STRUCTURAL PART STIFFNESS TEST IN COMPARISON TO THE FE-PREDICTION. A TEST COMBINING CONTINUOUS STRUCTURE WITH COMPLEX INTERFACES

Olaf Mierheim(1), Michael Lange(1), Sebastian Meyer(1), Jens Kosmann(1), Christian Hühne(1)
(1) *DLR Institute of Lightweight Systems, Braunschweig, Germany, Email: olaf.mierheim@dlr.de*

KEYWORDS

Insert, additive manufacturing, testing, thermal testing, rover, rover structures, CTE, bonded interface, glue, RTV, structural part properties

ABSTRACT

In JAXA's (Japan Aerospace Exploration Agency) MMX (Martian Moons eXploration) mission [1] the two Martian moons, Phobos and Deimos, and the Martian environment shall be studied. In this regard DLR (German Aerospace Center) and CNES (Centre National d'Etudes Spatiales) developed the MMX rover IDEFIX that shall explore the surface of Phobos and will be launched onboard the Japanese MMX spacecraft in 2026 [2]. The MMX rover will be delivered to the surface of Phobos by the MMX spacecraft, where it is mounted on the MECSS (Mechanical, Electrical and Communication Support System) structure. This structure interconnects the rover with the spacecraft and provides interfaces to the HDRM (Hold-Down and Release Mechanism) and to a dedicated push-off mechanism, which are used to separate and eject the rover from the spacecraft.

This paper addresses mechanical tests in order to determine the MECSS in-plane stiffness in comparison to its predicted stiffness from a finite element (FE) simulation. Knowing this stiffness is important, because it highly influences the thermoelastic stresses and interface loads of the MECSS and its adjacent structures, mainly the MMX spacecraft aluminum sandwich panel.
The MECSS structure is a sandwich panel consisting of CFRP (Carbon-fiber-reinforced polymers) face sheets with aluminum honeycomb core and four rather large aluminum inserts in its corners, cf Fig. 1. The inserts at the corner provide the interface to the spacecraft and to the release mechanisms of the rover. While the prediction of the stiffness and thermoelastic properties of the continuous CFRP face sheets is a simple analytical task, the prediction of the MECSS's corner inserts interface stiffness is more complicated due to different parallel load paths. The inserts are manufactured via ALM (Additive Layer Manufacturing). Due to the very demanding thermal environment in combination with the high CTE (Coefficient of Thermal Expansion) mismatch between the materials used, a flexible glue (cf. Fig. 1, red markings) is used to interconnect the corner inserts to the facesheets. Locally the three screws that connect the release mechanisms cup interface to the corner inserts also clamp the facesheets to the inserts. This double load path in a complex setup makes the prediction of the actual ("effective") stiffness difficult, as different assumptions can be taken on how the interface will behave. Therefor a load test was conducted to measure the overall stiffness of the MECSS.

In the test, the deformation under load is measured with the help of the optical 3D measuring device GOM ARAMIS, which uses digital image correlation. As a result, the deformation of the visible side of the MECSS is given in 3D coordinates. This 3D deformation is calculated back to the in-plane deformation of the central plane of the MECSS and compared to the FE simulation. It is evaluated which assumption predicts the actual deformation best.

1. MECSS DESIGN DESCRIPTION

The interface between spacecraft and rover "MECSS" is a CFRP sandwich structure. It is attached to the MMX Spacecraft at four interface points by M8 bolts. The Rover is attached to the MECSS via HDRMs oriented in a slightly smaller rectangle formation than the interface to the MMX Spacecraft. In its centre the MECSS structure supports a push off mechanism for separating the rover and the umbilical plug. The height of the sandwich is mostly dictated by the space needed to accommodate the push of mechanism.
At the four corners additively manufactured aluminium inserts are used that provide the interface towards the spacecraft and the interface towards the rover. Since the distance of the two interfaces at each corner is small it was decided to combine them in one complex insert to avoid repeating bonded interfaces and to have a high geometric accuracy between the two interfaces. These inserts consist of two tube like sections, one around each of the interfaces and a grid in between. The interface to the spacecraft only accommodates one bolt each. The interface towards the rover accommodates the HDRMs.

