Experimental Bending Analysis of Strip Sandwich and Laminated Composite Plates

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Abstract: Simple theories have been developed so far for prediction of bending strains of the sandwich structures, under specific loading and support conditions. Although the theoretical predictions are often accurate enough, the role of experimentally validating of results of the theories on progress of the plate/beam theories cannot be ignored. The main goal of the present paper is presenting a test procedure for minimization of error of the data acquisition process and the relevant analyses. In this regard, effects of the specimen thickness, location of the strain gauge installation, and type of the strain gauge are investigated. Identification of the mechanical properties of the test specimens is another goal of the present study. Classic theories are used to validate the tests results and vice versa. Based on the large number of tests conducted on the samples, the results show that the major source of discrepancy between the experimental and theoretical results may be incorrect installation of the strain gauge. A method to check this issue, is comparing results of the loading and unloading conditions. Using a circuit with three wires omits the error of wire resistance. The test results of the composite specimens, obtained by strain gauges of TML Company, showed small differences with the results obtained by strain gauges of BLH Company. The discrepancies between the experimental and theoretical results of the sandwich specimens increased by increasing the core thickness, while the measurements obtained from the strain gauges were not reliable in compression. An important result was the fact that a half-bridge installation of the strain gauge decreases the error remarkably.

Keywords: Bending, Metal/Composite/Sandwich Strip Plates, Strain gauge

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1 INTRODUCTION

Majority of the manufacturing industries utilize some types of composite materials that are compositions of two or more substances with overall high strength-to-weight characteristics. On the other hand, according to ASTM standard, the sandwich structure may be defined as: “A structural sandwich is a special form of composite comprising of a combination of different materials that are bonded to each other so as to utilize the properties of each separate component to the structural advantage of the whole assembly”. In other words, a composite sandwich structure usually comprises thin face-sheet skins bonded around a lightweight core. They exhibit excellent bending performance, where the face-sheet skins withstand the compressive and tensile forces and the core takes the shear loading through the thickness.

This configuration presents an efficient cross-sectional moment of inertia and results in higher bending stiffness and strength per mass. Though composite sandwich structures may lead to a larger structure, less reinforcement is needed to maintain the rigid surfaces which in turn, leads to lower number of parts, fewer connections, and a more efficient structure. The general concept of the sandwich structures has been investigated and developed by many researchers over the past 50 years [1-3].

There are simple theories for prediction of the deflections of the sandwich structures under bending loads and specific support conditions [4-5]. Although theoretical predictions are highly effective, the role of the experiments in validation and progress of the theories cannot be ignored. As an example, Suresh Babu et al., performed a series of about 36 experiments in order to investigate and verify their analytical predictions of the mechanical responses, and observe the failure characteristics of the pin-loaded composites [6]. As a result, it can be seen that many tests have been accomplished to achieve this goal. In some papers, the authors developed methods for identification of the mechanical properties of the composite and sandwich structures [7-11].

Gupta et al., [12] studied responses of the syntactic foam core sandwich structured composites in three-point bending. The use of syntactic foam cores in sandwich composites was a relatively new application. These kinds of cores provide a smoother surface than the other available types of cores. They have a closed cell structure and are fabricated by mechanical mixing of hollow particles with matrix resin. Tagarielli et al., studied collapse of clamped and simply supported composite sandwich beams in three-point bending [13]. The composite sandwich beams consisted of glass-vinylester face sheets and a PVC foam core. These composites were tested by a three-point bending test under a quasi-static load and under simply supported and clamped boundary conditions. The experimental results were compared with finite the element predictions. Arbaoui et al., analyzed the influence of a multi-layer core using a three-point bending test and explored sandwich composites with glass/polyester skins and polypropylene honeycomb cores [14]. This experimental study showed that the multilayer structure was more rigid, however, a small increase in the final weight led to significant increase in the mechanical properties.

Chuda-Kowalska et al., considered panels with polyurethane foam cores and thin metal facings [15]. They proposed a new method, which was based on a bending test accompanied with measurement of the total rotation of the cross section and the slope of the deflection curve. They carried out numerous experiments and performed FEM analyses too. Flores-Johnson and Li presented experimental studies on the quasi-static indentation of a rigid indenter into sandwich panels with carbon fibre-reinforced polymer faces and polymeric foam cores [16]. They found that both nose shape and foam core density have large influences on the indentation response of the sandwich panels in terms of the absorbed energy, indentation at failure, and damage area. A dependency of the indentation load on the supporting condition was also observed. They also found that the difference in the indentation resistance between the sandwich panel and its core material depends on the core density.

The purpose of the study performed by Herranen et al., was to design light-weight sandwich panels for trailers [17]. The different types of sandwich composite panels were tested in 4-point bending conditions according to ASTM C393/C393M and virtual testing was performed by use of ANSYS software to simplify the core material selection process and to design the layers. Data of the FEA was obtained from the tensile tests of glass fiber plastic (GFRP) laminates. 3D FEA was conducted to virtually test the selected sandwich structure in service conditions. Vamja et al., selected an aluminium composite sandwich material (aluminium skin, polyethylene core, resin binder material) [18]. Tensile and bending strengths were determined using Universal Testing Machine (UTM) to optimize mass of the sandwich composite material. Using sandwich panels may lead to optimized masses and costs for various automobile, marine, aerospace and other common structures.

