Sliding Core Deployment Mechanism for Solar Sails based on Tubular Shell Masts

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The paper describes the design of a solar sail deployment mechanism for flexible, tubular shell masts of closed cross-section. The mechanism is based on a novel interface design between the mast and its deployment mechanism that enables an interconnection of high stiffness and high load carrying capability. The interface is designed similar to an extrusion nozzle consisting of a core that is sliding inside the boom and a support shell that is enclosing the boom. As the boom has a closed cross-section, the core is held contactless in position from the outside by an enforced form closure using the flexibility of the boom shell. Between core and enclosing support shell remains only a small gap whereby any lateral motion of the boom shell is prevented. This enables a stiff connection and good load transmission between boom and deployment mechanism which results in a high overall performance. Lateral bending tests show that the bending strength of the mast around its "weak" axis is increased by 90% through use of this interface while bending stiffness increases by 23%. The paper describes the mechanical principle of this sliding core interface and presents an overview of a mechanism prototype for solar sails and similar applications.

I. Introduction

Deployable space structures often utilize deployable booms as their main structural elements. Examples are tensioned blanket solar arrays, sun shields, solar and drag sails or instrument booms. A category of deployable masts that is widely used for such applications are tubular shell masts such as DLR's double omega boom [1] displayed in Figure 1. These masts consist of thin walled shells that form a closed cross-section of nearly tubular shape. The shells are made of a highly flexible material that enables the boom to be stowed through elastic deformation by flattening the boom to a band that is reeled afterwards on a drum. Special features of these tubular shell booms are compact packaging and high torsional stiffness.

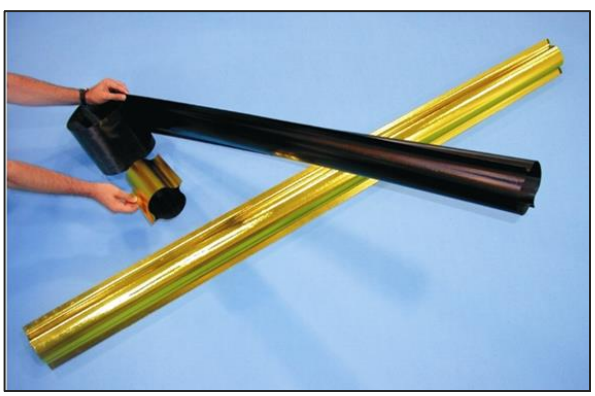

Figure 1: Tubular shell mast with double-omega cross-section developed by DLR that is stowed through reeling.

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A main challenge in the design of deployment mechanisms for such thin-walled, flexible shell booms are the losses in stiffness and strength at the interface between boom and mechanism. Maintaining the cross-sectional shape through preventing lateral deflection of the boom's shell under load is key to gain a high overall mechanical performance and good load transmission.

Current interface solutions for a shell boom of closed cross-section consist of a support shell that encloses the boom from the outside. Hence, lateral motion of the boom is constrained only to the outside while load induced deflection to the inside is not prevented. A typical failure mode of tubular shell mast supported only by a surrounding shell is displayed in Figure 2. With increasing bending load a buckle to the inside forms in the boom already at small load levels. This buckle grows continuously until the booms cross-section is significantly distorted and failure of the entire boom occurs.

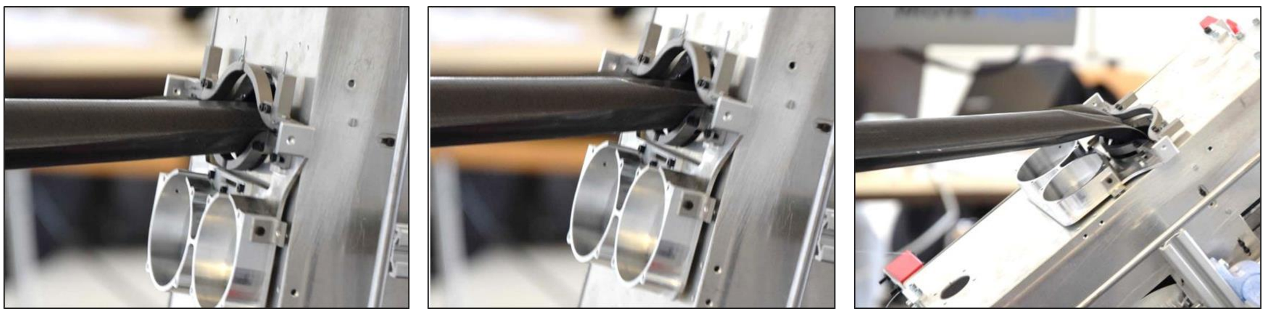

Figure 2: Typical buckling failure mode of a tubular shell mast at the interface towards the deployment mechanism due to insufficient support against shell deformation to the inside [Courtesy of DLR].

Within this paper a new type of interface between a boom of closed cross-section and its deployment mechanism is introduced that prevents the failure mode displayed in Figure 2. This interface features a core that is sliding inside the boom and is held contactless (with regard to the outer support shell) in position at the interface from the outside. Thereby any lateral motion to the in- and outside of the boom shell under load is prevented which increases both stiffness and strength of the overall deployment system.

II. Principle of the Sliding Core Interface

The analogue of the principle idea for the interface between mechanism and boom is an extrusion nozzle. The boom is able to move through the interface in deployment direction while all lateral motions are constrained. The main difficulty is that for such a type of interface a core inside of the boom is required. This core has to be fixed in its position at the interface although no direct attachment is possible as it is fully enclosed by the boom. Therefore means to apply contactless constraint forces to the core from the outside are necessary.

