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Study for Initial Load Effects on the Calibration of Load Cells

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ABSTRACT— ***This work was carried out by the National Institute of Standards NIS), Egypt, as a result of experimental cases in load cell applications. The aim of this study is to compare the behavior of load cell works under initial load with the ideal working case. The study was carried out using seven load cells from different manufacturers and with different types, capacities, working modes and classes. As a result of the behavior of the load cells during this study; it is clear that the response of the load cells previously loaded against applied load differ from the ideal case. Load cell operators have to carry out mathematical calculations to correct the reading rather than using electrical methods to readjust the zero signal and neglecting the initial applied load.***

Keywords— Load cell, initial load, strain gauges, calibration, loading frame.

1. INTRODUCTION

Load cell is a force transducer based on using a strain gauge bond to an elastic element which has to deform elastically under loads[1], in order to give an expected pre-determined response to indicate the applied true load. According to the international standards (ASTM E74[2] & ISO 376[3]) load cells are from zero output (no load case), but in some real applications load cells are initially loaded due to the design feature or nature of the application. In some applications there is a need to apply an initial load on the load cell before start measurements; one of these applications is using a load cell as a reference standard in carrying out secondary force calibrations using the universal loading frame (see fig. 1) [4]. Universal loading frame with a reference standard load cell – calibrated on a deadweight machine which realizes SI units- can be considered as a secondary standard in force measurements traceability chain.

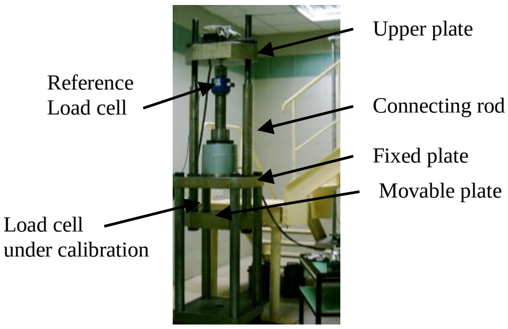

Figure 1: NIS universal loading frame

In the universal loading frame; the reference load cell has to be placed between the upper and the fixed plate while the load cell under calibration has to be placed in between the movable and the fixed plates. Thus, the upper plate, the movable plate and their connecting rods have to be loaded on the reference load cell before apply calibration loads. The weight of these objects has to be considered as an initial load on the load cell

(which may reflect on its response under calibration loads, another application is some bridges like the Burlington-Bristol Bridge,

In the spring of 2010, the expansion bearings of the Burlington-Bristol Bridge were replaced due to a poor condition rating that caused the bridge to be classified as structurally deficient). The replacement of these bearings represented a unique opportunity to configure the new bearings to monitor the dead load and live load actions as well as their variation with environmental conditions. In these cases; the elastic element of the load cell is already has percentage of deformation directly proportional to the applied load according to the elastic theories [5]. As a result; the range of calibration of the load cells differs from the working range because the calibration conditions differ from the working conditions.

2. STUDY PLAN

During the study seven different load cells from different manufacturers and with different types, capacities, working modes and classes were used. Each load cell was calibrated four times according to the international standard ISO/IEC 376 up to 100% of its capacity. The following table (Table (1)) summaries the study plan.

Table 1: Study schemes

Calibration scheme	Applied static load	Calibration points
First (1^{st})	No static load	10
Second (2^{nd})	10% of Capacity	9
Third (3^{rd})	20% of Capacity	8
Fourth (4^{th})	50% of Capacity	5

First calibration scheme is the standard calibration procedure. Second, third and fourth calibration schemes were carried out after applying a static load – on the load cell- according to Table (1). The load cell output was readjusted to zero signals before carrying out calibrations according to 2nd, 3rd and 4th calibration schemes.

3. MEASUREMENTS

Measurements were carried out using NIS 50 kN & 500 kN Deadweight machines (see figure (1)). The responses of the load cells under calibration load (kN) were monitored using DMP-40 (mV/V) manufactured by HBM Company [5] to get trustable data. Taken into considerations not to apply the load cell nominal capacity on the load cell which is already loaded by a static load (in case of the 2nd, 3rd & 4th calibrations) to avoid overloading process.

