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MODELLING AND ANALYSIS OF THE FOLDING PRINCIPLE USED IN SELF-DEPLOYABLE DEORBITING SPACE STRUCTURES

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ABSTRACT

An initial prototype of the Self-deployable Deorbiting Space Structure (SDSS) for semi-controlled debris removal was launched in 2014. The SDSS module consists of 3 main systems, i.e. the Drag Sail Unit (DSU), the Release Unit (RU) and the Housing Unit (HU). In the redesign, a storage lid is introduced whereby the folded drag sail is completely separated from the HU during the release process. During the research, an updated version of the SDSS version is made for CubeSat. The prototype is for a CubeSat which will be scalable.

A crucial part of the deorbiting satellite with SDSS is the size of the DSU. Thus by obtaining a higher folding ratio from 1:3 up to 1:9 the area will increase 9 times. An unique physical behaviour is utilised in the SDSS module for semi-controlled debris removal. Folding elastic structures by twisting, i.e. applying a torsional moment, triggers instability in the form of bifurcation. Multiple bifurcations can be obtained, and for highly elastic structures the elastic material behaviour is maintained. The number of bifurcations determines the unfolded to folded ratio. This research evaluates the behaviour of a Highly Flexible Frame (HFF) during folding identifying several parameters by which bifurcation is influenced, e.g. slenderness, cross sectional. Non-linear geometrical FEA are used for parameter studies identifying relevant force-displacement and/or moment-angle relations for determination of bifurcation points. This will be compared to an analytical solution and experiment. A redesigned SDSS module is outlined. Friction forces which are influenced by the elastic energy stored during folding are eliminated. Thereby an increased folding ratio can be obtained. A number of analytical methods, FEA and experiments have been done showing good agreement. Based on parameter studies of the instability an optimum cross section of the HFF has been determined.

1 INTRODUCTION

Semi-controlled removal of debris using drag augmentation concepts has been devised in for example [1], [2] etc. Vital parameters for the success of these drag augmented space structures are the stowed size of the drag systems, the deployment technology and the drag area after deployment. A drag augmented concept invented by Anders Schmidt Kristensen and Lars Damkilde [3],[4] resulted in developing a debris removal concept based on the patented self-deployable structure using a HFF. The debris removal technology is called a Self-deployable De-orbiting Space Structure (SDSS) [5] and [6]. A CubeSat equipped with 2 prototype SDSS modules was on a failed launch in October 2014 and was later recovered and both SDSS modules were successfully deployed in lab. The in-line model of the SDSS [6] developed is seen in Fig 1. Due to the in-line placement in the CubeSat limited design space were available, therefore a sliding tray mechanism were devised in order to maximize robustness and reliability.

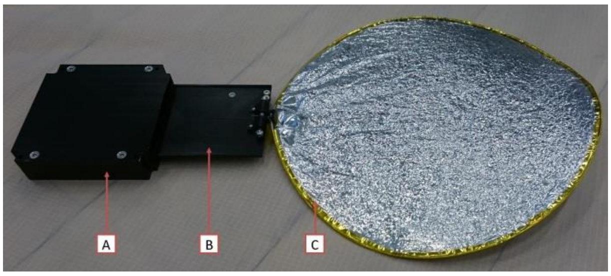

Figure 1. In-line SDSS model launched in 2014 A: HU B: RU C: DSU. The main issue with this initial design [6] was friction between HU (A) the sliding of the RU (B) and the DSU (C) inside the housing.

When the drag sail is folded and stowed, DSU in Fig. 1, on the RU see Fig. 1 and locked in the un-deployed state, the stress state resulting from the folding process of the HFF (blue line in Fig. 2) combined with the torsional release spring (A in Fig. 2), cause friction forces between the DSU and the HU ($F_{friction,\ HFF}$ in Fig. 2), and between the HU and the RU ($F_{friction,\ guide}$ in Fig. 2). This friction increase the force ($F_{release}$ in Fig. 2) required pushing the RU thus increasing the requirement to the torsional release spring (B in Fig. 2).

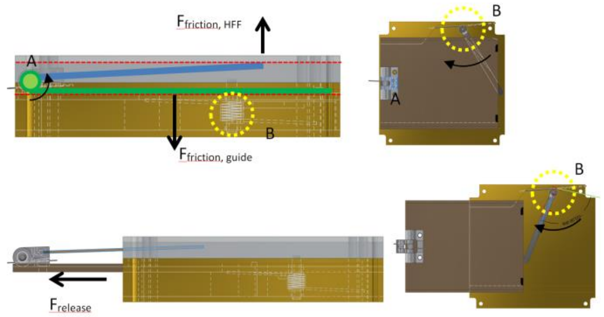

Figure 2. In-line SDSS model launched in 2014 A: Torsional release spring connected to HFF and RU. B: Torsional release spring connected to RU and HU. The main issue with this initial design [6] was friction.

