# Comparative Analysis Program for Experimental and Calculated Data

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DOI: 10.13111/2066-8201.2017.9.4.6

*Received: 18 October 2017/ Accepted: 14 November 2017/ Published: December 2017*


***Abstract:*** *This article aims to provide an interactive in-house tool to quickly asses the stress in the critical points of the aeronautical structures. The software compares the results between the stress values obtained from the experimental tests using the resistive electrical tensometry technique (RET) and the stress values calculated with FEM software. RET refers to the stress and strains measured by strain gauges applied to the critical points of the structures. The finite element analysis was carried-out with MSC. PATRAN/ NASTRAN using shell and solid elements in order to identify the critical points based on the stress and strain results. The validation of the results obtained by the finite element modelling has been made experimentally using the resistive electrical tensometry method. The results from these two methods have been compared with the in-house software developed in Visual Basic with Excel interface. The program evaluates the relative error between the experimental and calculated data at critical points.*

***Key Works:*** *finite element method, resistive electrical tensometry method, strain gauge, critical points of structures, Visual Basic, in-house software, comparative analysis, RET*

## 1. INTRODUCTION

The finite element method is one of the efficient and well-known numerical methods for various engineering problems. Over the past 30 years it has been used to solve many types of problems. Finite element results are validated with either analytical solution or experimental studies. FEM method is satisfactory when the component loads are known both qualitatively and quantitatively.

Problems arise particularly where the loads are unknown or where they can only be roughly approximated. Formerly the risk of overloading was countered by using safety margins, i.e. through over dimensioning. However, modern design strategies demand savings in material, partly for reasons of cost and partly to save weight; this is clearly illustrated in aeronautics. In order to satisfy the safety requirements and to provide an adequate component service life, the material stresses must be known. Therefore, measurements under operational conditions are necessary. An important branch of experimental stress analysis is based on the principle of strain measurement. This paper presents a comparative analysis between experimental and computed data via an in-house software system, which allows to display both values of experimental and calculated stress and standard deviation in the critical points. The next chapters present the theoretical notions of resistive electrical tensometry that set the background and the methodology of the comparative analysis program.

## 2. ELECTRICAL TENSOMETRY AND ITS APPLICATIONS

The resistive electrical tensometry is a method for measuring the deformations by using transducers. These transducers turn the variation of a mechanical quantity into variations of an electric quantity. The resistive transducer used in electrical tensometry is a resistor built-up of one or more metallic conductors connected in series, with a small diameter ($0.015 \div 0.02\ mm$) and an electrical resistance of$R = 50 \div 1000\ \Omega$.

To avoid the difficulties caused by the direct mounting of the resistive sensor on the test specimen, the electrical conductors are placed as a grid embedded in a special paper casing or a phenolic envelope. Due to its shape and small size, the resistive transducer is also called strain gauge – see Fig. 1, 0.

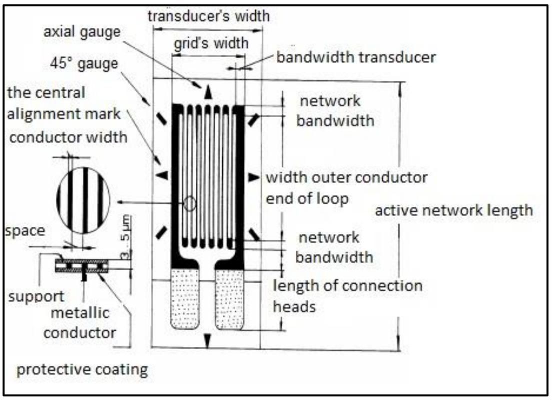



Fig. 1 Resistive transducer – component parts 0

The strain gauge is glued to the test specimen under a specific load condition in order to follow its deformations, which suffers a variation of its electrical resistance caused by a deformation. The phenomenon of electrical resistance variation of a conductor by means of mechanical deformation is called “tenso-effect” and it is the basis of the resistive electrical tensometry (RET). The electrical resistance $R$ of a wire with constant cross section is defined by the relation:

$$R = \rho \cdot \frac{l}{S} \tag{1}$$

where $\rho$ is the resistivity of the wire material [Ωm], $l$ is the wire length [$m$] and $S$ is the wire cross section [$m^2$].

Using logarithms and by deriving equation (1) it results the following relation:

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{dS}{S} \tag{2}$$

which for finite variations of the quantities becomes:

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta l}{l} - \frac{\Delta S}{S} \tag{3}$$

where $\frac{\Delta l}{l} = \varepsilon$, $\frac{\Delta S}{S} = -2\nu\varepsilon$ and $\nu$ is the Poisson ratio.

The Bridgman's law is applied in order to evaluate the term $\frac{\Delta \rho}{\rho}$:

$$\frac{\Delta \rho}{\rho} = c \cdot \frac{\Delta V}{V} \tag{4}$$

where $c$ is a constant of the material – Bridgman's constant whose value is determined experimentally by testing the wires traction, and $V = l \cdot S$ is the wire volume.

$$\frac{\Delta V}{V} = \frac{V_{final} - V_{initial}}{V_{initial}} = \frac{dx(1+\varepsilon_x)dy\left(1+\varepsilon_y\right)dz(1+\varepsilon_z) - dxdydx}{dxdydz} = \\ = (1+\varepsilon_x)\left(1+\varepsilon_y\right)(1+\varepsilon_z) - 1 \cong \varepsilon_x + \varepsilon_y + \varepsilon_z = (1-2\nu)\frac{\Delta l}{l} \tag{5}$$

Neglecting the terms of 2nd and 3rd order of equation (5) and considering $\varepsilon_x = \varepsilon$, $\varepsilon_y = -\nu \cdot \varepsilon$, $\varepsilon_z = -\nu \cdot \varepsilon$, it results:

$$\frac{\Delta \rho}{\rho} = c(1-2\nu)\frac{\Delta l}{l} \tag{6}$$

Equation (6) is an approximation because the term ρ is dependent not only on the volume of material, but also on the material crystal orientation. In fact, the value of $c$ differs with the crystallization direction. An engineering hypothesis is based on the Ohm's law applied on a cubic crystal under specific loading condition with small deformations:

$$E_i = \rho_{ij} \cdot J_j \cdot (\delta_{ij} + \pi_{\mathrm{ijkl}} \cdot T_{kl}) \tag{7}$$

where $E_i$ is the electric field, $J_i$ is the electrical density, $\rho_{ij}$ is the electrical resistivity, $\delta_{ij}$ is the Kronecker's symbol, $\pi_{ijkl}$ is a 4th order tensor – tensor of the piezo resistivity coefficients and $T_{kl}$ is the stress tensor.

