VANESSA Deliverable D3.3

Calibration ILS Report

Grant Agreement number:	319116
Project acronym:	VANESSA
Project title:	Validation of Numerical Engineering Simulations: Standardisation Actions
Funding Scheme:	FP7-NMP-2012-CSA-6

Date of Annex I against which the assessment will be made: 30th April 2012

Task 3.1:	Reference Material for dynamic strain calibration
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Issued:	28 May 2014
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1 Executive summary

This report collates and interprets results from the Inter Laboratory Study on Calibration (Calibration ILS) conducted on an international scale under Task 3.1 of the VANESSA project and constitutes Deliverable D3.3 "Calibration round-robin report" due by month 16. The Calibration ILS made use of the Calibration round-robin protocol (Deliverable D3.1) and the Cantilever Reference Material (Milestone MS1).

Two dozen exemplars of the Cantilever Reference Material were manufactured and assessed. From these, eight were sent out in dedicated shipping boxes to the Calibration ILS participants who had been recruited by direct mailing, advertisement at conferences and meetings, through the website and by serial mails. The results of the Calibration ILS are collated and interpreted in this document. The feed-back of the ILS participants suggested a number of modifications to the relevant chapter of the CEN Workshop Agreement (CWA 71).

The Calibration ILS has proven that the Cantilever Reference Material is sufficiently stable and reproducible to be used as a calibration artefact for systems capable of measuring displacement and strain fields in static and dynamic loading. Participants applied the Reference Material in a range of tip deflections from 2 μm to 4.7 mm. The first bending mode in dynamic loading has proven especially useful for the purpose of calibration; static bending was shown to be linear up to the highest loads applied thus providing evidence that the analytical reference values are appropriate. The calibration process proved to be viable, but some changes and simplifications, e.g. as to the estimation of calibration uncertainty, were suggested for and incorporated into the CWA.

2 Introduction

The objectives for VANESSA Work Package "WP3: Inter-comparison Studies" are

a) To prepare protocols, organise and collate the results from an international *round robin* exercise on a reference material for the calibration of strain measurement systems capable of measuring dynamic strain fields.

b) To prepare protocols, organise and collate the results from an international *round robin* exercise on a validation procedure for computational solid mechanics models.

c) To provide evidence that the reference materials for calibration and the validation protocol form a solid base for the proposed standardisation activity.

Preliminary work had established that *Inter-Laboratory Studies (ILS)* was a more accurate description of the planned activities than *round robins*. Task 3.1 is concerned with the Calibration ILS, with EMPA acting as task-manager.

In the first 6 months the Calibration ILS protocol (Deliverable D3.1) was established and published through the project website. The protocol provides a step-by-step guidance for the calibration of optical systems for strain and displacement measurement. The Calibration ILS involved the use of a Calibration Reference Material (RM), which had been specified based on earlier work, and 24 specimens were manufactured for distribution to participants of the ILS, constituting project Milestone MS1. Table 1 lists the Milestones and Deliverables related to Task 3.1.

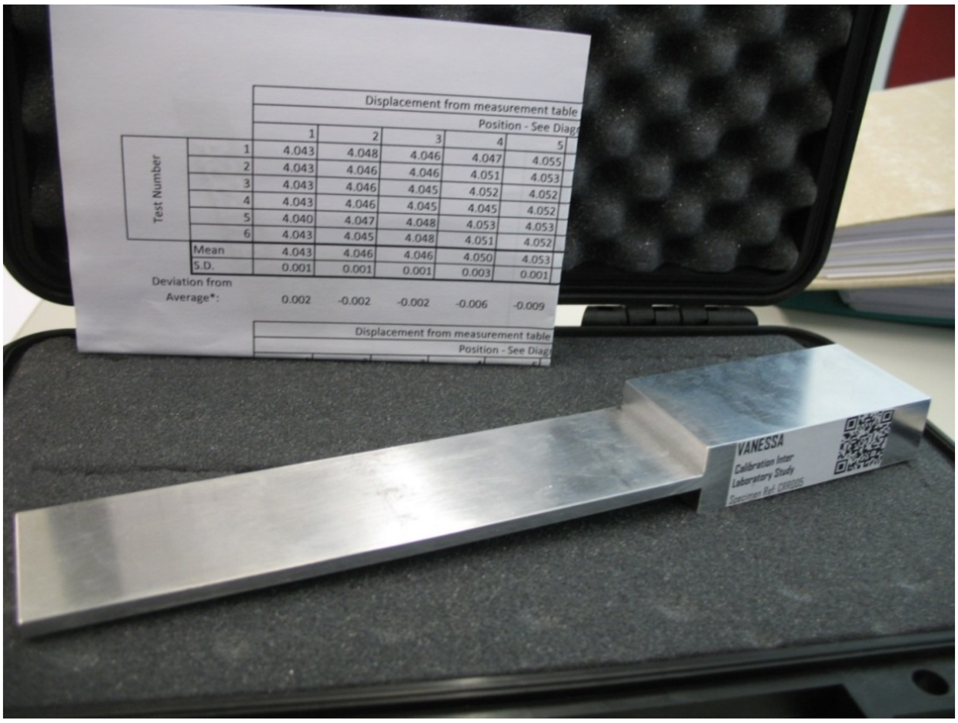
Table 1: Deliverables and Milestones related to Task 3.1

