1 Introduction

The study carried out within the present project has the objective of demonstrating the feasibility, use and functionality of Carbon Fiber Reinforced Flexible Epoxy materials (CFRFE) for self-deployable space structures such as deployable tape-spring hinges by means of designing, simulating, manufacturing, testing and correlating a classic (100% carbon fiber reinforced plastic -rigid resin- CFRP) deployable tape-spring hinge and a CFRFE deployable tape-spring hinge and compare their mechanical and dynamic behaviours.

This project justifies the efficacy of the use of CFRFE materials in a real space case. For this purpose, a self-deployable full composite boom has been designed, manufactured, tested and validated so that in can deploy a tip payload with a relevant mass with less final impact at the final deployment than a typical CFRP hinged boom.

When a boom (a long and slender mast) is needed for a space mission, two different design approaches can be done:

- a CFRP boom with metallic hinges which are usually motorised or self-deployed by springs.
- a thin walled CFRP boom which is hinged by means of slots in its walls that allows its folding and a quick and uncontrolled deployment, due to the high stiffness of this kind of carbon fibre tape springs.

An example of these technologies can be found on ESA Juice mission platform, which contains a number of deployable booms with several technologies. The magnetometer boom, developed by Sener Aerospace[1] , is deployed by springs, and its deployment is controlled and synchronised by springs, cables and pulleys. The RIME antenna, developed by STI[2], consists of a full composite boom which consists of a tube with dedicated slots that act as hinges, following the principle of tape-spring hinges. This design is lighter and simpler.

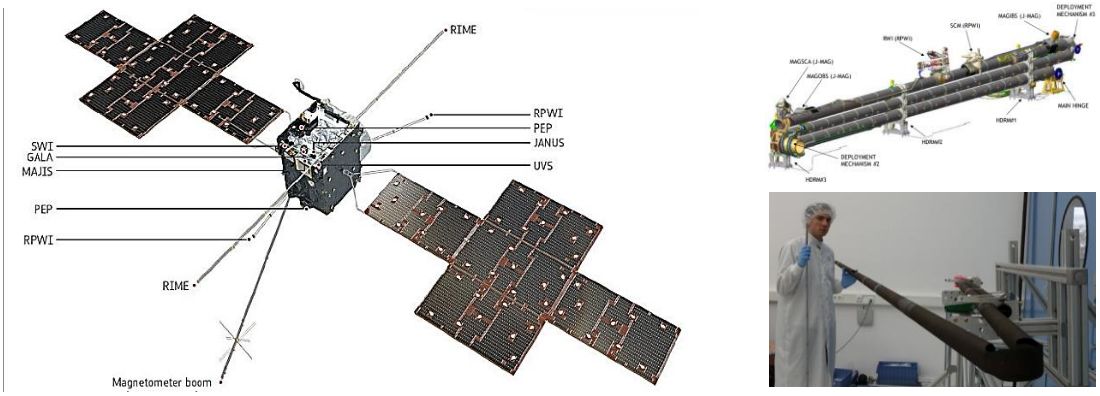

Figure 1. ESA Juice Mission booms (L): Magnetometer boom (TR) and RIME antenna (BR).

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[1] Juice magnetometer boom subsystem. A. Arce et al. European Space Mechanisms and Tribology Symposium 2019, Munich, Germany, 18.-20. September 2019

[2] https://www.spacetech-i.com/products/mechanisms/juice-rime-antenna. Accessed 6/12/2020

This study demonstrates that the use of CFRFE hinged booms can take the advantage of a simpler design with the advantage of a smoother deployment that mitigates the potential damage that the deployed payload or the platform can suffer. It includes the test at sample level of the properties of stiffness, damping, creep and thermal expansion of various materials formed from the mixture of the two resins in different proportions.

The viability of the designed structure has been justified by means of finite element models, in order to later manufacture and test hinge prototypes with the resin proportions that provide the best results for the desired purposes. Tests of these prototypes have been used to correlate the finite element models and to have a better approximation to the real properties of the structure than the one offered by coupons.