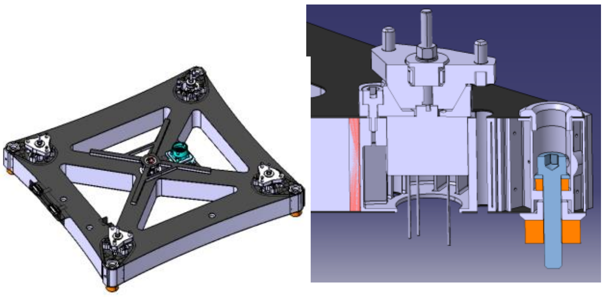

Figure 1: MECSS assembly (left) and sectional view of a corner insert

This design provides a decent stiffness with low material effort. It can hardly be produced by another mean of manufacture than additive methods.

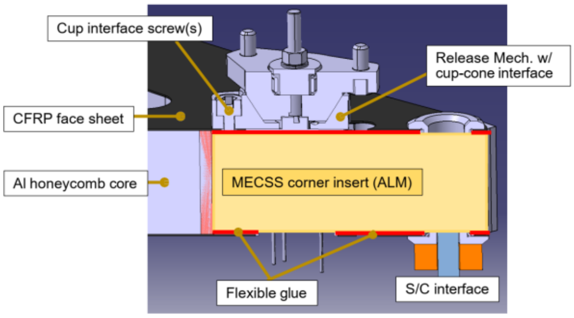

Figure 2: MECSS sectional view of a corner insert

2. INSERT INTERFACE DESCRIPTION

The insert which is manufactured by additive manufacturing has three bonding surfaces. All three interfaces are glued by RTV, a silicon-based glue with high strain allowable before fracture. This glue is able to even out the expansion mismatch between the inserts and the CFRP. It has been used for a similar purpose in the interface structure of the MASCOT Asteroid-Lander [3]. For the basis of the decision to use the RTV glue on the inserts see [4].

Figure 3: Insert with RTV glue applied on facesheet interface

At the vertical interface a thin CFRP layer is bonded via RTV glue towards the insert (see Figure 4). This CFRP layer is than glued with Araldite potting towards the honeycomb core. This was done to avoid any form of cutting of the softer RTV glue by the very sharp edges of the honeycomb core.

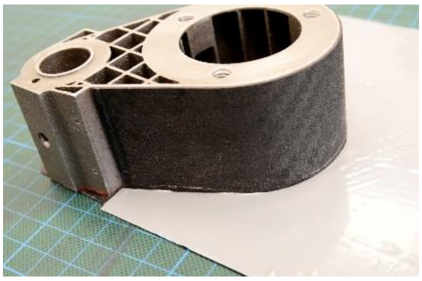

Figure 4: Insert with CFRP layer attached via RTV glue

In addition to the bonded interfaces the facesheets are clamped by the washers (cup-cone interface, S/C interface, additional clamping nut) at the interfaces to the facesheet. At the rover side of the MECSS an additional clamp is added to secure the facesheets. This is done to have a second load path and thus a fail-safe design. A third load path via form closure is given by small extensions beneath the washers as can be seen in Figure 4.

The challenge to the design is the temperature environment derived in the project. The thermal mismatch between the aluminium inserts and the CFRP facesheets lead to high strains in the bonding layers at colder temperatures. Stresses are estimated and tested to be damaging. Even at the interface towards the core a damage may occur as the CTE of the aluminium in core and insert is lower than that of the potting. Depending on the thickness of the potting this can also lead to problems. In Figure 5 the RTV gluing concept is shown in more detail.