Initial considerations for realization of an internal core were based on magnets but were dropped as the forces that can be provided may not be sufficient and the magnetic fields can cause conflicts with the spacecraft's attitude control system. The finally selected approach makes use of the flexibility of the boom's shell. The shell is locally deformed from the outside at the location of the core. The core counters this deformation from the inside and thereby achieves a form closure to the outer support shell which holds it in position. To minimize friction when the boom is sliding through the interface, roller bearings are used to enforce this local deformation from the outside and counter it from the inside.

Figure 3 shows the principle design of the sliding core interface. The core (green) is subdivided into two parts: The rear part (relative to the deployment direction) enables mounting of the roller bearings (grey) for fixation of the core by form closure while the front part possesses the shape of the boom and thereby forms the extrusion nozzle together with the surrounding support shell (orange).

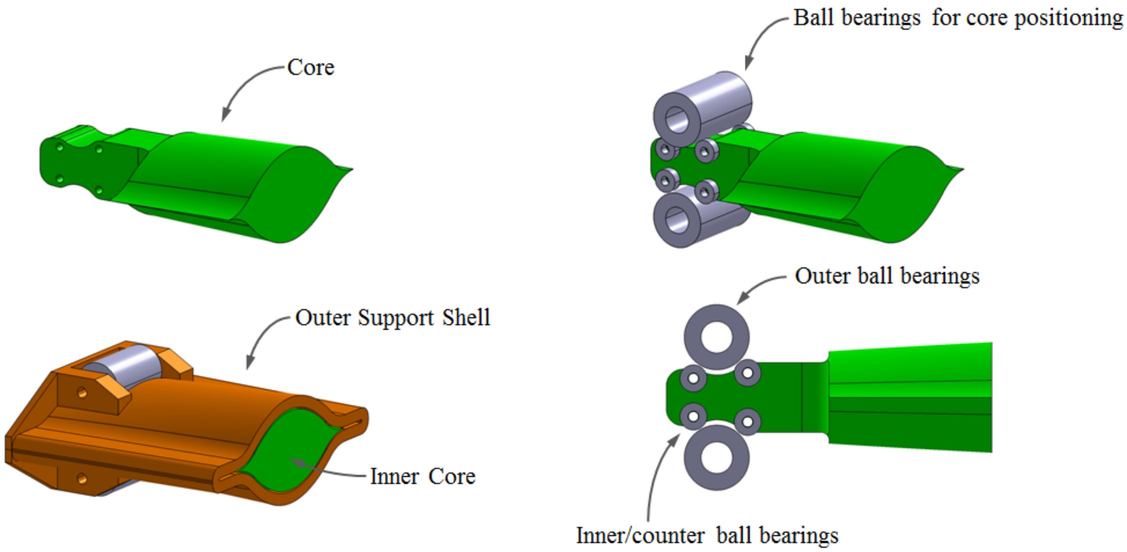

Figure 3: Principle design of the sliding core interface consisting of an inner core (green), a set of roller bearings (grey) to enforce the form closure through the boom shell and an outer support shell (orange).

Figure 4 shows the same interface realized as a 3D-printed plastic model for prove of concept displayed with a boom sample sliding in between the core and the outer support shell. Thereby the gap between both parts is only slightly wider than the boom's shell thickness. This reduces lateral motion of the shells under load and thereby minimizes losses in stiffness and strength at the interface. The resulting mechanical performance of this type of interface is potentially close to that of a fully clamped boom.

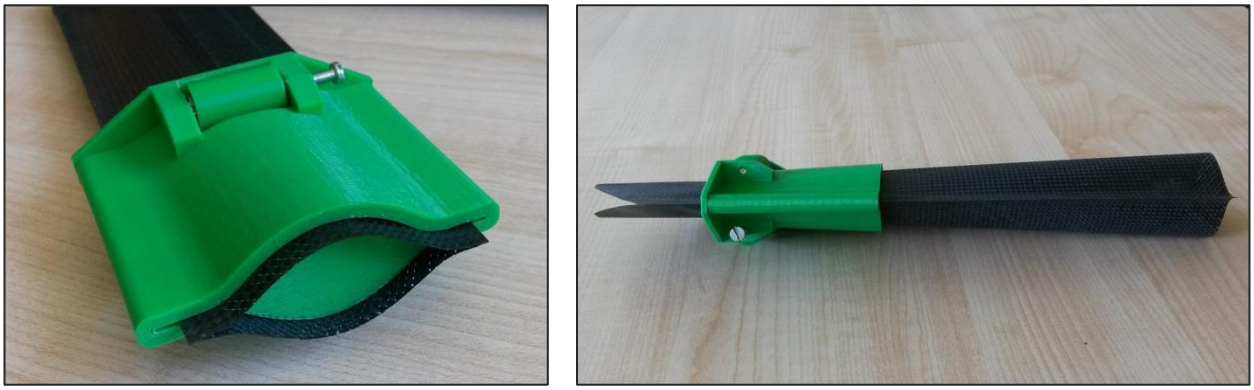

Figure 4: 3D-printed prototype of an early version of the sliding core interface.

