ARTIFICIAL SATELLITES, Vol. 59, No. 1 – 2024
DOI: 10.2478/arsa-2024-0001

SPACE DEBRIS CAPTURE - ABOUT NEW METHODS OF TETHERED SPACE NET OPENING BY TUBULAR BOOMS

Tomasz PAŁGAN, Adam DACKO, Mirosław RATAJ, Szymon POLAK
Space Research Centre, Polish Academy of Sciences, Warsaw, Poland
e-mail: tpalgan@cbk.waw.pl

ABSTRACT. Nowadays, space debris is one of the main subjects of discussion regarding satellites in Earth's orbit. Right now, there are about 26,000 orbiting satellites and only few of these satellites are operational. Recently, the Polish space sector has been strongly growing and delivering instruments working in space. The first part of this paper describes the several space instruments designed in the Space Research Centre Polish Academy of Science (SRC PAS). Instruments such as SWI, RPPWI, LPPWI, Ebox or Pre-boxes have been created for a mission to Jupiter named "JUICE". After fulfilling their scientific mission, these instruments can increase the amount of debris in space. This is one of the reasons for taking up the topic of space debris reduction and the use of technical solutions used in this mission for the proposed solution presented later.

The second part of this paper describes the new methods related to space debris. The activities can be related to the space debris removal programmes. The paper describes two methods developed by Polish scientists used for removal

of space debris. One of them is the new capture method and mechanism designed for it. The special mechanism is based on tubular boom application for opening the net, to capture the space debris. The main parts of the mechanism are mechanisms which have been used in the JUICE space mission. The paper describes the main idea for these new methods, and for the design part prepared the strength confirmation by structural analysis. The main function of the mechanism has been verified by simulations and tests performed in laboratories.

Keywords: space debris, tubular boom, FEA, structural analysis, MSC.NASTRAN, JUICE

1. INTRODUCTION

Deployable structures like tubular booms have been very useful for space applications. Small in size during the stowed configuration and large after deployment they are very essential for designing the space parts and instruments. A tubular boom is a long tube (thin-walled, open-section) formed by unwinding a flat spring metal tape. Tubular booms used in the Space Research Centre Polish Academy of Science (SRC PAS) started from the RELEC mission and are still developing.

A good example of a tubular boom application is the de-orbitation system designed by Polish students from the Warsaw University of Technology. This is another approach for space debris removal, a system designed to cause de-orbitation of the satellite and burning in the atmosphere.

An example is the PW-Sat2 CubeSat, a small satellite project designed by students as part of an activity of the Student's Space Association at the Faculty of Power and Aeronautical Engineering, at the Warsaw University of Technology.

The tasks of this system include the correction of the satellite's orbit after the deployment and, at a later stage of the mission, de-orbitation of the entire system. The system tested in a previous mission (Figure 1) has already been used for de-orbitation. The main mechanism of deploying the sail is based on an elastic boom mechanism similar to the one described in this paper.

Another option for debris removal (by deorbiting the satellite) is based on a cold gas propulsion. This method is based on the PW-Sat3 development (Mochol et al., 2021).

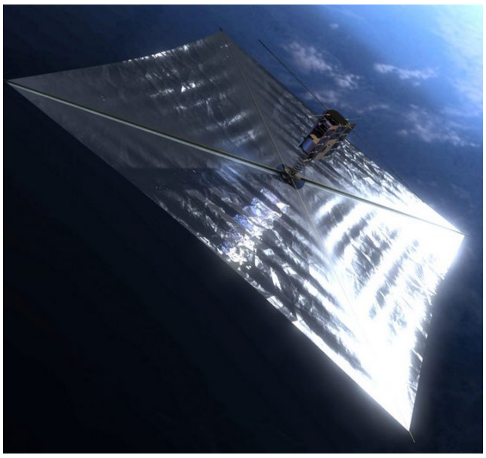

Figure 1. PW-Sat2 with de-orbitation sail system opened by tubular booms (photo: https://pw-sat.pl)

The scientists and engineers from Poland have been strongly involved in a space project named "JUICE". JUICE (JUpiter ICy moons Explorer) is the first large-class mission in the European Space Agency (ESA). A spacecraft was launched on April 14, 2023 and will arrive at Jupiter in 2030. Some of the instruments on the spacecraft are: SWI Radiator, RPWI, LPPWI, Ebox, and Pre-box, which were designed by engineers and scientists from the SRC PAS. Poland is involved in the design and production of satellite elements — in this sense is also responsible for future potential creation of space debris.

