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CONCRETE TESTING MACHINES – VERIFYING THE UPPER PLATEN AND MACHINE COMPONENTS WITH 3D PRINTED POSITIONING MECHANISMS

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Abstract – A practical case of substituting the upper platen of a concrete compression testing machine will be presented, where original 3D printed positioning mechanisms are used in the verification of the machine according to Standard NP EN 12390-4:2021. Due to time constraints for this maintenance operation, the dimensions of these first prints were not properly verified and were later found to be out of the specified tolerances. However, machine verification results did, unexpectedly, turn out to be satisfactory and were validated by comparison to a later verification made by an ISO 17025-accredited laboratory. The dimensional inaccuracy was a consequence of the lack of calibration of the printer's axis and extruder motors, which has been successfully accomplished. In spite of the ongoing difficulties, these tools are worth it for their lightness, simplicity of usage and adaptive design, as well as the low costs and ease of production with a 3D printer.

Keywords**:** 3D printer; compression machine; positioning mechanism; Standard NP EN 12390-4:2021

1. INTRODUCTION

The Laboratory for Civil Engineering (LREC) at the Azores archipelago has an NP EN ISO/IEC 17025-accredited system for testing hardened concrete. Standard NP EN 12390-4:2021 establishes requirements for the construction, maintenance and calibration of the machines used in these tests. Special attention is given to the verification of the machine's upper platen self-alignment and movement restrictions, as well as the alignment of the remaining compression component parts. A transducer with four Wheatstone bridges, manufactured according to the Annex A of the given standard, is used on these verifications. However, care must be taken in the placement of this transducer on the lower platen of the machine, in order to ensure that checking operations are executed correctly. Regarding the upper platen's self-alignment and the machine's component alignment, the standard specifies a centre positioning tolerance of 0.1 mm, which is impossible to accomplish by the use of a ruler tape. Recommendations on the application of mechanised precision spacers or specific positioners are given in Section A.4 of the standard but, since no mentions are made about possible raw materials or drawing procedures, developing such devices can result in impractical use and expensive production costs. As for the restrictions on the movement of the upper platen, the transducer must be displaced 6 mm from the centre position to the side of the lower platen, with a tighter tolerance of 0.05 mm. Two special tools were designed by the Metrology Unit of LREC and manufactured on a 3D printing machine using PLA Pro plastic. The first tool was used for the centre positioning of the transducer in its verification, according to Section A.3 of the standard, and in the verifications of the machine. The second tool was made to permit the controlled deviation of 6 mm.

In Section 2, results of the verification of two force transducers, according to Section A.3 of the standard NP EN 12390-4:2021, are presented.

In Section 3, results of the machine's verification according to Section A.4 of the standard NP EN 12390-4:2021, are presented.

In Section 4, dimensional verifications on a coordinate measuring machine and a new design of the "AP1" tool are presented.

In Section 5, results of the transducers verification with the new positioning mechanism are presented.

2. VERIFICATION OF THE FORCE TRANSDUCERS

This procedure is necessary to examine the uniformity of the transducer's four Wheatstone bridges, in order to evaluate its suitability to execute the machine's verification. Two transducers were tested, i.e., a GTM model KTN – DZY transducer and an HBM model KDB transducer. The verification method, as well as the calculation formulae, is described in Section A.3 of [1]. The positioning of the transducers was executed with the "AP1" tool presented in Figure 1.

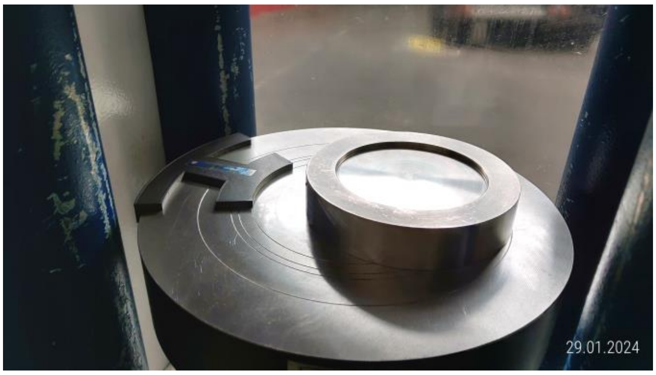

Figure 1. "AP1" positioning tool and HBM transducer's loading pad.