Figure 2: NIS500 kN DWM & NIS 50 kN DWM respectively

4. RESULTS AND DISCUSSION

Measurements were carried out on seven different load cells. The following table (Table (2)) shows the coefficients of the a 3rd degree fitting equation (equation 1) resulted from curve fitting of the calibration data

$$\text{Force} = A \times \text{Deflection} + B \times \text{Deflrction}^2 + \text{Force} \times \text{Deflrction}^3 \quad (1)$$

Table 2: Coefficient of a 3rd degree calibration equation

Load cell Identification	Calibration Scheme	Coefficients of a 3rd degree fitting equation (equation 1)		
		A	B	C
Load Cell 1 (20kN)	1st	7.370429	-0.009069	0.002176
	2nd	7.362052	-0.003825	0.001328
	3rd	7.360948	-0.003465	0.001533
	4th	7.361162	-0.005715	0.004519
Load Cell 2 (20kN)	1st	7.373493	-0.008433	0.001677
	2nd	7.363901	-0.002314	0.000516
	3rd	7.363812	-0.002993	0.000825
	4th	7.363786	-0.007438	0.003970
Load Cell 3 (450 kN)	1st	221.669883	-0.023151	0.056362
	2nd	221.421979	0.304828	-0.040313
	3rd	221.518748	0.309955	-0.051282
	4th	221.862484	0.159565	-0.015800
Load Cell 4 (450 kN)	1st	221.206486	0.208403	-0.000329
	2nd	221.181073	0.340835	-0.044118
	3rd	221.275287	0.365046	-0.062774
	4th	221.651840	0.221934	-0.037464
Load Cell 5 (5 kN)	1st	2.497390	-0.000649	0.000256
	2nd	2.502559	-0.006867	0.002353
	3rd	2.496741	-0.000858	0.000626
	4th	2.496764	-0.000886	0.001428
Load Cell 6 (10 kN)	1st	4.993285	-0.002514	0.001464
	2nd	4.991371	-0.000332	0.001031
	3rd	4.991489	0.000117	0.001095
	4th	4.992491	0.002771	0.000701
Load Cell 7 (5 kN)	1st	2.499918	-0.001274	0.000070
	2nd	2.499568	-0.001397	0.000123
	3rd	2.498635	-0.000796	-0.000074
	4th	2.498236	-0.002558	0.000970

The actual resulted data resulted from the four calibration schemes were compared to each other for the same calibration load. Tables (3), (4) and (5) show the relative error between the 2nd, 3rd, and 4th scheme respectively with respect to the 1st (standard) calibration scheme. It is clear form the results of the relative error calculations that each load cell has a unique trend when calibrated under initial static load, however the relative error decreases as the calibration load increase

Table 3: The percentage error between 1st and 2nd calibration results

Load cell Identification	Relative Error between 1st & 2nd calibration scheme results								
	10%	20%	30%	40%	50%	60%	70%	80%	90%
Load Cell 1 (20kN)	0.153	0.081	0.060	0.045	0.035	0.027	0.022	0.020	0.004
Load Cell 2 (20 kN)	0.189	0.093	0.066	0.054	0.039	0.040	0.028	0.033	0.017
Load Cell 3 (450 kN)	0.178	0.071	0.030	0.012	-0.001	-0.003	-0.008	-0.010	-0.010
Load Cell 4 (450 kN)	0.030	0.005	-0.023	-0.030	-0.031	-0.034	-0.032	-0.031	-0.031
Load Cell 5 (5 kN)	-0.481	-0.092	-0.060	-0.045	-0.038	-0.031	-0.029	-0.029	-0.030
Load Cell 6 (10 kN)	0.052	0.022	0.015	0.005	0.003	-0.002	-0.004	-0.010	-0.011
Load Cell 7 (5 kN)	-0.005	0.021	0.017	0.019	0.014	0.017	0.017	0.018	0.015