2. INTRODUCTION FOR A NEW METHOD OF TETHERED SPACE NET OPENING BY TUBULAR BOOMS

The new method will have an impact on the space debris issue. From the beginning of human space activities, many missions were created, and some of them stopped their scientific activity but still stay in orbit as space debris. Currently, the clean space programme is strongly focused on avoiding collisions between space objects. The space debris is extremely dangerous because it stays in space without control. One of the promising methods of debris removal is a tethered space net (TSN) presented in Figure 2, used for the capture of space debris (Zaho et al., 2018; Lim and Chung, 2019; Liu et al., 2018; Yang et al., 2019).

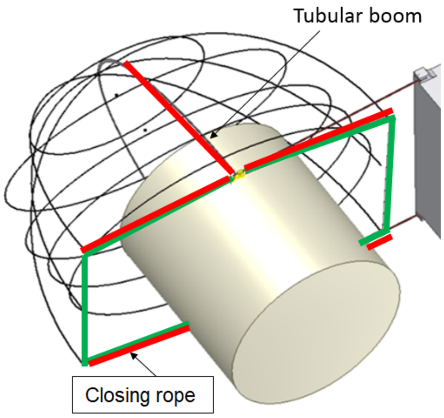

Figure 2. Tethered space net (TSN)

A paper (Zaho et al., 2018) proposed the investigation of the net opening area and closing time for a deployable net during capture process. Considering the previous investigations, opening area and closing time parameters have been analysed as the most crucial for the success of capturing space debris. Some papers (Zaho et al., 2018; Lim and Chung, 2019) provide the investigation for the velocity needed for the capture. A previously discussed paper (Zaho et al., 2018) proposed that the masses used for the net opening should keep the proper velocity. The different shapes of the nets have also been considered.

The modelling of the tethered satellite systems was presented in a paper (Lim and Chung, 2019). The tether connects dynamic bodies where one of the bodies can be controlled and the other is uncontrolled. In the same paper (Lim and Chung, 2019), it was mentioned that the rope connection was used as the best solution to eliminate the reaction forces.

The deployable structure described by Yang et al. (2019) has been very useful for space application. The small size needed in stowed configuration and the large one in the deployment configuration are very useful for space applications. In the paper (Yang et al., 2019), the bending and torsional stiffness of the deployable boom have been analysed. These parameters are crucial to provide the proper stiffness during the capture process.

In a paper by Liu et al. (2018), they presented the investigation about opening the net based on inflatable booms. Creating an opening area gives the area stability during the time. The paper shows the impact of the stiffness for the tubular boom.

3. DEPLOYMENT DYNAMICS OF TSN OPENING BY TUBULAR BOOMS

The part consisting elements of the new method was previously applied to several instruments in the JUICE space mission. One instrument is the RPWI — an instrument for in situ (and remote) sensing investigations of the highly dynamic and, in many respects, very different space plasma environments, which will be encountered by the JUICE spacecraft in Jupiter's magnetosphere and around Jupiter's icy moons Europa, Callisto, and Ganymede. The others are LPPWI Langmuir probes that give crucial information about the surrounding bulk plasma; in particular, they are used to measure plasma density and temperature.

The set used for the new method includes the following: satellite, stiff deployed booms, and a net deployed by the tubular booms. The tubular booms are used for controlling the opening of the net (Lim and Chung, 2019). The new tubular net system can complete specific capture, by the deployable rope network that could be supported by the tape spring booms.

Deployable structures, such as antennae and optical telescopes, have been essential for space applications. They are small in size during the stowed configuration and large after deployment. The use of the tubular boom deployment is limited by the cross-sectionality and length of the boom. The length is determined by current technology; now, it is possible to produce the booms with 2.5 m length.

This method gives the possibility for capturing the debris with less precise location between chaser satellite and other (debris) objects. Velocity difference between the net and target object can be less controlled.

Extensive studies have focused on TSN, which include studies on dynamics modelling, deployment analysis and mechanism design and ground experiment for separate parts. Based on previous studies of the space nets, the dynamic models of TSN have been delivered as a rigid model (Zaho et al., 2018). The opening area and closing time have been considered. The opening area has been determined by the length of the tubular boom. The closing time is controlled by the rope and elastic shape of the tubular boom (Lim and Chung, 2019).