The transducers were connected to an HBM MX1615B strain gauge amplifier and the electrical signals of the four bridges were read simultaneously through a custom program made in LabVIEW.

2.1. GTM model KTN – DZY transducer

The mean strain ratio results for the GTM transducer are shown in Figure 2.

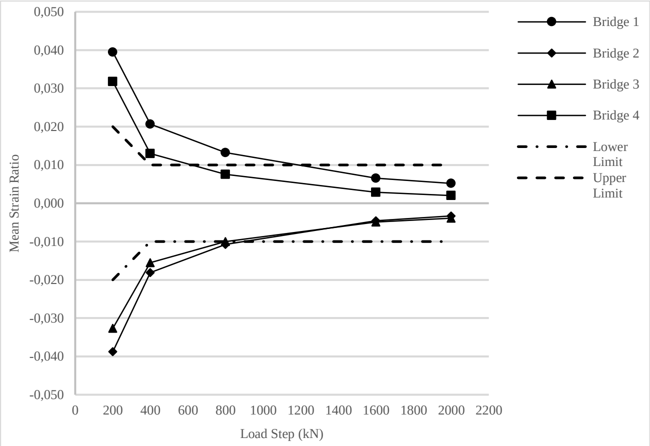

Figure 2. GTM transducer's mean strain ratio results for each bridge and load step.

From Figure 2, it is possible to observe that the transducer exceeds the limits of acceptance, given in Table A.1 of [1], for strain gauged column uniformity. However, calculated mean strain ratio values are at least one third of the maximum permissible mean strain ratio limits, defined in Table 1 of [1], for the alignment of machine component parts. Therefore, the transducer can be considered suitable for the machine's verification as a last resort.

2.2. HBM model KDB transducer

The mean strain ratio results for the HBM transducer are shown in Figure 3.

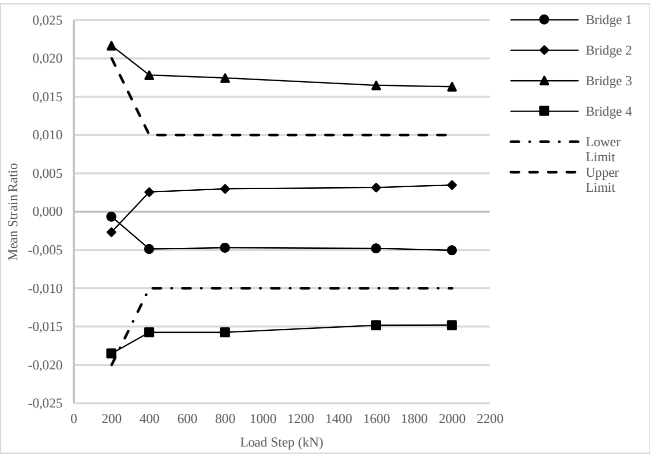

Figure 3. HBM transducer's mean strain ratio results for each bridge and load step.

The results presented in Figure 3 show that only bridges 1 and 2 comply with the required specifications, which might be an indication of the transducer being slightly off centre when doing the test. Both transducers had maximum values at the 200 kN load step, but the HBM transducer's values were lower than the GTM's values. Hence, this transducer is also considered adequate for the machine's verification, in case of an emergency, and is a better choice than the GTM transducer.

3. VERIFICATION OF THE MACHINE

The machine was tested with the GTM transducer because it was the only one available at the time. Since LREC is not accredited to do this verification, the performed tests were only intended to check the state of the machine before and after the upper platen substitution. Our facilities are at a remote location, namely the Azores islands, and at the moment there is only one calibration laboratory in Portugal with the required accreditation to do this test. Since this laboratory is located on the mainland, their availability becomes an issue and, in this particular case, the machine verifications were scheduled at the last minute and the upper platen needed replacement. Therefore, the checking of the platen with the best available transducer was necessary in order to make the required mechanical adjustments before the final accredited verification.

The "AP1" accessory shown in Figure 1 was used for the positioning of the transducer on the tests for examining the self-alignment of the upper platen and the alignment of the machine component parts according to Section A.5 and Section A.6 of [1], respectively.