III. Interface Design

The design of the sliding core interface starts by defining its required shape. The core and the outer support shell both have to match the form of the boom at the location of the interface. In general the interface is mounted within the transition zone of the boom which describes the region between its fully flattened and fully deployed state. Within this zone the boom undergoes a complex, three-dimensional change in shape. The shape of the transition zone is retrieved from an according finite element model as is displayed in Figure 5 for a tubular boom with a double-omega cross-section. Thereby the shape of the boom core has to match the shape of the inside of the boom's transition zone while the shape of the outer support shell has to match that of the outside.

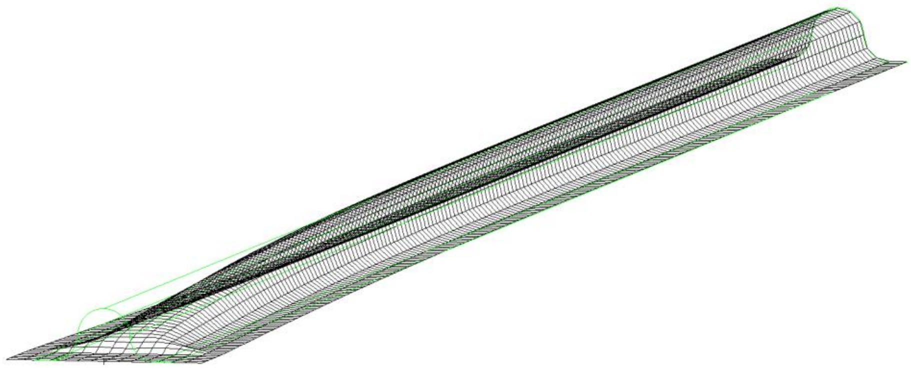

Figure 5: Finite element model of the transition zone of a single half-shell of a tubular shell mast with double-omega cross-section.

Once the shapes of the two main components are defined, their interconnection through the roller bearings needs to be designed. The related goals in this design step are displayed in Figure 6 and are as follows:

(1) Ensure proper fixation of the core through an undercut h between inner and outer roller bearings,
(2) Ensure strains induced into the boom shell to stay within the elastic region of the material to avoid boom damaging,
(3) Prevent rotational and lateral motion of the core through proper alignment of the contact points,
(4) Minimize the lateral motion of the boom shell in the interface by minimizing the gap depth t between core and surrounding shell,
(5) Minimize the increase in deployment force caused by the interface by minimizing the friction μ within the interface.

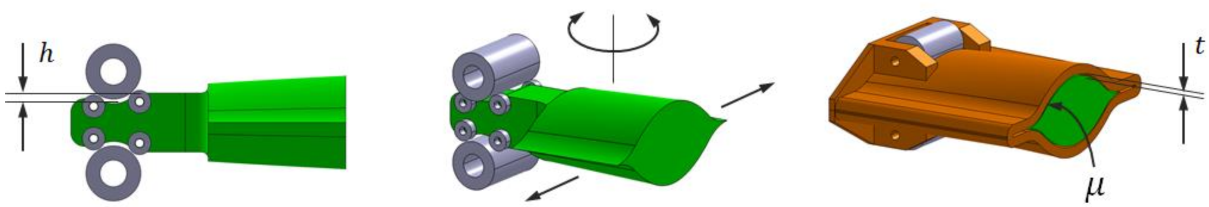

Figure 6: Design requirements of the sliding core interface: Depth of the undercut h (left), translational and rotational guidance stability (middle) and gap depth t and friction coefficient μ (right).

These design goals are considered in the design of the core and the surrounding support shell which are described separately in the following.

A. Core Design

The core is split into two parts: one rear part (relative to the deployment direction) used for mounting of the roller bearings and one front part forming the “extrusion nozzle” together with the outer support shell.

The design of the rear part is defined by the required alignment of the roller bearings that enforce the form closure between core and outer support shell. From the outside a single, larger bearing presses into the boom shell. The induced local deformation is countered on the inside by two smaller bearings that are screwed directly to the core. Their alignment depends on the local shape of the transition zone and the desired depth of the form closure between outer and inner bearings. All three bearings are thereby lying in the same plane. This plane is defined by the local normal vector $\overrightarrow{V_N}$ of the boom surface and the local motion vector $\overrightarrow{V_M}$ of the boom shell at the position where the outer bearing presses into the boom. Normal and motion vectors are thereby derived through a geometry analysis displayed in Figure 7 using the finite element model of the transition zone shown in Figure 5. Thereby only a single contact point needs to be analyzed as for a symmetric boom cross-section the mounting points and alignment vectors of the other three are symmetric to the center planes.

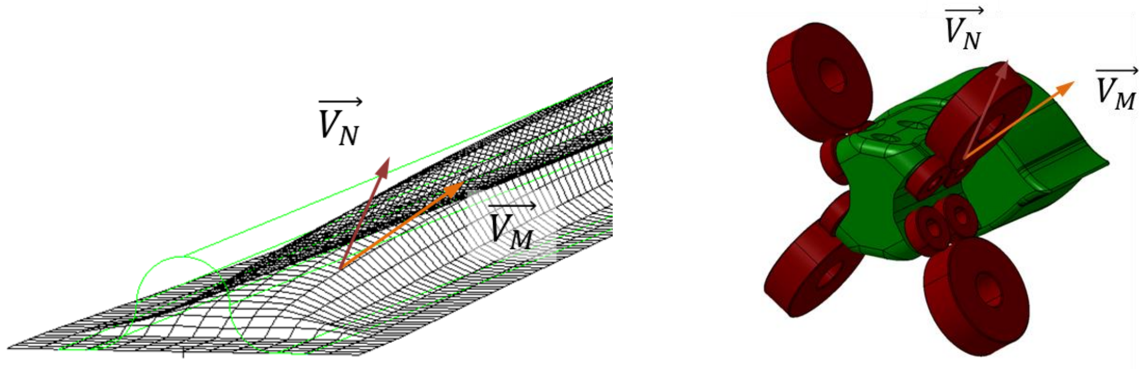

Figure 7: Local normal vector $\overrightarrow{V_N}$ and motion vector $\overrightarrow{V_M}$ of the boom shell with consideration of the transition zone at the contact point of the roller bearings.