The variation of the resistivity on the $j$ direction is:

$$\left(\frac{\Delta \rho}{\rho}\right)_j = \sum_k \pi_{jk} \cdot T_k \tag{8}$$

In the case of a wire under a uniaxial loading condition the following relation is obtained:

$$\frac{\Delta \mathrm{\rho}}{\rho} = \pi \cdot T = \pi \cdot \sigma = \pi \cdot E \cdot \frac{\Delta l}{l} \tag{9}$$

where $\pi$ is the piezoresistivity coefficient and $E$ is the elasticity modulus.

From the previous relations it results: $c \cdot (1-2\nu) = \pi \cdot E$. Finally, the relation can be written as follows:

$$\frac{\Delta R}{R} = (1 + 2\nu + \pi E) \cdot \frac{\Delta l}{l} = k \cdot \varepsilon \tag{10}$$

where $k$ is the tensosensibility coefficient of the wire, also called the transducer's constant and $\varepsilon$ is the strain of the test specimen on which the strain gauge is applied.

This is the first law of the resistive electrical transducer's operation, describing the dependency between a mechanical variation of the strain and a variation of the electrical resistance $\Delta R$. The coefficient $k$ mostly depends on the material. For example, if the strain gauge material is defined by $\nu = 0.3$ and $\pi \cdot E = 0.4$, it results $c = 1$ and $k = 2$. The value of $k = 2$ is also obtained by experimental determinations.

The usual values of the tensosensibility coefficient for gauges are around $k = 2$ and the usual values for electrical transducer are $R = 120\ \Omega, 240\ \Omega, 360\ \Omega, 500\ \Omega, 5000\ \Omega$.

To achieve an accurate measurement in electrical tensometry the transducers are assembled using a bridge mounting. So, if using a resistive transducer with $R = 120\ \Omega$ and $k = 2$ in order to measure a strain of $\varepsilon = 10^{-6} \div 10^{-3}$ the measuring circuit should sense the resistance variation:

$$\Delta R = k \cdot R \cdot \varepsilon = 2 \cdot 120 \cdot (10^{-6} \dots 10^{-3}) = 0.00024 \dots 0.24\ \Omega \qquad (11)$$

In practice, it is difficult to achieve measurements with such precision, which implies the use of an assembly in bridge. The bridge becomes the principal component of any apparatus for tensoelectrical measurements.

The easiest mounting type in bridge is the Wheatstone bridge. In the classical mounting this type of bridge is powered with a DC power source, where the internal resistance is very high $r_i \approx \infty$ or with a DC power source, where the internal resistance is very small$r_i \approx 0$.

The following picture represents a classical mounting of the Wheatstone bridge, where the power voltage $U_i$ flows through one diagonal of the bridge and the measured voltage $U_e$ flows through the other diagonal of the bridge, 0.

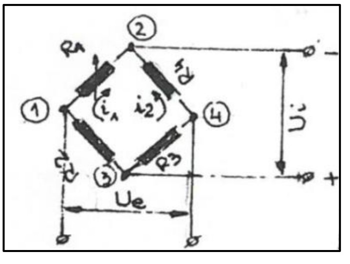



Fig. 2 Wheatstone bridge

Applying the Kirchhoff theorems, the following relations can be written:

$$U_i = i_1 \cdot (R_1 + R_2) = i_2 \cdot (R_3 + R_4) \qquad (12)$$

$$U_e = i_1 \cdot R_1 - i_2 \cdot R_4 = i_1 \cdot R_2 - i_2 \cdot R_3 \qquad (13)$$

From equation (12) it results the terms $i_1 = \frac{U_i}{R_1+R_2}$ and $i_2 = \frac{U_i}{R_3+R_4}$, which can be replaced in equation (13):

$$\frac{U_e}{U_i} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \qquad (14)$$

From relation (14) three particular cases can be discussed:

- **Case 1**, where $\frac{U_e}{U_i} = 0$, the Wheatstone bridge is in equilibrium and it results $R_1 \cdot R_3 = R_2 \cdot R_4$. This is the second law of operation of the resistive transducer and some important observations can be drawn from it: the variations of the resistances on the same arm or opposite arms are added algebraically while the variations on the adjacent arms are subtracted algebraically.

- **Case 2**, where $R_1 = R_0 + \Delta R$ and $R_2 = R_3 = R_4 = R_0$, the gauge is active (quarter of bridge); it results:

$$\frac{U_e}{U_i} = \frac{R_o + \Delta R}{2 \cdot R_0 + \Delta R} - \frac{1}{2} = \frac{\Delta R}{2(2R_0 + \Delta R_0)} \approx \frac{1}{4} \cdot \frac{\Delta R}{R_0} = k_m \cdot \varepsilon_m = \frac{1}{4} \cdot k_{ap} \varepsilon_{read} \quad (15)$$

where $k_m$ is the strain gauge constant, $k_{ap}$ is the apparatus constant, $\varepsilon_m$ is the strain measured by the gauge and $\varepsilon_{read}$ is the strain indicated by the apparatus.

From the relation above one can write $\varepsilon_m = \frac{k_{ap}}{k_m} \cdot \varepsilon_{read}$. From this relation, it results that the apparatus has as output $\varepsilon_{read}$. The interest for the strength analysis is $\varepsilon_m$. If $k_{ap}$ differs from $k_m$, then a correction must be applied for the value of $\varepsilon_{read}$ which is proportional to the ratio $\frac{k_{ap}}{k_m}$. It should be underlined that modern appliances have the capability to adjust $k_{ap}$ as a function of $k_m$.

In this case, the correction is no longer applicable and $\varepsilon_m = \varepsilon_{read}$.

- **Case 3**, where $R_1 = R_0 + \Delta R_1$, $R_2 + \Delta R_2$, $R_3 = R_0 + \Delta R_3$, $R_4 = R_0 + \Delta R_4$, all the transducers are active; it results:

$$\frac{U_e}{U_i} = \frac{R_0 + \Delta R_1}{2R_0 + \Delta R_1 + \Delta R_2} - \frac{R_0 + \Delta R_4}{2R_0 + \Delta R_3 + \Delta R_4} \quad (16)$$

Bringing to the same denominator, we get:

$$\frac{U_e}{U_i} = \frac{R_0(\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4) + \Delta R_1 \Delta R_3 - \Delta R_2 \Delta R_4}{(2R_0 + \Delta R_1 + \Delta R_2)(2R_0 + \Delta R_3 + \Delta R_4)} \quad (17)$$

Neglecting the higher order small infinites, it results:

$$\frac{U_3}{U_1} \approx \frac{1}{4}\left(\frac{\Delta R_1}{R_0} - \frac{\Delta R_2}{R_0} + \frac{\Delta R_3}{R_0} - \frac{\Delta R_4}{R_0}\right) = \frac{1}{4}(k_1 \varepsilon_1 - k_2 \varepsilon_2 + k_3 \varepsilon_3 - k_4 \varepsilon_4) = \frac{1}{4} k_{ap} \varepsilon_{read} \quad (18)$$

With $k_1 = k_2 = k_3 = k_4 = k_m$, it results:

$$\frac{U_e}{U_i} = \frac{1}{4} k_m (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) = \frac{1}{4} k_{ap} \varepsilon_{read} \quad (19)$$

From equation (19) it results that $\varepsilon_m = \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4$, so the measured value is equal to the algebraic sum of the strains from every transducer, with the mention that the effects on the opposite arm are added and the effects on the adjacent arms are subtracted.

