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Beam Deflection under Static Loading: Comparison Between Dial Gauge and Total Station Measurements

Gamal H. Seedahmed

Department of Surveying Engineering, Faculty of Engineering University of Khartoum
Khartoum, Sudan (E-mail: Gamal.Seedahmed@gmail.com)

Abstract: This paper presents the results of experimental findings for beam deflection measurements under static loading using dial gauges and a reflector-less Total Station. The ultimate objective of this work is to compare the performance of the Total Station with respect to the Dial Gauge (DG). Cement bags were utilized for loading test. These loads are accumulated evenly in six steps. The total tested load was 4.2 tons. The tested beams were located in the Sport City-Khartoum State. This work reveals that the reflector-less Total Station-Leica 1202 (RLTS) produces a very strong correlation and an acceptable accuracy that stands within the limits of its minimum decimal fraction of the metric units. Several tests were carried out to confirm the linearity of the deflections against the loads. These tests are very important since they convey the information about the elastic behavior of the tested beams. In this regards, both measuring techniques produce correlation factors and R^2 values for the loads vs. the deflections of more than 0.98. The deflection accuracy of the Total Station, in terms of root-mean-square-error ***(RMSE***), for the three beams were: ± 0.30 mm, ± 0.36 mm, and ± 0.39 mm, respectively. This finding indicates that the Total Station can provide sub-millimeter accuracy with respect to the dial gauge. The maximum deflection was found in beam number 3, which amounts to 7.9 mm from the Total Station and 7.85 mm from the dial gauge. Both measurement techniques produce recovery percentages that were greater than 88%. The overall findings of this experiment indicates that this reflector-less Total Station can be used for on-site measurement of deflection and for a wide range of deflection/deformation measurement applications.

Keywords: *Beam Deflection Measurement; Static Loading; Dial Gauge; Total Station.*

1. INTRODUCTION

With the escalating burden of new and ageing structures throughout the world and here in Sudan, efficient, reliable, portable, accurate, and easy-to-use technologies for deformation monitoring and measurement are becoming very vital. While visual inspection can detect cracking of structural or non-structural elements due to ageing, extreme vibrations, earthquake, abnormal loading, or differential settlement, the ability to measure and quantify structural changes prior to their appearance in the form of visual cues, such as cracks, would insure that the deformation could be detected in its earliest possible stages and time for proper risk's mitigation [1].

Deformations are quantified in terms of direct and shear strain. The cumulative effect of the strains in a component/member (here in this work refers to beams) is a deformation or shape's changes, such as a bend, twist, and a stretch. Extreme deformation, particularly if permanent, is often destructive. Deformation that appears quickly upon loading can be classified as either elastic deformation or plastic deformation. Elastic deformation is recovered immediately upon unloading. On the other hand, plastic deformation is not recovered upon unloading and is therefore permanent [2].

Many tasks in material testing and structural engineering require the monitoring and measurement of the deformation of test objects under varying conditions of loading and unloading. Structural engineering requires precise and reliable technologies to address the emerging concerns of high rise buildings in terms of deflections, tilt, linear displacements, and vibrations [3]. In particular, geometrical measurements are performed to examine the behavior of individual component/member and to verify the underlying physical models and assumptions that were used for their design. These tests are often executed by the use of static, quasi-static, or dynamic loads. During these load tests, several parameters have to be acquired such as loads values at different epochs, deformation/deflection, displacement, and crack/s formation.

In this work the deflections of three different beams were measured by three dial gauges and the same measurements were acquired by a reflector-less Total Station. These dial gauges are considered proven techniques since they provide very high geometric precision and reliability. A general disadvantage of the dial gauges, however, is their one-dimensional information and are best suited to laboratory setting. They do not provide 3D dimensional measurement. If simultaneous two- or three-dimensional measurement are required at several positions, then at each required position a dial gauge should be installed. The dial gauges are generally not suited for tasks requiring a large number of measurement points distributed over an object surface or for complete surface measurements. On the other hand, the use of a reflector-less Total Station for deflection measurement is non-contact, requires no manual reading of dials, yields three dimensional measurements, and provides a direct digital records for the measurements. Moreover, reflector-less Total Station (RLTS) is ideally suited for field work and destructive and non-destructive testing. In light of these benefits that will be offered by the use of a reflector-less Total Station, one of the main tasks of this work is to evaluate its accuracy for deflection measurement to provide a solid basis for its use in this kind of tests. In fact, this is a must do test to qualify the Total Station for this kind of works [4]. This kind of test is a fundamental task in survey work. For example, Chekole (2014) [5] provides a comparative analysis for the accuracy of GPS, Total Station, and a laser scanner.

In general, analysis and understanding of deformation (here: in this work refers to vertical deflection) of any type of a deformable body (here: beam) includes geometrical measurement and analysis and physical computation and interpretation [6]. Geometrical measurement and analysis provide in-situ or field information about the change in shape and dimensions of the monitored or observed body/object, as well as its rigid body motions (scales, translations, shears, and rotations). Although this work is concerned with the measurement of vertical deflection, the ultimate objective of the geometrical measurement and analysis is to determine the overall deformation of the object/body under concerns in terms of its displacement and strain fields in spatial and time domains.

Direct and indirect observations and their analysis explain the underlying relationship between the contributing factors (here: loads by cement bags) and the deformation (here: deflection). This relationship can be analyzed either by statistical approach, such as the correlation to infer the underlying dependency between the observed deformations and their corresponding loads, or by physical/mathematical models that use information about loads, properties of the materials, dimensions of the object, and the physical laws that govern the stress-strain relationship [7,8].