2 Requirements

A set of requirements have been provided by Airbus DS, which is a potential customer of this technology in the future. A tip mass (a reflector) of 11.1 kg will need to be deployed from the platform. The boom mass will need to be lesser than 3.3 kg. The resulting tip mass with the boom will need to have a first natural frequency higher than 1.5Hz.

Morphology of the boom and its position on the platform must conform to the scheme shown in Figure 2.

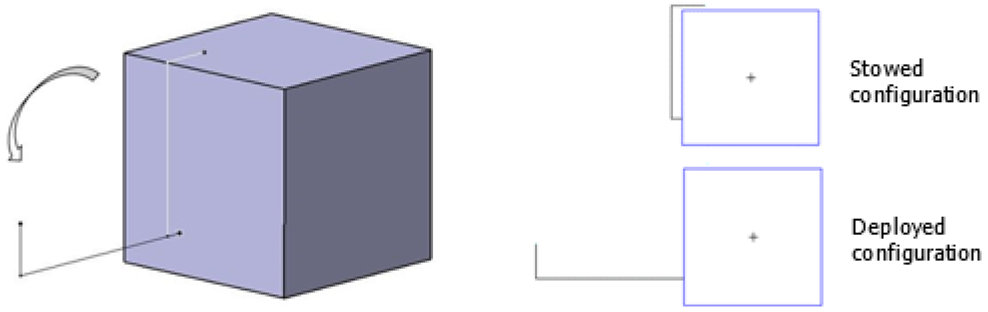

Figure 2. Global geometry of the boom

3 Preliminary Hinges Design

An average CFRP material property has been used to preliminary design the boom so that it can fulfil the overall deployed stiffness requirement of the reflector and the boom. A FEM model has been developed with this purpose. Figure 3 shows this finite element model. A punctual mass of 11.1 kg has been included at the boom tip. The results of the modal analysis carried out on the model are shown in Table 1.

Table 1. Achievements for the preliminary design.

Achievements	
Boom mass (kg)	1.48
1st frequency (Hz)	1.89

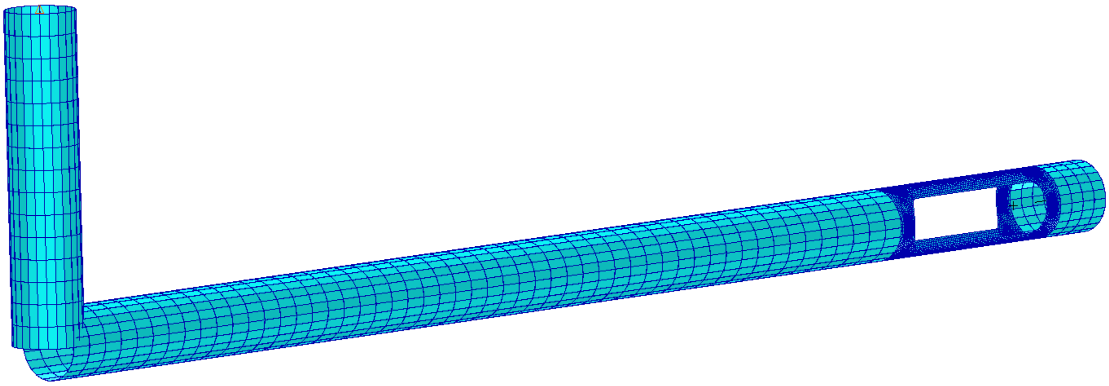

Figure 3. FEM model for the preliminary design of the boom.

4 Test Coupon Campaign

A set of CFRFE material coupons have been tested, considering that the flexible epoxy resin can be mixed with rigid epoxy resin in different proportions, allowing a customization of stiffness and damping of the resulting composite laminate. Unidirectionally reinforced CFRFE material at various flexible epoxy resin percentages have been characterised. Additionally, multiaxial laminates have been defined and tested on terms of tensile, bending, damping and thermal expansion behaviours.

Once the unidirectional material has been characterised, and based on the material requirements established in the previous section, a multiaxial laminate will be defined and then tested on terms of tensile, bending, damping and creep behaviours. Thermal cycling has also been applied to the coupons.