The (TSN) mechanism is located on satellite in the stowed configuration. The opening and capture process is performed as follows (see the scheme in Figure 3):

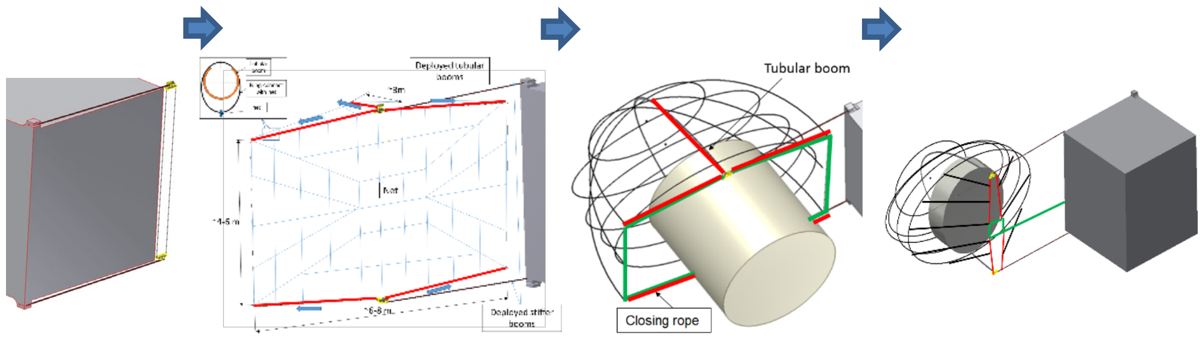

Figure 3. Tether space system step-by-step operation. **Start**: stowed structure on the satellite; **first step**: deployment of the stiffer boom; **second step**: deployment of the tubular booms and opening of the net, checking the opening area; **third step**: contact of the net with the debris; **fourth step**: retracting the tubular boom, checking the closing time.

4. STRUCTURAL ANALYSIS FOR THE MAIN COMPONENTS OF THE MECHANISM DESIGNED FOR THE NEW METHOD

This research describes several types of structural analyses used in the modelling launch of the rocket. Analyses were conducted to confirm if the design of the net mechanism system will survive the rocket launch. The paper describes the investigations concerning optimisation of the main part — the boom made from carbon fibre reinforced polymer (CFRP) (presented in Figure 4). At the end of the "primary" CFRP booms, the "secondary" metal open-section tubular booms and a net are located. The main components of the mechanism are presented in Figure 4.

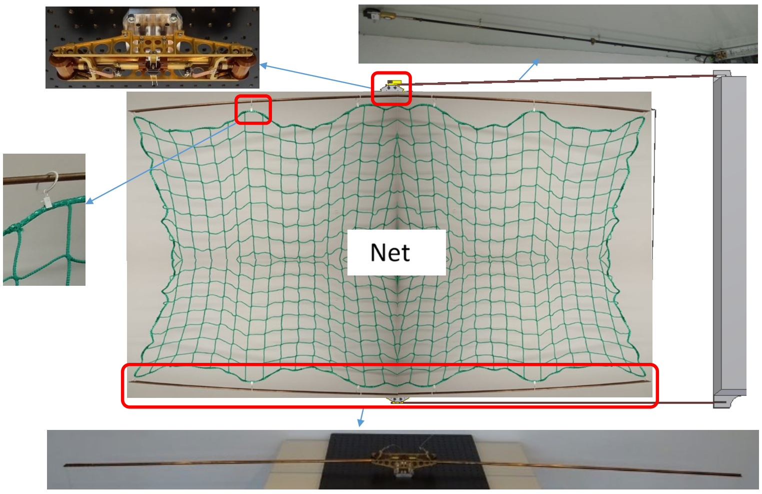

Figure 4. Mechanism in open configuration (photo: T. Pałgan and SRC PAS)

For the main parts of the mechanism, the structural analysis has been performed to determine the margin of safety for loads generated by the rocket during the lift-off. The analysis determines if the design can be launched and will work in orbit.