In most practical cases, it is necessary that a structure should be not only strong enough for its purpose, but also that it should have the required stiffness, that is, it should not deflect from its original position by more than a certain amount. In fact, by comparing the geometrical information for deformation with the one that will be obtained from the physical laws, we can gain very insightful information about the real performance of the designed object, which may not show up during the design stage and this is due to several factors such as the heterogeneity of the construction materials and the underlying assumptions of the design process. If the difference between the geometrical deformation and the one that will be computed by the equation is small, then the object/structure behaves as expected and the equation is justified. Otherwise, a search for reason/s of the large discrepancies and inconsistencies should be undertaken.

With properly designed surveys scheme in terms of network design, optimization, and observations [7, 8], the deformation process can be used to determine its underlying mechanism that explains the causes of the deformation. Thus, the role of deformation measurement and analysis goes much more beyond the conventional determination of the geometrical status or measurement of the deformable object. Therefore, the comparison of the geometrical information with the one that will be obtained from the physical laws and the design parameters has an impact on: redesign of the investigated object/structure, safety and risk management, economy of design, environment, and gaining experience for future work.

The analysis of the deformation/deflection typically deals with very small quantities, which are at the margin of the measuring errors or the limiting factors of the instruments in light of the intended task [9]. Therefore, a very careful selection of instruments, accuracy analysis, and statistical testing of the results should be carried out for the correct evaluation of the obtained results and proper decision making in order to accept the values of the deformation/deflection. Accordingly, the survey work and method, their design, and the analysis of the deformation/deflection results become a very complex task. This complexity, if not tackled and understood properly, may jeopardize the overall process of deformation measurement and analysis. In fact, one of the main objectives of this work is to evaluate the accuracy of a particular RLTS (Leica TCR-1202) against a dial gauge, which is a classical tool for deflection measurement.

This paper is organized as follows. Section two provides an overview of the objectives of this work. Then followed by section three, which shows the general mathematical framework for deflection modelling. Section four presents the underlying methodology of this work. Section five highlights the utilized instruments for data collection. Section six shows the test site. Section seven provides the experimental results and analysis. Section eight concludes the paper and lists some recommendations.

1. WORK'S OBJECTIVES

This work was performed jointly with the Structure Laboratory at the Department of civil engineering and the Department of surveying engineering at University of Khartoum. This work is driven by practical needs; and it has two main objectives:

I. First and as stated, this work is motivated by a practical needs for deformation measurement. In particular, to evaluate the deflection and the recovery percentage of a beam under static loading (see **Fig. 1**). The deflection will be measured at the mid-point of each beam.

II. Second, to analyze and compare the measurements accuracy of a reflector-less Total Station (RLTS) with respect to dial gauges. In other words, the objective of this work is to promote and position the Total Station for deflections measurement in the field. Both the dial gauge and the Total Station yield geometrical information about the deflection in the vertical direction. The Total Station can be viewed as a 3D sensor since it measures (X, Y, Z); and the dial gauge can be viewed as 1D sensor since it measures only the vertical distance. Although, the information about the displacement in the X and Y coordinates will not be used in this work, they will provide vital information about the shear, which may be of a great value in future work. Therefore, the Total Station and the dial gauge will be compared in terms of the vertical distances. From a practical point of view, this comparison is very vital in terms of bringing the confidence to the use of surveying equipment and techniques in deflections measurement. This confidence is typically conveyed by the evaluation of the accuracy of the Total Station in light of the one that will be obtained from the dial gauge.

3. GEOMETRICAL MODELING OF DEFLECTION

From a geometrical point of view, the deflection/deformation can be specified by a displacement function (***d***) for different pairs of epochs (***t***). This function can be stated as follows:

$$d(x,y,z,t_{i+1}-t_i)=\begin{bmatrix}u(x,y,z,t_{i+1}-t_i)\\ v(x,y,z,t_{i+1}-t_i)\\ w(x,y,z,t_{i+1}-t_i)\end{bmatrix} \qquad (1)$$

with ***u***, ***v***, and ***w*** are the components of the displacement in the ***x***, ***y***, and ***z*** directions respectively. These components are both functions in position and time as indicated in equation (1). An important step in the analysis of the pairs of epochs of observations or measurements is to identify the underlying nature of the deflection pattern in the spatial domain. For example, does this deflection pattern behave in the elastic region of the particular material, does it reach its yield stress, does it reach its ultimate stress, what is the range of its plasticity, and what is the value of its fracture stress. In fact, the answers to these questions provide an empirical reconstruction of the stress-strain diagram [10] of the particular structure, which contains almost all of the required information for as-built analysis of this particular structure/component. Moreover, this empirical stress-strain diagram can be compared with its ideal diagram to gain more information about the discrepancies between the as-built structure and its design parameters. This comparison will reveal very critical information about the design in terms of over-design, under-design, or optimal design.

