stable network of compressive members (bars/struts) and tensile members (strings/cables) (M. Chen & Skelton, 2020). From the definition, it is straightforward to see that the fundamental property of the tensegrity is that all the bars and strings are axially loaded. Since the bars and strings are best in taking compression and tension and there is no material bending, the structure mass can be greatly reduced. Indeed, biological structures also indicate that tensegrity concepts yield the most efficient structures. For example, the bones, muscles, and elbows of animals and humans are tensegrity models. Wang et al. found that microtubules and microfilaments in the living cells work as compressive and tensile members to change the traction of the cell surfaces (N. Wang et al., 2001). Simmons et al. showed that the DNA bundles are consistent with tensegrity prism (Liedl et al., 2010). After decades of study, many lightweight structures have been redesigned by the tensegrity paradigm. For example, Skelton and de Oliveira proved that T-Bar and D-Bar structures require less mass than a signal rod in taking compressive buckling load (Skelton & Oliveira, 2009). Ma et al. showed a mass efficient tensegrity cantilever structure subject to yield and buckling constraints (Ma et al., 2020). Barbarigos et al. designed and analyzed a lightweight pedestrian bridge (Rhode-Barbarigos et al., 2010). And many space applications are employing tensegrity solutions, for example, lightweight space habitat (M. Chen et al., 2021b), deployable lunar towers for space mining (M. Chen et al., 2021a), and planetary landers (Luo & Liu, 2017; Sabelhaus et al., 2015). Moreover, the many advantages of tensegrity have also attracted researchers to find new ways to design soft robotics, i.e., six-bar tensegrity robot (Booth et al., 2020; K. Wang et al., 2020), robotic spine (Sabelhaus et al., 2020), morphing wings (M. Chen et al., 2020), robotic fish (B. Chen & Jiang, 2019), debris capturing robot (Feng et al., 2021). The statics and dynamics analysis of tensegrity structures is essential to get insight into the structure properties.

Assumptions

Based on the following assumptions, the FEM equations for the statics and dynamics of any tensegrity structures are formulated:

1. All the structural members are axially loaded and are connected by frictionless ball joints.
2. The structural members are allowed to have elastic or plastic deformation.
3. The rotation of the structure member along its longitudinal axis is neglected.

4. Each structural member is homogeneous along its length and of an equal cross-section. Thus, the mass of each structural member is distributed uniformly along its length.

5. A string can never push along its length; tension in the string is substituted to zero. Based on the FEM and Lagrangian methods with nodal vectors as the generalized coordinates given in (M. Chen & Skelton, 2020; Ma et al., 2022), we developed TsgFEM (Tensegrity Finite Element Method).

Statement of need

For the FEM analysis for tensegrity structures, little research has been conducted. For example, Zogoul et al. conducted a static study for a tensegrity bridge by FEM (Zgoul et al., 2012). Jensen et al. showed the finite element analysis of tensegrity structures in offshore aquaculture installations by ABAQUS (Jensen et al., 2007). Kan et al. formulated the dynamics of clustered tensegrity structures by FEM (Kan et al., 2018). However, most of these analyses use commercial software or assume the structure members are elastic. Few software packages have been developed for the analysis of tensegrity statics and dynamics. For example, STEDY (Tadiparthi et al., 2019) is a package for conducting tensegrity dynamics with rigid bars based on the Lagrangian method. MOTES (Goyal et al., 2019) is software for the analysis of both statics and dynamics with rigid bars and linear elastic strings. Both of them are rigid body dynamics and developed in non-minimum Cartesian coordinates. However, for many applications, the elastic or plastic deformation of structure members cannot be neglected. It is possible to do the FEM analysis by commercial software, i.e., ANSYS and ABAQUS, but the licenses are expensive, and the modeling and setups require much experience. To this end, we derive a closed-form dynamics equation based on Lagrangian's method with a nodal vector as the generalized coordinate, allowing the user to perform simulations for bars and strings with any given strain-stress properties. The proposed dynamics equation is in a compact form.

The developed software is capable of dealing with large deformation for structures with elastic or plastic materials. The results of the software are compared with analytical solutions as well as commercial software ANSYS. In fact, this software also provides an interface to ANSYS. That is, one can modify the settings in the example source codes based on the simulation needs and run the codes. This software can generate a text file that allows users to run the simulation in ANSYS automatically by using the APDL (Ansys Parametric Design Language) interface. The software has been used for the design and analysis of various tensegrity structures, i.e., tensegrity lunar tower, tensegrity morphing wings, tensegrity cable domes, tensegrity lander, and tensegrity dolphin, where we integrate structure, control design, and signal processing to get the required performance and control law.

References

Booth, J. W., Cyr-Choiniere, O., Case, J. C., Shah, D., Yuen, M. C., & Kramer-Bottiglio, R. (2020). Surface actuation and sensing of a tensegrity structure using robotic skins. *Soft Robotics*. https://doi.org/10.1089/soro.2019.0142

Chen, B., & Jiang, H. (2019). Swimming performance of a tensegrity robotic fish. *Soft Robotics*, *6*(4), 520–531. https://doi.org/10.1089/soro.2018.0079

Chen, M., Goyal, R., Majji, M., & Skelton, R. E. (2021a). Deployable tensegrity lunar tower. *Earth and Space 2021*. https://doi.org/10.1061/9780784483374.100

Chen, M., Goyal, R., Majji, M., & Skelton, R. E. (2021b). Review of space habitat designs for long term space explorations. *Progress in Aerospace Sciences*, *122*, 100692. https://doi.org/10.1016/j.paerosci.2020.100692

Chen, M., Liu, J., & Skelton, R. E. (2020). Design and control of tensegrity morphing airfoils.