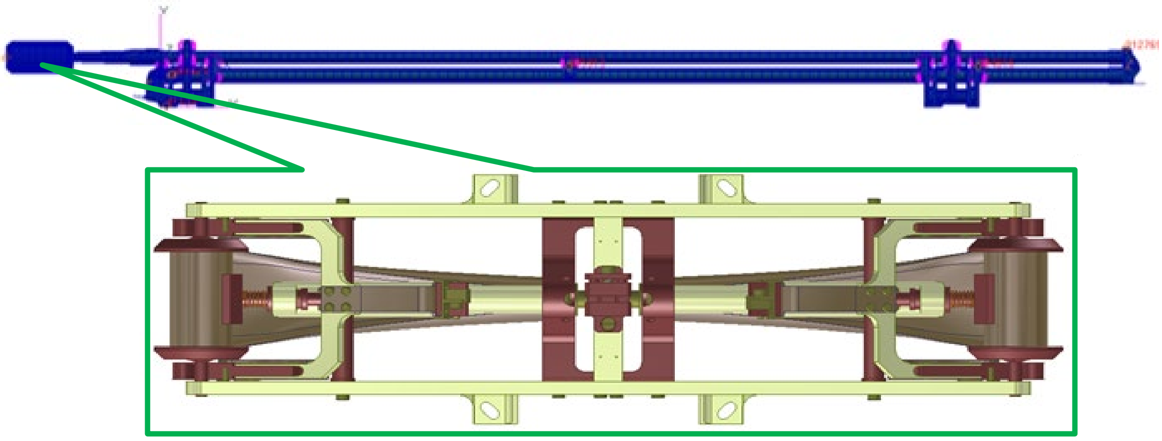

Figure 5. Top: JUICE LPPWI ("primary", CFRP) booms and bottom: RPWI ("secondary", metal, thin-walled) booms, located at the end of a "primary" one

Several types of structural analyses described in the space standards (European Cooperation for Space Standardization [ECSS]) were performed: modal analysis, sine sweep analysis or random vibration analysis. Based on received results from structural analyses (presented as an example in Figure 6), the proper materials and details of the mechanism design have been determined.