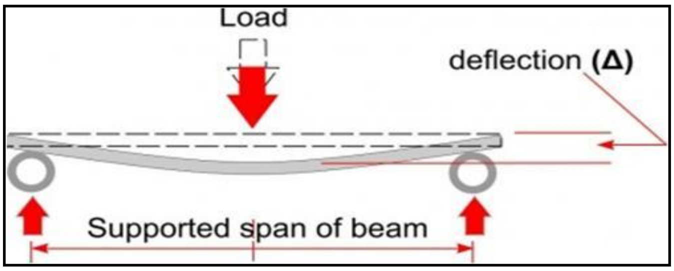

Fig. 1. Schematic diagram for a beam and its deflection under a load

4. METHODOLOGY FOR DIAL GAUGE AND REFLECTOR-LESS TOTAL STATION

This section presents the measurement and the computational methodologies or procedures for the dial gauge (see Fig. 2.a) and the reflector-less Total Station (see Fig. 3). The use of a reflector-less Total Station is very key in this work; otherwise the measurement procedure will be very cumbersome with a reflector-based Total Station. Both techniques require a particular procedures for proper field's setting; and repeated sets of geometrical measurement under different loading/unloading conditions. Only one setting is required for the Total Station and this is regardless of the number of beams for a particular job, which is the case of this work. On the other hand, several settings are required for a single dial gauge, or several dial gauges should be used if there is more than one beam. Although the Total Station delivers 3D dimensional coordinates, only the third dimension or the height information (Z-values) was used in this work. In other words, the produced data sets from both techniques will be brought into equivalent representation to facilitate apple-to-apple comparison. After representing both data sets in a similar format, similar computational procedures were applied to them. Step-wise the detailed procedure is as follows:

- Setting of the dial gauge/s for field measurement (see **Fig. 2.b**). It should be observed that the dial gauge should be in physical contact with the beam and this is not the case for the Total Station.
- Setting of the Total Station (see **Fig. 3**), which amounts to its leveling, setting an initial coordinates values, and establishing an arbitrary azimuth for orientation.
- Measure the reading of the dial gauge before loading at the midpoint of each beam. This is the base-line measurement for the dial gauge. This process will be repeated for each beam.
- Measure the reading of the Total Station, in terms of 3D coordinates, before loading at the midpoint of each beam. This is the base-line measurement for the Total Station. This process will be repeated for each beam.
- Measure the reading of the dial gauge at an equal increment of loading and at the center or the midpoint of the beam.

- Measure the reading of the Total Station, in terms of 3D coordinates, at an equal increment of loading and at the center of the beam.
- Repeat the previous two steps for the dial gauge and the Total Station until the last loading step.
- Compute the deflection from the dial gauge after full-loading.
- Compute the deflection from the Total Station after full-loading.
- Compute the Root-Mean-Square Error (*RMSE*) between the dial gauge readings and the Total Station readings. The *RMSE* is computed by two ways. First, the *RMSE* is computed from the comparison of height differences at different epochs. Second, the *RMSE* is computed by a direct comparison of the deflections from the Total Station and their counterparts from the dial gauges. The first *RMSE* quantify the relative difference of the deflections while the second one quantify the absolute difference of the deflections.
- Measure the reading of the dial gauge and with full-loading after 24 hours at the center of the beam.
- Measure the reading of the Total Station and with full-loading, in terms of 3D coordinates, after 24 hours at the center of the beam.
- Compute the deflection from the dial gauge readings with full-loading and after 24 hours.
- Compute the deflection from the Total Station readings with full-loading and after 24 hours.
- Measure the reading of the dial gauge without loading after 24 hours at the center of the beam.
- Measure the reading of the Total Station and without loading, in terms of 3D coordinates, after 24 hours at the center of the beam.
- Compute the deflection from the dial gauge without-loading and after 24 hours between the first reading at zero load before 24 hours to determine the recovery percentage.
- Compute the deflection from the Total Station reading without-loading and after 24 hours between the first reading at zero load before 24 hours to determine the recovery percentage.
- Compute the recovery percentage from the dial gauge and the Total Station (see equation 2). This recovery percentage explains the relative elasticity of the beam. This generally refers to how much of the strain is recoverable when the load is removed from the beam.

$$Recovery\_Percentage = (1 - \frac{Deflection\_after\_Unloading}{Total\_Deflection\_after\_24hrs}) \times 100 \qquad (2)$$

4.1 Instruments

I. A Dial gauge-50 mm travel with a decimal reading accuracy of 1/100 of a mm (see Figure 2.a). Figure 2.b shows the setup of three dial gauges for deflection measurement.

II. Reflector-less Total Station, Leica-1202, with a decimal reading accuracy of 1/10 of a mm (see Figure 3). This is a 2" Total Station.

4.2 Test Site

The tested beams are located in the Sport City at Khartoum City (see **Figs 4 and 5**). The length of the clear distance between the beam's support is 8.05 meters (see **Fig.1**).

Fig. 2.a. Dial gauge with 0-50 mm travel

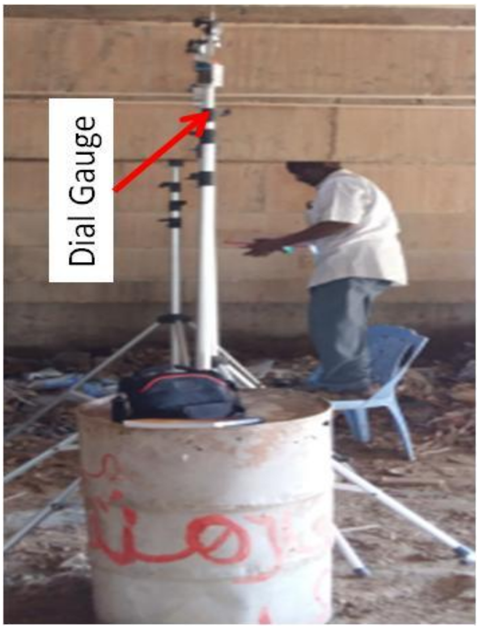

Fig. 2.b. Setup of three dial gauges for deflection measurement

Fig. 3. Leica-1202 RLTS.