The objectives of the present paper can be listed as follows:

1- Identification of the mechanical properties of strip plates under bending: A mechanical characterization is carried out on aluminium/composite/sandwich panels.

2- Proposing a test procedure for error minimization of the data acquisition and analysis. In this regard, effects of the thickness, place of strain gauge installation, strain gauge type, etc. are also investigated.
3- Validation of experimental results with the classical theories.

2 THE EXPERIMENTAL PROCEDURE

2.1. Specimen materials

Three kinds of specimens are used in the present research. The calibration aluminium specimen was made of 7075T6 aluminium. The mass density (ρ), tensile yield strength (σ_{xt}), modulus of elasticity (E), and Poisson's ratio of this material are: 2810 kg/m^3, 503 MPa, 71.7 GPa, and 0.33, respectively. Mechanical properties of the composite specimen are presented in Table 1. The core material of the sandwich strip plate was made of two different materials, Airex C70.90 foam and Balsa wood. The mechanical properties of these two materials can be found in Table 2.

Table 1 Mechanical properties of the composite specimen

Property	Value
Modulus of Elasticity, E_x , E_y (GPa)	15.1
Shear Modulus of Elasticity, G_{xy} (GPa)	4.5
Tensile Strength, σ_{xt} , σ_{yt} (MPa)	227
Compressive Strength, σ_{xc} , σ_{yc} (MPa)	150
Shear Strength, τ_{xy} (MPa)	80
Poisson's Ratio	0.1

2.2. Preparation of test specimens

Aluminium specimen, which was used for calibration test, was prepared by cutting a piece of 300 mm length and 49.78 mm width from a blank of 4.03 mm thickness. For composite material specimens, a composite plate of 7.2 mm thickness was fabricated. It was composed of 30 (0, 90) glass textile layers with 200 gr/m^2 density. The weight fraction of the textile to resin used in constructing the composite was 50%. The desired specimen was a rectangular piece of 300 mm length and 45.60 mm width cut from the mentioned composite sheet. The sandwich strips were made up of two materials: Airex foam and Balsa wood as core materials, and a composite material for face sheets. Face sheets were made of the same textile and resin composition, but with a whole thickness of 1 mm. 5 and 10 mm thicknesses were used for the Airex foam cores and only a 8 mm thickness was used for the Balsa wood.

2.3. Test equipment

To perform the calibration tests of the strain gauges, the following equipment was used:

1- Simple unidirectional strain gauges for installation on the strip plates (for aluminium strip plate: model CEA-13-062UW-350 of Vishay company; for composite and sandwich strip plate: series SR4 of model FAP-25-35-S6 of BLH Company and model ULFA-5-11 of TML Company were used),
2- Homogeneous flat aluminium strip plate of uniform cross-section ($50\,\text{mm} \times 4\,\text{mm}$),
3- Cleaner and glove materials for cleaning the installation location of the strain gage and pasting it onto the strip plate surface,
4- Weights of specified masses in order to apply specific loads on free end of the strip plate,
5- Data logger (Vishay P3500 Strain Indicator),
6- Measurement gauges for measuring the transverse displacement of free end of the strip.

Strain gauge resistance changes were measured using Wheatstone bridge of the data logger. In this experiment, the Vishay P3500 Strain Indicator was used to measure the strain.

Table 2 Mechanical properties of the composite specimen

Property	Value	
	PVC-AIREX	Probalsa
Mass Density (kg/m^3)	100	90
Modulus of Elasticity, E_z (MPa)	84	1850
Shear Modulus of Elasticity, G_{xy} (MPa)	38	96
Tensile Strength, σ_{xt} (MPa)	2.7	7
Compressive Strength, σ_{xc} (MPa)	1.9	5.4
Shear Strength, τ_{xy} (MPa)	1.6	1.6
Poisson's Ratio	0.1	0.1

2.4. Calibration

For accurate measurement of the strains through the strain gauge, the output voltage of Wheatstone bridge is measured for known deformations and based on this data, the strain values associated with other deformations are determined. By measuring the output voltage of the strain gauge, certain relationships can be obtained to determine the maximum forces that can be exerted on the strain gauge.

Usually the gauge factor is given on the package of the strain gauges. However, after installing the strain gauge and by considering the connections, terminals, and wiring resistance, this coefficient has to be modified. In

fact, this factor should be considered in a modified form to ensure that the whole resistance of the wires does not affect the measurement results [19]. This can be done automatically, using the system shunt calibration or the CAL button on the Strain Indicator.
In the P3500 data logger, an internal resistor is intended for the shunt calibration. This resistor and the internal 120 and 350 Ohms resistors are in parallel. Calibration resistors simulate a strain applied to the device by a gauge factor of 2.000. If the resistances of the wires are negligible, the number on the display of the Strain Indicator appears as follows:

$$5000\mu\varepsilon \times \frac{2.000}{GF\ Setting} \pm 0.05\%$$

Where, $GF\ Setting$ is a number that has been set in the device for the gage factor [19]. In the case of using a quarter-bridge circuit, the CAL button as well as adjustment of the gage factor can be used to remove the wires resistance. The method is as follows:

i) Press the CAL button.

ii) Calculate the calibration number according to the following equation:

$$\frac{2.000}{PKG\ Gage\ Factor} \times 5000\mu\varepsilon = Calibration\ Number$$

where $PKG\ Gage\ Factor$ is the gage factor that is written on the strain gage package.

iii) Verify the gage factor tuning button, so that the above-mentioned calibration number is shown.

iv) Lock the gauge factor tuning button in its right condition.