In practice, there are two types of strain gauges: simple strain gauge and rosette strain gauge.

**Simple strain gauge**: is used in the case of simple loadings: tension – compression, bending, torsion and/ or when the principal directions of loading are known.

a) Tension – compression

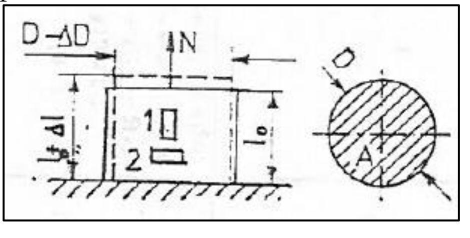



Fig. 3 Bar loaded in tension with the force *N*

If the strain gauge is mounted on the direction 1 and 2, then the value $\varepsilon_m$ has to be equal to the calculated value $\varepsilon_{calc}$ , according to:

$$\varepsilon_{1,calc} = \frac{\Delta l}{l_0} = \frac{N}{E \cdot A}, \varepsilon_{2,calc} = \frac{\Delta D}{D} = -\nu \varepsilon_{1,calc} \tag{20}$$

b) Simple bending:

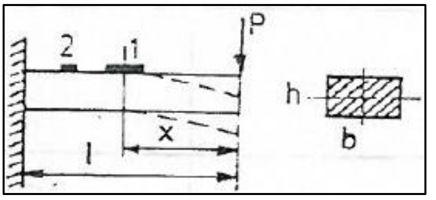



Fig. 4 Bar loaded in bending with the force *P*

$$\varepsilon_{1,calc} = \frac{6 \cdot P \cdot x}{E \cdot b \cdot h^2}, \varepsilon_{2,calc} = -\nu \cdot \varepsilon_{1,calc} \tag{21}$$

c) Simple bending with two strain gauges mounted up – down on a rectangular bar:

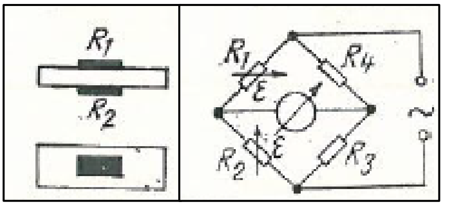



Fig. 5 Bar loaded in bending with two active strain gauges

In this type of mounting (Fig. 5), called semi-bridge, the two strain gauges are mounted on the adjacent arms and their effects will be subtracted algebraically. The bar will be tensioned on the surface where the strain gauge 1 is mounted and will be compressed where the strain gauge 2 is mounted.

This leads to $\varepsilon_m = \varepsilon_1 - (-\varepsilon_2) = 2 \cdot \varepsilon = \varepsilon_{read}$, resulting $\varepsilon_m = \frac{1}{2}\varepsilon_{read}$, which has to be equal to $\varepsilon_{1,calc}$ from the previous example. From this example, it should be remarked that the reading accuracy has twice increased.

d) Torsion with the moment $M_t$:

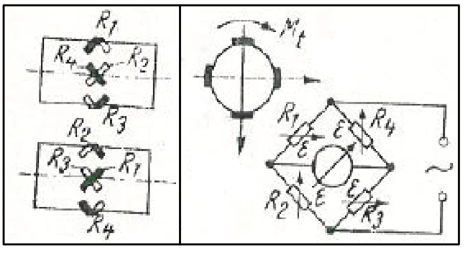



Fig. 6 Bar loaded in torsion with four active strain gauges

In the mounting presented in Fig. 6 four active strain gauges were used, forming a complete bridge. The bar of ring cross section, with the exterior diameter $D$ and interior diameter $d$ is loaded in torsion with a given moment $M_t$.

From the theory of elasticity, it is known that tensile stress, respectively compressive stress, equal to the torsion stress $\tau = \pm\sigma$ occur at 45° degrees from the principal direction.

$$\tau = \frac{M_t}{W_p} = G \cdot \gamma = G \cdot 2 \cdot \varepsilon_{45}, \varepsilon_{45} = \frac{M_t}{2 \cdot G \cdot W_p} = \frac{M_t}{2 \cdot G \cdot \frac{\pi(D^4 - d^4)}{16D}} = \frac{8 \cdot M_t \cdot D}{\pi \cdot G \cdot (D^4 d^4)} \tag{22}$$

where $\varepsilon_{45} = \frac{\gamma}{2}$, $G = \frac{E}{2(1+\nu)}$, $W_p = \frac{\pi(D^4 - d^4)}{16D}$.

Therefore, the measured strain is equal to $\varepsilon_m = \frac{1}{4} \cdot \varepsilon_{read}$ and should have the same calculated value of $\varepsilon_{45}$, 0.

**Rosette strain gauge**: is used in the case of combined loadings or when the principal directions of loading are unknown. The most common form is presented in the figure below:

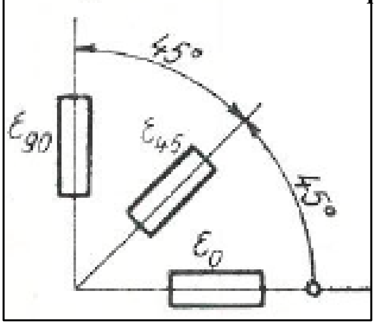



Fig. 7 Rosette strain gauge 0

From the rosette strain gauge presented in the figure below the strains are obtained for the three directions $\varepsilon_0$, $\varepsilon_{45}$ and $\varepsilon_{90}$.