In relation to the H2020 research project TeSeR, more design proposals are suggested. In this paper, the focus is on presenting a redesigned SDSS reducing the previously mentioned friction issues for an in-line positioning in a spacecraft suitable for CubeSats or where there is restrictive payload envelope requirements. The redesigned SDSS allows for an increased number of folds of the HFF whereby the deployed and unfolded drag area can be increased. However, increasing the number of folds in the HFF causes the stress state to change. Thus, this research aims to identify the mechanical properties controlling the folding of HFF and the stress state in an HFF during folding and in the folded/stowed state.

1.1 Redesigned in-line Self-deployable De-orbiting Space Structure

The H2020 project TeSeR focuses on the development of 3 types of debris removal systems, i.e. solid propulsion [D-Orbit Srl, Italy], electrodynamic tether force tether [Surrey Space Center, United Kingdom] and drag augmentation [Aalborg University, Denmark], i.e. the SDSS concept. This paper works solely with the drag augmented debris removal system using a self-deployable structure to span the drag sail, i.e. the SDSS [6]. The positioning of the removal system is addressed in the TeSeR project, however, this paper present a redesign of an in-line placed SDSS module as shown in Fig. 3.

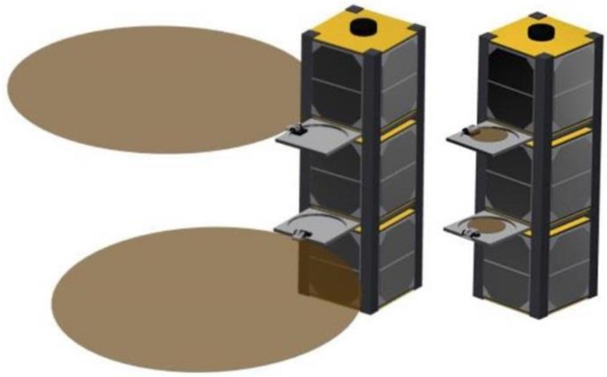

Figure 3. Illustration of inline module placed on a 3U CubeSat[5].

In order to avoid the friction between the DSU and the HU ($F_{friction, HFF}$ in Fig. 2) as well as between the HU and the RU ($F_{friction, guide}$ in Fig. 2) a hook and a lid is introduced into the design as illustrated in Fig. 4.

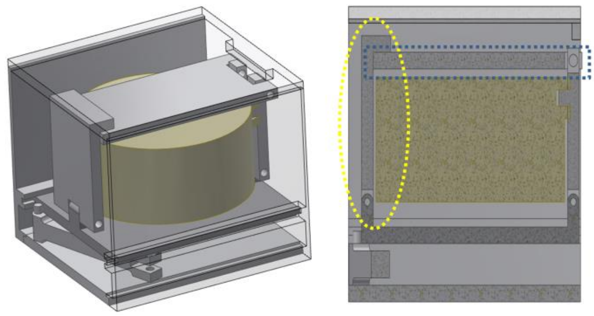

Figure 4. A transparent view through an in-line SDSS module (left) and a half section view (right). The release mechanism is similar to the mechanism presented in [2 AAIA]. The sail is now stowed and locked by the hook (yellow) locking the lid (blue).

In Fig. 4 is shown an in-line SDSS module utilizing a release mechanism similar to the mechanism presented in [6], i.e. a release arm pushing the RU during deployment. The deployment sequence is shown in Fig. 5.

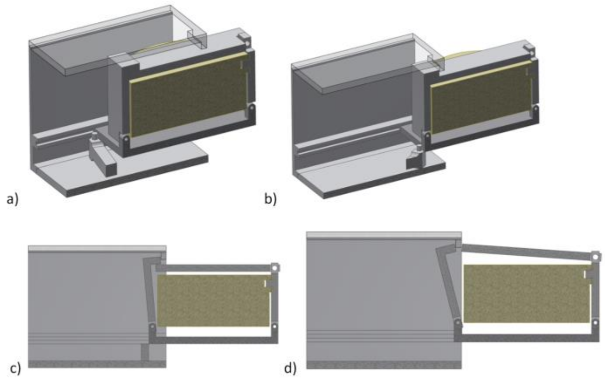

Figure 5. a) The deployment is initiated, i.e. the RU slides to the right. The DSU (beige) remains stowed. The RU with the hook hits a protrusion/tap b+c) which unhook the lid d) and the DSU can unfold.