Four different composite materials are considered for both types of specimen, mixing the rigid and the flexible resins in proportions with 0%, 25%, 50% and 75% of the flexible one respectively.

Tensile and bending tests have been done following normalised standards. Damping tests have been done by means of acoustic measuring of the vibration produced by a cantilever laminate when played with a spike and response analysis of the oscillations decay from one bounce to the next. Creep behaviour has been measured by means of inducing in a coupon a similar bending shape to the one than it will have when the boom hinge is in folded state.

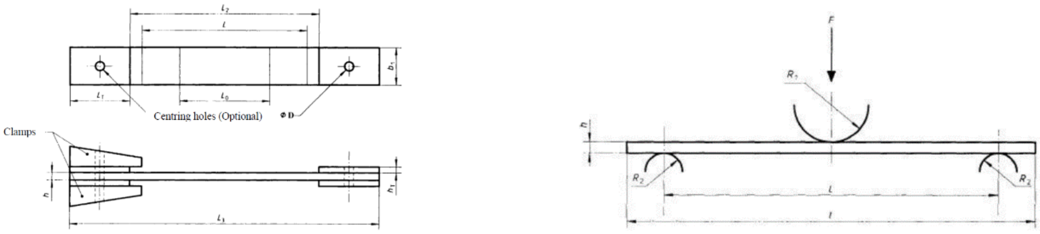

Figure 4. Tensile (L) and bending (R) tests configurations for laminates characterization.

Figure 5. Damping test (L) and creep test (R) setups.

Tensile properties in the direction of the fibre have been shown to be barely dependent on the matrix, so a small deviation has been found in different epoxy resins proportions. Nevertheless, flexural behaviour of laminates with different epoxy resins proportions have shown to be considerably different: there is a very significant reduction in the flexural modulus of elasticity with respect to the tensile modulus for the more flexible mixtures. The same trend can also be seen in the strength limits, being particularly noticeable the low bending strength of the laminates with high proportion of flexible epoxy resin.

Damping tests have confirmed that, for the same geometry and boundary conditions, laminates with more flexible resins have a greater damping than rigid ones (1.8% compared to 0.5% of loss factor respectively). This data is not reliable when extrapolating to other geometries (damping is not only a material property), so the damping of the hinge must be calculated by testing it.

Creep tests have shown that coupons recover their initial shape after thermal cycling, providing good results and establishing an excellent starting point for validating flexible epoxy resins for space applications. Thermal expansion coefficients have also been estimated in dedicated tests.

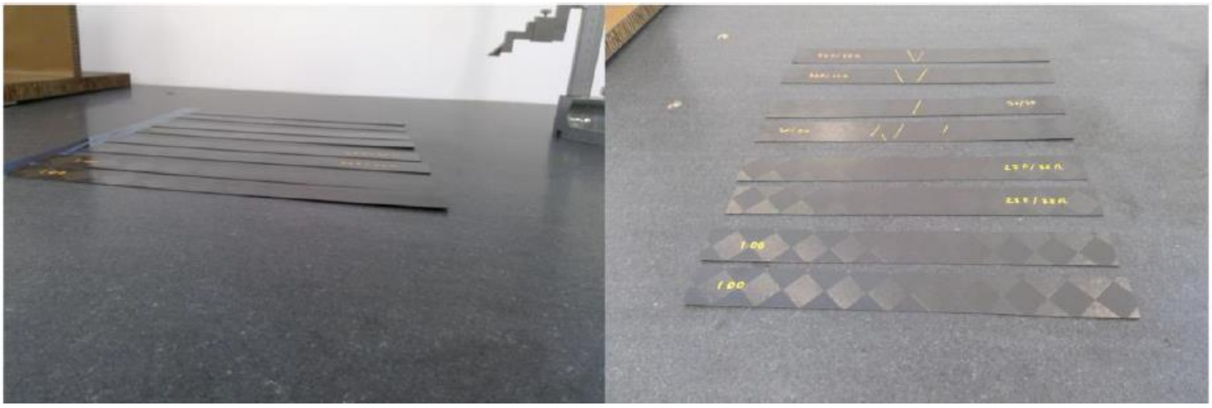

Figure 6. Flatness verification of creep coupons after cycling.