These strains are in the plane of the solid's face, where the strain gauge is glued. With their help, the principal strains, $\varepsilon_1$ and $\varepsilon_2$, the principal stresses $\sigma_1$ and $\sigma_2$ ($\sigma_3$ is perpendicular to the plane formed by the two principal directions and is equal to zero) and the angle $\phi_1$ between the principal direction $\varepsilon_1$ and the transducer's direction $\varepsilon_0$ can be calculated, 0.

$$\varepsilon_{1,2} = \frac{\varepsilon_0 + \varepsilon_{90}}{2} \pm \frac{\sqrt{2}}{2}\sqrt{(\varepsilon_0 - \varepsilon_{45})^2 + (\varepsilon_{45} - \varepsilon_{90})^2} \tag{23}$$

$$\sigma_{1,2} = \frac{E}{2}\left[\frac{\varepsilon_0 + \varepsilon_{90}}{1-\nu} \pm \frac{1}{1+\nu}\sqrt{(\varepsilon_0 - \varepsilon_{90})^2 + (2\varepsilon_{45} - \varepsilon_0 - \varepsilon_{90})^2}\right] \tag{24}$$

$$tg2\phi_1 = \frac{2\varepsilon_{45} - (\varepsilon_0 + \varepsilon_{90})}{\varepsilon_0 - \varepsilon_{90}} \tag{25}$$

In order to compare the principal stresses $\sigma_1$and $\sigma_2$ obtained from the test records $\varepsilon_0$, $\varepsilon_{45}$ and $\varepsilon_{90}$ and the data calculated using the finite element method (FEM), two aspects need to be clarified:

- If the structure has been modelled with shell elements (2D elements), then from FEM analysis two values of the principal stresses $\sigma_{1,FEM} > \sigma_{2,FEM}$ are obtained, in the element plane at $z_1$ and $z_2$; depending on the face on which the rosette strain gauge was mounted, the third component which is perpendicular to the plane of the two components is equal to zero, except for the case when a local load, for example a type of pressure, acts on the element;

- If the structure has been modelled with volume elements (3D elements), then from the FEM analysis three values of the principal stresses $\sigma_{1,FEM} > \sigma_{2,FEM} > \sigma_{3,FEM}$ are obtained. It should be made clear that principal stresses have random directions and the two first principal stresses are no longer on the solid's face. If a fine mesh is used for the FEM model, then $\sigma_{3,FEM} \approx 0$ and the two principal stresses $\sigma_{1,FEM} > \sigma_{2,FEM}$ can be compared to the stresses $\sigma_{1,2}$, obtained from the test records $\varepsilon_0$, $\varepsilon_{45}$ and $\varepsilon_{90}$ within the error margin of up to 15%,0.

## 3. GENERAL DESCRIPTION OF THE PROGRAM

The steps for static testing are:

- the structure is loaded up to a factor of 60% of LL and is unloaded using the same loading curve, which is called settlement. The purpose of this step is to check the correct operation of all strain gauges, whether they indicate zero strain. In case of a failed strain gauge, it is replaced and the process is repeated;
- the structure is loaded up to limit load (LL), at a load factor of $j = 1$, and is unloaded using the same loading curve, at which the structure must not have any permanent deformation. This applies to flight cases taken from the flight envelope;
- the structure is loaded up to ultimate load (UL), at a load factor of $j = 1.5$, where permanent deformation may be allowed as long as there is no structural failure. This applies to cases of emergency landing conditions.

The general rule is that these test values are considered real values that are to be compared to the those calculated by structural analysis. If there are relative errors of more than 15%, the computing technique is changed: either a finer mesh size is chosen or, in case of hand-calculation, the computing procedure is revised or changed.

This program manages the comparative analysis between the stress values obtained experimentally and the stress values calculated by the engineering department using FEM software.

Also, the relative error between such values is computed by this software. The necessary input files for the comparative analysis are the following: the file containing the stress values obtained experimentally and the file with the stress values calculated with FEM software. The first file has the following format:

The first line contains these data, as follows: 'No. Gauge', which represents the name of the strain gauge, 'E' Young's modulus, 'nu' Poisson's ratio.

On the same line, and separated by a comma, there are the load factor values for which the respective laboratory tests were carried out. These values must be written in ascending order.

For each strain gauge the next lines contain, in the following order and separated by a comma: the name of the strain gauge, Young's modulus in [MPa], Poisson's ratio and the strain values in [μm/m] recorded by the strain gauge for the corresponding load factor from the first line. In order to identify the type of strain gauge, the user has to add to its name the letter 'G', in case of a simple strain gauge, and, the letter 'A' for the 0 degrees component, 'B' for the 45 degrees and 'C' for 90 degrees, in case of a rosette gauge. In that last case, all three lines of data must be on top of each other, in the following order: 'A','B','C'.

```
No. Gauge,E,nu,0.0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0,1.1,1.2,1.3,1.4,1.5
49301G,73100,0.3,0.000000000,72.7613297,146.245071,202.986237,283.637268,365.814301
,415.218964,457.633911,540.588806,577.140015,662.255798,762.176086,842.401855,864.1
64673,944.184387,1111.63647
49302G,73100,0.3,0.000000000,75.4666824,159.545746,225.337296,317.534668,424.090240
,496.801392,505.699097,618.057251,694.520020,825.815735,907.637634,870.410278,1016.
66614,1037.78027,1159.11987
49365A,73100,0.3,0.000000000,148.120300,284.544769,461.853577,624.785645,688.807495
,795.728699,973.855591,1213.25342,1368.97815,1531.37744,1541.42480,1869.88611,1740.
58899,2148.69751,2053.46802
49365B,73100,0.3,0.000000000,53.2709236,102.501488,165.889557,224.765976,248.031631
,286.463501,351.534576,435.358093,492.451141,549.299377,556.509460,671.424500,628.1
22681,773.668518,738.697449
49365C,73100,0.3,0.000000000,-41.5784645,-79.5418015,-130.074463,-175.253723,-192.7
44278,-222.801682,-270.786438,-342.537201,-384.075897,-432.778748,-428.405884,-527.
037048,-484.343719,-601.360657,-576.073059
49317A,73100,0.3,0.000000000,134.299927,256.510498,365.491943,487.129517,657.917480
,793.659790,965.257751,953.381592,1227.15540,1310.95386,1298.27283,1411.14026,1579.
65283,1753.70276,1790.36536
49317B,73100,0.3,0.000000000,47.6425934,91.0314407,129.872177,173.070618,233.495819
,281.537506,342.393982,338.854980,435.355591,465.536743,462.141907,501.664886,561.6
68762,623.598022,636.800476
49317C,73100,0.3,0.000000000,-39.0147476,-74.4476242,-105.747604,-140.988297,-190.9
25827,-230.584747,-280.469757,-275.671631,-356.444305,-379.880371,-373.989044,-407.
810425,-456.315186,-506.506775,-516.764343
```

Fig. 8 Testing Values file

In the example above (Fig. 8), there are two simple strain gauges on the first two lines: 49301G and 49302G, and two rosette gauges on the next six lines: 49365A, 49365B, 49365C and 49317A, 49317B, 49317C.