In the redesign shown in Fig. 4 and Fig. 5, the sail is now stowed and locked by the hook (yellow) locking the lid (blue). Thereby, the DSU cannot come into contact with the HU. This completely eliminate $F_{friction,\ HFF}$ in Fig. 2 and $F_{friction,\ guide}$ in Fig. 2 whereby the required torsional moment to push the RU can be significantly reduced or kept in order to further increase the robustness of the release mechanism. Furthermore, the stress built up (pre-tension) in the HFF and DSU (beige) due to the folding will have no impact on the release mechanism which was a critical design parameter in the original design allowing only 3 folds in the prototype [6]. In the following the mechanical behavior of the HFF is studied.

2 DRAG SAIL FRAME

One of the main objectives is to make the DSU area as large as possible in order to obtain more drag area. Due to this it is necessary to understand what triggers the folding process in the HFF. This research considers a circular HFF which is relative simple to fold. By holding one end fixed and then twisting the opposite point 360°, see Fig. 8, this results in a new diameter (folded) that is 3 times smaller than the initial diameter (unfolded) as seen on Fig. 6.

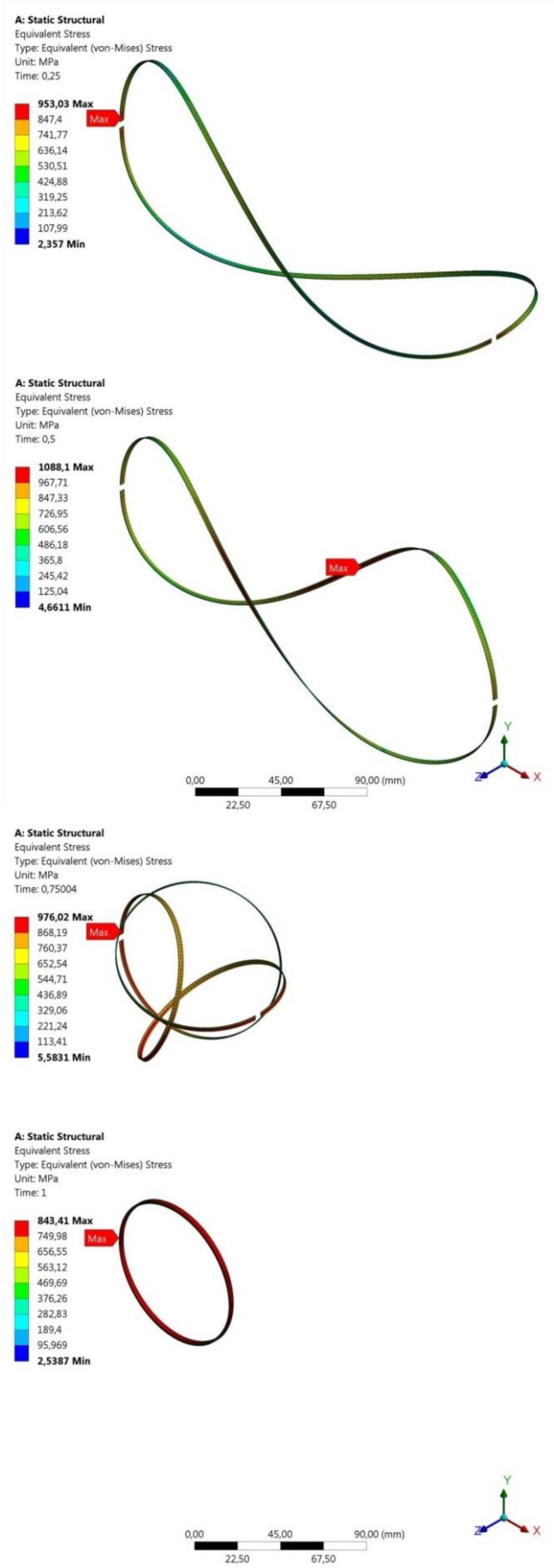

Figure 6. The folding of the HFF for every 90°, at 180° it is seen that the stresses are close to the peak.

By changing the cross section, the necessary moment to twist the HFF can be adjusted and the natural ability (instability modes) to fold into 3 small rings. An earlier study [7] has been made on this effect where the rectangular cross section height and width ratio are adjusted from 1 to 3 as seen on Fig. 7.