When the position and alignment of the roller bearings are fixed, the form of the core's rear part is defined. The front part is directly attached to the rear part and matches the shape of the inside of the boom. Thereby a small offset towards the inner side of the boom shell needs to be considered to account for inhomogeneity in the thickness of the shell. The size of this offset determines the quality of the support given by the interface and should be selected as small as possible. However, the size of this gap also determines the friction within the interface together with the material selection and surface treatment of the core's front part and thereby influences the potential increase in deployment force the drive motor has to overcome.

B. Support Shell Design

The support shell encloses the boom from the outside. In the front it matches the outside shape of the boom and forms together with the front part of the core the "extrusion nozzle" that constrains the lateral motion of the boom.

In the rear the outer roller bearings are mounted. These press into the boom shell to establish the form closure to the two counter bearings mounted to the core. When selecting the alignment and relative distance of the three bearings, the shell thickness of the boom that is sliding through needs to be considered. Furthermore the local deformation induced into the boom needs to be taken into account during this design step. To prevent damaging the strains have to stay within the elastic limits of the boom material. To determine the complex three-dimensional deformation that is also superimposed by the already deformed state within the transition zone, finite element analysis is the favored way.

Once the alignment of the three roller bearings is defined, the structural design of the rear part is done. The outer roller bearings press with considerable force into the boom shells. However, to ensure proper fixation of the core, these forces shall not widen the undercut between the three bearings as otherwise the core will come loose. Hence the rear part of the support shell has to provide sufficient stiffness to minimize the relative deformation to an acceptable level.

IV. Development History

The development of the sliding core interface has passed several iterations. After the first prove of concept displayed in Figure 4 particularly the alignment and number of contact points between core and outer shell are subjects of optimization.

Functional tests on the initial prototype revealed a lack in lateral guidance of the core. When the boom moves through the interface the core rotates slightly and moves sideward which increases friction and finally causes the core to become stuck. Furthermore upon inspection of the boom after frequent test cycles, it is found that the edges of the roller bearings cut into the boom shell thus causing permanent damage.

The first iteration of the interface is displayed in Figure 8. The number of contact points between core and outer support shell is increased from 4 to 10. Thereby two of the contact points enforce the form closure while eight are inclined sideward to suppress lateral motion and rotation. To prevent damaging of the boom, all roller bearings are aligned carefully along the local normal and motion vector of the boom's shell as displayed in Figure 7 to avoid that there is excessive pressure exerted along their edges. Functional testing revealed that both means, the sideward inclination of the contact points and the proper alignment of the roller bearings, are effective to prevent undesired motion of the core and damaging of the boom even after frequent tests is prevented. However, the required number of roller bearings increases from 12 to 22 for this new design.

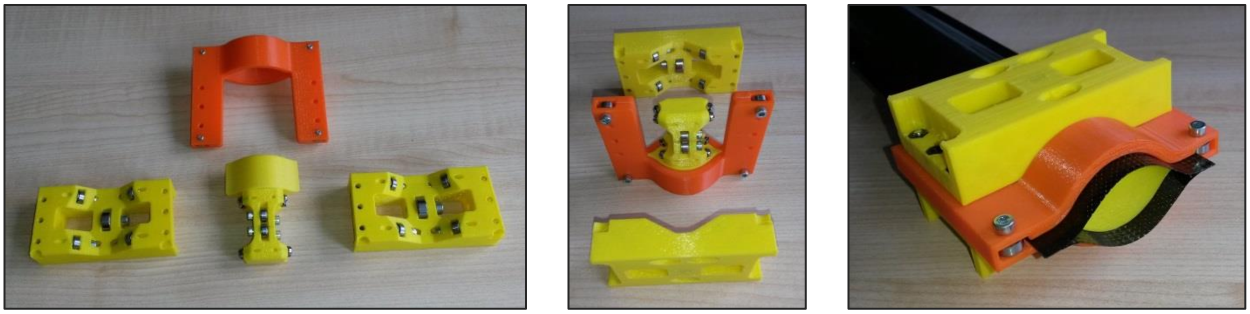

Figure 8: Sliding core interface design with two contact points with enforced form closure and eight contact points without form closure for translational and rotational guidance.

The second iteration of the sliding core interface is shown in Figure 9 (the related core design and bearing alignment is also displayed in Figure 7). The number of contact points is again reduced to four. To gain the required lateral and rotational guidance all four are tilted towards each other and form closure is enforced in all of them. Functional testing showed good position stability of the core and no damaging of the boom. In comparison with the previous iteration the length of the core is significantly reduced and the number of required roller bearings is back to 12.