The second type of file, the one containing the stress values calculated using FEM software, has the following format:

```
49301G,73100,0.3,75.18
49302G,73100,0.3,85.90
49365A,73100,0.3,158.71
49365B,73100,0.3,3.47
49365C,73100,0.3,0
49317A,73100,0.3,139.84
49317B,73100,0.3,1.64
49317C,73100,0.3,0
```

Fig. 9 Computed Values file

The file starts with lines containing the gauge values, without having to write a first line enumerating the load factors used by the laboratory staff. These values are automatically stored by the software from reading the first type of file.

The lines contain the following data, in order and separated by a comma: name of the strain gauge, Young modulus in $[MPa]$, Poisson coefficient and the stress value in $[MPa]$ calculated for the maximum load factor from the previous file.

When opening the excel file the user will find two buttons on the first sheet:

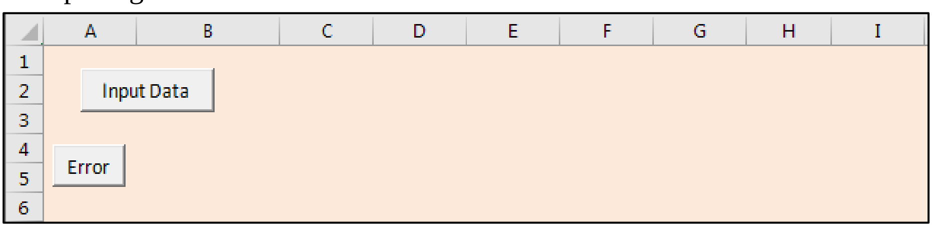



Fig. 10 Opening sheet

To read the two input files the user shall click the ‘Input Data’ button. First, he shall select the laboratory results file and then the FEM results file. After the files are read, the software will organize the data into three different sheets: ‘Computed Values’, ‘Experimental Values’ and ‘Captions’.

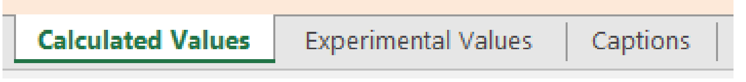
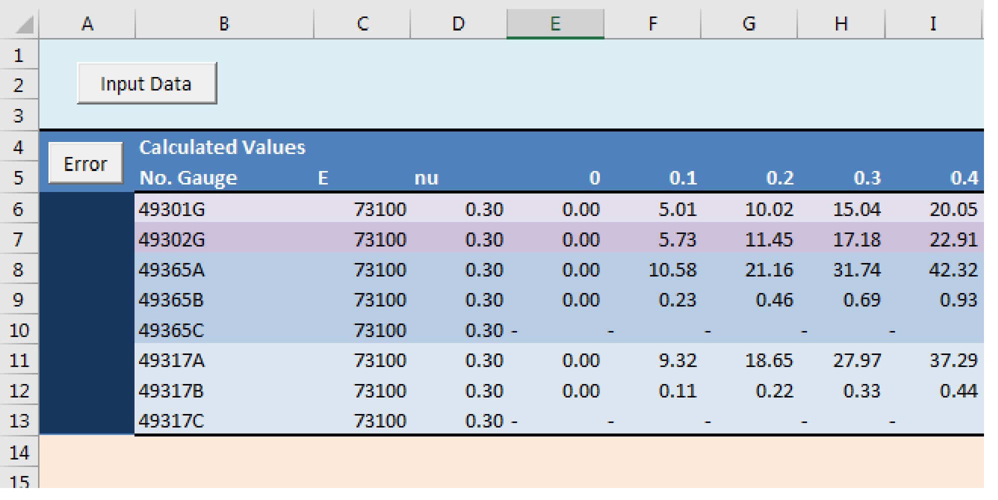



Fig. 11 Sheet names

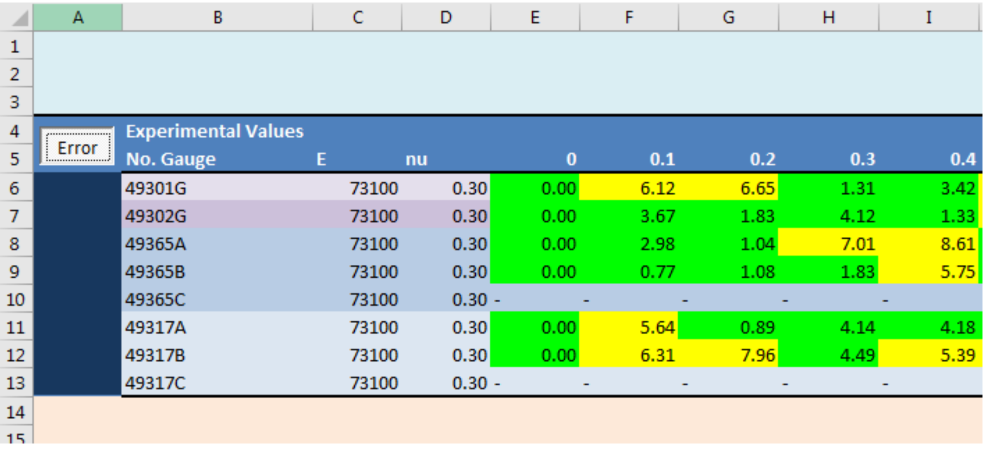
The sheets ‘Computed Values’ and ‘Experimental Values’ will contain the stress values in MPa, the first sheet containing the FEM stress values and the second the experimental principal stress values, obtained using the formulas presented in the second chapter.




| No. Gauge | E | nu | 0 | 0.1 | 0.2 | 0.3 | 0.4 |
|---|---|---|---|---|---|---|---|
| 49301G | 73100 | 0.30 | 0.00 | 5.01 | 10.02 | 15.04 | 20.05 |
| 49302G | 73100 | 0.30 | 0.00 | 5.73 | 11.45 | 17.18 | 22.91 |
| 49365A | 73100 | 0.30 | 0.00 | 10.58 | 21.16 | 31.74 | 42.32 |
| 49365B | 73100 | 0.30 | 0.00 | 0.23 | 0.46 | 0.69 | 0.93 |
| 49365C | 73100 | 0.30 | - | - | - | - | - |
| 49317A | 73100 | 0.30 | 0.00 | 9.32 | 18.65 | 27.97 | 37.29 |
| 49317B | 73100 | 0.30 | 0.00 | 0.11 | 0.22 | 0.33 | 0.44 |
| 49317C | 73100 | 0.30 | - | - | - | - | - |