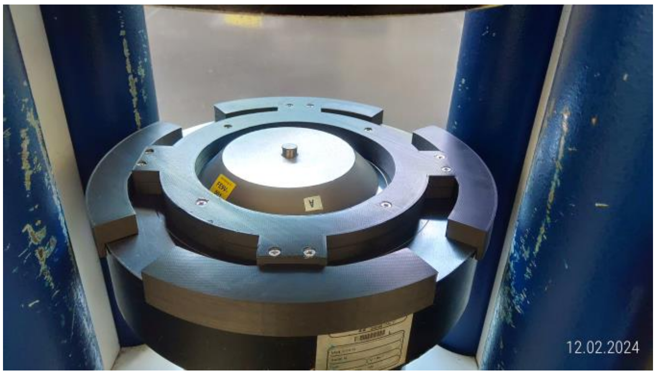

Figure 4. "AP2" positioning tool and GTM transducer's loading pad.

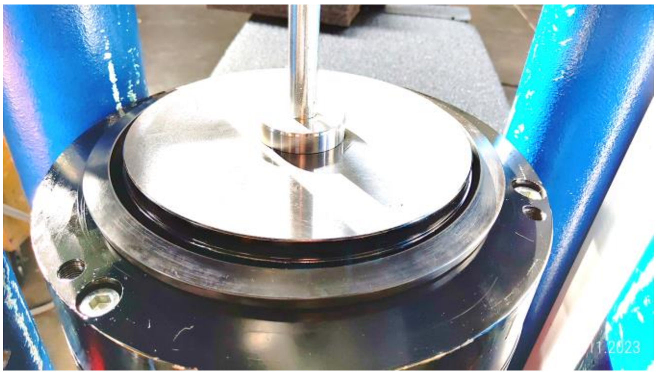

Figure 5. Image of the dismounted upper platen with the rubber sealant inserted into the ball-seating.

The "AP2" tool shown in Figure 4 was used on the test for verifying the restraint on the movement of the upper platen, according to Section A.7 of [1]. In this test, it is necessary to determine the strain ratios, per mm of displacement, along the

AC axis (W_{AC}) and the BD axis (W_{BD}), respectively, as shown in Figure A.2 of [1].

Before the maintenance, it was observed that the platen did not move has expected. After dismounting the platen, a rubber sealant was found inserted into the ball-seating fitting and this was the reason for the movement restrain (see Figure 5). The function of this sealant is to prevent oil from spilling out of the ball-seating. After its mounting correction (see Figure 6) it was possible to produce the required upper platen inclinations for the self-alignment test.

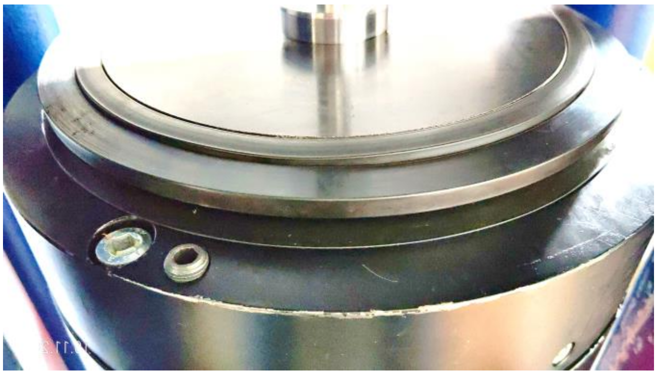

Figure 6. Image of the dismounted upper platen with the rubber sealant properly mounted.

3.1. *Verification before the upper platen replacement*

The mean strain ratio results for the alignment of machine component parts test are shown in Figure 7.

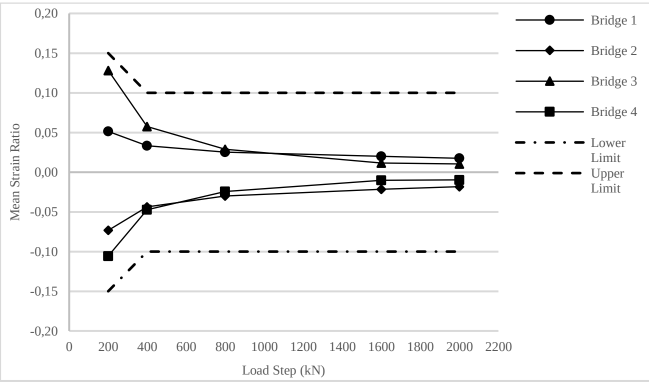

Figure 7. Alignment of the machine component parts. Mean strain ratio results for each bridge and load step before the upper platen substitution.