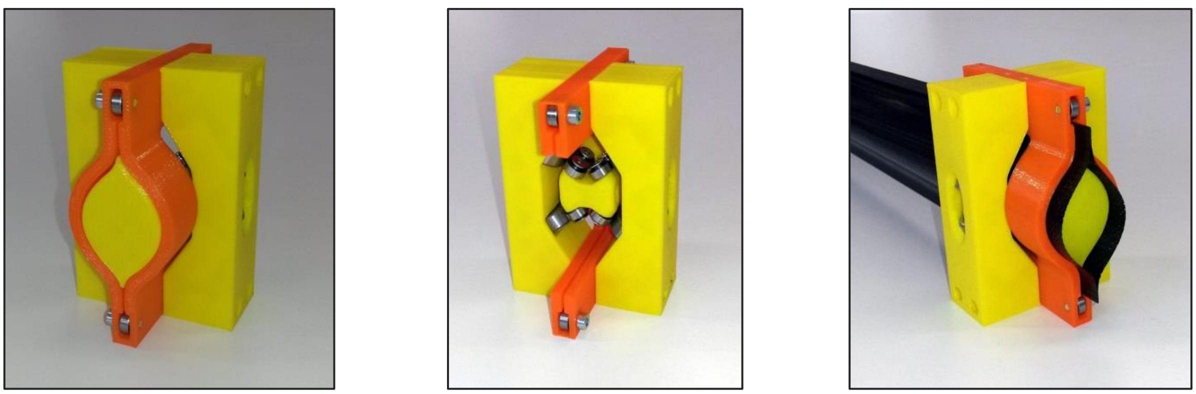

Figure 9: Sliding core interface design with four tilted contact points of the core with enforced form closure.

In both design iterations the outer support shell is split into two components. The front parts (see orange parts in Figure 8 and Figure 9) form the "extrusion nozzles" while the rear parts consist of two massive beams for mounting of the outer roller bearings (see yellow brackets in Figure 8 and Figure 9). They provide the necessary high bending stiffness to limit the lateral deformation at the mounting points under load and thereby ensure maintaining the form closure with the core.

V. Lateral Force Bending Tests

The mechanical performance of the sliding core interface is determined through lateral force bending tests. Subsequently the results are compared to those of an interface consisting only of an outer support shell. For the tests an interface is designed and manufactured through 3D-printing that possesses an elongated outer support shell and allows removing of the core. Thereby the influence of the core on the mechanical performance can directly be determined.

The lateral force bending tests are performed in the two main lateral axes of the boom. The axis lying in the plane of the flanges is called "flange axis" while the other is named "convex axis". Within the test stand the boom is aligned vertically to minimize lateral forces resulting from gravitation. The test interface is mounted to the top of the test stand while the lateral forces are applied to the boom tip at the bottom. The tested boom sample has a length of

2.95 m and its translational and rotational tip deflection under load is measured by an optical tracking system. The test stand and the boom alignment are displayed in Figure 10.

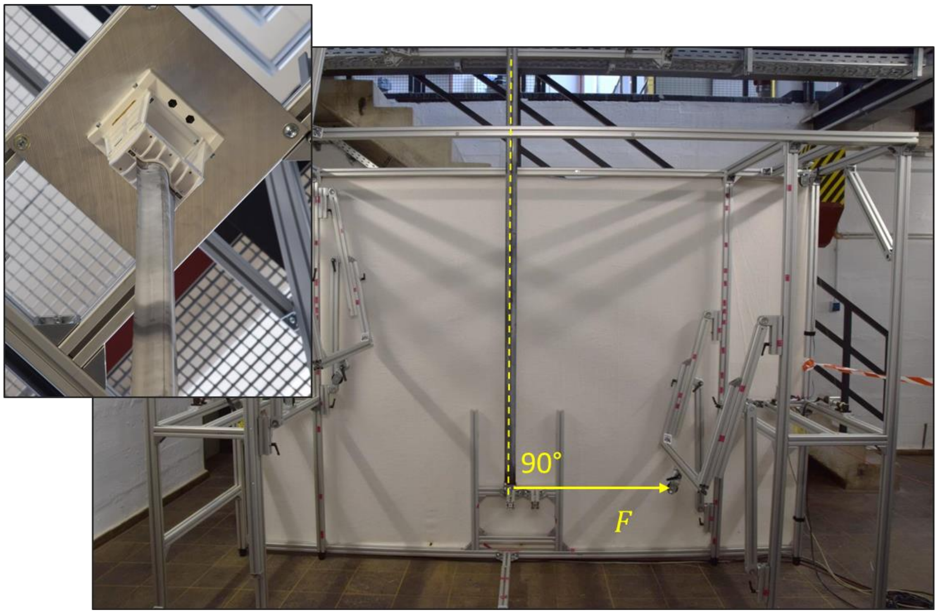

Figure 10: Tests stand for lateral force bending tests with vertically aligned boom under right angle force application and detailed view on the boom mount with the removable sliding core (small image, top left).

The first test cycle is performed along the flange axis whereby two test runs are made for each interface type. Figure 11 shows the starting position of the boom and the post buckling pattern for the tests with and without the sliding core. There is no noticeable difference in the failure behavior between both. Early in the test an s-shaped buckle forms in the compression loaded flange. This buckle is growing with increasing load until suddenly the adjacent curved shell buckles and mechanical failure of the entire boom occurs. Only a slight difference in the buckling patterns is observed between the two types of interfaces as the distance towards the interface of the location where the buckles form is higher in the tests with the core.