Item	Description	due	approval
MS1	Reference materials available: Supply of reference materials for dynamic strain field measurement	m4	approved by PSC on June 13, 2013
MS2	Calibration round-robin initiated: Protocol, reference materials and promotion strategy for round robin on calibration for strain field measurement in dynamic loading agreed	m4	approved by PSC on June 13, 2013
D3.1	Protocol for round robin on calibration for strain field measurement in dynamic loading	m3	approved by PSC on June 13, 2013
D3.3	Calibration round-robin report	m16	the present report

The Calibration ILS was formally launched at the second CEN workshop on September 4th, 2013, in Cardiff, Wales. It was promoted, among other means, by more than three dozen personalised invitation letters sent to engineers and researchers carefully selected by the VANESSA consortium and mainly from the industrial sector. Subsequently, an open invitation was issued via the project website and at conferences, followed by some 100 serial emails.

3 Production of Reference Material

A set of 24 specimens of the Reference Material (RM) had been manufactured in two batches and quality assessed. They were provided in shipping boxes, see Figure 1, for participants of the Calibration ILS. The specifications of the Reference Material are summarized in Table 2. The values provide evidence that the material is "sufficiently homogeneous and stable with reference to specified properties, which has been established to be fit for its intended use in measurement", as the International Vocabulary of Metrology defines it [1].



Displacement from measurement table

Position - See Diag

Test Number	1	2	3	4	5
1	4.043	4.048	4.046	4.047	4.055
2	4.043	4.046	4.046	4.051	4.053
3	4.043	4.046	4.045	4.052	4.052
4	4.043	4.046	4.045	4.045	4.052
5	4.040	4.047	4.048	4.053	4.053
6	4.043	4.045	4.048	4.051	4.052
Mean	4.043	4.046	4.046	4.050	4.053
S.D.	0.001	0.001	0.001	0.003	0.001
Deviation from Average*:	0.002	-0.002	-0.002	-0.006	-0.009

Displacement from measurement table

Position - See Diag

Figure 1: An exemplar of the Calibration Reference Material with QR identification tag, specification sheet and box for delivery to the ILS participants.

Table 2: Specifications of RM

Property	value	comments
Thickness reproducibility	4.000±0.012 mm	average of a batch of 10 specimen
Thickness variation	< 0.003 mm	max. std of 9 measurements across the face of a single specimen
Resonance frequency Mode 1	127.2±0.6 Hz	average of a batch of 10 specimen
Resonance frequency Mode 2	785.2±3.9 Hz	average of a batch of 10 specimen

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[1] International vocabulary of metrology – Basic and general concepts and associated terms (VIM), 3rd edition, JCGM 200:2012

4 Results from Calibration ILS

4.1 Quantitative results

From the protocols and reports received from the participants of the Calibration ILS the quantitative results for dynamic loading were extracted and collated in Table 3, while quantitative results for static loading are collated in Table 4.

Table 3: Results from calibration ILS using dynamic loading.