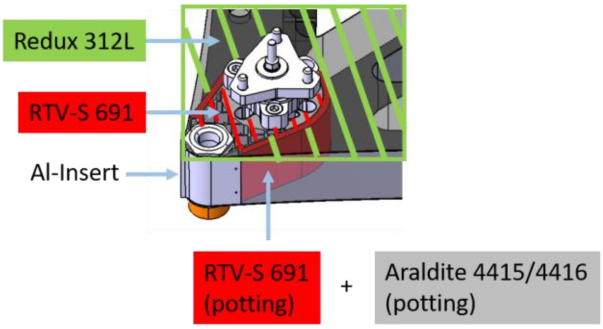

Figure 5: RTV glueing concept

3. INFLUENCE OF MECSS STIFFNESS

To understand the influence of the MECSS stiffness one has to look at the MMX-Rover interface architecture. The MMX Rover, a CFRP sandwich structure, is fixed to the spacecraft via the interface structure called MECSS, a CRFP sandwich structure with a thickness of 40mm and face sheets of 0.65mm thickness except for the insert areas that feature aluminium inserts. The MECSS is attached to the spacecraft at four corner points via bolts. This gives a fixed interface to the aluminium sandwich structure of the MMX spacecraft.

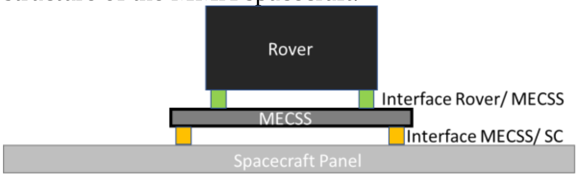

Figure 6: Interfaces to the Rover and to the Spacecraft Panel

The interface is structurally over defined, meaning that thermal stresses will occur between the CFRP MECSS structure and the aluminium spacecraft panel structure. There also is a slight potential for strain between the rover and the MECSS since the area with the inserts of the MECSS has higher CTEs than the all CFRP structure of the Rover interface plate.

This forms a cascade of – if unconstrained – thermal deformation:

- The aluminium spacecraft interface plate makes the full thermal deformation
- The MECSS structure has a much lower

deformation, mostly in the insert area.

- The Rover bottom plate thermal deformation is very low, practically zero compared to the other parts.

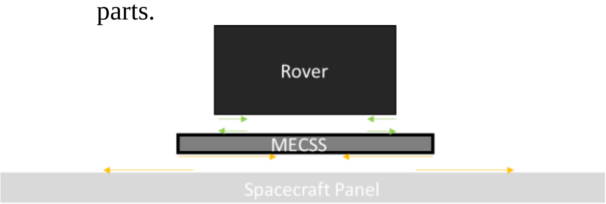

Figure 7: Thermal Interface loads between MECSS and Rover and MECSS and Spacecraft Panel (cold case)

The thermal interface loads between spacecraft and MECSS and the loads between MECSS and the Rover depends on the stiffnesses of the adjacent parts.

The MMX Rover bottom plate stiffness can be simulated with high confidence as it is a very standard sandwich part. The same is true for the spacecraft panel. The MECSS however has a combination of materials bonded together via several load paths with bolts, flexible glue and form closure.

- The most direct load interface is the layer of RTV-glue. Even though it is a direct interface the stiffness of the glue is significantly lower than the stiffness of the composite or aluminium parts. If the glue was the only interface a dedicated modelling of the glued layer would be required to predict the loads at the MECSS correctly.
- The interface between screwed parts on the facesheets to the insert clamp the facesheet. As long as there is no slipping of screws this would be an interface which typically is simulated as a stiff connection in FE-models. Still, part of the stiff interface would be the clamped – and thus compressed – layer of RTV-glue.
- Lastly there is a form closure between the facesheets and the insert. If the other load paths deform or slip this form closure would create a stiff interface, but only after a certain deformation.

There is the assumption that the clamping gives similar stiffness as one would usually assume for bolted connections. But the bolts clamp the facesheet and the RTV-glue layer. Therefor it is a valid assumption that a clamping might not be as stiff as it would be without the flexible layer. Then again there is the form closure in between the facesheets and insert at the spacecraft-interface tubes. It is typical for form closure that there is a little tolerance involved and thus the load transfer has a slight play.