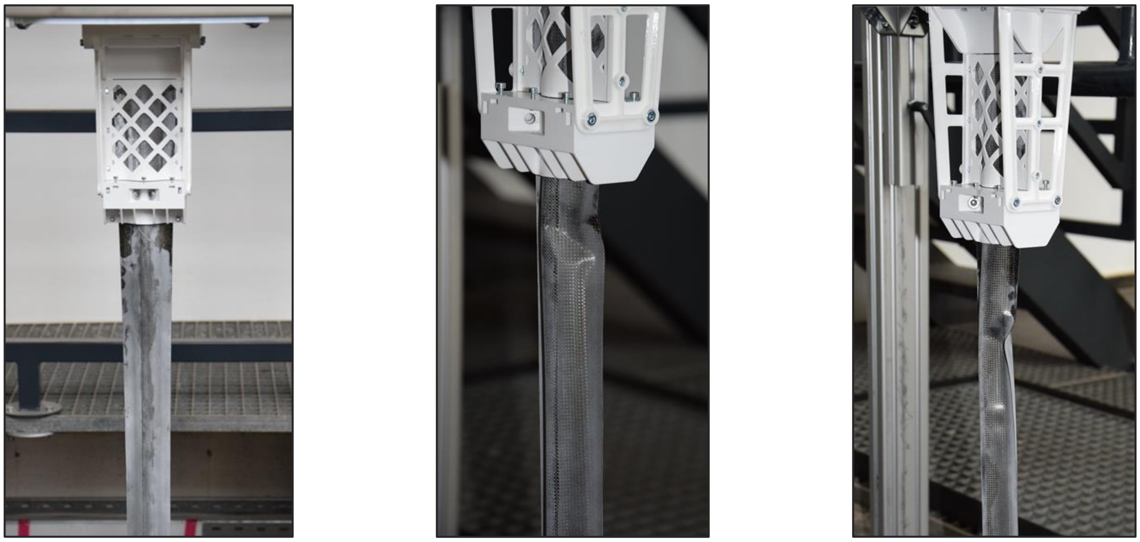

Figure 11: Test configuration for force application along the flange axis (left) and resulting buckling patterns for the boom interface without (middle) and with inserted sliding core (right).

The corresponding load displacement diagrams are shown in Figure 12. In both diagrams a pronounced non-linear progression is visible and for most curves a slight increase in the maximum loads over the first point of failure is observed in the post-buckling region. However, the maximum loads of 1.09 N and 1.13 N, with the sliding core interface are below those without the core which amount to 1.19 N and 1.17 N. The average difference is a loss in strength of 6.3%.

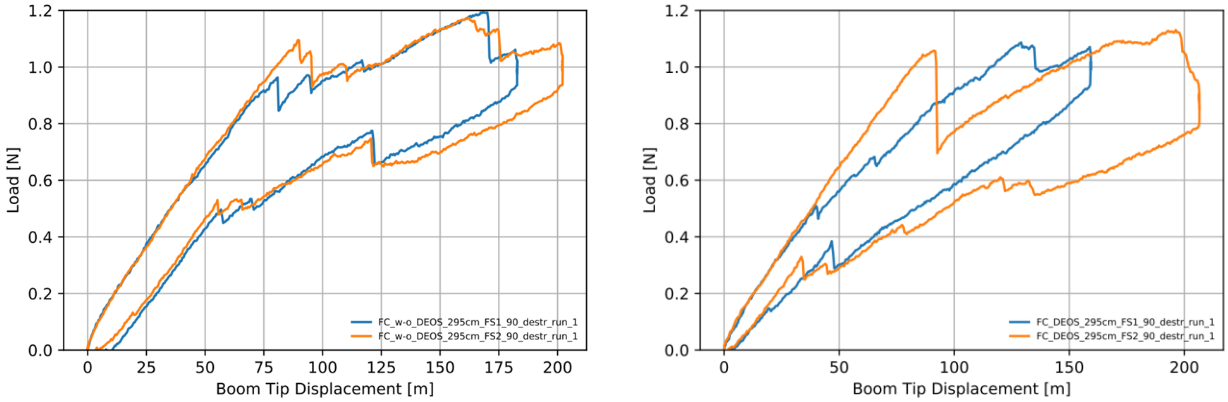

Figure 12: Force-displacement diagrams for lateral force bending along the flange axis without (left) and with the inserted core (right) for a boom of 2.95 m length.

The second test cycle is performed along the convex axis and again two test runs are performed for each interface type. The initial configuration and the buckling patterns of the failed booms are displayed in Figure 13. In this loading direction a strong difference between both failure modes is observed. For the interface without the core buckling starts within the support shell where the boom is still almost flat. This buckle grows under increasing load until it reaches the end of the supported region and failure of the entire boom occurs. The failure mode is the same as the behavior displayed in Figure 2. For the interface with the sliding core the boom buckles in a significant distance to the interface while at the interface itself no shell deformation is observed. Thereby failure occurs abruptly and without prior notice.