Table 4: The percentage error between 1st and 3rd calibration results

Load cell Identification	Relative Error between 1st & 3rd calibration scheme results							
	10%	20%	30%	40%	50%	60%	70%	80%
Load Cell 1 (20kN)	0.163	0.095	0.069	0.050	0.037	0.027	0.023	0.005
Load Cell 2 (20 kN)	0.186	0.098	0.075	0.056	0.049	0.041	0.039	0.028
Load Cell 3 (450 kN)	0.143	0.027	-0.013	-0.033	-0.040	-0.042	-0.045	-0.044
Load Cell 4 (450 kN)	0.010	-0.044	-0.072	-0.075	-0.077	-0.075	-0.072	-0.070
Load Cell 5 (5 kN)	-0.183	0.060	0.040	0.028	0.021	0.016	0.007	-0.002
Load Cell 6 (10 kN)	0.044	0.019	0.005	-0.004	-0.010	-0.016	-0.023	-0.029
Load Cell 7 (5 kN)	0.042	0.049	0.044	0.038	0.035	0.037	0.038	0.035

Table 5: The percentage error between 1st and 4th calibration results

Load cell Identification	Relative Error between 1st & 4th calibration scheme results				
	10%	20%	30%	40%	50%
Load Cell 1 (20kN)	0.173	0.092	0.058	0.038	0.002
Load Cell 2 (20 kN)	0.197	0.123	0.085	0.080	0.051
Load Cell 3 (450 kN)	-0.005	-0.101	-0.133	-0.143	-0.143
Load Cell 4 (450 kN)	-0.152	-0.192	-0.205	-0.199	-0.192
Load Cell 5 (5 kN)	-0.189	0.052	0.029	0.009	-0.010
Load Cell 6 (10 kN)	0.016	-0.025	-0.041	-0.063	-0.075
Load Cell 7 (5 kN)	0.070	0.088	0.084	0.086	0.081

The following table (Table (6)) shows the response values calculated from the 3rd degree fitting equation (Table (2)) at 10%, 20% 30% and 50% of each load cell nominal capacity. In this table the force (as a percentage of the nominal capacity) is used and corrected according to the fitting equation (equation 1) resulted from the four calibration schemes used in this study.

Table 6: Force values after correcting using 3rd degree fitting equations

Load cell Identification	% Nominal capacity	Nominal Force (kN)	Calculated force (kN) after correcting the nominal force using the 3rd degree fitting equation (1)			
			Normal	10%	20%	50%
Load Cell 1 (20kN)	10%	2.0	1.997735	2.000783	2.000989	2.001188
	20%	4.0	3.998518	4.001772	4.002310	4.002192
	30%	6.0	5.999507	6.003093	6.003645	6.002983
	50%	10.0	10.002163	10.005617	10.005837	10.002340
Load Cell 2 (20kN)	10%	2.0	1.997358	2.001137	2.001071	2.001292
	20%	4.0	3.998496	4.002208	4.002407	4.003402
	30%	6.0	5.999567	6.003545	6.004082	6.004679
	50%	10.0	10.002578	10.006512	10.007484	10.007676
Load Cell 3 (450 kN)	10%	45.0	44.961387	45.041201	45.025681	44.959170
	20%	90.0	90.002588	90.066882	90.026975	89.911690
	30%	135.0	135.028269	135.068176	135.010533	134.848690
	50%	225.0	225.013121	225.010904	224.922223	224.691651
Load Cell 4 (450 kN)	10%	45.0	45.013580	45.026865	45.018008	44.944942
	20%	90.0	90.040445	90.044873	90.000590	89.867742
	30%	135.0	135.058453	135.027455	134.961031	134.781685