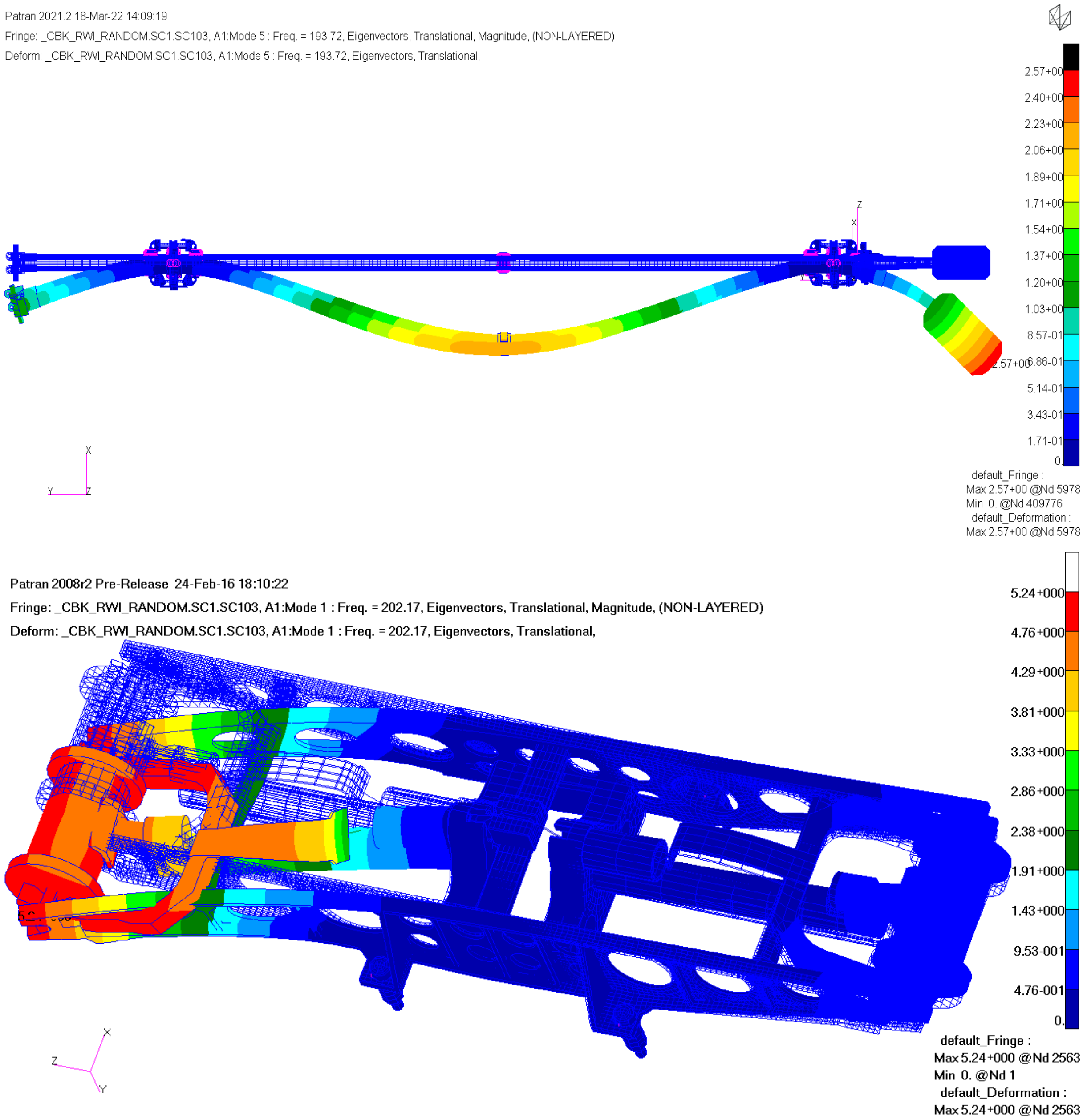

Figure 6. Top: modal analysis results for JUICE LPPWI ("primary" CFRP booms); bottom: modal analysis results for RPWI ("secondary", metal, thin-walled booms)

5. DEPLOYABLE BOOM TECHNOLOGY IN SPACE APPLICATION

The tubular boom technology is useful in space construction due to different sizes in stowed and deployed configuration. In a paper by Yang et al. (2019), a composite tubular boom configuration used for similar applications has been described with focus on the stress analysis. Unusual thin-walled open-section with N-shaped cross-section tubular booms have been analysed for bending and torsional stiffness.

Tubular booms used in the SRC PAS started from the RELEC mission and have a proud history of being developed as a lock and release mechanism. Using the beryllium copper for tubular booms plays a special and important role in the development of the booms. Briefly, a tubular boom is a long tube (thin-walled, open-section) formed by unwinding a flat spring metal tape. This produces a very lightweight structure. This deployable structure developed in the SRC PAS has features perfect for space missions. The small size needed in stowed configuration and the large configuration after deployment are very useful for space application, as presented in Figure 7.

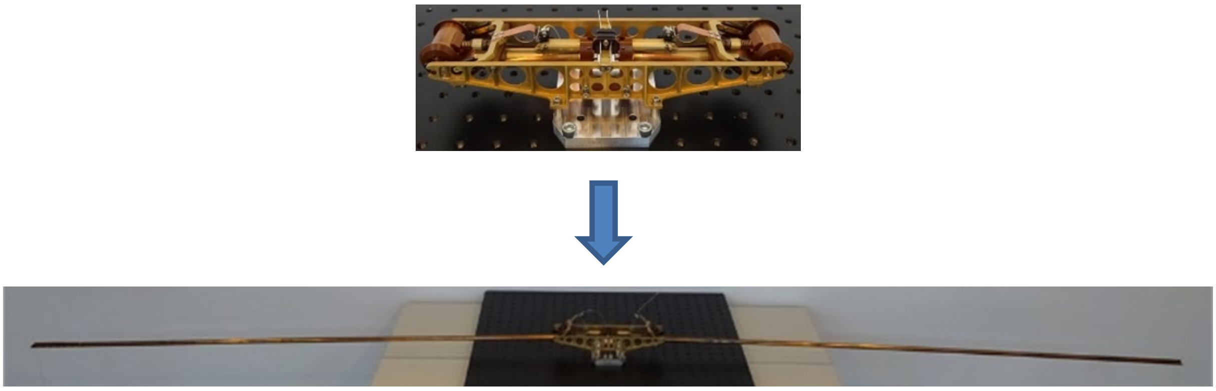

Figure 7. Prototype mechanism with tubular boom in stowed (top) and deployed (bottom) configuration (photo: SRC PAS)

The tapes made from beryllium cooper have good strength and mechanical properties. These tapes have been analysed in the previous chapter to check the stiffness of the construction in stowed conditions, to confirm that it will be successfully launched in space. In the next step, the tubular boom will be checked. This is when the real-time strength capability of the deployment tubular boom will be investigated.