The higher the stiffness of the MECSS the higher direct thermal interface forces in between the MECSS and the spacecraft panel and the lower the influence of the spacecraft panel deformation to the Rover interface plate. If the MECSS stiffness is lower, thermal interface forces between spacecraft panel and MECSS will be lower, but the MECSS deformation will be higher, leading to a higher interface force between the MECSS and the rover. Only test can verify, what assumption on the elastic behaviour of the MECSS insert interface is correct.

The main Finite Element model considers the interface between the insert and the facesheets as stiff, no additional flexible element is added. This assumes the stiffest possible variant. While this assumption is conservative with respect to the interface between MECSS and spacecraft panel, loads may be underestimated with respect to the interface between MECSS and rover.

Therefore, the correct stiffness across the interface points of the MECSS is vital for correct finite element predictions.

4. QUESTIONS TO BE ADDRESSED BY TESTING

To predict thermal loads due to the different deformation of the MMX-spacecraft interface plate and the MECSS the correct stiffness of the MECSS from one interface point to the other is an important value. The difficulty is to derive the correct stiffness of the interface between insert and facesheet. As described this interface features several load paths between the facesheets and the insert:

- The most important outcome of the test is the stiffness of the MECSS. This will be compared to the FE-prediction of the stiffness. If the stiffness of the MECSS is lower it cannot be assumed that the facesheets are securely clamped.
- If clamping does not work, a displacement between the clamping nut (point 1 in Figure 13) and the facesheet (point 3) should be obvious.
- For the case that clamping does not work and the glue is deformed until the facesheet touches the form closure a nonlinear behaviour is expected.

5. TEST SETUP FOR LOAD TESTING

Under thermal loads the MECSS is compressed in cold conditions and elongated in warm conditions. Driver of these deformations is the elongation of the aluminum spacecraft panel. The direction of the force during cold conditions is roughly towards the middle of the MECSS.

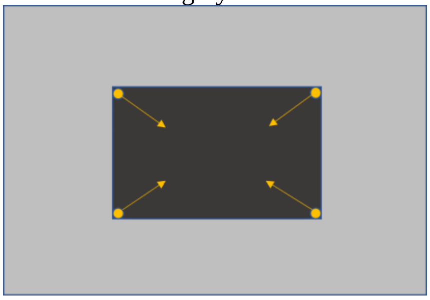

Figure 8: thermal forces acting on the MECSS (black) by the spacecraft panel (grey) for the cold case

The test is reduced to one of the diagonals. The MECSS is fixed on one side and the load is introduced on the other side.

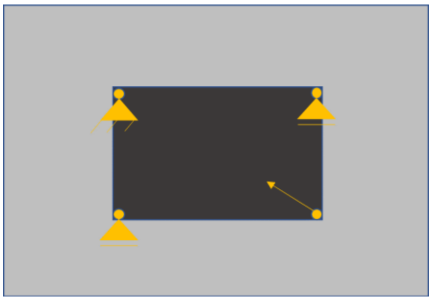

Figure 9: test force and boundary condition for the MECSS on the testbed

For testing the MECSS, a modular testbed is used. The MECSS is attached at the spacecraft interfaces via bolts similar to the attachment at the spacecraft. Only the bolt opposite of the load introduction is torqued, point 1 and 3 (see Figure 10) provide rotational support but can slip. The load is introduced by a Dunker BG45 Cl Motor including a 1:600 reduction gear. The load is measured by a KM30z 10kN load cell. As the name suggests the nominal force goes up to 10kN. The load is introduced via a rope on a gushing around the load introduction bolt. By the way the force is introduced “below” the MECSS it causes not only a compression of the MECSS but also a bending.