Load cell Identification	% Nominal capacity	Nominal Force (kN)	Calculated force (kN) after correcting the nominal force using the 3rd degree fitting equation (1)			
			Normal	**10%**	**20%**	**50%**
	50%	225.0	225.001476	224.932837	224.828772	224.569717
Load Cell 5 (5 kN)	10%	0.5	0.501018	0.498605	0.500099	0.500069
	20%	1.0	0.999623	0.998704	1.000220	1.000142
	30%	1.5	1.499722	1.498825	1.500328	1.500159
	50%	2.5	2.499951	2.499002	2.500471	2.499692
Load Cell 6 (10 kN)	10%	1.0	0.999675	1.000199	1.000117	0.999837
	20%	2.0	1.999874	2.000316	2.000249	1.999370
	30%	3.0	2.999991	3.000448	3.000133	2.998758
	50%	5.0	5.000008	5.000170	4.999503	4.996276
Load Cell 7 (5 kN)	10%	0.5	0.499845	0.499820	0.500058	0.500198
	20%	1.0	0.999666	0.999878	1.000158	1.000543
	30%	1.5	1.499723	1.499978	1.500386	1.500980
	50%	2.5	2.500051	2.500404	2.500928	2.502065

From the previous table (Table (6)) it is clear that substituting by the same nominal force in the four fitting equations leads to different values, which indicate that using a fitting equation resulted from an standard calibration scheme to predict an additional load on load cell initially loaded will result in a different response.

The following Figures (Fig. 3 – 9) plot the deviations between the Standard calibration scheme (1st) and the other calibration schemes (2nd, 3rd& 4th). It is clear that each load cell has different behavior when works under initial load but for a specific load cell, the deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th) have the same trend.