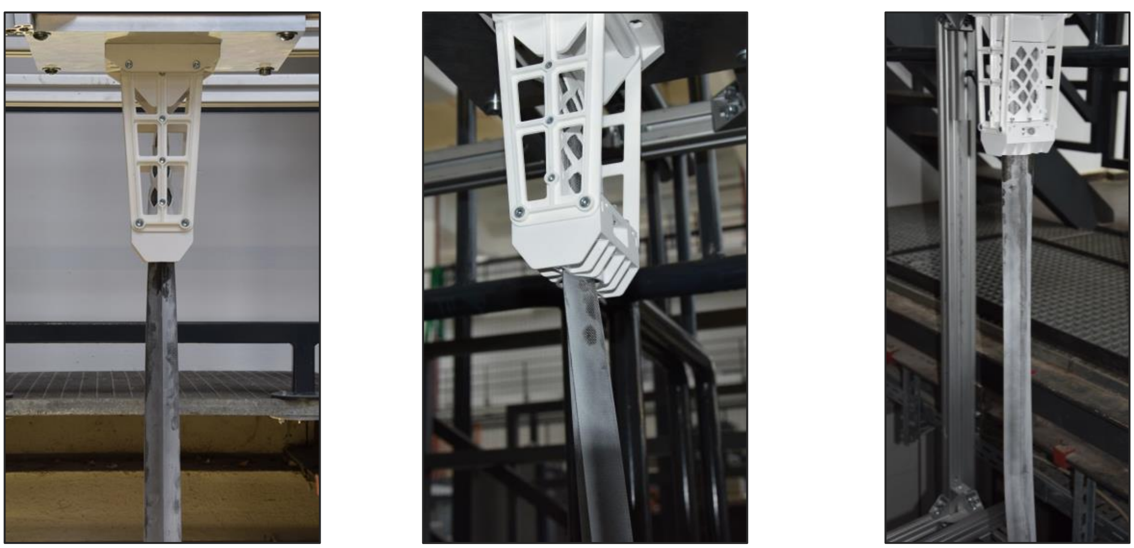

Figure 13: Test configuration for force application along the convex axis (left) and resulting buckling patterns for the boom interface without (middle) and with inserted sliding core showing a high distance of the point of failure to the interface (right).

The corresponding load displacement diagrams are given in Figure 14. In comparison to the tests along the flange axis, the progression is more linear particularly in case of the sliding core interface. Furthermore a pronounced post-buckling region with similar or even increasing maximum load does not exist. Comparing the failure loads, much higher values are achieved with the sliding core interface. Here the values reach 1.05 N respectively 1.14 N while without the core only 0.57 N and 0.58 N are achieved. Hence with the sliding core an average increase of 89.7% is gained.

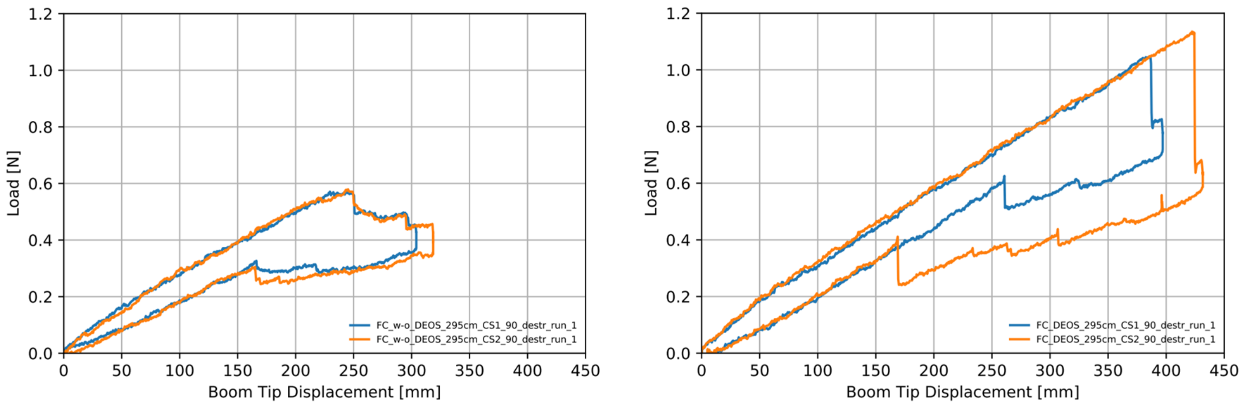

Figure 14: Force-displacement diagrams for lateral force bending along the convex axis without (left) and with the inserted core (right) for a boom of 2.95 m length.

The test results are summarized regarding bending stiffness in Table 1 and strength in Table 2. A comparison of the bending stiffness shows for both loading directions an increase in case of the sliding core interface. Along the flange axis a slight average increase of 8.2% is gained while along the convex axis an average increase of 22.8% is observed.

Boom Bending Stiffness	**Flange Axis**		**Convex Axis**	
	Without core	Core	Without core	Core
Stiffness [Nm²]	105.83	114.51	20.08	24.66
Increase due to Core [%]	**+8.2**		**+22.8**	

Table 1: Bending stiffness results from the lateral force bending tests and relative change due to the different interfaces for a boom of 2.95 m length.

Boom Bending Strength	**Flange Axis**		**Convex Axis**	
	Without core	Core	Without core	Core
Maximum Lateral Load [N]	1.18	1.11	0.58	1.09
Increase due to Core [%]	**-6.3**		**+89.7**	

Table 2: Bending strength results from the lateral force bending tests and relative change due to the different interfaces for a boom of 2.95 m length.

In conclusion to the mechanical testing it is found that the differences in failure mode, stiffness and strength for lateral force bending along the flange axis are small and potentially lie within the general scatter. For a more extensive assessment more tests on different booms are necessary.

The differences in the failure mode and test results are considerably more pronounced for lateral force bending along the convex axis. In the vicinity of the sliding core interface no lateral motion of the boom's shell under load is observed which shows the effectiveness of the sliding core to provide lateral support. In consequence, both bending stiffness and strength increase by 23% respectively 90%. Hence, application of the sliding core interface leads to a significant enhancement of the deployable booms overall mechanical performance.