Mechanics Research Communications, 103480. https://doi.org/10.1016/j.mechrescom.2020.103480

Chen, M., & Skelton, R. E. (2020). A general approach to minimal mass tensegrity. *Composite Structures*, 112454. https://doi.org/10.1016/j.compstruct.2020.112454

Feng, X., Wu, Z., Wang, Z., Luo, J., Xu, X., & Qiu, Z. (2021). Design and experiments of a bio-inspired tensegrity spine robot for active space debris capturing. *Journal of Physics: Conference Series*, *1885*, 052024. https://doi.org/10.1088/1742-6596/1885/5/052024

Fuller, R. B. (1982). *Synergetics: Explorations in the geometry of thinking*. Estate of R. Buckminster Fuller. https://doi.org/10.2307/3103256

Goyal, R., Chen, M., Majji, M., & Skelton, R. (2019). MOTES: Modeling of tensegrity structures. *Journal of Open Source Software*, *4*(42), 1613. https://doi.org/10.21105/joss.01613

Jensen, Ø., Wroldsen, A. S., Lader, P. F., Fredheim, A., & Heide, M. (2007). Finite element analysis of tensegrity structures in offshore aquaculture installations. *Aquacultural Engineering*, *36*(3), 272–284. https://doi.org/10.1016/j.aquaeng.2007.01.001

Kan, Z., Peng, H., Chen, B., & Zhong, W. (2018). Nonlinear dynamic and deployment analysis of clustered tensegrity structures using a positional formulation FEM. *Composite Structures*, *187*, 241–258. https://doi.org/10.1016/j.compstruct.2017.12.050

Lalvani, H. (1996). Origins of tensegrity: Views of emmerich, fuller and snelson. *International Journal of Space Structures*, *11*(1-2), 27–27. https://doi.org/10.1177/026635119601-204

Liedl, T., Högberg, B., Tytell, J., Ingber, D. E., & Shih, W. M. (2010). Self-assembly of three-dimensional prestressed tensegrity structures from DNA. *Nature Nanotechnology*, *5*(7), 520–524. https://doi.org/10.1038/nnano.2010.107

Luo, A., & Liu, H. (2017). Analysis for feasibility of the method for bars driving the ball tensegrity robot. *Journal of Mechanisms and Robotics*, *9*(5). https://doi.org/10.1115/1.4037565

Ma, S., Chen, M., & Skelton, R. E. (2020). Design of a new tensegrity cantilever structure. *Composite Structures*, 112188. https://doi.org/10.1016/j.compstruct.2020.112188

Ma, S., Chen, M., & Skelton, R. E. (2022). Tensegrity system dynamics based on finite element method. *Composite Structures*, *280*, 114838. https://doi.org/10.1016/j.compstruct.2021.114838

Rhode-Barbarigos, L., Ali, N. B. H., Motro, R., & Smith, I. F. (2010). Designing tensegrity modules for pedestrian bridges. *Engineering Structures*, *32*(4), 1158–1167. https://doi.org/10.1016/j.engstruct.2009.12.042

Sabelhaus, A. P., Bruce, J., Caluwaerts, K., Manovi, P., Firoozi, R. F., Dobi, S., Agogino, A. M., & SunSpiral, V. (2015). System design and locomotion of SUPERball, an untethered tensegrity robot. *2015 IEEE International Conference on Robotics and Automation (ICRA)*, 2867–2873. https://doi.org/10.1109/ICRA.2015.7139590

Sabelhaus, A. P., Zhao, H., Zhu, E. L., Agogino, A. K., & Agogino, A. M. (2020). Model-predictive control with inverse statics optimization for tensegrity spine robots. *IEEE Transactions on Control Systems Technology*. https://doi.org/10.1109/TCST.2020.2975138

Skelton, R. E., & Oliveira, M. C. de. (2009). *Tensegrity systems* (Vol. 1). Springer. https://doi.org/10.1007/978-0-387-74242-7

Tadiparthi, V., Hsu, S.-C., & Bhattacharya, R. (2019). STEDY: Software for tensegrity dynamics. *Journal of Open Source Software*, *4*(33), 1042. https://doi.org/10.21105/joss.01042

Wang, K., Aanjaneya, M., & Bekris, K. (2020). A first principles approach for data-efficient system identification of spring-rod systems via differentiable physics engines. *Learning for Dynamics and Control*, 651–665. http://proceedings.mlr.press/v120/wang20b.html

Wang, N., Naruse, K., Stamenović, D., Fredberg, J. J., Mijailovich, S. M., Tolić-Nørrelykke, I. M., Polte, T., Mannix, R., & Ingber, D. E. (2001). Mechanical behavior in living cells consistent with the tensegrity model. *Proceedings of the National Academy of Sciences*, *98*(14), 7765–7770. https://doi.org/10.1073/pnas.141199598

Zgoul, M., Alzamer, A., Elayyan, M., & Quran, M. (2012). Static analysis of a tensegrity bridge using the finite element method. *International Conference on Applications and Design in Mechanical Engineering*, 27–28. http://dspace.unimap.edu.my/123456789/20244