Using this feature of the P3500 device, one can modify the gage factor of the strain gauge in order to remove the connecting wires resistance.

2.5. Mechanical testing of the composite/sandwich strip plates

Mechanical properties of the composite material specimens were obtained by performing standard tests according to ASTM standards. Standard specimens were prepared based on the ASTM manual and tensile, shear, and bending tests were accomplished according to D3039, D7078, and D7264 ASTM standards, respectively. The test results are presented in Table 1. Mechanical properties of the sandwich strip plates were determined by the simple theory of multi-material bending members. The properties of the two cores, i.e., the Airex foam and Balsa wood, are given in Table 2.

3 THEORY AND TEST PROCEDURE

3.1. Test theory

The tests were designed assuming homogeneity of the strip plate, small deformation, and a linear stress-strain relationship. In addition to the design validation of the test, the accuracy of the theoretical modelling was also examined. Figure 1 shows a schematic of a cantilever strip test. Lateral deflection of the free end of the strip plate (where the force P is applied) is calculated based on the following equation:

$$y = \frac{PL^3}{3EI} \tag{1}$$

According to the relation between stress and strain, the following equation exists:

$$\sigma = E\,\varepsilon \tag{2}$$

The bending stress may be determined as:

$$\sigma = \frac{Mc}{I} \tag{3}$$

Therefore, it may be concluded that:

$$\varepsilon = \frac{Mc}{EI} \tag{4}$$

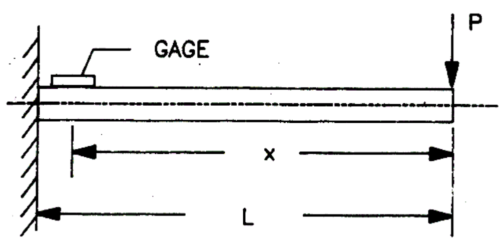


Fig. 1 A schematic of the cantilever strip and location of the employed strain gauge

The moment of the sections may be derived according to the following equation:

$$M = Px \tag{5}$$

where, x is the distance between the load P and location of the strain gauge. There are also two additional relations as follows:

$$c = \frac{t}{2}, \quad I = \frac{bt^3}{12} \tag{6}$$

where, t and b are thickness and width of the strip plate, respectively. As a result, Eq. (4) may be rewritten as follows:

$$\varepsilon = \frac{6Px}{Ebt^2} \quad (7)$$

If the maximum lateral deflection of the strip plate (which occurs at the free end) is measured; it can be used in calculation of the strain at any arbitrary section, through the following equation:

$$\varepsilon = \frac{3tx}{2L^3} y_{max} \quad (8)$$

In this test, the experimental results of the strain gauge can be calibrated by measuring the amount of strain and comparing it with the theoretical results.

3.2. Bending test of the metal/composite/sandwich strip plates

The strip plate, strain gauge, and Wheatstone bridge are schematically shown in Fig. 2, both before and after applying the load. After installing the strain gauge, the strip plate is secured by a clamp in the form of a cantilever (Figure 3(a)). Vertical forces are applied to the strip plate using weights with known masses (Figure 3(b)). For calibration of the strain gauge, a strip plate with known geometric specifications is used. Two unidirectional strain gauges are mounted on the strip plate.

The strip plates are then fixed and vertical loads are applied to the free end, as shown in Figure 4. After installing the strain gauges on the strip plate, their bases are connected to a terminal which is connected to the data logger by special wires. The resistance of these wires affect the accuracy of the measurements. As a result, the material and length of the wires used in the calculations should be quite similar in order to consider their resistances in the calculations.

4 RESULTS AND DISCUSSIONS

Results of the present study are derived through three stages. First, calibration tests were done on an aluminium strip plate. Then, several tests were performed on a composite strip plate, and finally some other tests conducted on a sandwich strip plate.

4.1. The aluminium strip plate

This test was accomplished in accordance with the mentioned procedure, for calibration of the strain gauge. In this regard, 11 tests were conducted on an aluminium strip plate. Since two strain gauges were installed at different locations, and that the device was a single-channel one, only one strain gauge was connected to the device in every test. For better distinction, each test was denoted by an identification code. The tests with AB code were related to the aluminium strip plate tests. The next number in the code denotes the number of experiment and the suffix S1 and S2 indicates the strain gauge for which the data are measured.

Two strain gauges were mounted on the aluminium strip plate according to the dimensions shown in Figure 2. Hanging weights on the free end, a vertical load was applied on the strip plate (Figure 5). The authors tried to accurately measure the strains using the strain gauges and reduce the test errors by repeating the tests and removing sources of error. The purpose of the first AB-1-S1 test was to apply specified loads to a strip plate with known conditions and comparing the theoretically predicted strains with the strains measured by the strain gauge. The measured data were compared with the theoretical results and the discrepancies were from 52.3 to 54.5 percent. This discrepancy was greater for higher loads. More tests were done to determine the sources of the error.