Fig. 12 Resulting data on sheets

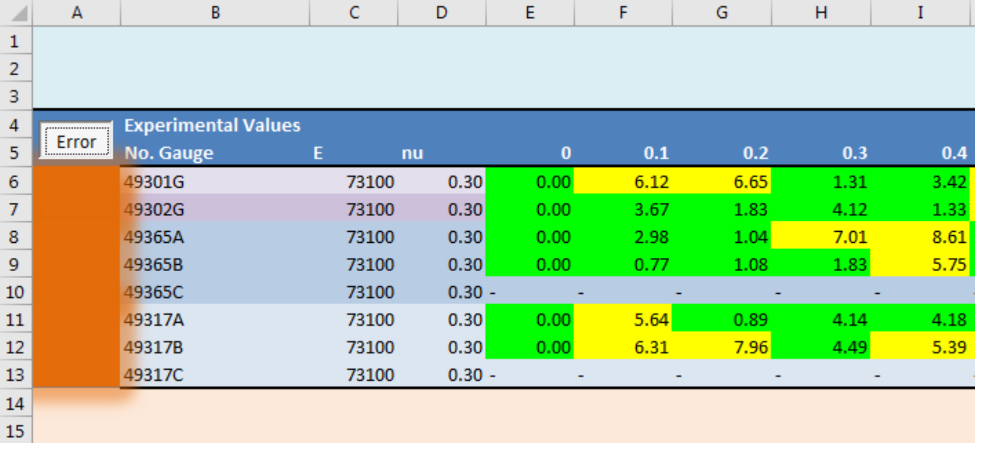
The next step consists in checking the relative errors between the computed stress values and the experimental ones. The user performs the verification by clicking the ‚Error’ toggle button from either of the first two sheets.




| No. Gauge | E | nu | 0 | 0.1 | 0.2 | 0.3 | 0.4 |
|---|---|---|---|---|---|---|---|
| 49301G | 73100 | 0.30 | 0.00 | 6.12 | 6.65 | 1.31 | 3.42 |
| 49302G | 73100 | 0.30 | 0.00 | 3.67 | 1.83 | 4.12 | 1.33 |
| 49365A | 73100 | 0.30 | 0.00 | 2.98 | 1.04 | 7.01 | 8.61 |
| 49365B | 73100 | 0.30 | 0.00 | 0.77 | 1.08 | 1.83 | 5.75 |
| 49365C | 73100 | 0.30 | - | - | - | - | - |
| 49317A | 73100 | 0.30 | 0.00 | 5.64 | 0.89 | 4.14 | 4.18 |
| 49317B | 73100 | 0.30 | 0.00 | 6.31 | 7.96 | 4.49 | 5.39 |
| 49317C | 73100 | 0.30 | - | - | - | - | - |

Fig. 13 Error color coded data

The worksheet will now output the relative error numerically, as well as color coded with the following legend: green (0,255,0) for error less than 5%, yellow (255,255,0) for error less than 15% and red (255,0,0) for error exceeding 15%, 0. Displaying the error in a color-coded format facilitates the process of identifying the critical strain gauges where the error is colored red, meaning that the design of the structure must be revised and sent through another iteration of analysis by the stress department. This technique makes the process much faster and more efficient. After completing the design iteration process, and after the error colors are either green or yellow, the user can go to the next step of preparing the captions for the actual stress report.



| Error | Experimental Values | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No. Gauge | E | nu | 0 | 0.1 | 0.2 | 0.3 | 0.4 |
| | 49301G | 73100 | 0.30 | 0.00 | 6.12 | 6.65 | 1.31 | 3.42 |
| | 49302G | 73100 | 0.30 | 0.00 | 3.67 | 1.83 | 4.12 | 1.33 |
| | 49365A | 73100 | 0.30 | 0.00 | 2.98 | 1.04 | 7.01 | 8.61 |
| | 49365B | 73100 | 0.30 | 0.00 | 0.77 | 1.08 | 1.83 | 5.75 |
| | 49365C | 73100 | 0.30 | - | - | - | - | - |
| | 49317A | 73100 | 0.30 | 0.00 | 5.64 | 0.89 | 4.14 | 4.18 |
| | 49317B | 73100 | 0.30 | 0.00 | 6.31 | 7.96 | 4.49 | 5.39 |
| | 49317C | 73100 | 0.30 | - | - | - | - | - |

Fig. 14 Enabled captions for stress report

From either of the first two sheets, the user selects the desired captions to be included in the final report by clicking the first cell of the strain gauge's line. These will automatically appear on the 'Captions' sheet. The small etiquettes contain the following data, in the following order: FEM stress value, laboratory test stress value and relative color-coded error between them, all the values corresponding to the maximum load factor from the first input file. They can be dragged in their respective positions on the imported screenshot of the structure. The strain gauge placeholder shapes have been added for ease of use. Alongside the former features, there is also a graph object that plots all the stress values from a certain strain gauge. To start the plotting process the user shall click the gauge caption button.

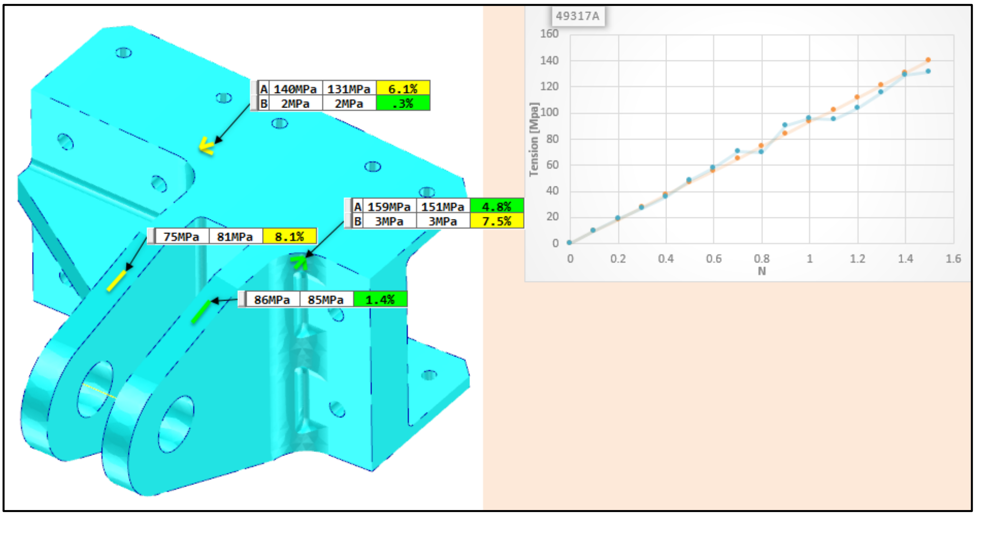



Fig. 15 Stress report sheet

In Fig. 15, the stress values of the fitting part were calculated, using linear and buckling analysis, 0, 0 and 0.