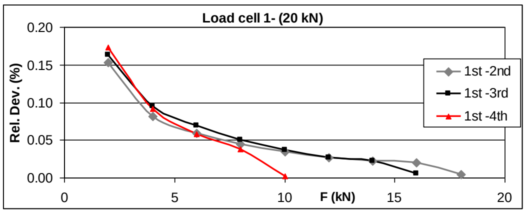

Figure 3: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 20 kN-A

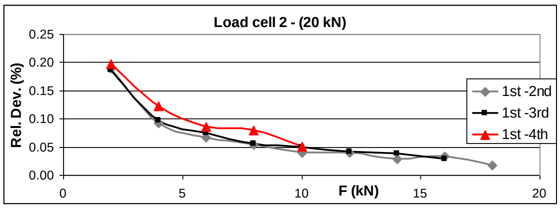

Figure 4: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 20 kN-B

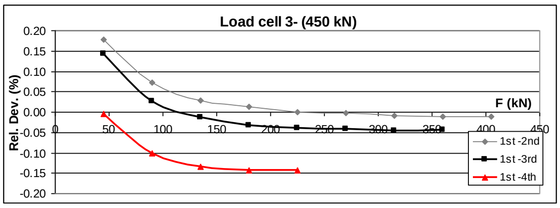

Figure 5: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 450 kN-B

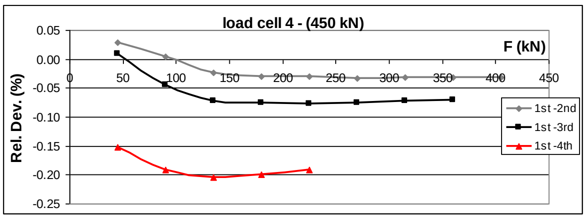

Figure 6: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 450 kN-A

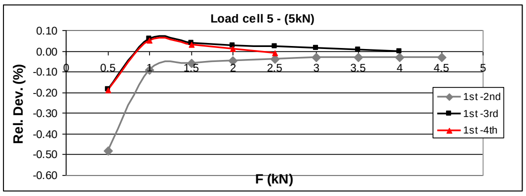

Figure 7: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 5 kN-A

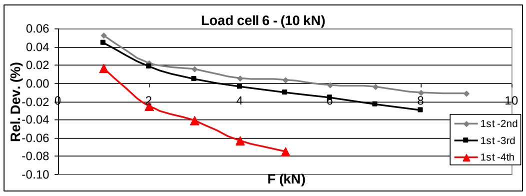

Figure 8: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 10 kN

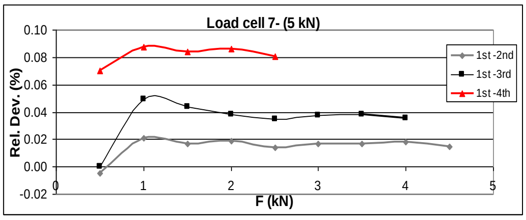

Figure 9: Deviation between the 1st calibration scheme and the other calibration schemes (2nd, 3rd& 4th); L.C: 5 kN-B

As a result of the behavior of the load cells during this study; it is clear that the response of the load cells previously loaded against applied load differ from the ideal case. The initially loaded load cell response will be a result from different stage in the response curve. Figure (10) is a virtual response of a 100 kN load cell which is used to demonstrate the case study. Figure (10.A) shows a normal response of the load cell from 10-100% of its capacity, if the 100 kN load cell is initially loaded by 20 % (20 kN) then the left hand side (Figure 10.B) will be neglected and the load cell will react to further applied loads according to the right hand side (Figure 10.C). Figure (10.D) is the response curve of 100 kN load cell after being initially loaded by 20% (20 kN) which is differ from the standard response curve (Figurer 10.A).

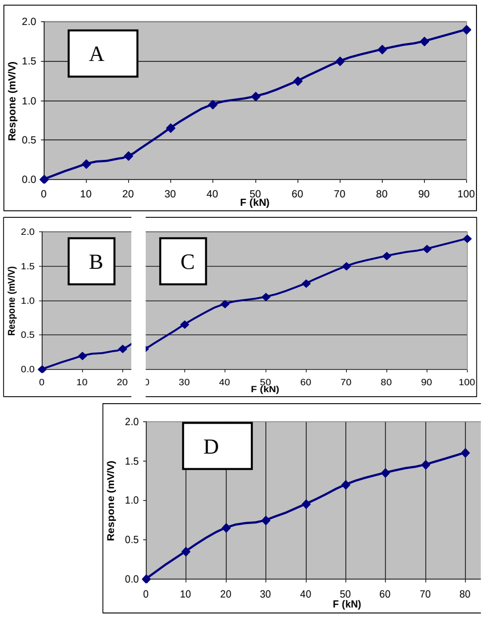

Figure 10: Virtual 100 kN L.C. without & with 20% initial load

5. STATISTICAL ANALYSIS

To study the previously mentioned results of the Standard calibration scheme (1st) and the other calibration schemes (2nd, 3rd& 4th), Preliminary approach [7] normal distribution was used for comparison of the results of the two methods.

If x, and y are standard and other calibration schemes respectively, and normally distributed values, then the following equations can be applied.

$$\bar{x} = \sum_{i=1}^{n} \frac{xi}{n} \qquad (2)$$

$$\bar{y} = \sum_{i=1}^{n} \frac{yi}{n} \qquad (3)$$

$$t_2 = \frac{(\bar{x} - \bar{y})}{\sqrt{\frac{(nx-1)s^2{}_x + (ny-1)s_y{}^2}{n_x + n_y - 2}}\sqrt{\frac{1}{n_y} + \frac{1}{n_x}}} \qquad (4)$$

Where:

Sx, and Sy are the standard deviations of the results of the standard, and developed method respectively.

nx = 3 $\qquad$ $n_y = 3$

υ=nx+ny-2=4

For 95% confidence level 1-α=0.95 , α/2=0.025

t0.025:4 from t- distribution tables= 2.776

since, $t_2 > t\ \alpha/2$ for most of calibration steps ,so the three calibration schemes is significantly different from the standard method.

Table (7) summarizes the results of the preliminary approach comparison method, for all calibration schemes,

It is concluded from the experimental work that; using a force transducer (load cell) loaded with initial load gives different response values from that if the load cell has no initial load.