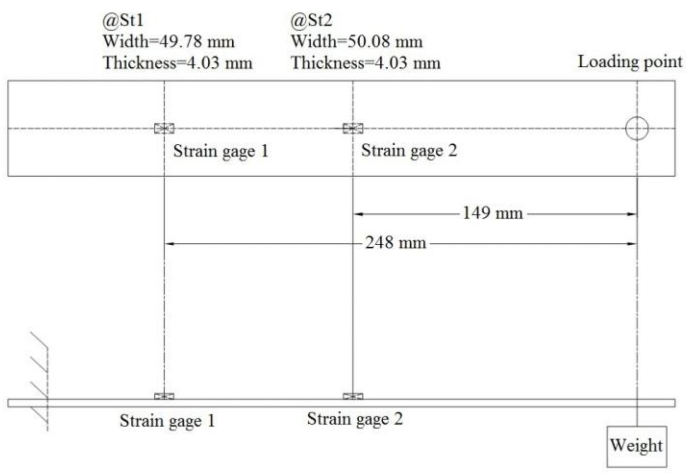
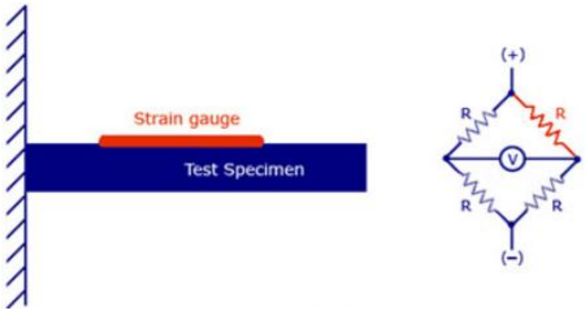
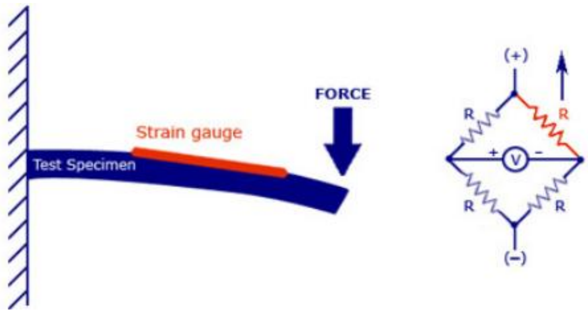


Fig. 2 Schematic of the strip plate and the installed strain gauges



(a)



(b)

Fig. 3 Schematic of the strip plate, strain gauge and Wheatstone bridge, (a) before and (b) after loading

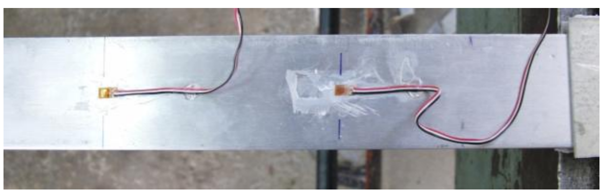


Fig. 4 The real strip plate and the installed strain gauges.

Fig. 5 Test setup of the aluminum strip, installed strain gauges, and loading of the strip plate

It seemed that a probable source of error was the short distance between the strain gauge and the clamp. To check this suggestion, the previous test was repeated by increasing the distance between the clamp and the strain gauge, i.e. by using the S1 strain gauge (test AB-2-S1). Thus, the initial distance between the strain gauge and the clamp was increased from 151 mm to 199 mm. The discrepancies range from 52.3 to 54.6% with respect to theoretical results. As can be seen, changing the distance of strain gauge from the clamp did not change the error. As a result, the significant difference between the experimental and theoretical results was not related to the distance between the strain gauge and the clamp. However, this suggestion strengthened the idea that the experimental error was due to the strain gauge malfunction.
AB-3-S1 Test was set with the same test procedure for assessing the accuracy of the strain gauge S1. In this experiment, shunt calibration of the device was used and results of both the loading and unloading were measured. There was a significant difference between the theoretical and experimental results in both the loading and unloading conditions. This issue increased the possibility that the strain gauge did not work properly. On the other hand, it was observed that the results of the unloading differed from those of the loading, which were another indication for improperly installing the strain gauge. For this reason, the AB-4-S2 test was organized on the same strip plate using the same method, but with a different strain gauge (S2). Shunt calibration of the device was used again. Table 3 shows that the results of this experiment are in a good harmony with the theoretical results, where the error is about 3.9 to 6.9 percent. According to results of similar tests conducted on the S1 and S2 strain gauges, the authors were assured about the proper installation and performance of the strain gauge S1.

Table 3 Strain measurements from the AB-4-S2 test

Mass (gr)	Theoretical strain (με)	Experimental strain (με)	Error percentage (%)
200	30.08	28	6.9
700	105.3	100	5.0
1124	169.0	162	4.2
1324	199.1	191	4.1
1824	274.3	263	4.1
2317	348.5	335	3.9

In the AB-5-S2 test, the authors tried to evaluate the permanent error due to the unloading. According to the data extracted from the experiment, the error of the measured data for the strain gauge was much smaller, which might be due to its correct installation. By removing the load, the strain gauge indicated a zero value, confirming that the loading and unloading did not cause a permanent error in the experiment. Three tests, entitled AB-6-S2 to AB-8-S2, were performed using the S2 strain gauge, but presented errors in the results. That's why the authors avoided to report them. However, the tests were repeated by a correct technique and the results are declared. In the previous experiments the shunt calibration circuit of the device was used. Internal calibration helps to remove the unwanted factors that affect the resistance of the strain gauges.