After the editing has been done, the sheet is ready to be included in the final stress report using a screen capturing software.

## 4. SOFTWARE SOURCE CODE

The program flowchart is presented in Fig.16, followed by the program source code. The flowchart represents a graphical resume of the previous chapter regarding the main user-events from excel visual basic code: the data input button, the error toggle button and the caption selection process, followed by the actual preparation of the report sheet, 0.

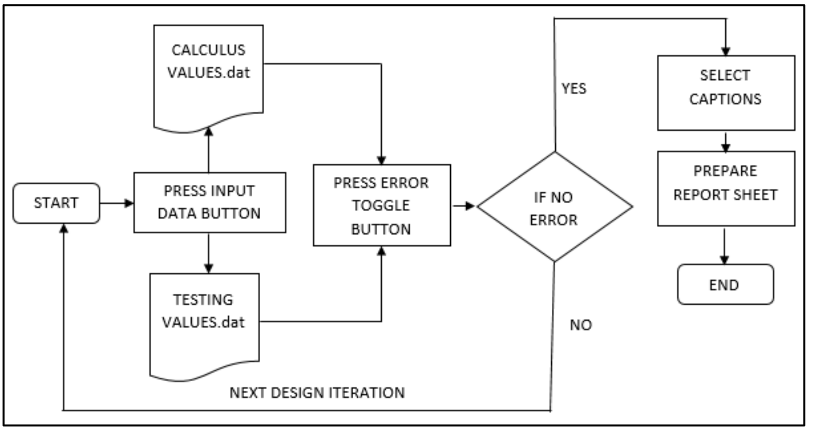



Fig. 16 Program flowchart

```
Module1:
Public Sub Caption_Create()
 Dim Ox, Oy As Single
 Ox = 500#
 Oy = -60#

 Application.ScreenUpdating = False
 With ActiveWorkbook.VBProject.VBComponents(Worksheets(3).CodeName).CodeModule
  .insertlines .CountOfLines + 1, Chr(39) + "s1_code" '+ vbCrLf
 End With
 For i = 6 To 6 + Worksheets(4).Cells(1, 2)
  text = Right(Worksheets(1).Cells(i, 2), 1)
  Select Case text
   Case "G"
    Set NewButton = Worksheets(3).OLEObjects.Add("Forms.commandbutton.1")
    With NewButton
     .Name = "c" + CStr(i) + "00_btn"
     .Object.Caption = ""
     .Object.Accelerator = "M"
     .Top = Oy + i * 13
     .Left = Ox
     .Width = 6
     .Height = 12
     .Object.Font.Size = 8
     .Object.Font.Name = "Tahoma"
     .Object.BackStyle = fmBackStyleOpaque
```

```
     .Visible = False
    End With

    Set NewLabel = Worksheets(3).OLEObjects.Add("Forms.label.1")
    With NewLabel
     .Name = "c" + CStr(i) + "01_lbl"
     .Object.Caption = Format(CStr(Worksheets(1).Cells(i, Worksheets(4).Cells(1, 1)
+ 1)), "#") + "MPa"
     .Top = Oy + i * 13
     .Left = Ox + 6
     .Width = 40
     .Height = 12
     .Object.BackColor = RGB(255, 255, 255)
     .Object.BorderStyle = fmBorderStyleSingle
     .Object.BackStyle = fmBackStyleOpaque
     .Object.TextAlign = fmTextAlignCenter
     .Object.Font.Size = 10
     .Object.Font.Bold = True
     .Object.Font.Name = "Consolas"
     .Visible = False
    End With

    Set NewLabel = Worksheets(3).OLEObjects.Add("Forms.label.1")
    With NewLabel
     .Name = "c" + CStr(i) + "02_lbl"
     .Object.Caption = Format(CStr(Worksheets(2).Cells(i, Worksheets(4).Cells(1, 1)
+ 1)), "#") + "MPa"
     .Top = Oy + i * 13
     .Left = Ox + 45
     .Width = 40
     .Height = 12
     .Object.BackColor = RGB(255, 255, 255)
     .Object.BorderStyle = fmBorderStyleSingle
     .Object.BackStyle = fmBackStyleOpaque
     .Object.TextAlign = fmTextAlignCenter
     .Object.Font.Size = 10
     .Object.Font.Bold = True
     .Object.Font.Name = "Consolas"
     .Visible = False
    End With

    Set NewLabel = Worksheets(3).OLEObjects.Add("Forms.label.1")
    With NewLabel
     .Name = "c" + CStr(i) + "03_lbl"
     j = Worksheets(4).Cells(1, 1) + 1
     er = Abs((Worksheets(4).Cells(i, j) - Worksheets(5).Cells(i, j)) /
(Worksheets(4).Cells(i, j) + 0.0000001))

     If er < 0.05 Then
      .Object.BackColor = RGB(1, 255, 1)
     ElseIf er < 0.15 Then
      .Object.BackColor = RGB(255, 255, 1)
     Else
      .Object.BackColor = RGB(255, 1, 1)
     End If
     .Object.Caption = Format(CStr(Abs(er) * 100), "#.0") + "%"
     .Top = Oy + i * 13
```

```
      .Left = Ox + 84
      .Width = 40
      .Height = 12
      .Object.BorderStyle = fmBorderStyleSingle
      .Object.BackStyle = fmBackStyleOpaque
      .Object.TextAlign = fmTextAlignCenter
      .Object.Font.Size = 10
      .Object.Font.Bold = True
      .Object.Font.Name = "Consolas"
      .Visible = False
    End With

    With ActiveWorkbook.VBProject.VBComponents(Worksheets(3).CodeName).CodeModule
      '====================================BUTTON 1
      .insertlines .CountOfLines + 1, "Private Sub c" + CStr(i) +
"00_btn_MouseDown(ByVal Button As Integer, ByVal Shift As Integer, ByVal X As
Single, ByVal Y As Single)"
      .insertlines .CountOfLines + 1, "   If Button = XlMouseButton.xlPrimaryButton
Then"
      .insertlines .CountOfLines + 1, "      Worksheets(3).ChartObjects(""Chart
5"").Activate"
      .insertlines .CountOfLines + 1, "      ActiveChart.ChartTitle.text =
Worksheets(4).Cells(" + CStr(i) + ", 2)"
      .insertlines .CountOfLines + 1, "    ActiveChart.SeriesCollection(1).XValues =
Worksheets(5).Range(Worksheets(5).Cells(5, 5), Worksheets(5).Cells(5, 1 +
Worksheets(5).Cells(1, 1)))"
      .insertlines .CountOfLines + 1, "    ActiveChart.SeriesCollection(1).Values =
Worksheets(4).Range(Worksheets(4).Cells(" + CStr(i) + ", 5), Worksheets(4).Cells("
+ CStr(i) + ", 1 + Worksheets(4).Cells(1, 1)))"
      .insertlines .CountOfLines + 1, "    ActiveChart.SeriesCollection(2).XValues =
Worksheets(5).Range(Worksheets(5).Cells(5, 5), Worksheets(5).Cells(5, 1 +
Worksheets(5).Cells(1, 1)))"
      .insertlines .CountOfLines + 1, "    ActiveChart.SeriesCollection(2).Values =
Worksheets(5).Range(Worksheets(5).Cells(" + CStr(i) + ", 5), Worksheets(5).Cells("