Universal loading frames and reference standard load cell as a force secondary standards face the initial load case (static load) presented through this study and this may affect their calibration results.

Load cell operators have to carry out mathematical calculations to correct the reading rather than using electrical methods to readjust the zero signals and neglecting the initial applied load. Elsewhere, a new source of uncertainty shall be estimated and depends on the percentage of the applied load

Table 7 result of Preliminary approach comparison method

Load cell Identification	% Nominal capacity	Nominal Force (kN)	Standard	Sy			t_2		
			Sx	10%	20%	50%	10%	20%	50%
Load Cell 1 (20kN)	10%	2	0.0002	0.0005	0.0004	0.0005	-4.9017	-6.30134	-5.98077
	20%	4	0.0003	0.0005	0.0006	0.0007	-4.83291	-4.89545	-4.54539
	30%	6	0.00049	0.0006	0.0005	0.001	-4.00894	-5.11893	-3.01030
	50%	10	0.0005	0.0008	0.00069	0.0005	-3.17072	-3.73398	-0.30657
Load Cell 2 (20kN)	10%	2	0.00015	0.0003	0.0002	0.0005	-9.75734	-12.8622	-6.81388
	20%	4	0.0003	0.00041	0.0005	0.0008	-6.32768	-5.8087	-5.31090
	30%	6	0.0006	0.0007	0.0008	0.0007	-3.73668	-3.9101	-6.32445
	50%	10	0.0007	0.0008	0.0009	0.001	-3.20498	-3.72637	-4.41499
Load Cell 3 (450 kN)	10%	45	0.003	0.004	0.006	0.007	-13.8242	-8.30032	0.274282
	20%	90	0.002	0.005	0.007	0.008	-10.3396	-2.90102	9.839997
	30%	135	0.008	0.006	0.008	0.009	-3.45605	1.35763	17.27999

Load cell Identification	% Nominal capacity	Nominal Force (kN)	Standard Sx	Sy 10%	Sy 20%	Sy 50%	t_2 10%	t_2 20%	t_2 50%
	50%	225	0.007	0.008	0.009	0.012	0.180616	6.904199	23.20009
Load Cell 4 (450 kN)	10%	45	0.0035	0.005	0.006	0.009	-1.88508	-0.55206	6.604694
	20%	90	0.0031	0.0042	0.0053	0.007	-0.73461	5.621378	21.3664
	30%	135	0.0065	0.0075	0.008	0.009	2.704869	8.185085	26.63201
	50%	225	0.0041	0.0063	0.008	0.008	7.908195	16.63798	46.7392
Load Cell 5 (5kN)	10%	0.5	0.0001	0.0002	0.0004	0.0005	9.345509	1.930286	1.64371
	20%	1	0.00021	0.0005	0.0006	0.0008	1.467569	-0.81332	-0.56183
	30%	1.5	0.0003	0.0006	0.0007	0.0009	1.158022	-0.68911	-0.42050
	50%	2.5	0.0002	0.0007	0.0008	0.0012	1.128909	-0.54611	0.186917
Load Cell 6 (10kN)	10%	1	0.00022	0.0003	0.0004	0.0006	-1.21981	-0.8385	-0.23382
	20%	2	0.0005	0.0006	0.0007	0.0008	-0.4901	-0.37753	0.5455
	30%	3	0.0006	0.0008	0.0006	0.0009	-0.39577	-0.14493	1.18645
	50%	5	0.0006	0.0007	0.0008	0.0011	-0.15217	0.437343	2.93818
Load Cell 5 (5kN)	10%	0.5	0.0001	0.0003	0.0005	0.0006	0.068465	-0.36176	-0.50951
	20%	1	0.0002	0.0004	0.0006	0.0007	-0.41054	-0.6737	-1.08500
	30%	1.5	0.0005	0.0006	0.0007	0.0006	-0.28275	-0.66746	-1.81432
	50%	2.5	0.0009	0.0008	0.0008	0.0008	-0.25388	-0.63073	-2.1802

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