However, in the conducted experiments, two main sources of error, i.e., the thermal effect and resistance of the wires, are negligible. Usually for temperatures in the range of $\pm 50^{\circ}C$, temperature effect is insignificant. Therefore the room temperature has little effects on the results. On the other hand, using a quarter bridge circuit and a three-wire connection, eliminates the error caused by the wire resistance. As a result, two tests were designed: one without the shunt calibration but using the gauge factor of the strain gauge mentioned on the package (PKG GF) and another, using the coefficients obtained from shunt calibration (EQV GF). The obtained results are compared with the analytical ones.

In this experiment, the strain was measured after loading and unloading in two separate stages In the experiment, a strip plate was used with the GF mentioned on the strain gauge package, which is called as PKG GF. Then this experiment was repeated with the calibration value calculated by the equivalent calibration equation (EQV GF), which is mentioned in the device and is:

$$\frac{2.000}{PKG\ Gage\ Factor} \times 5000\mu\varepsilon = Shaunt\ Calibration\ Number \quad (9)$$

According to Eq. (9), EQV GF would be:

$$EQV\ GF = \frac{2.000}{2.135} \times 5000\mu\varepsilon = 4683\mu\varepsilon \quad (10)$$

In Figure 6, results of the loading and unloading of four experiments with the S2 strain gauge are shown. Results of the loading and unloading cases are almost coincident. As seen in this figure, any change in GF does not lead to significant change in the results of the strain gauge. According to these results, it can be concluded that by using the GF denoted on the strain gauge package, smaller error occurs. Furthermore, considering that the wires are short (about 1 m) and a quarter-bridge strain gauge circuit is used with three wires, the resistance of the wires would be virtually negligible. On the other hand, there is no significant change in the test temperature and as a result, the changes in the temperature, do not lead to errors. Therefore, there is no need to use the equivalent calibration equation for GF.

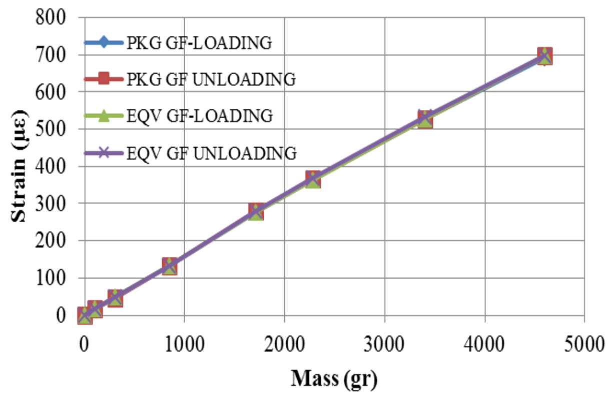


Fig. 6 Results of the loading and unloading cases of four experiments with the S2 strain gauge

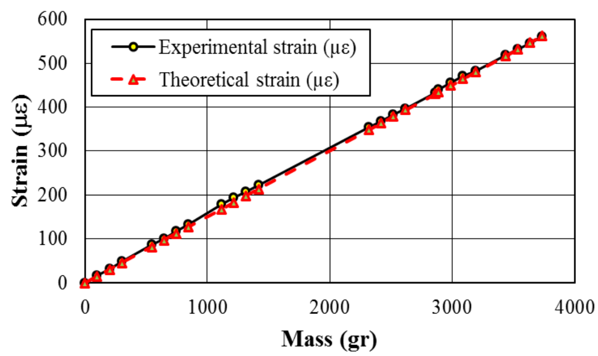


Fig. 7 A comparison between results of the AB-10-S2 test

The aim of the AB-10-S2 test was determination of the strain gauge sensitivity, using a strain gauge GF, which is specified on the package. To accomplish this goal, several loads were applied to the strip plate and the corresponding strains were recorded. In the previous tests, it was shown that accuracy of the strain gauge didn't change in the loading and unloading cases. As seen in Figure 7, a good agreement exists between the measured and the theoretical results and a linear trend of the strain may be observed in the strip plate.

In the previous AB-10-S2 test, acceptable results were obtained without using the shunt calibration circuit. However, the question is how does the shunt calibration increase the precision? By further inspecting performance of the P3500 device, it was concluded that the bridge must be balanced before the shunt calibration. According to this hint, the cause of the differences in test results of AB-9-S2 obtained with and without shunt calibration became clear. For this purpose, this test was repeated in a modified form as AB-11-S2. Since failure of the S1 strain gauge was noticed in previous tests, this test was only performed on S2 strain gauge. This calibration test was done using a PKG GF as well as EQV GF.

As mentioned earlier, in this test, the bridge was balanced before using the shunt calibration circuit. The experimental and theoretical results of the AB-11-S2 test using two values of GF are compared in Figure 8. Good agreement between the measured values of the two methods is observed. According to the test conditions and error reduction techniques (such as using a three-wire connection for the quarter-bridge), such a conclusion is justified. These results also show a good agreement with the theoretical values. However, the values obtained from the two methods differ slightly, but it can be concluded that this difference has a negligible effect on the measured results. Generally, a good reliability has been noticed for the results obtained by the both methods.

4.2. The composite strip plate

In this section, several tests were conducted on a composite strip plate based on the hints mentioned in the previous section. The dimensions of the strip plate and location of the strain gauge are depicted in Fig. 9. The experimental setup of the strip plate and the strain gauge are shown in Fig. 10.