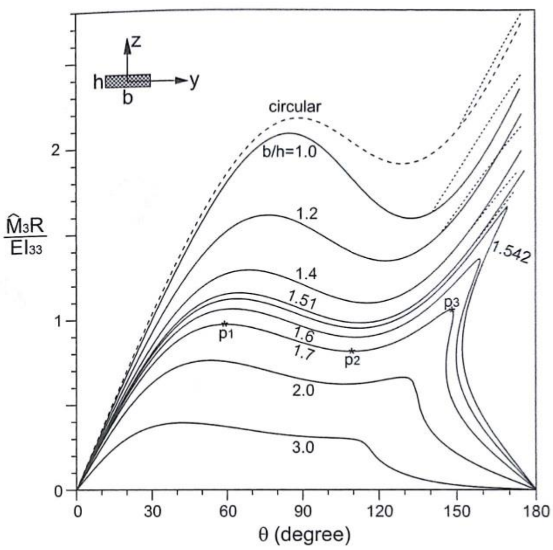

Figure 7. Normalised moment at the y-axis for a circular frame with different rectangular cross sections and the rotation angle θ [7].

By this former observation a DSU was made to fit a CubeSat. The aim is to work with cross section ratio from 3 and up as this gives the easiest bifurcation or folding process as seen in Fig. 7. With a cross section as shown in Fig. 8 having a height h = 2.7 mm and a thickness t = 0.5 mm, a height to width ratio h/t = 5.4 that is well above the mark set at 3. The diameter D of the unfolded sail is D = Ø 245 mm as seen on Fig. 8. This is because the folded sail needs to be smaller the 85 mm, i.e. the maximum folded size achievable for an in-line SDSS module as seen in Fig. 5.

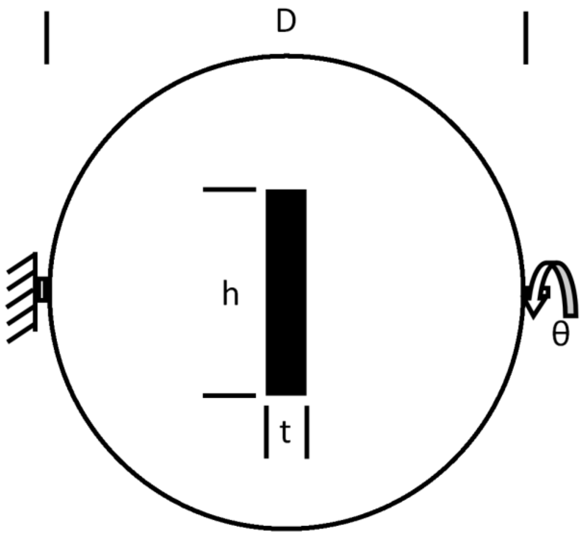

Figure 8. Cross section of the HFF h = 2.7 mm t = 0.5 mm i.e. h/t = 5.4. Boundary condition for the FEA and physical model D: 245 mm θ: 0-360° of the HFF.

The Young's modulus is equivalent to 210,000 MPa in spring hardened steel, and some of these steel types have up to 1200 MPa in yield stress.

With these parameters, a FEA was conducted, and the initial setup is without self-contact elements for the HFF as the assumption from Fig. 7 [7].

Boundary conditions are as seen on Fig. 8. Where the displacements x, y and z are set to zero for a small surface. The rotation is done by a remote displacement where the displacement for the rounded extension is set to zero for x, y and x is free, the rotation for y, z is free and x is changed from 0° to 360°. The behaviour of the remote displacement is set to rigid to ensure a full rotation as seen on Fig. 9.

Figure 9. Remote displacement for the HFF there are made round extension where the remote displacement is placed

Mesh is set to high order solid elements to give a better description of the folding process, with 2 elements in thickness (t) and 4 elements in the height (h). Analysis settings are large deformation and direct solver.

3 EXPERIMENT COMPARED TO FEA

Then compare it to experiments and see how well it fits up. A frame was made to control the alignment of the multiaxial measuring tool from HBM and the rotation of the HFF as seen Fig. 10. The HBM measuring tool is a K-MCS10-005-6C-FX-FY-FZ-MX-MY-MZ where the range for Fx, Fy is 1 kN and Fz is 5kN, the moments range is My, My and Mz is 0.05kNm [8].

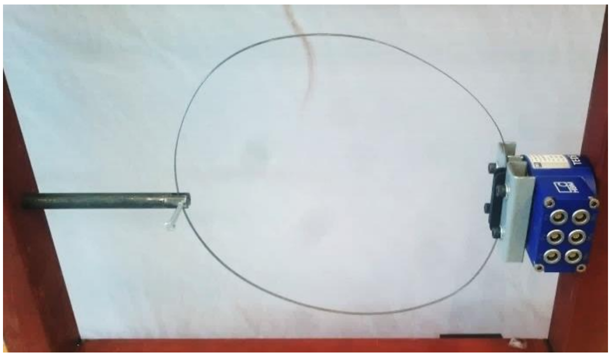

Figure 10. Test setup of a HFF with a diameter D = 245 mm in austenitic stainless steel using HBM multiaxial measuring tool.