5 Hinges Design

Two finite elements models have been built, one with a 100 % rigid resin laminate (CFRP) and the other with a mixture of rigid and flexible resins (CFRFE). The composition of this second laminate has been determined by the fulfilment of the requirements, especially the strength one. The most suitable flexible laminate that fulfil them contains a mixture of resins with 40% rigid and 60% flexible at the inner tape of the boom hinge.

Both rigid and flexible designs fulfill all the established requirements for the boom, including a common first natural frequency and mode shape, as the it is driven by the in-plane behaviour of the laminate, which has been demonstrated to be common to both flexible and rigid laminates for the selected application.

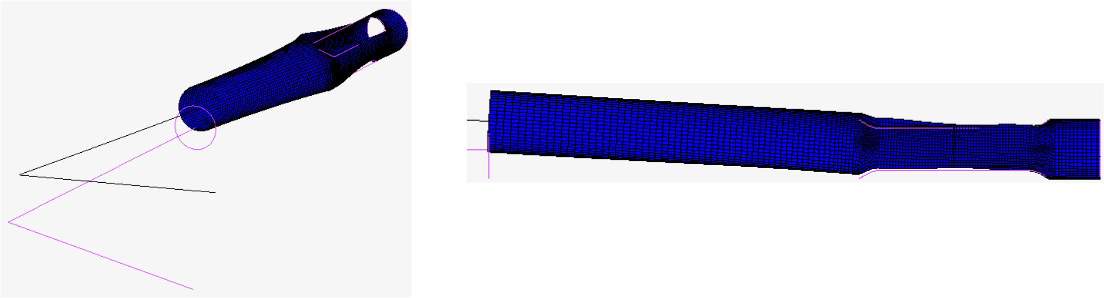

Figure 7. Boom 1st mode shape (1.54Hz).

5.1 Deployment Simulation

Deployment of both booms with flexible and rigid epoxy resins have been simulated, taking into account the energy loss factor, which has been introduced in the MSC/Marc simulation software by means a a Rayleigh's proportional damping model in which the damping matrix is supposed to be proportional to the stiffness matrix, where the proportionality constant β is calculated from the loss factor η as:

$$\beta = \frac{\eta}{\omega} \tag{1}$$

Where ω is a representative frequency of the movement. The first deployed mode frequency has been considered.

The deployment simulation show that both CFRFE and CFRP booms buckle after deployment, but the maximum deployment speed and the maximum angle developed by the hinge after buckling is lower for the CFRFE boom, as it can be seen in the following figures.

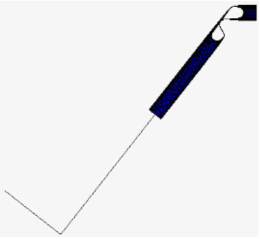

Figure 8 Most deviated position CFRP.

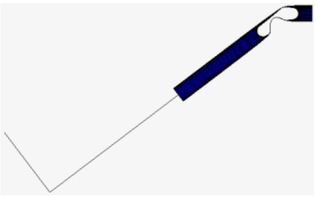

Figure 9 Most deviated position CFRFE.

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5.2 Strength Analysis

The failure theory used to extract the failure indices from the model is the Tsai-Wu criteria. The failure index of each ply of the laminate has been obtained through all the folding and deploying process. Table 2 shows the worst case for each boom (Hinge in folded state).

	CFRP	CFRFE
Tsai-Wu Failure Index	0.734	0.942

Table 2. Failure indices.

As was expected, the most critical failure index appears in the CFRFE model. The zone where it takes place is the outer layer, where it is shown in the Figure 10.