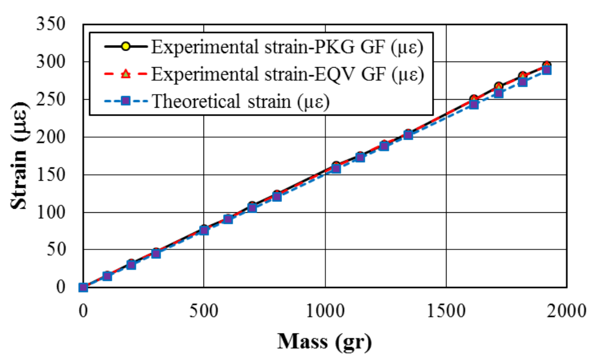


Fig. 8 A comparison between results of the AB-11-S2 test, using two values of GF

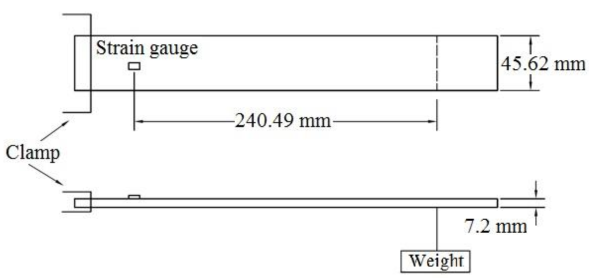


Fig. 9 The schematic of the composite strip and location of the installed strain gauge.

The purpose of the CB-1 test was to test a cantilever composite strip plate and compare the experimental and the theoretical strains. While shunt calibration was used in this test, the measured data are compared with theoretical results in Figure 11. As can be seen, the error increases with the applied load. In the second try, the CB-2 experiment was designed to study the effects of loading and unloading on the measurement error of the cantilever composite strip plate. In Figure 12, experimental strains, measured in the loading and unloading, are compared with the theoretical values. As can be seen in this figure, there is a good agreement between the experimental and theoretical results.

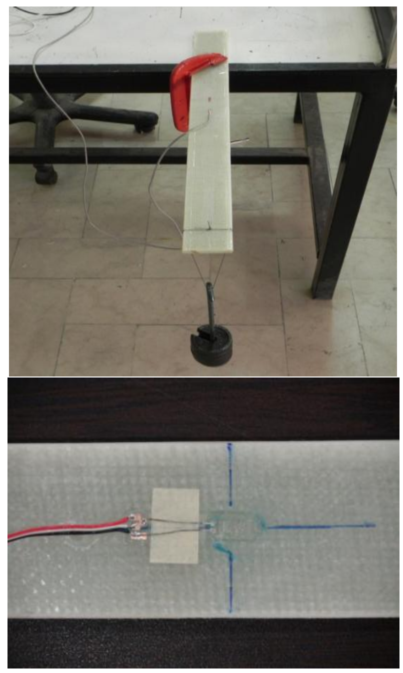


Fig. 10 The experimental setup of the composite strip plate and the strain gauge

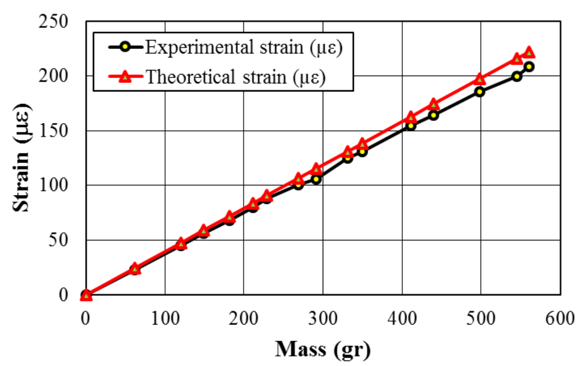


Fig. 11 A comparison between the measured data and the theoretical results

The error in the loading phase is almost constant and about 6%, however the error in the unloading is greater than that of the loading state. The strain in loading is greater than the theoretical one; while the strain value in unloading is smaller than the theoretical one and this indicates that some strains remain in the strip plate. By removing all the loads of the strip plate, the remaining strain was 7 με. In the former CB-1&2 tests, loading and unloading were performed in a constant trend. Thus, at first, loading was continued to its maximum value and then the unloading occurred.

In the operational conditions, loading is applied in a fluctuating manner between the minimum and maximum values. This kind of loading happens even in static cases. Due to this point, the CB-3 test was performed with random loads. Results of this experiment along with the theoretical results are shown in Fig. 13. The measurement errors are different for different loads, but the average is about 5%.

After complete removal of the loads, the remaining strain was 5 με. The linear behavior of the composite is apparent in this figure. However, this line has a slope which is different from the experimental one. This could be due to the deviation of the modulus of elasticity from the real value. Former, three tests were conducted by strain gauges of BLH Company. CB-4 test was performed by strain gauges of TML Company in order to investigate their accuracy. However, the results revealed small differences with the former tests (Fig. 14).