All forces and moments are measured, the torsional moment Mz is required to do the folding of the HFF. Where the moment Mz is recorded for every 10° and Fz is equal to zero, so it is similar to the condition in the FEA. The torsional moments from the experiment and FEA are compared to see how good the correlation is as seen in Fig. 11.

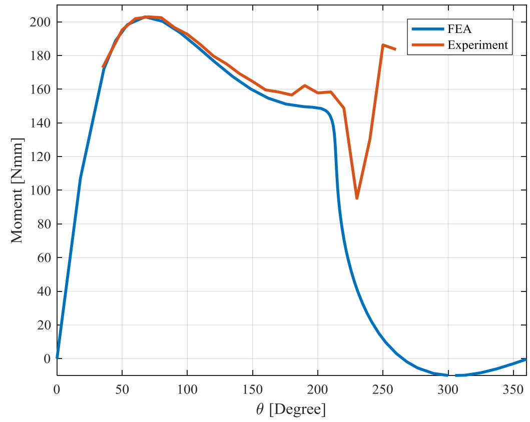

Figure 11. FEA results (blue graph) and test results (red graph) compared.

There is a good correlation between the FEA and the experiment as seen by the graphs, there is a difference around 200° and the rest. The reason is self contact in the experiment.

4 CROSS SECTION INFLUENCE

To understand how moment and stresses are influenced under the folding process when the cross sections are doubled either in h or t. Additional two FEA are conducted with the parameters seen in Tab. 1.

Table 1. Size of different cross sections to be compared the cross section is seen on Fig. 8.

	h	t	D	h/t
Cross section A	2.7mm	0.5mm	245mm	5.4
Cross section B	2.7mm	1.0mm	245mm	2.7
Cross section C	5.4mm	0.5mm	245mm	10.8

This parameter study gives a good understanding of the moment change when h is increased. In cross section C 2 times the moment is required to trigger the folding (bifurcation) while doubling t in cross section B results in 7 times the moment to trigger the folding as seen on the top graph in Fig. 12. If the equivalent Von Mises stresses are considered then cross section A and C has similar stress state under the folding process where cross section B has 1000 MPa more in peak value. When the cross sections are folded is the peak value of the equivalent stress in cross section B approximately the double compared to cross section A and cross section B and this is illustrated in Fig. 12.

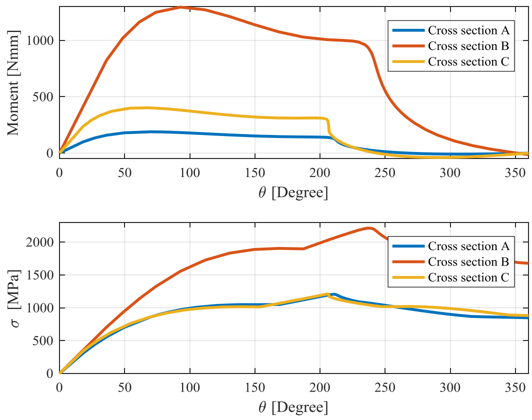

Figure 12. Effect of change of cross section the top graph how the moment change, the bottom graph how the Von Mises stress are effected by the cross section

The stresses in a given HFF is further described in the article "**Analysis of pretension and stress stiffening in a Self-deployable Deorbiting Space Structure**"

5 CONCLUSIONS

The SDSS is a robust solution for deorbiting satellites versatile in placement and low power needs as the launch process is mainly done by stored mechanical energy in springs and in the HFF. The main thing in designing the HFF for the DSU is to utilise the bifurcation possibility in the cross section. By making sure that the weak axis of the cross section is as low as possible and adjusting on the height to have enough moment for the unfolding process. With these FEA it is possible to determine that the stresses are at the limit for this spring steel material. With the FEA it is possible to do further study with a higher number of folds and its consequences.

6 ACKNOWLEDGEMENT

SDSS is enhanced within the H2020 project TeSeR (Technology for Self-Removal). The goal of TeSeR is to take the first step towards the development of a scalable, flexible, cost-efficient, but highly reliable Post-Mission-Disposal (PMD) module. This module is to be attached to the spacecraft (S/C) on ground and it shall ensure the PMD of the S/C at the end of the nominal operational lifetime or act as a removal back-up in case that the S/C cannot be controlled anymore. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 687295.

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