Table 1. Self-alignment of the machine's upper platen. Maximum difference in the strain ratio results before the upper platen substitution.

Load Step (kN)	**Maximum** ΔR_n	**Limit for** ΔR_n	**Acceptance** Pass / Fail
200	0.1613	0.15	Fail
400	0.0505	0.10	Pass
800	0.0194	0.10	Pass
1600	0.0078	0.10	Pass
2000	0.0071	0.10	Pass

The difference in the strain ratio (ΔR_n) results for the self-alignment of the machine's upper platen verification are shown in Table 1. The limits for all machine test variables are defined in Table 1 of [1].

From Figure 7, it is possible to observe that the machine complies with the requirements for the alignment of the component parts. However, from Table 1 it is verifiable that the machine fails the upper platen self-alignment at the 200 kN load step, which is a consequence of the restriction imposed by the rubber seal shown in Figure 5.

The strain ratio per mm of displacement results for the restraint on the movement of the upper platen test, for axes AC and BD, are presented in Table 2.

Table 2. Restraint on the movement of the upper platen. Strain ratio per mm of displacement results before the upper platen substitution, for both axes.

Load Step (kN)	W_{AC}	W_{BD}	**Limit for** W_{AC} or W_{BD}	**Acceptance (Pass / Fail)** W_{AC}	W_{BD}
200	0.046	0.042	0.06	Pass	Pass
400	0.038	0.035	0.05	Pass	Pass
800	0.034	0.030	0.05	Pass	Pass
1600	0.033	0.028	0.04	Pass	Pass
2000	0.033	0.028	0.04	Pass	Pass

The results in Table 2 show that the machine complies with the corresponding limits.

3.2. *Verification after the upper platen replacement*

The mean strain ratio results for the alignment of machine component parts tests made by LREC on 10-11-2023 and by the Reference Laboratory (Ref. Lab.) on 14-11-2023, are shown in Figure 8. For reasons of simplicity, only the reference minimum and maximum values are presented.

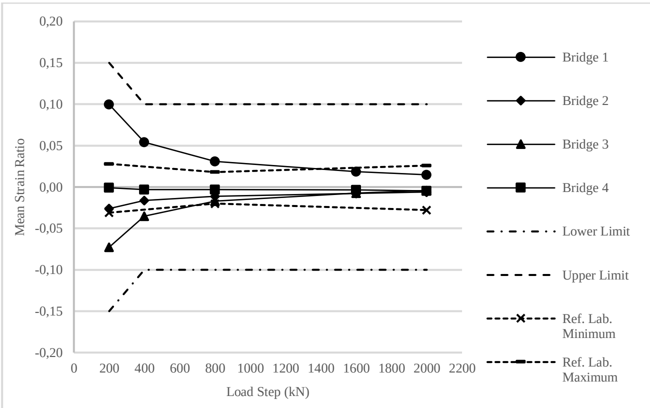

Figure 8. Alignment of the machine component parts. Mean strain ratio results for each bridge and load step after the maintenance.

From Figure 8, it is possible to observe that the results from LREC, for bridges 2 and 4, are within the Reference Laboratory values. However, LREC's bridges 1 and 3 values only get closer to the reference values from 800 kN on. Overall, the alignment of the machine component parts is compliant with the standard limits. Comparing Figure 7 and Figure 8, it is noticeable that at the 200 kN load step, the LREC values decreased after the substitution.

The difference in the strain ratio results for the self-alignment of the upper platen, for LREC and the Reference Laboratory, are shown in Table 3, where it is possible to observe that the values from LREC trend to 0.030, which is an indication that the upper platen was self-aligning uniformly just after the maintenance was finished. However, the reference value at 200 kN shows again a problem on the machine, just a few days after the conclusion of the maintenance. Regarding the load steps of 800 kN and 2000 kN, it is verifiable that LREC's values were very near the reference values.

Table 3. Self-alignment of the upper machine platen. Maximum difference in the strain ratio results after the maintenance, for both laboratories.