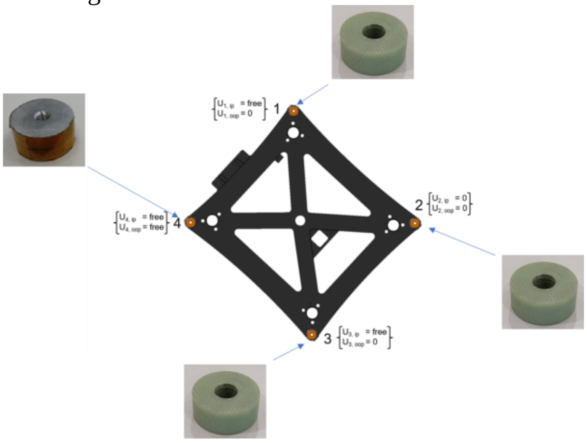

Figure 10: attachment points of the MECSS

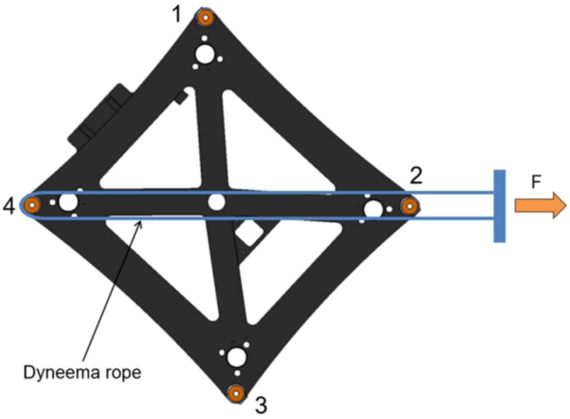

Figure 11: Load introduction during the test

The deformation is measured with digital image correlation and point tracking technique using a Zeiss ATOS 5 scanner with build in ARAMIS functionality. The system tracks the displacement at certain measurement points. The cameras of the ATOS system are calibrated for a measurement area of 1x1m and looking straight down on the MECSS.

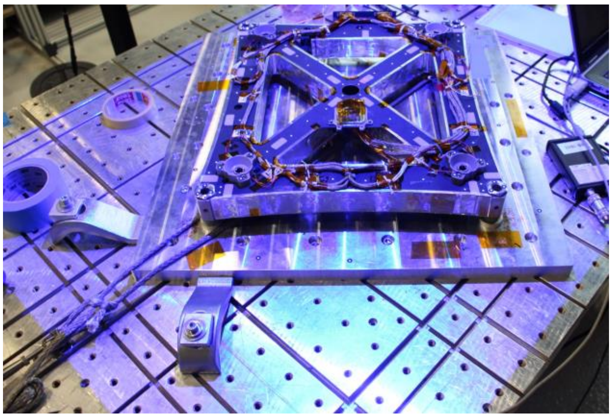

Figure 12: overview of the MECSS structure during testing

In the following the points evaluated in “Zeiss Inspect Correlate 2023” are depicted. The most important points are 1 and 40. At point 1 the load is introduced and at point 40 is the fixation point. As the fixation is not perfect with respect to the camera position it needs to be measured as well. The system then can calculate all movements corrected by the fixation movement. In addition, the out of plane deformation must be measured to. The linkage to the actual applied force is achieved with a corrected time stamp and imported in the measurement.

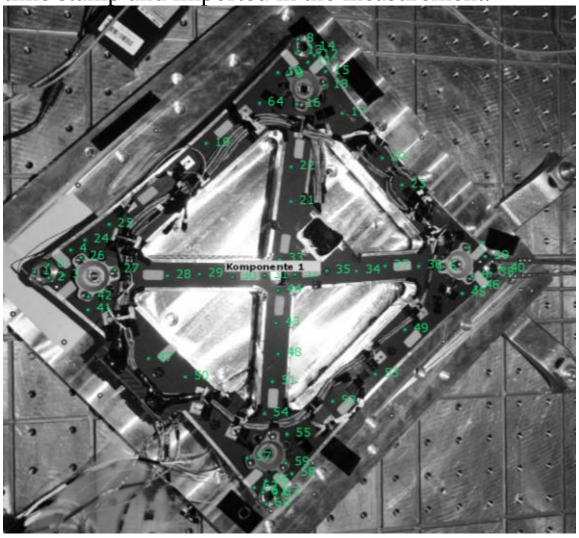

Figure 13: Aramis measuring points

6. REFERENCE FEM CALCULATION

To compare the measured values, the test setup has to be reproduced in finite element modelling. The important parameters besides the model itself are:

- The boundary conditions need to be representing the test setup
- The plane of deformation has to be similar, at least if bending is involved.