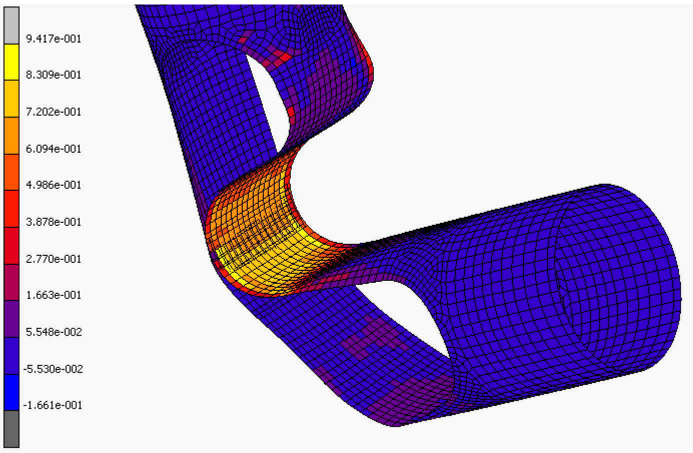

Figure 10. CFRFE Tsai-Wu failure criterion in ply 1.

6 Hinge Demonstrator Tests

Two boom breadboards, with a hinge each one, have been designed and manufactured, one of them using a standard CFRP material and the other one using CFRFE, measuring 900mm in length and 160mm in diameter. Following figure shows one of the breadboards, in the static characterization test machine in deployed position and during its folding.

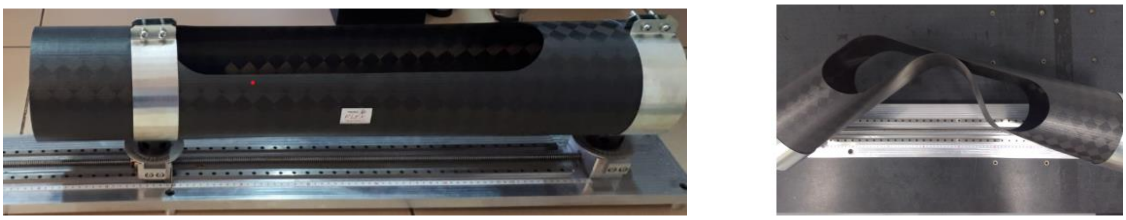

Figure 11. Demonstrator static characterization test: deployed position (L), during deployment (R).

Figure 12 shows the moment vs. hinge angle curves for both materials obtained during tests, which shows that the CFRFE hinge reduces the deployment torque to be applied to the payload with respect to the CFRP one, especially during the last stage of the deployment (from 155º to 180º).