Fig. 5. Test beams and the setup of dial gauges

Fig. 4. An image patch for the Sport City

Fig. 6. Cement bags used for loading's test.

5. RESULTS AND DISCUSSION

Three beams were tested in this work (see **Fig. 5**). Cement bags, each of which has a mass of 50 kg, were used for loading test. In particular, a load increment of 0.7 ton was used in six consecutive steps or epochs. Therefore, the total load at the final step is 4,200 kg or 4.2 tons (see Figure 6). The measurement regime starts with a base-line measurement for the midpoint in the three beams and this is without any load; and then continues with incremental loading in six steps. Two sets of additional measurements were taken after 24 hours. The first set was taken with full loading; and the second one without any loading. The information from the second set was used to determine the recovery percentage or the permanent deflection after unloading. All deflection measurements were performed at the midpoint of each beam in which the maximum deflection is expected.

Tables 1, 2, and 3 show the direct measurements from the Total Station and the dial gauges for the three beams. It is noteworthy that the results from the Total Station are expressed in meters and the ones from the dial gauges in millimeters. Table 4 shows the deflection values in millimeters from the dial gauges and the Total Station. These values are tabulated against their loads. **Figs 7, 8, and 9** provide visual display and comparison for the deflection information that was shown in Table 4. **Figs 10, 11, and 12** show graphical display for the deflections measured by the Total Station vs. the ones that were measured by the dial gauge for each beam. These three graphs confirm the

Table 1. Total Station and dial gauge readings for Beam no. 1.

Beam No. 1		Total Station-Leica 1202			Dial Gauge
Load (Ton)	Epoch	X (m)	Y (m)	Z (m)	Z (mm)
0	1_0	7.6598	14.7671	11.9761	3.36
0.7	1_1	7.6602	14.7665	11.9758	3.88
1.4	1_2	7.66	14.7669	11.9747	4.64
2.1	1_3	7.66	14.767	11.9736	5.59
2.8	1_4	7.6609	14.7671	11.9724	6.51
3.5	1_5	7.6604	14.7673	11.9717	7.53
4.2	1_6	7.6607	14.7672	11.9709	8.7
4.2	After 24 hours	7.6608	14.7672	11.9829	10.13
0	unloading _After 24 hours	7.6602	14.7665	11.9768	4.06

Table 2. Total Station and dial gauge readings for Beam no. 2.

Beam No. 2		Total Station-Leica 1202			Dial Gauge
Load (Ton)	Epoch	X (m)	Y (m)	Z (m)	Z (mm)
0	2_0	7.9117	13.966	12.6452	4.6
0.7	2_1	7.9116	13.9668	12.6448	5.56
1.4	2_2	7.9116	13.9665	12.6435	6.52
2.1	2_3	7.9118	13.9666	12.6429	7.55
2.8	2_4	7.9117	13.9669	12.6422	8.38
3.5	2_5	7.9115	13.9666	12.6406	9.69
4.2	2_6	7.9121	13.9671	12.6397	10.83
4.2	After 24 hours	7.9122	13.9671	12.653	12.35
0	unloading _After 24 hours	7.9116	13.9668	12.646	5.38

Table 3. Total Station and dial gauge readings for Beam no. 3.

Beam No. 3		Total Station-Leica 1202			Dial Gauge
Load (Ton)	Epoch	X (m)	Y (m)	Z (m)	Z (mm)
0	3_0	8.0987	13.4435	12.6725	4.74
0.7	3_1	8.0988	13.4441	12.6717	5.71
1.4	3_2	8.0994	13.4434	12.6699	6.63
2.1	3_3	8.0995	13.4437	12.6692	7.62
2.8	3_4	8.0997	13.4433	12.6681	8.62
3.5	3_5	8.0993	13.4433	12.6669	9.77
4.2	3_6	8.0997	13.4435	12.6656	10.92
4.2	After 24 hours	8.0998	13.4435	12.6804	12.59
0	unloading _After 24 hours	8.0988	13.4441	12.6734	5.43

Table 4. Deflections from the dial gauges (*def(DG)*) and Total Station (*def(TS)*).

For All Beams	Beam No.1		Beam No. 2		Beam No. 3	
Load (Ton)	def(DG)-mm	def(TS)-mm	def(DG)-mm	def(TS)-mm	def(DG)-mm	def(TS)-mm
0.7	0.52	0.3	0.96	0.4	0.97	0.8
1.4	1.28	1.4	1.92	1.7	1.89	2.6
2.1	2.23	2.5	2.95	2.3	2.88	3.3
2.8	3.15	3.7	3.78	3	3.88	4.4
3.5	4.17	4.4	5.09	4.6	5.03	5.6
4.2	5.34	5.2	6.23	5.5	6.18	6.9