+ CStr(i) + ", 1 + Worksheets(5).Cells(1, 1)))"
      .insertlines .CountOfLines + 1, "   End If"
      .insertlines .CountOfLines + 1, "End Sub"
      '====================================LABEL 1
      .insertlines .CountOfLines + 1, "Private Sub c" + CStr(i) +
"01_lbl_MouseDown(ByVal Button As Integer, ByVal Shift As Integer, ByVal X As
Single, ByVal Y As Single)"
      .insertlines .CountOfLines + 1, "   If Button = XlMouseButton.xlPrimaryButton
Then"
      .insertlines .CountOfLines + 1, "    mdOriginX = X"
      .insertlines .CountOfLines + 1, "    mdOriginY = Y"
      .insertlines .CountOfLines + 1, "   End If"
      .insertlines .CountOfLines + 1, "End Sub"
      .insertlines .CountOfLines + 1, "Private Sub c" + CStr(i) +
"01_lbl_MouseUp(ByVal Button As Integer, ByVal Shift As Integer, ByVal X As Single,
ByVal Y As Single)"
      .insertlines .CountOfLines + 1, "   If Button = XlMouseButton.xlPrimaryButton
Then"
      .insertlines .CountOfLines + 1, "   set obj0=worksheets(3).oleobjects(""c" +
CStr(i) + "00_btn"")"
      .insertlines .CountOfLines + 1, "   set obj1=worksheets(3).oleobjects(""c" +
CStr(i) + "01_lbl"")"
```

```
     .insertlines .CountOfLines + 1, "   set obj2=worksheets(3).oleobjects(""c" +
CStr(i) + "02_lbl"")"
     .insertlines .CountOfLines + 1, "   set obj3=worksheets(3).oleobjects(""c" +
CStr(i) + "03_lbl"")"
     .insertlines .CountOfLines + 1, "  obj0.Left = obj0.Left + X - mdOriginX"
     .insertlines .CountOfLines + 1, "  obj1.Left = obj1.Left + X - mdOriginX"
     .insertlines .CountOfLines + 1, "  obj0.Top = obj0.Top + Y - mdOriginY"
     .insertlines .CountOfLines + 1, "  obj1.Top = obj1.Top + Y - mdOriginY"
     .insertlines .CountOfLines + 1, " End If"
     .insertlines .CountOfLines + 1, "End Sub"


.insertlines .CountOfLines + 1, "Private Sub c" + CStr(i) + "02_lbl_MouseDown(ByVal
Button As Integer, ByVal Shift As Integer, ByVal X As Single, ByVal Y As Single)"
     .insertlines .CountOfLines + 1, "   If Button = XlMouseButton.xlPrimaryButton
Then"
     .insertlines .CountOfLines + 1, "    mdOriginX = X"
     .insertlines .CountOfLines + 1, "    mdOriginY = Y"
     .insertlines .CountOfLines + 1, "   End If"
     .insertlines .CountOfLines + 1, "End Sub"
     .insertlines .CountOfLines + 1, "Private Sub c" + CStr(i) +
"02_lbl_MouseUp(ByVal Button As Integer, ByVal Shift As Integer, ByVal X As Single,
ByVal Y As Single)"
     .insertlines .CountOfLines + 1, "   If Button = XlMouseButton.xlPrimaryButton
Then"
     .insertlines .CountOfLines + 1, "   set obj0=worksheets(3).oleobjects(""c" +
CStr(i) + "00_btn"")"
     .insertlines .CountOfLines + 1, "   set obj1=worksheets(3).oleobjects(""c" +
CStr(i) + "01_lbl"")"
     .insertlines .CountOfLines + 1, "   set obj2=worksheets(3).oleobjects(""c" +
CStr(i) + "02_lbl"")"
     .insertlines .CountOfLines + 1, "   set obj3=worksheets(3).oleobjects(""c" +
CStr(i) + "03_lbl"")"
     .insertlines .CountOfLines + 1, "  obj0.Left = obj0.Left + X - mdOriginX"
     .insertlines .CountOfLines + 1, "  obj1.Left = obj1.Left + X - mdOriginX"
     .insertlines .CountOfLines + 1, "  obj0.Top = obj0.Top + Y - mdOriginY"
     .insertlines .CountOfLines + 1, "  obj1.Top = obj1.Top + Y - mdOriginY"
     .insertlines .CountOfLines + 1, " End If"
     .insertlines .CountOfLines + 1, "End Sub"
    End With
  End Select
 Next i
 With ActiveWorkbook.VBProject.VBComponents(Worksheets(3).CodeName).CodeModule
  .insertlines .CountOfLines + 1, Chr(39) + "e1_code" '+ vbCrLf
 End With
End Sub
```

## 5. CONCLUSIONS

The manual analysis of a large number of results from the strain gauges used in a structural testing laboratory can take an extremely large amount of time and is prone to human errors.

The software is designed to accelerate such a process of comparative analysis of the stress values from the experimental tests and those calculated with the FEM software by using a user-friendly interface.

The process is partitioned into three stages: check of the critical strain gauges with a high degree of error, selection of the relevant strain gauges for each part and reporting of results. The program reduces the time needed to manage all of these stages. The color-coding of the relative error quickly shows where further design is needed and also gives an overview of the quality of the current design iteration. The user can then easily select the relevant strain gauges to be included in a graphical representation of a detailed report. This can be done as many times as needed, with as many parts are required.

The original contributions of the authors are as follows:

a) Setting up of a calculation procedure for a combined static and dynamic application.
b) Setting up of an Excel Visual Basic program for comparative analysis between experimental and calculated data.

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