The analysed numerical model of the tubular boom was created from shell elements. The boundary conditions applied to the model were as follows: at one end of the boom were blocked nodes with 6 degrees of freedom, and for the other side, force was applied.

In simulation, the bending characteristic of the tubular open-section boom was considered. As could be expected, the calculations in the linear range have not met the results received in a real test.

However, the simulation prepared using the LS-DYNA software provided similar results as received in a real test. Figures 8 and 9 show a comparison of the results from the finite element simulation using the LS-DYNA software and the results obtained in the laboratory.

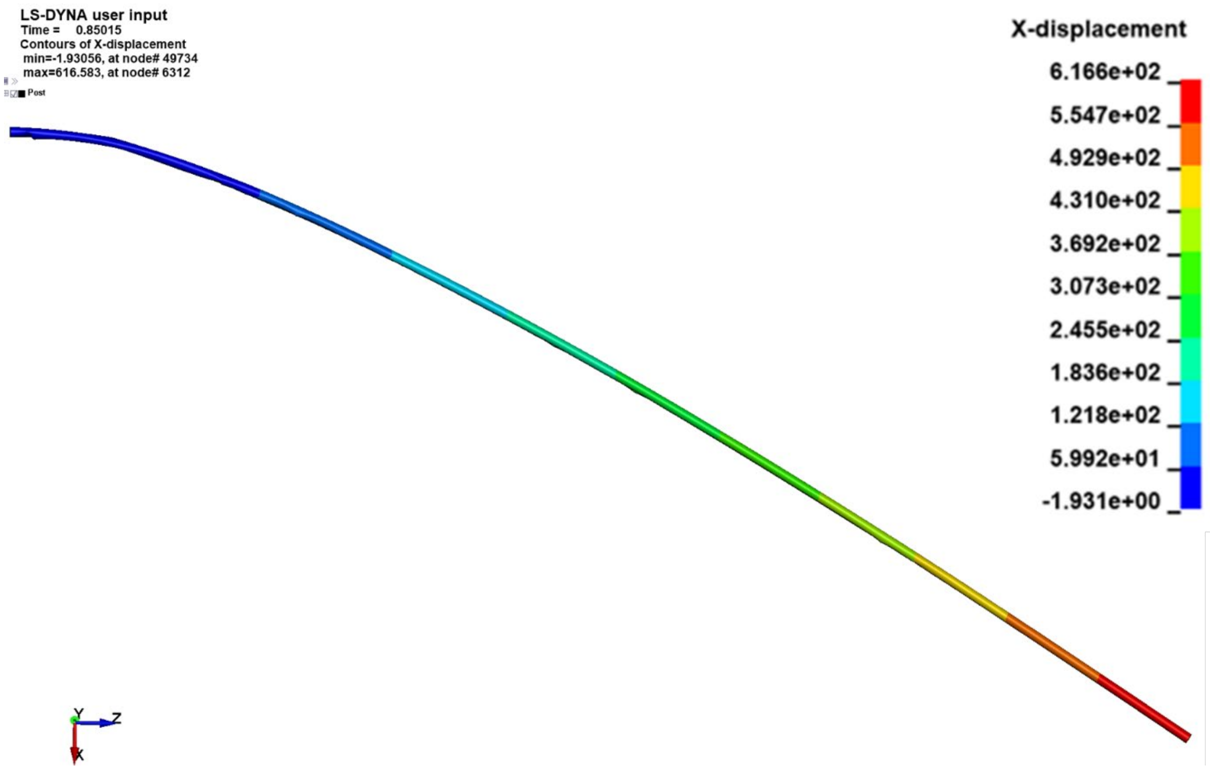

Figure 8. Finite element analysis for a deployed tubular boom under a tip load (analysis used the LS-DYNA software)