Load Step (kN)	**Maximum ΔR_n**		**Limit for** ΔR_n	**Acceptance** Pass / Fail	
	LREC	Ref. Lab.		LREC	Ref. Lab.
200	0.0279	0.1280	0.15	Pass	Pass
400	0.0236	---	0.10	Pass	---
800	0.0320	0.0360	0.10	Pass	Pass
1600	0.0299	---	0.10	Pass	---
2000	0.0268	0.0260	0.10	Pass	Pass

The strain ratio per mm of displacement results for axes AC and BD are presented in Table 4 and Table 5, respectively.

Table 4. Restraint on the movement of the upper platen. Strain ratio per mm of displacement results for the AC axis after the maintenance, for both laboratories.

Load Step (kN)	W_{AC}		**Limit for** W_{AC}	**Acceptance (Pass / Fail)**	
	LREC	Ref. Lab.		LREC	Ref. Lab.
200	0.042	0.040	0.06	Pass	Pass
400	0.037	---	0.05	Pass	---
800	0.033	0.030	0.05	Pass	Pass
1600	0.031	---	0.04	Pass	---
2000	0.032	0.030	0.04	Pass	Pass

Table 5. Restraint on the movement of the upper platen. Strain ratio per mm of displacement results for the BD axis after the maintenance, for both laboratories.

Load Step (kN)	W_{BD}		**Limit for** W_{BD}	**Acceptance (Pass / Fail)**	
	LREC	Ref. Lab.		LREC	Ref. Lab.
200	0.042	0.039	0.06	Pass	Pass
400	0.035	---	0.05	Pass	---
800	0.029	0.027	0.05	Pass	Pass
1600	0.026	---	0.04	Pass	---
2000	0.026	0.025	0.04	Pass	Pass

From Table 4 and Table 5, it is possible to observe that the machine was accordingly and that the values from both laboratories were very similar, in spite of the LREC's "AP2" positioning mechanism being out of tolerance.

4. DIMENSIONAL VERIFICATION OF THE POSITIONING MECHANISMS

The 3D printer normally produces a thicker first layer for a better adhesion to the printing bed. This leaves a thin layer sticking out of the intended dimensions, thus creating a small gap between the positioning mechanism and the transducer. This problem was solved by chamfering the edges whilst designing them. This technique was, for now, only applied to the "AP1" tool. Another problem found was the 3D printer positioning errors, which were solved by calibrating the X and Y axes motors and the extrusion motor (see [5]). This was a time-consuming process that required a trial-and-error approach by printing several pieces, measuring them, and determining the trend line constants for adjusting the mm per step parameter of the printer (chitu board).

The positioning mechanisms were measured on an optical coordinate machine using the bottom light at 30 % regulation. However, in the first versions of the mechanisms, the thickness of the protruding parts was measured with the machine upper lights because there was no aperture on the inside edge to allow the passage of the bottom light, and this resulted in inaccurate measurements.

4.1. *"AP1" tool dimensional verification*

The "AP1" tool was redesigned in order to make it more rigid and less prone to dimensional errors. Also, a better design was necessary to improve the measurement technique, since it was difficult to find adequate reference lines for the creation of the piece coordinate system on the measuring machine. The measurement schematics and results for the internal radius are presented in Figure 9 and Table 6.

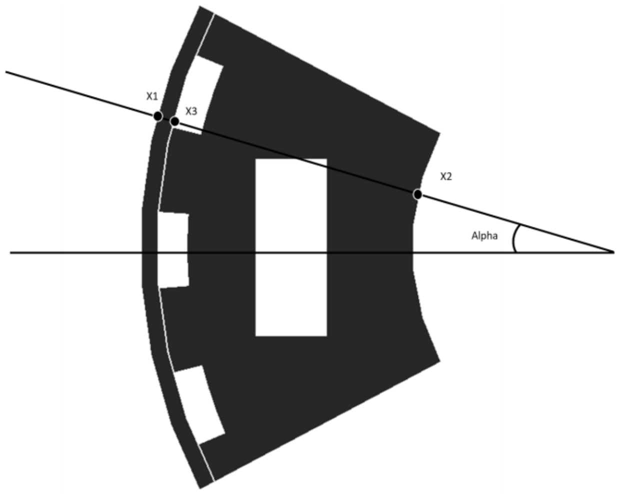

Figure 9. Measurement schematics for the latest design of the "AP1" positioning mechanism.

Table 6 – Internal radius measurements of the "AP1" positioning mechanism.