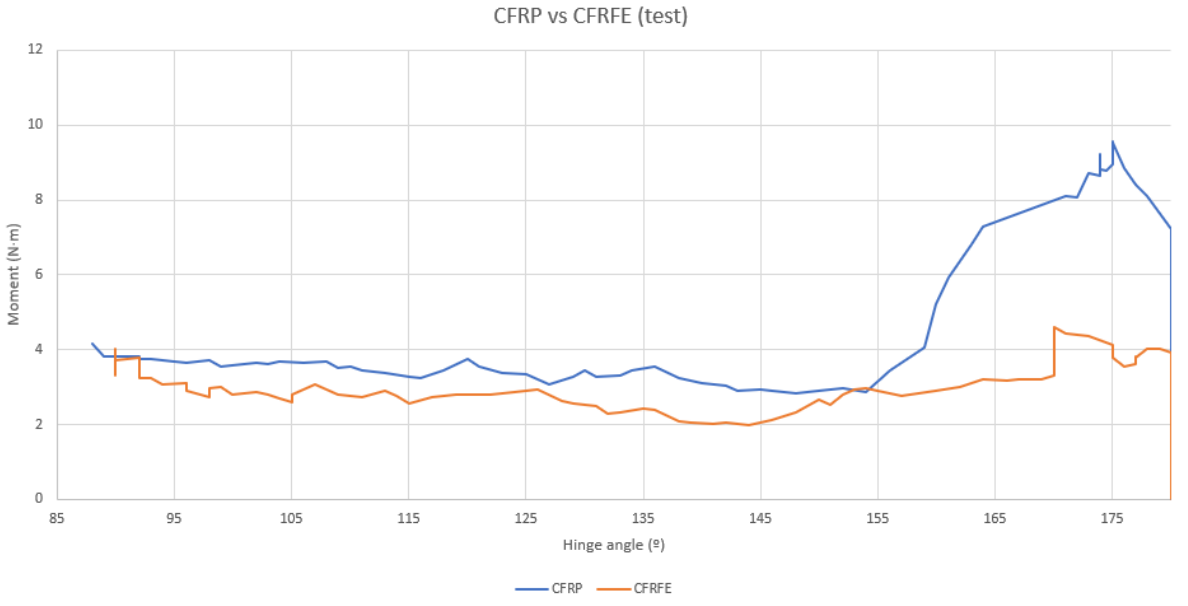

Figure 12. CFRP and CFRFE static moment tests results.

Figure 13 and Figure 14 show the loaded deployment sequence of the boom with CFRP and CFRFE hinges, respectively. A mass of 1 kg has been included is at the free tip, inside the tube (not visible in the pictures).

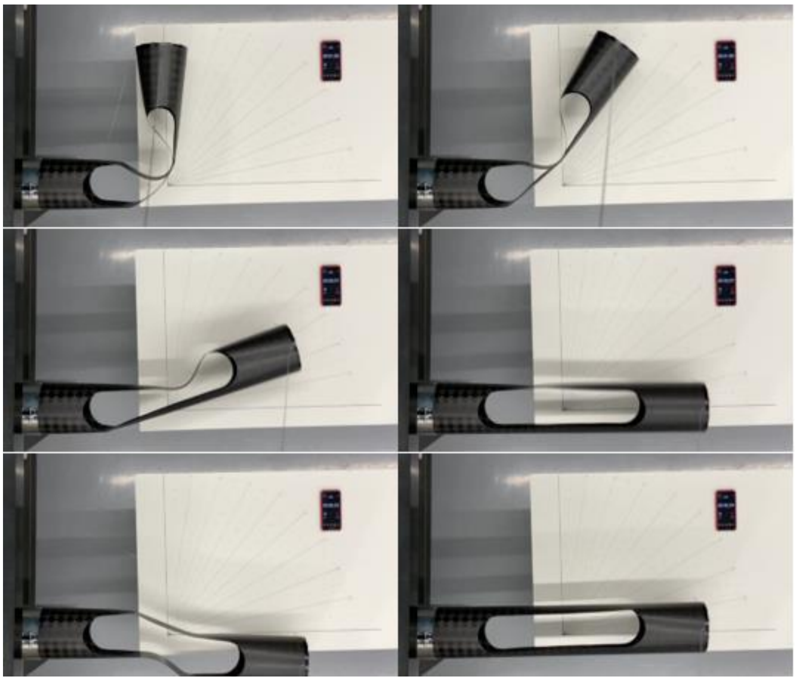

Figure 13. Loaded deployment sequence of the CFRP hinge (left to right and top to bottom).

As can be seen in Figure 13, the boom with the CFRP hinge is able to deploy carrying a mass its tip, but it buckles after fully deployed, allowing the boom to fold to the other side. This buckling affects both blades of the hinge, the intern one and the extern one.