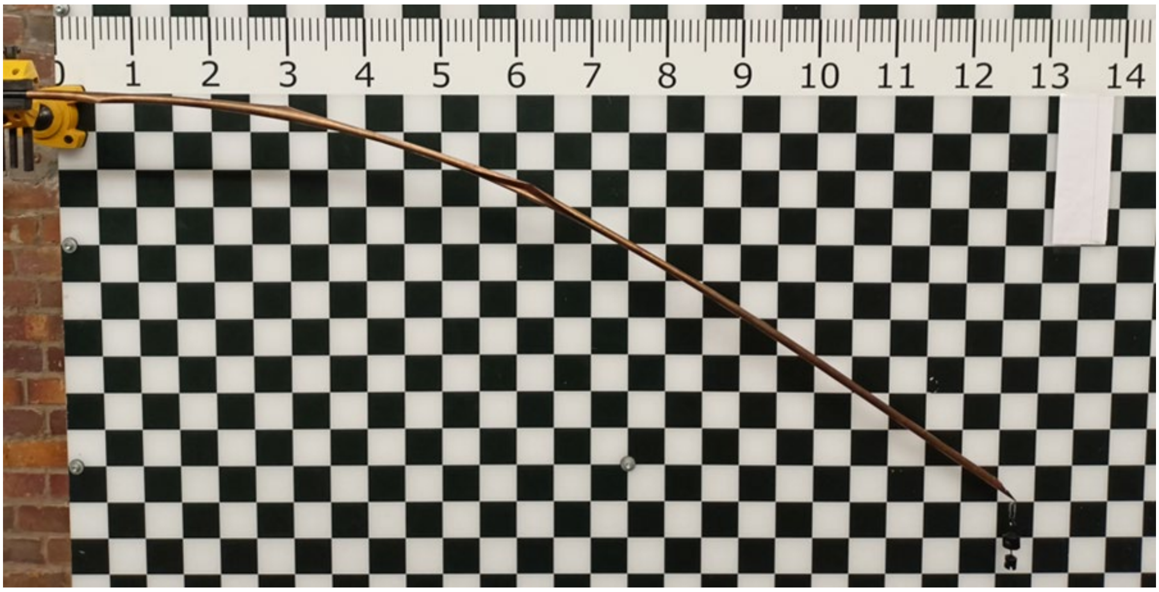

Figure 9. Laboratory test of bending of a tubular open-section boom (photo: T. Pałgan)

The highly plastic characteristic of the tubular boom has been simulated using the finite element analysis (FEA); the obtained results are presented in Figure 10 and Figure 11.