VI. Application to a Solar Sail

The sliding core interface is applied to the deployment mechanism of a solar sail that is based on DLR's GOSSAMER design and is further described in reference [2]. The mechanism features a modular design where one to four booms can simultaneously be deployed while sharing the same boom hub and deployment motor. The sliding core interface is thereby connected to the central mechanism structure with the boom hub by a box-shaped frame that also carries some additional guiding elements to further support the booms transition zone and particularly the flanges. The principle design of the remaining mechanism components is basically the same as described in reference [3]. The CAD-model of this deployment mechanism and the 3D-printed prototype is shown in Figure 15.

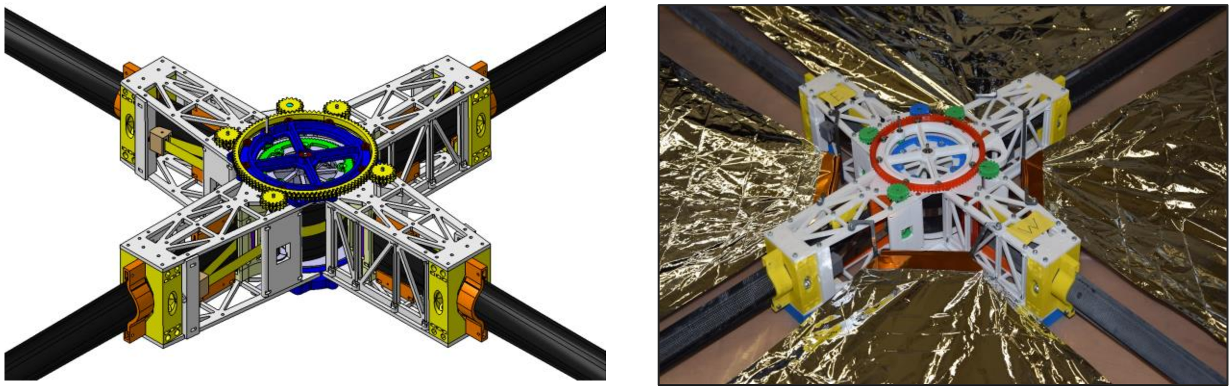

Figure 15: CAD-model of the modular boom deployment mechanism with the sliding core interfaces at the tips of the box-shaped frames (left) and 3D-printed prototype (right).

Based on this deployment mechanism a solar sail is realized that uses the same principles for sail folding and deployment as GOSSAMER. Thereby the sail is split into four quadrants which are stowed through folding and reeling. At first each quadrant is zigzag-folded along its symmetry axis. The thereby gained flat band is subsequently reeled from its tips onto two separate spools that meet in the middle. The spools are then attached to the boom tips of two neighboring booms wherefore on each tip finally two spools are mounted.

Deployment of the sail is driven by the central deployment mechanism. When the booms are deployed, the sail spools are moved outward and the sail quadrants are pulled off the spools located at the booms tips. Through unfolding from the boom tips, a highly defined deployment process is gained as the already deployed part of the sail is not exposed to any further unfolding movement and remains in its position. This is not the case for a deployment method where the sails are deployed out of the center of the sail.

The sail deployment sequence of a 1.5 m x 1.5 m breadboard model of the sail is shown in Figure 16. Testing of this prototype showed a well-defined boom and sail deployment. Some lateral bending in the plane of the sails is observed that results from different pull-off forces of two neighboring sail quadrants which cause lateral displacements of the boom tips. However, at the sliding core interfaces no distortions of the boom shells are observed and no sharp bends of the booms at the interfaces are visible. Both observations indicate a high quality of the mechanical support provided by the new sliding core interface during the deployment process of the sail.

Figure 16: Deployment sequence of the solar sail with the deployment mechanism based on sliding core interfaces.

VII. Conclusion and Outlook

The paper describes a new type of interface for reelable, tubular shell masts of closed cross-sections. The interface is based on a core that is inserted into the boom at the location of the interface. The difficulty in fixing the cores position without direct accessibility is solved through a form closure enforced from the outside by local deformation of the booms flexible shell through roller bearings. Together with the outer support shell, the interface prevents any lateral deformation of the boom shell similar to an extrusion nozzle whereby a stiff and stable connection between the boom and deployment mechanism is gained.

The design of the sliding core interface is advanced through several iterations, realized as 3D-printed prototypes and subjected to functional testing. Initially observed boom damaging could be prevented for the later design iterations. Subsequent mechanical characterization in lateral force bending tests and comparison with the conventional solution of a single outer support shell showed a significant increase both in bending stiffness and strength. For lateral force bending along the convex axis of the booms the stiffness increased by 23% while the bending strength increased by 90%. However, along the flange axis only small differences are observed which may lie within the normal scatter.

The effectiveness of the sliding core interface is also observed in the functional testing of a solar sail whose central deployment mechanism makes use of this new interface type. Lateral forces due to asymmetric sail deployment loads caused lateral tip motion but no shell deformations or sharp bends in the booms bending line at the interface are observed.

The design of the sliding core interface and its corresponding deployment mechanism are further advanced within DLR's GoSolAr (Gossamer Solar Array) project [4]. Flight demonstration of this solar array that is based on a solar sail architecture is scheduled for 2023.

Legal Situation

The patent for the sliding core interface is pending. The application number for the United States Patent and Trademark Office is 16/420,256. The application number for the Deutsches Patent- und Markenamt is 10 2018 112 690.5.

Acknowledgments

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