of the measurements from the Total Station with respect to dial gauges. On the other hand, they show some differences, which are expected. These differences can be quantified and tagged by the room-mean-square-error (*RMSE*), which is an empirical statistical measure for the accuracy. The *RMSE* is computed by two methods. The first method quantify the relative difference between the deflections while the second one quantify the absolute difference between the deflections in the sense of performing direct comparison between the two sets of measurement from the Total Station and the dial gauge. The *RMSE* for the relative differences is computed as a comparison between the difference in deflection between different epochs for the Total Station and their corresponding ones from the dial gauges, for the three beams (1, 2, and 3) are: ± 0.30 mm, ± 0.36 mm, and ± 0.39 mm respectively. As stated, the *RMSE* for the absolute differences is computed as a direct comparison between the Total Station measurements and the dial gauge readings for the three beams (1, 2, and 3). The values of the *RMSE* for the deflections in the three beams are: ±0.29 mm, ±0.600 mm, and ± 0.55 mm respectively. It is very interesting to observe that the relative and the absolute RMSE for beam number (1) are very close to each other; and this is can be seen in their graphs in **Fig. 10**. On the other hand, the *RMSE* for beams number 2 and 3 are a little bit higher than the one for beam number 1. In fact, Figures 11 and 12 suggest that there are some sort of small systematic errors for the measurements in beams number 2 and 3. In other words, the dial gauges at these two beam have systematic errors that need to modeled, will be a subject of a future work. In general and regardless of the comparison method and the minor differences between the Total Station and the dial gauges, these *RMSE* values for the relative and absolute differences are very small since they indicate that the Total Station can provide sub-millimeter accuracy with respect to the dial gauge.

A special attention was paid to characterize and analyze the relationship between the deflections and their corresponding loads from the Total Station and the dial gauges. In fact, this relationship was characterized and analyzed from several angles, namely, graphically, statistically, and functionally. Graphically, **Figs 13 to 18** show the plot of the deflections vs. their corresponding loads. These Figures are equivalent to the classical Figure of the stress-strain diagram. The six Figures show a strong linear relationship between the deflections and the loads and they suggest that they are behaving in the elastic limit of the three beams. It is very interesting to note that the

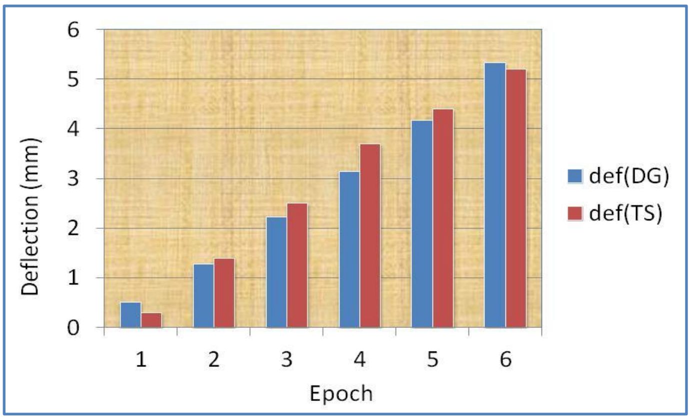

Fig. 7. A visual display for the deflection values for Beam no. 1.

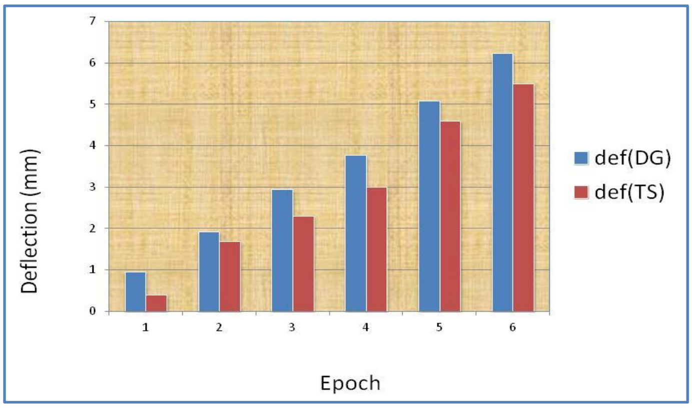

Fig. 8. A visual display for the deflection values for Beam no. 2.

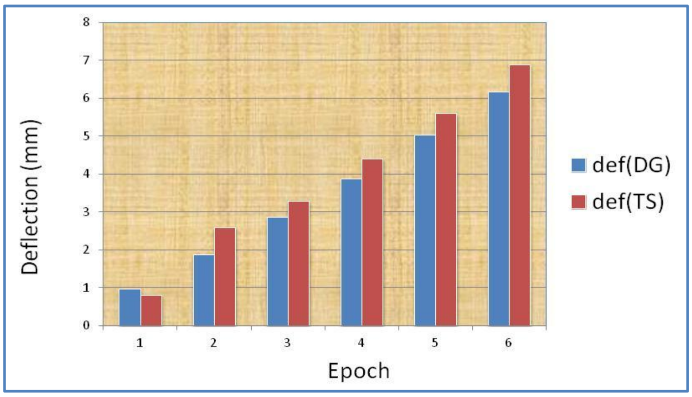

Fig. 9. A visual display for the deflection values for Beam no. 3.

dial gauge **Figs 14, 16, and 18** show more linearity than the ones for the Total Station and this is mainly due to the extra number of digits in the dial gauges.

Statistically, **Table 5** shows the cross-correlation coefficients between the deflections and the loads for the Total Station and the dial gauges. As is well known, the cross-correlation coefficient capture the linear dependency between two data sets, but from a statistical point of view. As shown in Table 5, the cross-correlations for the three beams are more that 0.99 and this is for the Total Station and the dial gauges and the maximum difference between the ones for the dial gauges and the Total Station is less than 0.007. This finding offers a very strong indication for the closeness and the correctness of the Total Station results with respect to the dial gauge results.