Property			
Identification	CRR004	CRR005	CRR010
Technique	DIC	DSPI	DIC
Thickness [mm]	4.016(1)	4.015(2)	3.980(8)
Mass [g]	254(5)	251.3(1)	251.60(1)
Mode 1 [Hz]	125.7	129.6	126.00(3)
Mode 2 [Hz]	NA	796.0	796.00(4)
Mode 3 [Hz]	NA	NA	2123.0(6)
tip deflection		6.31 μm 1.99 μm	0.600 mm 0.200 mm 0.030 mm
Number of data points	625	111’220	1’258
Offset α	0.0061(2)	-0.0437(1) 0.2177(1)	-0.49(4) -0.75(8) -3.70(8)
Slope β	-0.0163(14)	-0.0081(1) 0.0139(1)	10.5(3) -36.3(1.6) 69.3(11.1)
u(d)	0.0024	0.0181 0.0322	1.5 3.1 3.2
u_{cal}			2.5 μm 3.6 μm 3.6 μm

Table 4: Results from calibration ILS using static loading

Property				
Identification	CRR006	CRR007	CRR008	CRR016
Technique	DIC	DIC	DIC	DIC
Thickness [mm]	3.993(2)	4.006	4.000(5)	4.009(2)
Mass [g]	250.7	251.5(1)	254(5)	251.69(1)
static load [N]	33.46 43.47 53.46	2.51 5.10 7.70 10.71 13.24	2.51 5.10 7.70 10.71 13.24	NA
tip deflection [mm]	2.94 3.84 4.71	0.228 0.428 0.670 0.923 1.145	0.228 0.448 0.672 0.940 1.132	1.544
Number of data points	4647	48	200	429
Offset α	-0.0397(1) -0.0466(2) -0.0548(1)	-0.0092(5) test 1 final 0.0122(16) test2 final	-0.0062(1) final load	0.0264(4)
Slope β	-0.0089(1) -0.0058(1) -0.0025(1)	-0.0056(9) test 1 final -0.015(151) test2 final	0.0045(1) final load	0.0020(5)
u(d)	**0.0074** **0.0113** **0.0090**	0.0035 0.0108	0.0008	0.0081
u_{cal}	**0.0746** **0.0744** **0.0745**			

4.2 Assessment of calibration

An example of experimental results for dynamic measurements is provided in the following figures (CRR05).

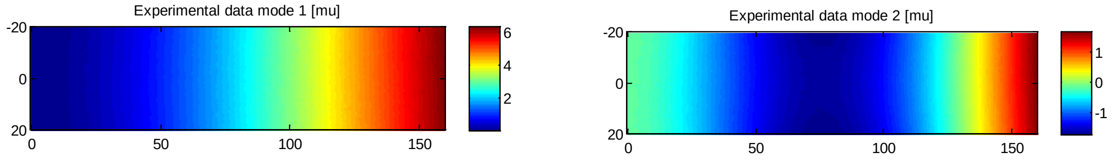

Figure 2: Experimental mode shapes, scale given in µm. Left: Mode 1; Right: Mode 2