Alpha (°)	**Internal Radius** (X3 – X2) (mm)	**Nominal Value** (mm)	**Error** (mm)	**Standard Deviation** (mm)
-20	73.8479	74	-0.1521	0.068
-15	73.8334		-0.1666	
0	73.8758		-0.1242	
15	73.7209		-0.2791	
20	73.7449		-0.2551	

From Table 6, it is evident that the piece is not symmetric because the radius error is greater on the bottom half. This means that there will be a gap when fitting the piece to the transducer's load pad. This asymmetry was worse in the first version because the piece was aligned with the X axis of the printer. The last version was produced in alignment with the printer's Y axis, which as a more stable structure. Unfortunately, this "AP1" mechanism does not comply with the tolerance because the absolute error is greater than 0.10 mm. However, the error can be corrected by adjustment of the X1 and X3 dimensions in Figure 9. The nominal value of 74 mm was calculated for a platen with a diameter of 288 mm, which is not the platen's real diameter value because the tool pushes the transducer a bit more to the side. This is visible through comparison to the platen's circular reference lines. Recent measurements of the platen with a calliper resulted in a maximum value of 287.30 mm. Therefore, the mechanism will be redesigned for a nominal internal diameter value of 73.65 mm.

4.2. "AP2" tool dimensional verification

This tool is still in its first version because of its complexity. It requires a compromise between internal and external dimensional errors because the printer produces the external dimensions with better accuracy.

The measurement schematics and results are presented in Figure 10 and Table 7.

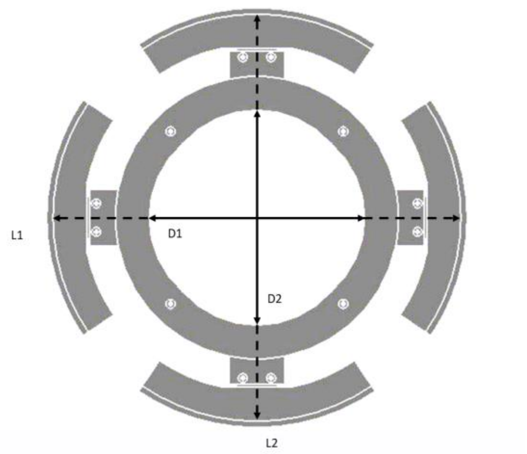

Figure 10. Measurement schematics for the "AP2" positioning mechanism.

Table 7. Internal radius measurements of the "AP2" positioning mechanism for a nominal value of 152 mm.

D1			D2		
Average (mm)	Error (mm)	Standard Deviation (mm)	Average (mm)	Error (mm)	Standard Deviation (mm)
151.39	-0.61	0.00	151.20	-0.80	0.00

Table 8. External radius measurements of the "AP2" positioning mechanism for a nominal value of 288 mm.

L1			L2		
Average (mm)	Error (mm)	Standard Deviation (mm)	Average (mm)	Error (mm)	Standard Deviation (mm)
287.74	0.26	0.00	287.03	0.97	0.01

Table 7 shows average values of measurements made on fixed location points in the centre of the piece, which resulted in very low standard deviation values. Assuming that the tool is well centred on the platen, the resulting errors for the D1 and D2 internal diameters mean that the transducer was aligned, on each side, with deviations of approximately -0.3 mm and -0.4 mm, respectively. These values greatly exceed the required tolerance of 0.05 mm. From Table 8, it is observable that L2 is shorter than L1 and this is possible to feel as the "AP2" is fitted into the lower platen. Figure 10 shows that there are four lateral pieces that connect to the centrepiece by means of two screws. This is not a very rigid connection and results in slight deformations. However, the mechanism stays attached to the platen through small magnets installed in the centrepiece, but the design needs improvement.

5. VERIFICATION OF THE TRANSDUCERS WITH THE NEW "AP1" TOOL

The mean strain ratio results for the GTM transducer are shown in Figure 11.

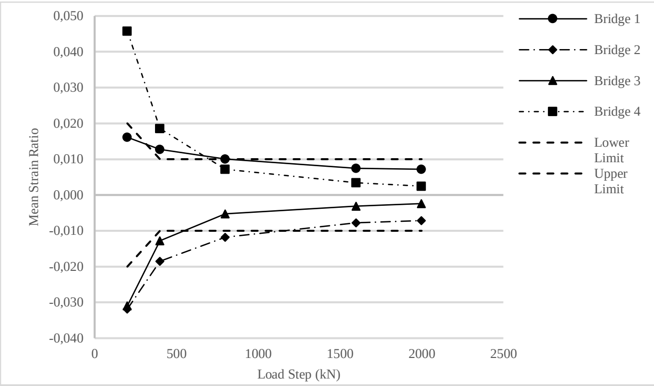

Figure 11. GTM transducer's mean strain ratio results for each bridge and load step. The new "AP1" tool was used in the centre positioning.