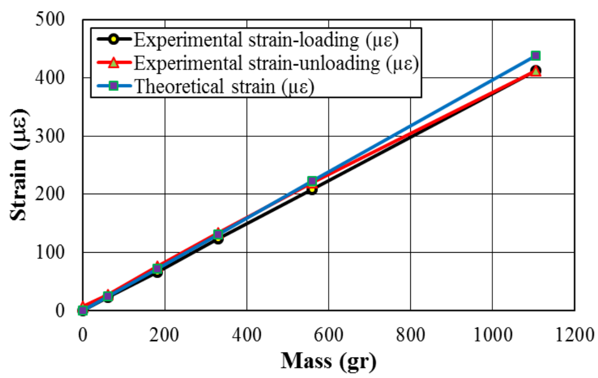


Fig. 12 A comparison between the measured and theoretical results, in the loading and unloading states.

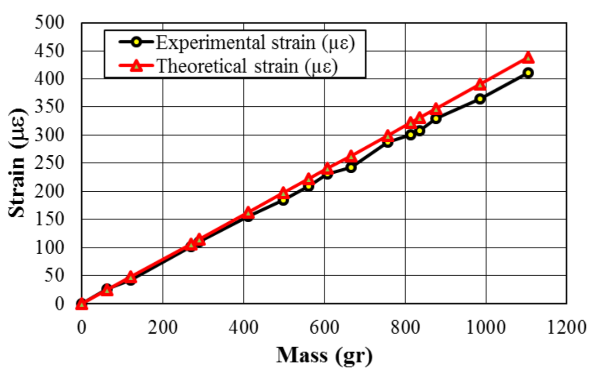


Fig. 13 Results of the CB-3 test along with the theoretical results in a fluctuating loading.

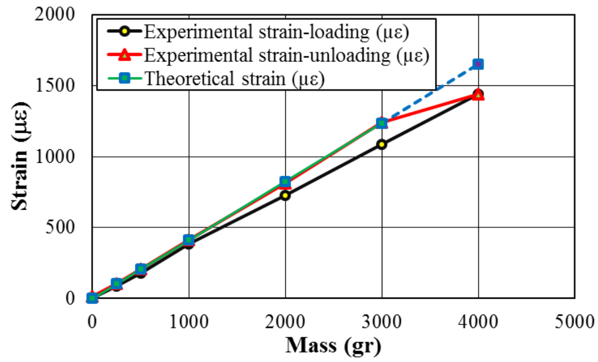


Fig. 14 A comparison between the measured and theoretical results of the CB-4 test, in the loading and unloading states.

4.3. The sandwich strip plate

In the present section, results of six tests conducted on a sandwich strip plate, using the procedures mentioned in the foregoing sections, are reported. The aim of these tests is to study the capability of the tests to measure the correct amount of the strain in a sandwich strip plate specimen. The dimensions of the strip plate and location of the installed strain gauge are depicted in Fig. 15.

In the first SB-1 test, the purpose was to test a sandwich cantilever strip plate with Airex foam core and comparing the theoretical strains with the experimental ones. Thickness of the core was 5 mm and the strain gauge used to measure the strains was made by TML Company. Shunt calibration was used in this test, where the measured data are compared with theoretical results in Table 4. According to results of this table, the maximum error is -4%, which is reasonable.

Table 4 Strain measurements from the SB-1 test

Mass (gr)	Theoretical strain (με)	Experimental strain (με)	Error percentage (%)
250	186.0	189	-2
500	372.0	381	-2
1000	744.0	769	-3
2000	1488.1	1548	-4
2500	1860.1	1930	-4

In order to investigate effects of the core thickness on the measured data, an Airex foam core of 10 mm thickness was employed and strain gauges of TML company were used to measure the strains, in both the of loading and unloading states. Results of the SB-2 test presented in Table 5, indicate an increase in the discrepancies between theoretical and experimental strains. This means that an increase in the thickness of core has an adverse effects on the results.

In the third try, the SB-3 experiment was performed with a different core material, i.e., Probalsa wood. The core thickness was 8 mm and the strain gauge used to measure the strains was made by TML Company. According to the results shown in Table 6, the mean error has been reduced, but the maximum error is yet 11%. The SB-3 test was repeated, but with a different strain gauge, which was made by BLH Company. Results of the SB-4 test, presented in Table 7, shows a reduction in the error percentage.

The former test was repeated, but with a different state of strain gauge. The only difference was that fact that the strain gauge of the SB-5 test, was under compression. The relevant results are shown in Table 8. As may be seen, the error is not allowable. Results of this test show that the measurements obtained by strain gauge in compression are not reliable and the error has decreased by increasing the load. The last SB-6 test, is very important, because of the obtained results. In this test, unlike all other tests, half bridge of the strain gauge indicator was used in the installation of strain gauge. Probalsa wood core of 8 mm thickness and the strain gauge of BLH Company were used in the SB-6 test. According to the results presented in Table 9, the error percentage is too small. As a result, half bridge installation decreases the error so much.

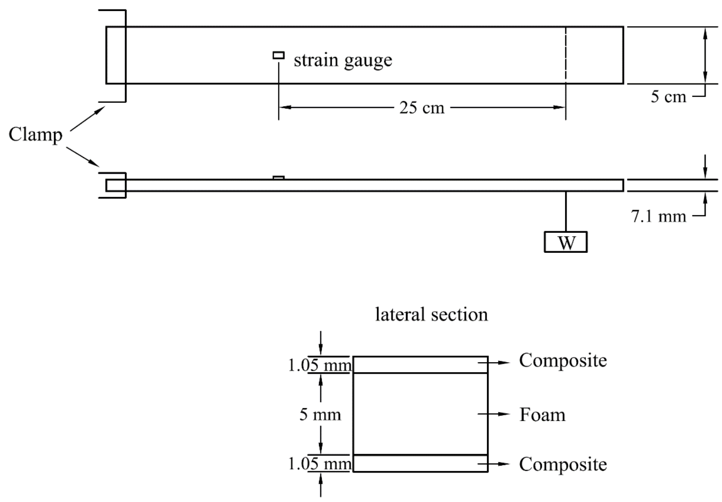


Fig. 15 Schematic of the sandwich strip plate and location of the installed strain gauge.