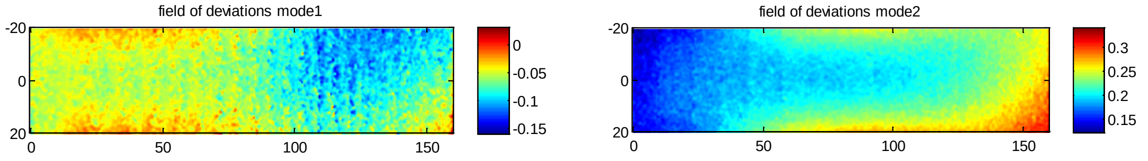

Figure 3: Field of deviations from reference values. Left: Mode 1; Right: Mode 2

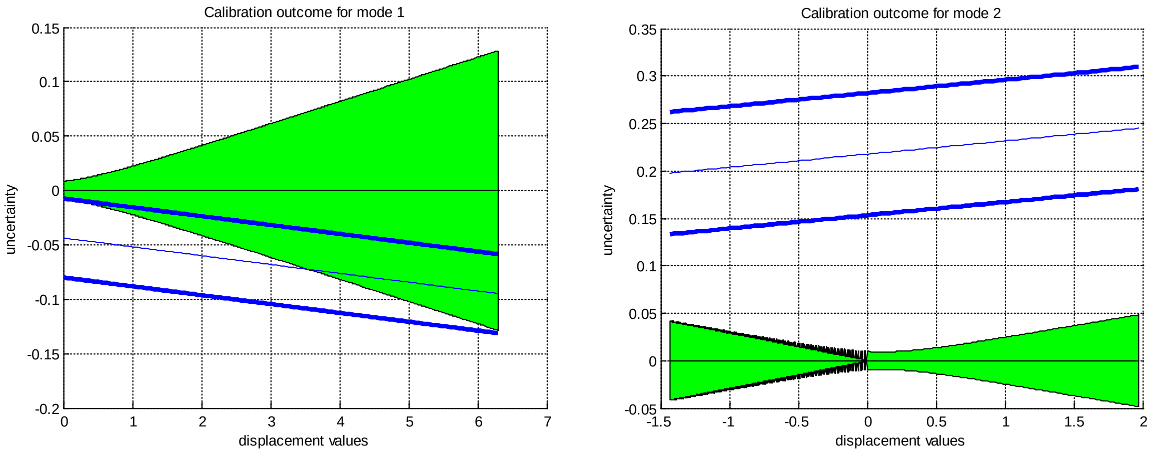

Figure 4: Assessment of calibration uncertainty against uncertainty of RM. Left: Mode 1; Right: Mode 2 (CRR005). The green areas are the uncertainty of the RM as a function of displacement values, while the band delineated by blue lines is the experimental field of deviations.

An example of experimental results for static measurements is provided in the following. Figure 5 and Figure 6 show experimental data and difference to the Reference Material data for CRR016, while Figure 7 shows the deviation along the central line for CRR008.

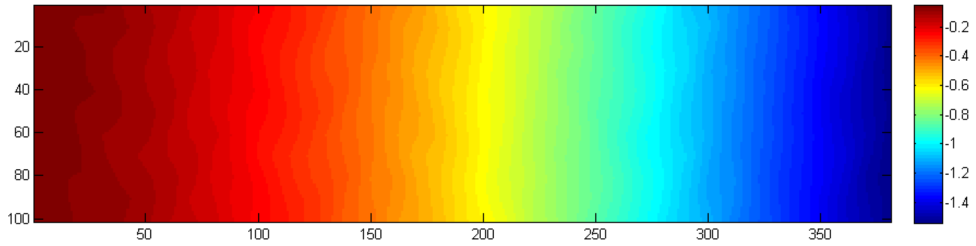

Figure 5: Out-of-plane displacement field from experiment (CRR016).

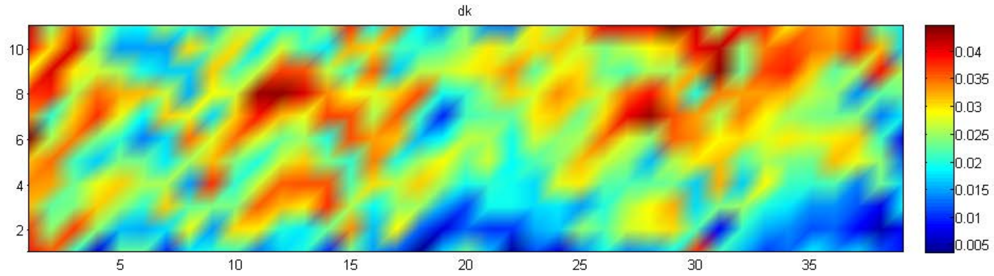

Figure 6: Difference between measured and predicted values (CRR016).