As suggested in Figure 9 one point is fixed opposite of the load introduction. The interface points diagonal to the loaded ones are free in the in plane direction but fixed in the out of plane direction. The numerical boundary condition of the load introduction point is depending on the deformation of the MECSS. The interface point in the test is not attached to the test bed but touches it. Due to the test conditions the MECSS bends towards the testbed. Therefor it is safe to assume that the deformation in vertical direction is hindered thus fixed. Regarding the rotation a free interface is assumed since the touching area is not that big to hinder any rotation.

This gives the following expected in plane deformation curve at the middle plain of the MECSS

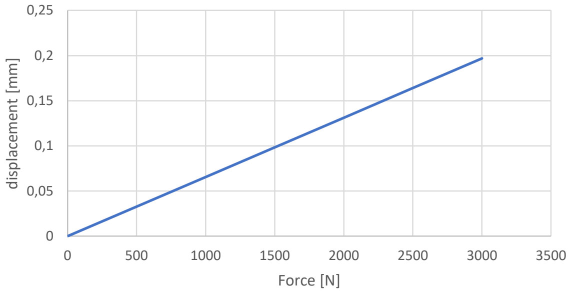

Figure 14: predicted displacement over force for the load introduction point in the middle plane of the MECSS

7. STATIC LOAD TEST CONDUCTION

For testing the Motor tightens the rope to the MECSS at a constant deformation. The force in the rope is measured. Simultaneously the displacements of the measurement points on the MECSS are measured. The displacement is at the lower end of what the optical system can resolve, therefore some noise in the signal can be observed.

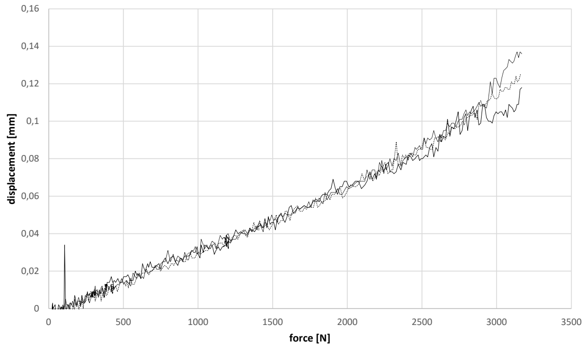

Figure 15: measured displacement at the load introduction insert nut (point 1)

The displacement at the load introduction area is obviously a lot smaller than the predicted value in the FEM calculation which assumes the stiffest value. This is due to the fact that only surface values are measured, not the middle plane of the sandwich.

The following figure gives a graphical impression of the displacement with a vector given for each point.

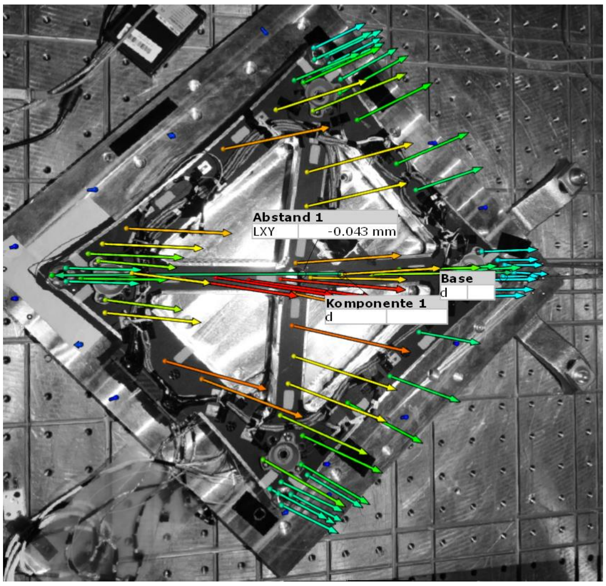

Figure 16: displacement vectors for each measurement point

It may surprise that the displacement at the load introduction is smaller than the displacement in the middle. But this is due to the fact, that a lot of Bending is involved in the load test. It should also be noted that the “fixed” point on the righthand side makes quite a significant displacement as well, about halve the displacement as the load introduction. To get a comparable value to the simulated one two transformations have to be made.