Table 5 Strain measurements from the SB-2 test

Mass (gr)	Theoretical strain (με)	Experimental Strain-Loading (με)	Experimental Strain-Unloading (με)	Error percentage - Loading (%)	Error percentage - Unloading (%)
0	0	0	14	-	-
250	105.4	89	105	16	0
500	210.9	180	186	15	12
1000	421.7	365	375	13	11
2000	843.5	734	753	13	11
3000	1265.2	1111	1126	12	11
4000	1687.0	1485	1495	12	11
4500	1897.9	1685	1685	11	11

Table 6 Strain measurements from the SB-3 test

Mass (gr)	Theoretical strain (με)	Experimental Strain-Loading (με)	Experimental Strain-Unloading (με)	Error percentage - Loading (%)	Error percentage - Unloading (%)
0	0.0	0	13	-	-
250	112.9	105	127	7	11
500	225.8	212	242	6	7
1000	451.6	422	465	7	3
2000	903.3	852	900	6	0
3000	1354.9	1290	1334	5	2
4000	1806.6	1740	1740	4	4

Table 7 Strain measurements from the SB-4 test

Mass (gr)	Theoretical strain (με)	Experimental Strain-Loading (με)	Experimental Strain-Unloading (με)	Error percentage - Loading (%)	Error percentage - Unloading (%)
0	0.0	0	-8	-	-
250	67.7	71	64	-5	6
500	135.5	141	134	-4	1
750	203.2	215	204	-6	0
1000	271.0	276	278	-2	3
1500	406.5	436	421	-7	3
2000	542.0	560	561	-3	3
3000	813.0	840	840	-3	3

Table 8 Strain measurements from the SB-5 test

Mass (gr)	Theoretical strain (με)	Experimental Strain-Loading (με)	Experimental Strain-Unloading (με)	Error percentage - Loading (%)	Error percentage - Unloading (%)
0	0.0	0	-12	-	-
250	-67.7	-72	-84	-6	-24
500	-135.5	-144	-156	-6	-15
750	-203.2	-216	-227	-6	-12
1000	-271.0	-287	-298	-6	-10
1500	-406.5	-430	-441	-6	-8
2000	-542.0	-570	-580	-5	-7
3000	-813.0	-855	-855	-5	-5

Table 9 Strain measurements from the SB-6 test

Mass (gr)	Theoretical strain (με)	Experimental Strain-Loading (με)	Experimental Strain-Unloading (με)	Error percentage-Loading (%)	Error percentage-Unloading (%)
0	0.0	0	-3	-	-
250	135.5	135	139	0	3
500	271.0	270	276	0	2
750	406.5	405	414	0	2
1000	542.0	540	550	0	1
1500	813.0	812	818	0	1
2000	1083.9	1078	1082	1	0
3000	1625.9	1610	1610	1	1

5 CONCLUDING REMARKS

In the present paper, the authors tried to perform comprehensive tests to assess effects of various factors including the thickness, location of the strain gauge installation, and the strain gauge type, in order to propose an efficient and practical procedure for future tests. Before the main tests, the mechanical properties of the samples were obtained according to the ASTM standards. Tests on three different materials namely metal, composite, and sandwich strip plates were accomplished. Based on the large number of tests conducted on the samples, which are introduced in detail in the preceding sections, the results may be summarized as follows:

1- The discrepancies between the experimental and theoretical results are not affected by the distance between location of installation of the strain gauge and the clamped support.

2- An important source of error between the experimental and theoretical results is due malfunction of the strain gauge, which means that the strain gauge is not installed correctly.

3- Another method to find out whether the strain gauge is installed correctly or not, is comparing the results of the loading and unloading cases. If these results are coincident, they may be used with more confidence.

4- The method of using the gauge factor of the strain gauge indicated on the package (PKG GF), rather than the method of using the coefficients obtained from shunt calibration (EQV GF), gives better results and leads to smaller errors.

5- The method, wherein the bridge of the device (strain indicator) is balanced before using shunt calibration, gives good results too.

6- Using a circuit with three wires omits the error of the wire resistance in the results.
7- A perfect test must have identical results in both the loading and unloading cases, whether the applied load is increased uniformly or randomly.
8- Results of the tests on composite specimens obtained by strain gauges of TML Company show small differences compared to the results obtained by those of BLH Company.
9- By using the right test procedure, the maximum error between the experimental and theoretical results of the composite specimens may be reduced to 6%. This value of error may be due to the manufacturing process.
10- The error between the experimental and theoretical results in the sandwich specimens increases by increasing the core thickness.
11- Using strain gauges of BLH Company reduces the error between the experimental and theoretical results in sandwich specimens.
12- The measurements obtained in compression are not reliable, though the error decreases by increasing the load.
13- Half-bridge installation of the strain gauge decreases the error between the experimental and theoretical results remarkably.

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