Functionally, **Table 6** shows the results of least squares fitting for the deflections and the loads to the equation of the straight-line. The R^2 values for the Total Station and the dial gauges are greater than 0.98, which indicates that the straight-line model accounts for the whole variability between the deflections and the loads. In fact, this is another support for elastic behavior of the three beams and the ability of the Total Station to capture this linear dependency. The intercept or the bias values in Table 6 can be interpreted as the lack of knowledge about the prior information about the load-deflection response. Yes in part they carry some latent information about the systematic errors in the measuring instruments. In Table 6, the slope of each least squares fitted straight-line can be viewed as an estimate of the average rate at which the line was changing during the time span covered by the different epochs [11]. As such, some aspects of the deflection problem is reduced to the estimation of the deflection rate. Moreover, it is very interesting to observe that the slope values from the RLTS and the dial gauges are very close to each other, which suggests that both instruments capture the same underlying process.

Tables 7, 8, and 9 reveal that the recovery percentage from the Total Station and the dial gauge are very close to each other. In fact, they are very identical for beam number 1 and 2 (89%) and they differ by less than 3% for beam number 3 (88% from the Total Station).

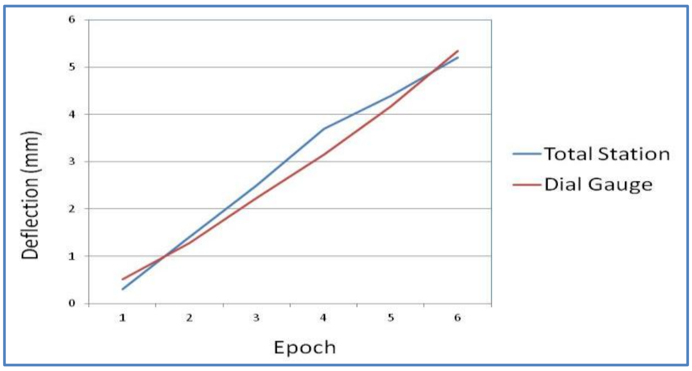

Fig. 10. Deflections from Total Station vs. deflection from dial gauge for Beam no. 1.

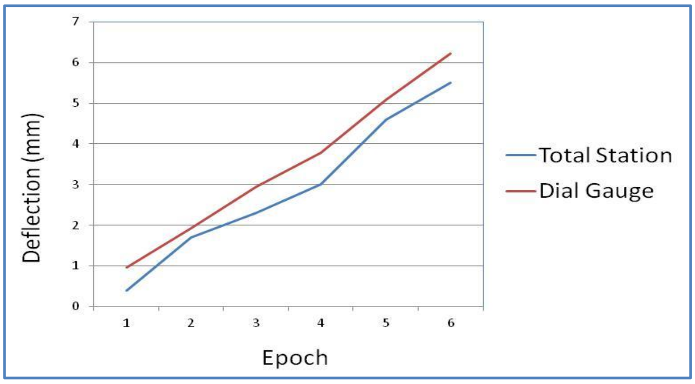

Fig. 11. Deflections from Total Station vs. deflection from dial gauge for Beam no. 2.

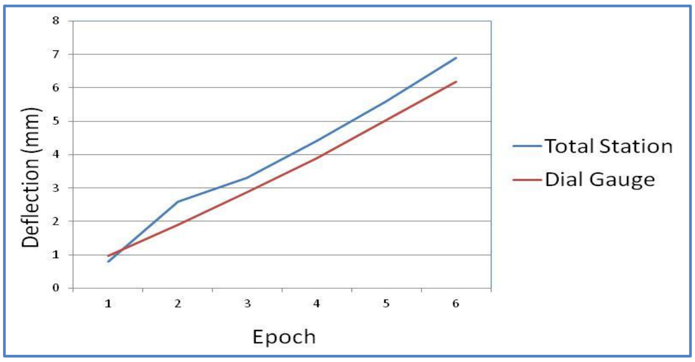

Fig. 12. Deflections from Total Station vs. deflection from dial gauge for Beam no. 3.

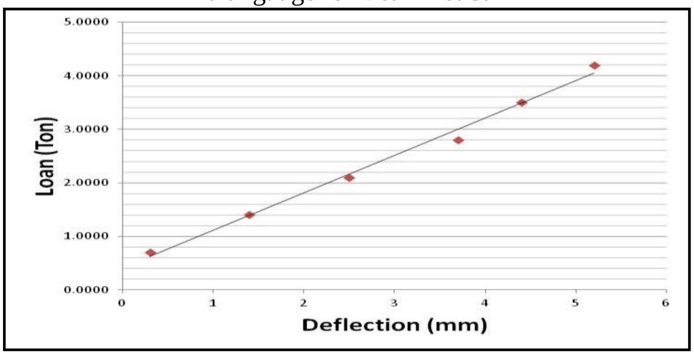

Fig. 13. Relationship between loads and deflection for Beam no. 1 (Total Station).

