Nonlinear analysis of compliant mechanisms : application to tape springs

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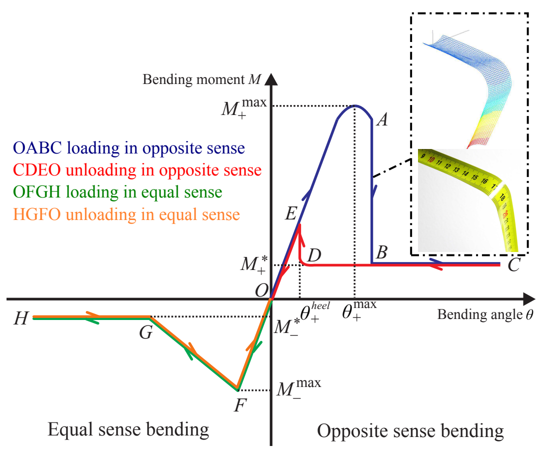
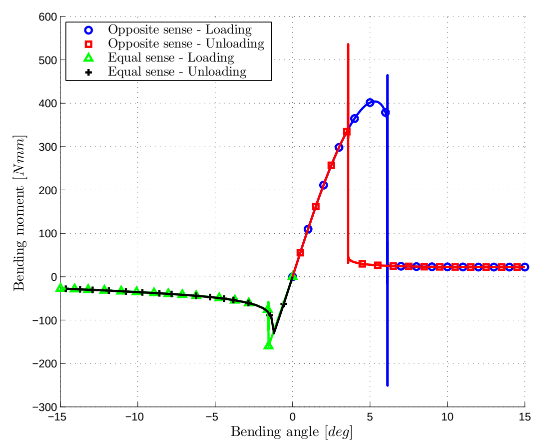
Abstract Among compliant mechanisms, tape springs present several mechanical assets for deployable space structures due to their nonlinear behaviour. This study aims at developing a nonlinear finite element model of tape springs and to validate this model experimentally using a dedicated set-up.

In deployable structures, compliant mechanisms such as tape springs are used as an alternative to common mechanisms composed of kinematic joints. Their main assets rely on a passive and self-actuated deployment, an elastic behaviour, a compact folded configuration, the self-locking of the structure in the deployed configuration, and an improved robustness due to the structural simplicity. For example, their benefits have been highlighted for the deployment of reflectors around a solar panel [1].



(a) Theoretical model [2].



(b) Finite element model [3].

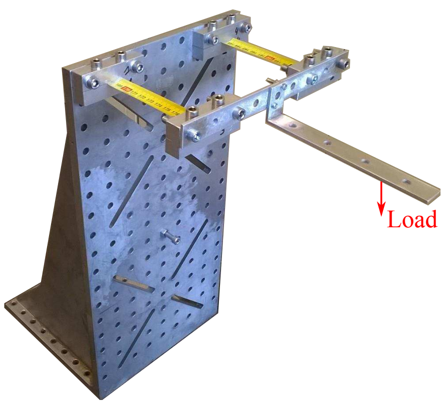
Figure 1: Evolution of the bending moment M with respect to the bending angle θ in pure bending.

These advantageous characteristics results from the highly nonlinear behaviour of tape springs which is theoretically illustrated in Figure 1a and describes the evolution of the bending moment M measured at the clamped extremity of the tape spring when the bending angle θ is controlled at the other end. First of all, it can be seen that the loading curve in opposite sense undergoes a sharp drop which is due to the buckling of the structure. This nonlinear phenomenon leads to the formation of a fold in the middle of the tape spring, while the parts on both sides remain straight and can easily be moved until they are parallel to each other. Then, the loading and unloading behaviours of the tape spring in opposite sense follow different paths. This difference is responsible for an hysteresis phenomenon which leads to the self-locking of the structure in its straight configuration. Furthermore, the non-zero residual bending moments M_+^* and M_-^* for large bending angles θ explain that the unconstrained structure tends to get back to its equilibrium state which is its straight configuration, hence the passive and self-actuated deployment. Finally, in equal sense, it is commonly accepted in theory that the cycles of loading-unloading are superimposed.

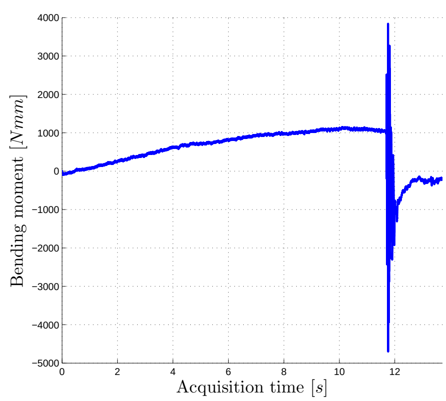
Due to the high complexity of the tape spring behaviour, high-fidelity mechanical models are required to accurately predict their evolution in various applications. To this end, finite element analyses, experimental tests and correlations are performed.

With finite element models, the evolution of the bending moment M theoretically described in Figure 1a can be recovered thanks to a slow dynamic analysis as illustrated in Figure 1b. It can be seen that the main features (buckling, hysteresis, residual moments) are present in opposite sense and that the evolution is more complex in equal sense than the one described in theory. To accurately capture all the nonlinear phenomena, a campaign of numerical tests showed that the introduction of structural damping is mandatory to capture the damping of the tape spring oscillations after deployment and leading to its self-locking. Furthermore, the dependence of the results to the numerical damping, inherent to the dynamic analyses, is reduced [3].

In the light of these results, the determination of the structural damping is essential to the development of accurate finite element models. An experimental set-up (Figure 2a) is then designed in order to perform vibrations tests of small amplitude, the damping of which gives the sought information on the structural damping. The same set-up is also exploited to perform quasi-static foldings (Figure 2b) and passive dynamic deployments [2]. The correlation between the equivalent finite element model and the experimental data is currently under study.



(a) Experimental set-up.



(b) Experimental result.

Figure 2: Experimental folding test under a tip load [2].

References

[1] F. Dewalque, J.-P. Collette and O. Brüls, Mechanical behaviour of tape springs used in the deployment of reflectors around a solar panel, Acta Astronautica 123, 271-282, 2016.

[2] F. Dewalque and O. Brüls, Experimental validation of structural damping models for tape springs, in: 6th European Conference for Aerospace Sciences, Krakòw, Poland, 29 June - 3 July 2015.

[3] F. Dewalque, P. Rochus and O. Brüls, Importance of structural damping in the dynamic analysis of compliant deployable structures, Acta Astronautica 111, 323-333, 2015.