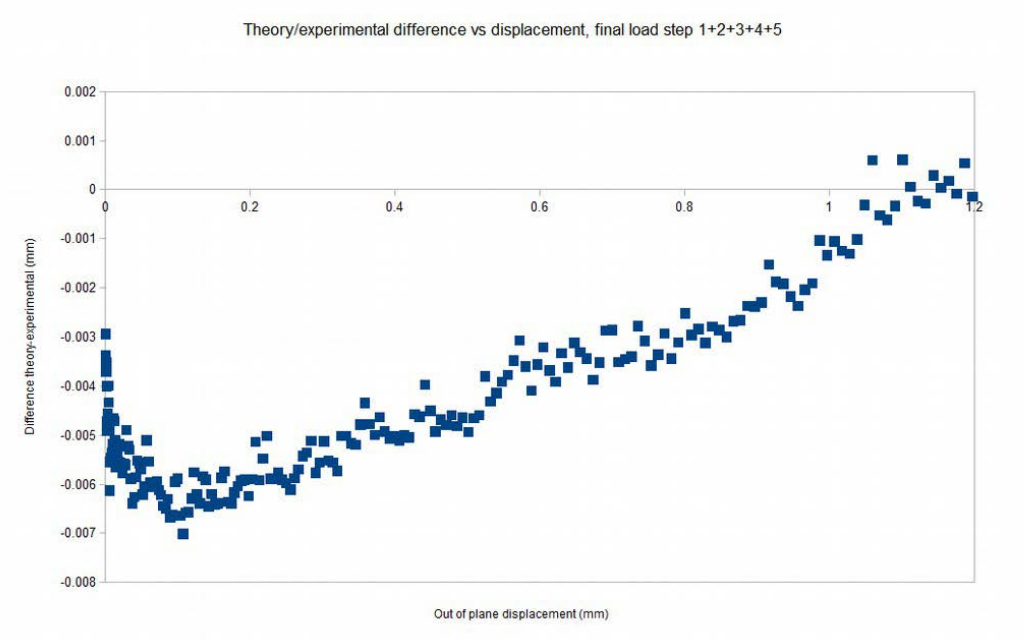

Figure 7: Difference between theoretical and experimental out of plane displacement for a static load of 13.2 N (CRR008).

4.3 Feed-back on protocol

- "Eq. (1) lacks a sqrt(L)." The correct formula reads $f_k = \frac{\lambda_k^2}{2\pi L^2}\left(\frac{EIL}{M}\right)^{\frac{1}{2}}$
- "Eqs. (6) and (7) lack a factor of 1/6 and 6, respectively. The subsequent formulae are not affected."
- "I have found the exercise somewhat distasteful! By which I mean I think we did a reasonably good experiment, but the results are inelegant. Or rather, the analysis of the results does not reach a satisfactory conclusion."
- "I believe the DIC test is OK, but I have doubts of how useful (or not?!) such a calibration coupon is out in the industrial world."

4.4 Reported problems

- "I had problems calculating u_{cal}. Appendix C is not clear for me (Eqs C1 highlighted in yellow)"
- "Our imaging camera does not have sufficient working distance to observe the full cantilever beam length (approximately 40 mm only observed)."
- "The RM was too small for my field of view, i.e. it did not cover 80% of the image."
- "Our LVDT transducer is not sufficiently reliable for us to trust its calibration."
- "We had a compliant loading rig and some uncertainty in the way in which the beam was deflecting (perhaps I may say uncertaintIES)."

5 Conclusions

5.1 Summary of observations

- The third resonance mode is very broad and the resonance is difficult to identify and excite acoustically.
- Participants rarely reported a plot of the calibration uncertainty vs. the RM uncertainty. Some compare the central line rather than the full field for calibration assessment.
- Some participants preferred using an Excel sheet rather than the ILS protocol.
- The relative positioning uncertainty of the load has not been accounted for.
- The calculation of the uncertainty budget posed problems.
- The fit-parameters α and β do not show a clear trend, rather they show somewhat arbitrary values.
- The size of the RM does not match the FOV used by some participants. It was either too large or too small.

5.2 Recommendations for the CWA

- It is recommended to use the RM in the first resonant mode only, since the second and third modes are difficult to excite with a loudspeaker.
- It is recommended to allow for the use of a shaker, but the relative displacement of tip and root must be reported.
- It is recommended that the use of the RM be allowed for larger fields of view, e.g. by allowing tiling repeated calibration measurements in the FOV.
- It is recommended that Appendix C on determining the measurement uncertainty be simplified. It is suggested to include the simplifications in the Appendix. It is recommended that the parameters α and β – meant to describe systematic offset and slope of the measurement deviation – should be removed and the field of deviations be directly used to determine $u(d)$.

5.3 Concluding Remarks

The preparation of the protocol for this round-robin (D3.3) as outlined in section 3, the organisation of the round robin and the collation of the results as reported in section 4 fulfil one of the three objectives of WP3. The conclusions from the round-robin provide evidence that the calibration protocol enshrined in the CEN Workshop Agreement (CWA) has a solid base, which is a second objective of WP3. Together these activities contribute very substantially to the achievement of one of the VANESSA project's three S & T objectives, namely 'to conduct international comparison (round-robin) exercises that will generate evidence that the reference material, for calibration of optical systems for strain field measurement, and the validation protocol for computational solid mechanics models, form a solid base for standardisation'. Finally, the widespread promotion of the calibration ILS or round robin has contributed to a second VANESSA S&T objective 'to raise awareness in the EU industrial base and international engineering community of the validation protocol' of which calibration is a vital feature.