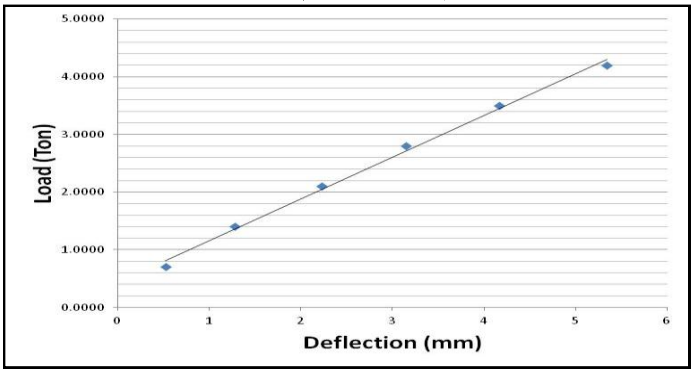

Fig. 14. Relationship between loads and deflection for Beam no. 1 (Dial Gauge).

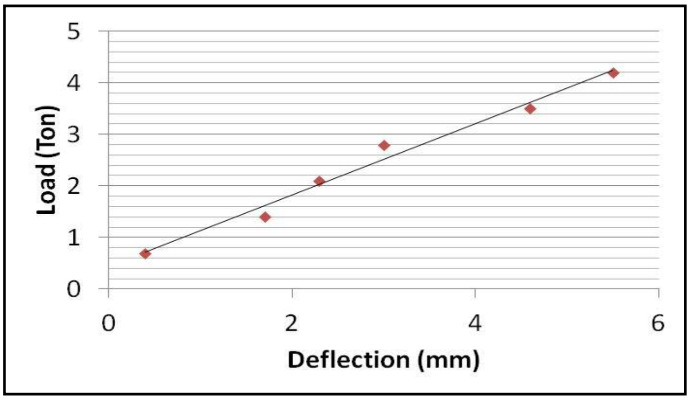

Fig. 15. Relationship between loads and deflection for Beam no. 2 (Total Station).

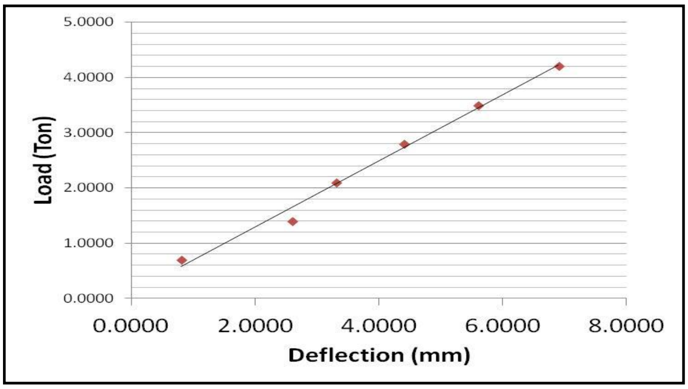

Fig. 17. Relationship between loads and deflection for Beam no. 3 (Total Station).

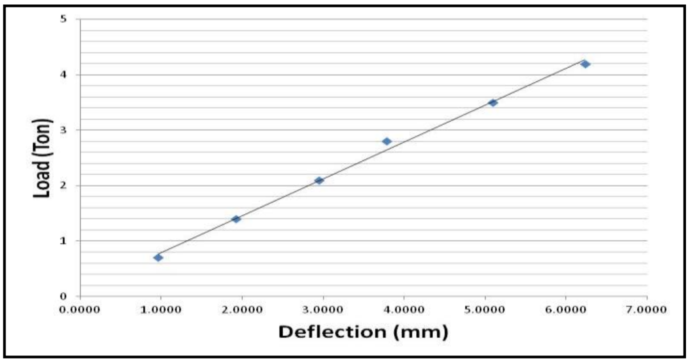

Fig. 16. Relationship between loads and deflection for Beam no. 2 (Dial Gauge).

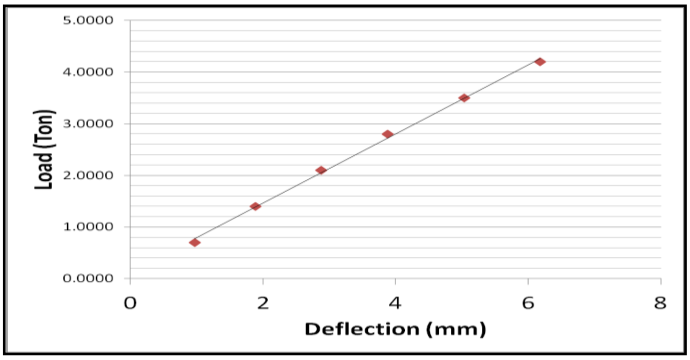

Fig. 18. Relationship between loads and deflection for Beam no. 3 (Dial Gauge).

Table 5. Cross-Correlations coefficients between the loads and the deflections.

Beam No.	Correlation: Total Station	Correlation: Dial Gauge
1	0.9958	0.9979
2	0.9913	0.9980
3	0.9948	0.9990

Table 6. Results of least-squares fitting of the loads and the deflections to straight-line

Beam No.	Total Station			Dial Gauge		
	Slope	Intercept	R^2	Slope	Intercept	R^2
1	0.7001	0.4081	0.9915	0.7242	0.4356	0.9958
2	0.6898	0.4381	0.9826	0.665	0.1301	0.9959
3	0.5972	0.1009	0.9897	0.6704	0.1226	0.9979

Table 7. Computed deflections and recovery percentage for Beam no. 1.

Beam No. 1	Total Station-Leica 1202	Dial Gauge
Total deflection before 24 hours (mm)	5.2	5.34
Total deflection after 24 hours (mm)	6.8	6.77
Deflection after unloading (mm)	0.7	0.7
Recovery percentage (%)	89.7	89.7

Table 8. Computed deflections and recovery percentage for Beam no. 2.