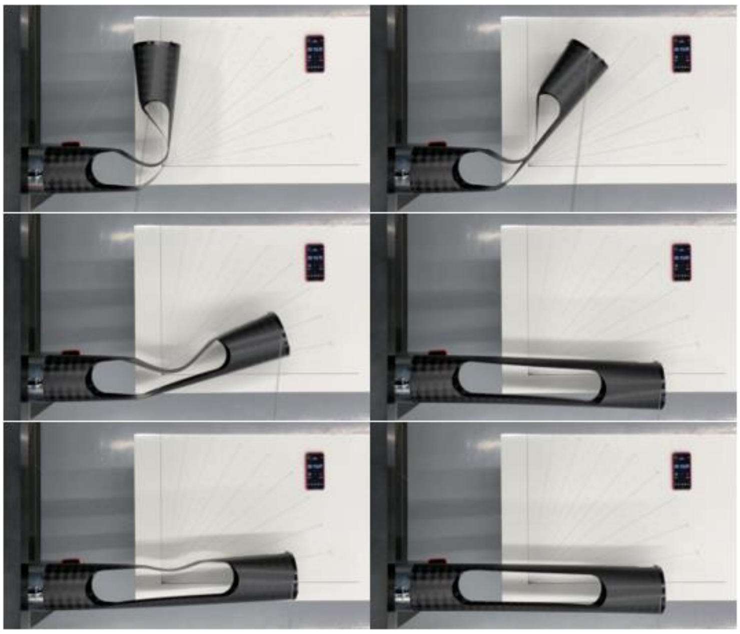

Figure 14. Loaded deployment sequence of the CFRFE hinge (left to right and top to bottom).

On the other hand, the boom with the CFRFE hinge is also able to deploy when loaded with the same mass. A slight bending beyond the fully deployed position can be observed, but the hinge does not buckle at all. A rebound is produced that causes the buckling of the intern blade, but with minor effects .

Table 3 shows the time that it takes each boom to get the straightened shape and its angular velocity at this moment, along with the uncertainty of the measurement. It can be seen that the final speed at the deployment has been reduced by a 30%, which implies a promising result.

Table 3. Loaded dynamic deployment tests results

	CFRP	**CFRFE**
Time to deploy (s)	0.49	0.53
Final angular velocity (rad/s)	6.8	4.7

The last test done to both breadboards has been verifying their stiffness by means of a free vibration test. Results are shown in Table 4 below, and show that the breadboard stiffness remains almost the same (less than 3% lower) for the CFRFE breadboard, which confirms the predicted behaviour during the hinge design phase.

Table 4. Dynamic free vibration test results.

	CFRP	**CFRFE**
Frequency (Hz)	115.4	112.7
Loss factor	0.008	0.010

As it was expected, CFRFE hinge damping loss factor is higher than the CFRP one.

7 Lessons learnt, conclusions and Future Work

The utility of Carbon Fibre Reinforced Flexible Epoxy Resin for its use in the passive deployment of full composite structures has been demonstrated, and its stiffness, strength and damping characteristics have been tested and used for a space application: a full carbon fibre self-deployable boom with a damped behaviour with respect to simple CFRP booms.

In particular, for the selected application, several key-issues have been confirmed:

- The miscibility between the rigid and epoxy resins used has allowed to customize the CFRFE properties for the purpose of the selected application within some limits (basically the material strength, but also its stiffness), maximizing the damping effect of the deployment of the boom.
- The bending stiffness of CFRFE thin laminates is lower than the CFRP's one, which allows reducing the deployment speed of the composite boom.
- The damping characteristics of CFRFE are higher than the CFRP ones. When this is combined with the lesser deployment final speed of the CFRFE boom, it drives to a smoother deployment with less impact at the end of the hinge trajectory,
- Bending strength capabilities of CFRFE thin laminates remain at remarkable levels. Its tensile strength capabilities are excellent.
- The use of CFRFE in thin laminates does not alter the membrane characteristics of the laminate with respect to CFRP thin laminates, which becomes an advantage when it is used in self-deployable booms, because the boom overall stiffness remains unchanged.
- CFRFE thin laminates do not have remarkable creep values after long storage in folded positions.

These facts enable this material to be used in space booms and other potential applications to be found, even out of space applications.

The material and the boom mechanical properties have been obtained via tests and correlated with mathematical models with promising results. Nevertheless, some aspects need to be investigated for the future:

- The damping characteristics of the resulting CFRFE boom are extremely difficult to obtain via mathematical models, as damping of a structure is not an intrinsic material property, and they need to be extracted from dedicated tests.
- The bending behaviour of CFRFE and CFRP needs to be further studied at large deformation stages.

Further studies will be devoted to investigating these characteristics and consequently improve the knowledge of the material and its application.

Future works to be done in the frame of the study of CFRFE are the following:

- Raise its TRL in order to be able to use it in the development of full composite hinged booms for space applications.
- Continue with the development of a full composite boom with damped deployment within a complete system/subsystem and raise its TRL to 5.
- Look for other applications for this promising material.