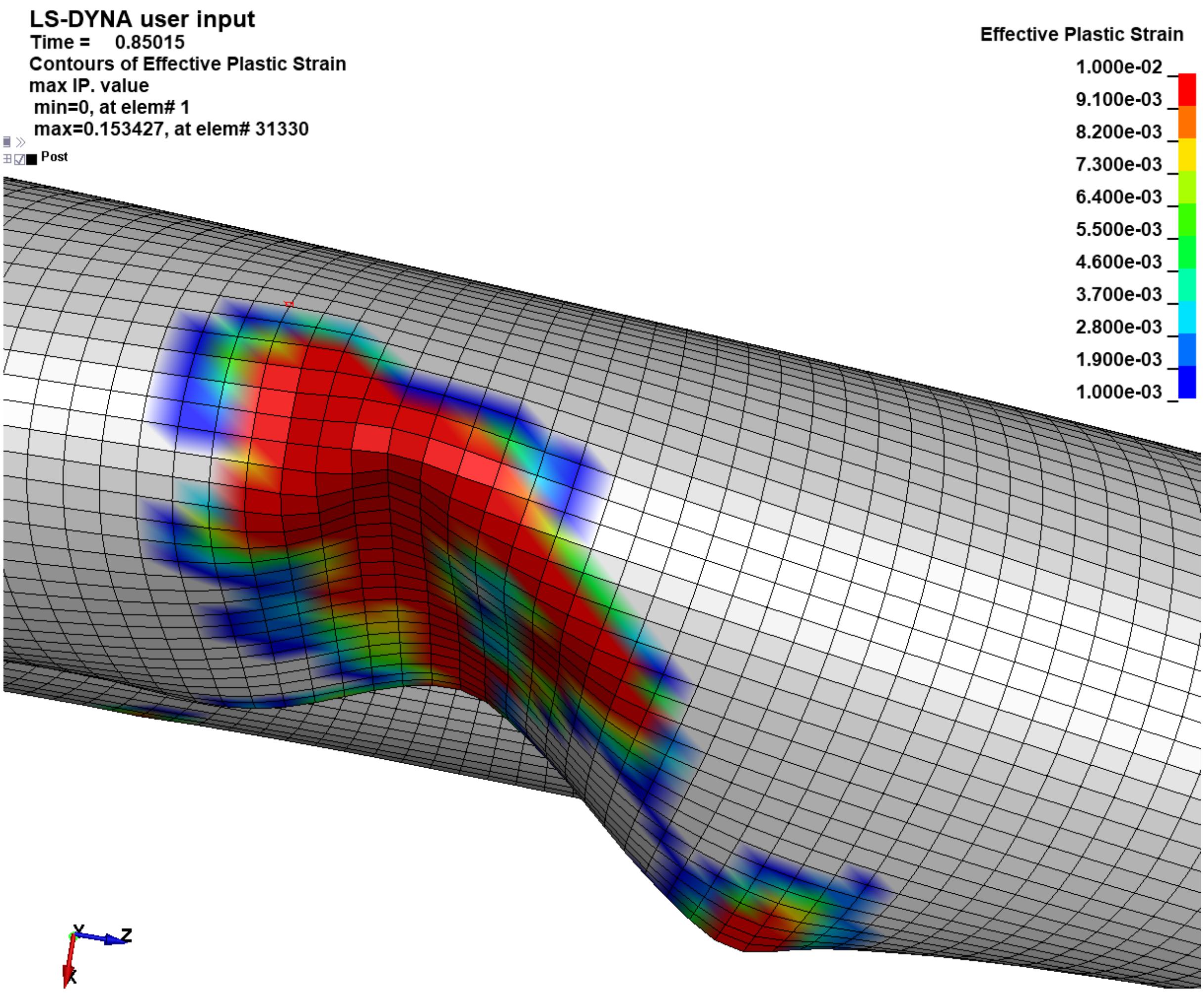

Figure 10. Plastic zones around the “kink” of deformation

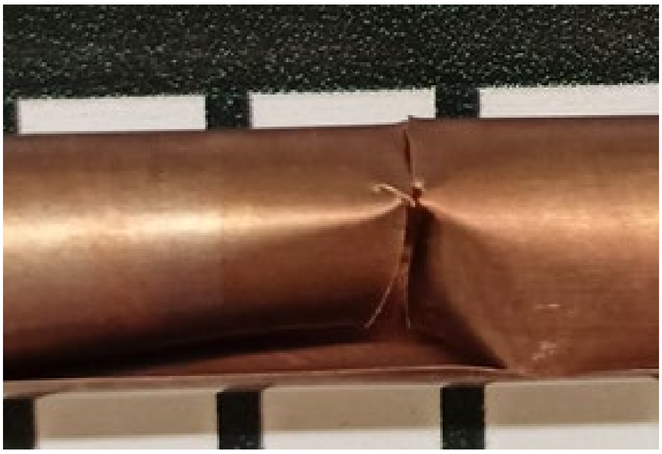

Figure 11. Plastic deformation results received in a laboratory test (photo: T. Pałgan)

7. CONCLUSIONS

The presented new method is very promising for space debris capturing and removal. The technology of open-section tubular booms used for opening the net can be utilised in future missions dedicated to space debris removal. The opening of the net by tubular booms gives a possibility for a better controlled opening of the net and keeping it open. For the new method, the opening time is very short in the case of a free-forming tubular boom but can be controlled by a braking mechanism. The open area is determined by the length of the tubular boom. The space mechanism was verified by structural analysis to confirm that the whole device will survive the rocket launch phase. The prepared structural analysis calculation shows that the designed mechanism can be successfully lift off into the orbit, and the net can be opened by tubular booms in orbit. The received results were verified by the tests prepared in laboratories and confirm the design and analysis assumptions for the mechanism. The very strong plastic echaracteristic of the tubular boom, shown in Figure 10, has been simulated using the LS-DYNA software, and met the results observed during the real test.

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Received: *2023-12-07*

Reviewed: *2023-12-21 (undisclosed name); 2023-12-29 (J. Kindracki)*

Accepted: *2024-01-19*