Beam No. 2	Total Station-Leica 1202	Dial Gauge
Total deflection before 24 hours (mm)	5.5	6.3
Total deflection after 24 hours (mm)	7.8	7.75
Deflection after unloading (mm)	0.8	0.78
Recovery percentage (%)	89.7	89.9

Table 9. Computed deflections and recovery percentage for Beam no. 3.

Beam No. 3	Total Station-Leica 1202	Dial Gauge
Total deflection before 24 hours (mm)	6.9	6.18
Total deflection after 24 hours (mm)	7.9	7.85
Deflection after unloading (mm)	0.9	0.69
Recovery percentage (%)	88.6	91.2

6. CONCLUSIONS AND RECOMMENDATIONS

This work reveals that the reflector-less Total Station (Lecia TCR 1202) produces an acceptable accuracy that stands within the limits of its minimum decimal fraction of the metric units; and this result is very comparable to the dial gauge. The root-mean-square-error ***(RMSE***) is used as empirical statistical testing for the accuracy. *RMSE* is computed from a comparison between the difference in deflection values (here: Z values) for different epochs for the Total Station and their corresponding ones in the dial gauges. The deflection accuracy for the three different beams are: ± 0.30 mm, ± 0.36 mm, and ± 0.39 mm respectively. The *RMSE* is also computed as a direct comparison between the Total Station measurements and the dial gauge readings for the three beams (1, 2, & 3). The values of the *RMSE* for the three beams are: ±0.29 mm, ±0.600 mm, and ± 0.55 mm respectively. The RMSE for the second and the third beams are a little bit higher than the first beam, which suggest that there is some sort of systematic errors in the dial gauges that were used for the measurement under those two beams. Regardless of the comparison method, this finding is very important sine it indicates that the Total Station can provide sub-millimeter accuracy with respect to the dial gauge. This finding indicates that the Total Station can provides sub-millimeter accuracy with respect to the dial gauge. In particular, this finding ensures that the systematic and random errors propagated in the measurements are less than the smallest deflection that is being detected or expected.

Several tests were carried out to confirm the linearity of the deflections against the loads. These tests are very important since they convey the information about the elastic behavior of the tested beams. In this regards, both measuring techniques produce correlation factors and R^2 values for the loads vs. the deflections of more than 0.98.

Both measurement techniques, produce recovery percentages that are greater than 88%. The overall findings of this experiment indicates that this reflector-less Total Station can be used for on-site measurement of deflection and for a wide range of applications in which the deflection measurement is part of their diagnosing aspects.

Although the deflection in the current work is confined to the vertical distances, the measured coordinates from the Total Station can be used to obtain the displacement of the shear in the other two directions (X, Y). The finding of this work will support the use of surveying techniques and instruments in other applications that require deflection/deformation measurement such as bridges, high rise buildings, large satellite dishes, shell of oil tanks, and all other types of engineering structures. The main attractiveness of reflector-less Total Station for deformation/deflection measurement stems from its portability, ease of use, accuracy, contactless data acquisition, and its ability to do the measurement, virtually, for a wide class of engineering structures.

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REFERENCES

[1] Correa, T. K., 2005. GPS: A New Tool for Structural Displacement Measurements. APT Bulletin: Journal of Preservation Technology. Vol. 36. No. 1. pp. 13-18.

[2] Dowling, N. E., 2007. Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue, 3rd Edition. Pearson-Prentice Hall. 912 p.

[3] Ogaja, C., Rizos, C., and Wang, J., 2003. Toward The Implementation of On-Line Structural Monitoring Using RTK-GPS and Analysis of Results Using The Wavelet Transform. The 10th FIG International Symposium On Deformation Measurements, California, USA. pp. 284-293.

[4] Psimoulis, P. A. and Stiros, S. C., 2013. Measuring Deflections of a Short-Span Railway Bridge Using

Robotic Total Station. Journal of Bridge Engineering. Vol. 18. pp. 182-185.

[5] Chekole, S. D., 2014. Surveying with GPS, Total Station, and Terrestrial Laser Scanner: A Comparative Study. Published Master of Science In Geodesy. Royal Institute of Technology, Stockholm, Sweden. 55 p.

[6] Chrzanowski, A. S., Chrzanowski, A., Deng, N., and Bazanowski, M., 2008. Design and Analysis of Multi-Sensor Deformation Detection Systems. 13th FIG Symposium On Deformation Measurement and Analysis, LNEC, Lisbon. 10 p.

[7] Caspary, W. F., 1987. Concepts of Networks and Deformation Analysis. School of Surveying, The University of New South Wakes, Kensington, N.S.W., Australia. 183 p.

[8] Kuang, S., 1996. Geodetic Network Analysis and Optimal Design: Concepts and Applications. SAMS Publications. 368 p.

[9] Chrzanowski, A., Chen, Y. Q., and Secord, J. M., 1983. On The Strain Analysis of Tectonic Movements Using Crossing Geodetic Surveys. Tectonophysics. Vol. 97. pp. 297-315.

[10] Patnaik S. and Hopkins D., 2004. Strength of Materials: A New Unified Theory for 21st Century. Elsevier. 750 p.

[11] Prescott, W. H., 1981. The Determination of Displacement Fields for Geodetic Data Along A Strike-Slip Fault. Journal of Geophysical Research. Vol. 86. pp. 6067-72.

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