Figure 11 shows that the GTM transducer continues out of tolerance and comparing with the results in Figure 2, it is observable that there were no significant changes.

The mean strain ratio results for the HBM transducer are shown in Figure 12.

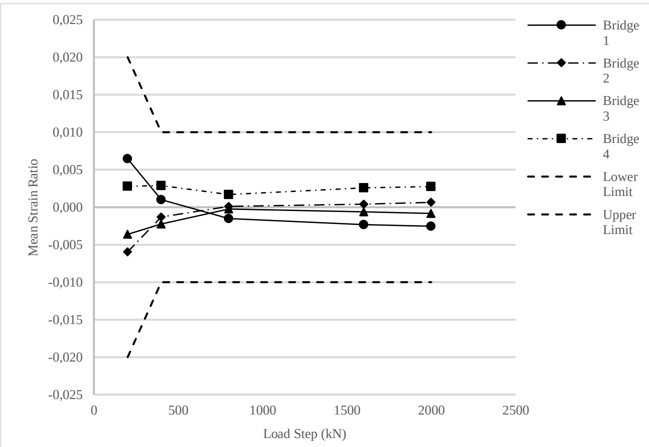

Figure 12. HBM transducer's mean strain ratio results for each bridge and load step. The new "AP1" tool was used in the centre positioning.

From Figure 12, it is evident that the HBM transducer finally complies with the required tolerances, even though the new "AP1" tool is out of tolerance. Both transducers have load pads with a diameter of 140 mm and were positioned with the same tool. The first "AP1" has an internal diameter value of about 74 mm, while the new "AP1" has an average value of 73.80 mm. The difference in internal diameter values between the first and latest "AP1" tools is roughly 0.2 mm, not considering the asymmetry of the pieces, which could lower or increase this value. From this, it would be possible to suggest that the HBM was more sensitive to a change in centre positioning than the GTM transducer. However, it is not possible to arrive to any solid conclusions because there are no reliable dimensional measurements for the first version of the "AP1" mechanism.

6. CONCLUSIONS

The initial verifications of the force transducers resulted in non-compliance with the required limits given in Table A.1 of [1]. However, these verifications resulted in mean strain ratio values lower than one third of the machine's limit, given in Table 1 of [1], for this parameter. This allowed the successful verification of the machine with LREC's GTM transducer, validated by the verification results of the ISO 17025-accredited laboratory.

The verification results in Section 3 show that the machine has a problem in the ball-seating, which was initially thought to be caused solely by the incorrectly mounted sealant. However, this will have to be investigated by dismounting and checking the ball-seating mechanical parts. A possible simple correction might be to better lubricate the parts.

The dimensioning of the positioning mechanisms depends on the accurate measurement of the machine's lower platen top surface diameter. In this particular case, there was some difficulty on determining this parameter because the edges were not clear enough to permit a reliable measurement with a ruler. Recent measurements with a calliper resulted in a maximum diameter value of 287.30 mm, which gives a new starting point of 73.65 mm for the internal diameter of the next "AP1". If possible, the best procedure would be to measure the top surface diameter on a coordinate measuring machine, in order to minimise the trial-and-error process.

The lateral stickers also contribute to the positioning error; therefore, the user should avoid using the tools on sides with stickers.

The second verification results of the HBM transducer in Section 5 prove that the "AP1" mechanism's internal diameter is near the optimal dimensional point. Therefore, it is necessary to continue with the trial-and-error process, involving the dimensioning of both the external diameter and the thickness of the protruding lateral, the printing and measurement of the new tool and the testing with the positioning of the transducer whilst executing the verification according to the procedure in Section A.3 of [1].

Finally, it has been found that, in spite of the ongoing difficulties, these positioning mechanisms are worth it for their lightness, simplicity of usage and adaptive design, as well as the low costs and ease of production with a 3D printer.

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