8. EVALUATION OF THE MEASUREMENT

The displacement of the central plane has to be calculated for the load introduction point and the fixation point, followed by the subtraction of the displacement at the fixation.

The following graph depicts the out of plane deformation

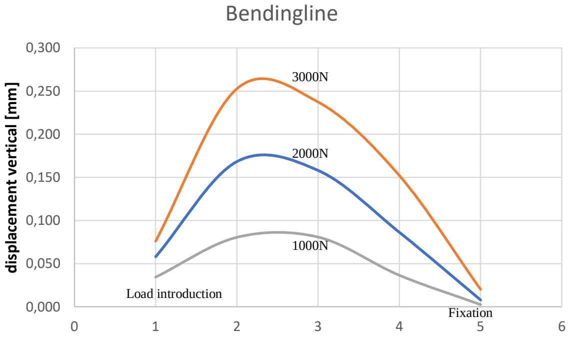

Figure 17: out of plane deformation (spline depection from 5 points). The horizontal distance is not perfectly to scale.

To cope for the bending displacement the angle at the point where the displacement is measured must be evaluated. This is done by using the out of plane deformation of two points at the load introduction area and at two points at the fixed edge. Knowing the distance of the two points the angle can be derived. From the thickness of the sandwich the offset due to this angel can be calculated.

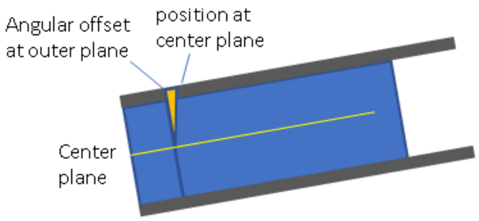

Figure 18: geometrical displacement at the surface in contrast to displacement at the center plane

The mentioned transformation is done for each full 1000 N, averaging the values above and below each full 1000 N to reduce the influence of the noisy measurement. In the following figure the middle plain deformation is depicted in comparison to the predicted curve:

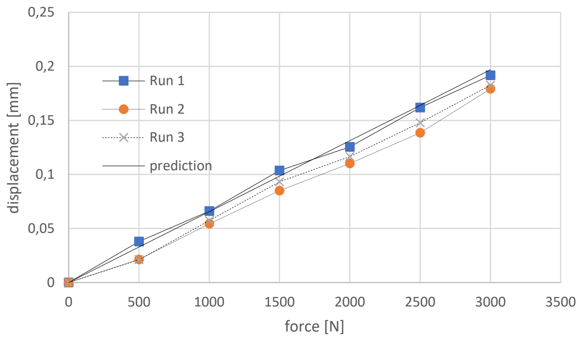

Figure 19: corrected displacement at the center plane in comparisson to the predicted displacement

The displacement is nearly equal or lower than the prediction. The first load run fits the prediction best. The second one has the lowest displacements and the third load run is in between. The average offset to the prediction is 0.5% for the first run, 16% for the second run and 10% for the third run. The average offset over all runs is 9%. The offset seams to be caused by the Tara of the optical system, which has some scatter. Checking the incline, the stiffness of the three runs is within 2 to 4% of the prediction.

There is no systematic change in stiffness visible during the single runs. The lower deformation of the second run might lead to the assumption that a flexible part slipped to some kind of form closure in the first run, making the system stiffer in the second run. But then the third run shows a bigger deformation than the second. Thus, it does not seem to be a systematic behaviour but rather a result of the averaged values around the measuring points. This is also supported by Figure 15 that does not show the same offset.

9. CONCLUSION

The MECSS in the test has similar stiffness or even higher stiffness than the prediction suggests. The assumption that the facesheets are clamped to the inserts seems to be valid, an influence of the elastic RTV layer reducing the expected stiffness is not visible. The optical displacement measurement is very useful to compare the calculated stiffness to a measured value. Only the 3d displacement allowed to correctly calculate the deformation of the central plane. The displacements would actually require a finer resolution regarding the noise of the signal, but even with this restriction a useful comparison could be made.

10. REFERENCES

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