DOR: 20.1001.1.27170314.2022.11.2.4.2

Research Paper

Measurement of Residual Stress in Composites Using Central Hole Drilling and Digital Image Correlation Methods

Peyman Ghasemi Tamami[1], Davood Akbari[1*], Farid Azadi[1]
[1]Tarbiat Modares University, Faculty of Mechanical Engineering, Tehran, Iran
[*]Email of Corresponding Author: Daakbari@modares.ac.ir
Received: June 17, 2022; Accepted: August 3, 2022

Abstract
Residual stress measurement is important in composite components. Due to the non-uniform structure of the composite components, the measurement of residual stress in these components cannot be easily performed. In this study, the composite components of polyester resin with glass fiber were presented as a novel structure for a vehicle segment. These materials are manufactured by hand layup method and will generate residual stresses after curing. To calculate the number of residual stresses generated in these parts, the combined central hole drilling-digital image correlation method was used. This method has advantages over drilling by installing a rosette strain gauge. To measure the residual stresses of the desired piece, the drill was positioned on the set, and three points of bending have been done. Then the experimental test conditions are simulated in the ANSYS finite element software. By comparing the results of the experimental test and software simulation, the residual stress values in composite components were calculated with good accuracy.

Keywords
Residual Stress Measurement, Composite, Hole Drilling, Digital Image Correlation

1. Introduction

Residual stress is the stress that will remain in the part after the removal of the main loading factor. The formation of residual stresses occurs in various processes, such as inelastic deformation (plastic), temperature changes (during thermal cycles), or structural changes (phase conversion) [1]. The presence of uncontrolled residual stresses on mechanical components is an undesirable factor. However, some designs are based on these types of stresses. There are various methods for measuring residual stress that is divided into three categories: destructive, semi-destructive, and non-destructive [1]. The choice of each method depends on the information required and the nature of the sample being tested. The penetration depth of the measurement (on the surface or in the depth direction), the length scale of the required information, as well as the geometry and location of the sample are also effective factors in the choice of method. Destructive methods cause large and irreversible changes in the structure. In these methods, it is not possible to reuse the test sample. Thus, either a spare should be used to replace the sample in the structure or a precise physical model to be used as a laboratory sample. For this reason, destructive methods are used more limited to investigate residual stresses, and two semi-destructive and non-destructive methods are used more widely. The basis of semi-destructive methods is similar to destructive methods on strain release. But in semi-destructive methods, only a small section of the material is removed and the overall structure will remain unchanged [1]. Among the semi-destructive methods, the central hole drilling method is more widely used than other methods [1]. Mathar introduced this method in 1934 as a method for measuring residual stress [2]. The method is based on strain release due to the formation of a shallow hole and a grid strain gauge. Due to available difficulties in installing a strain gauge, its single use, its limited use of special direction, and high cost, a suitable replacement for them can have many benefits for industrial applications. Schajer et al. reviewed improvements in measuring residual stresses and considered using optical methods the most important issue in the development of the hole drilling method [3]. Optical methods are capable of measuring residual stresses full screen and in situ. These methods have the advantages of high speed, high precision, low cost, and no dependence on microstructure and surface quality. Among all-optical methods, Digital Image Correlation (DIC) is superior to other optical methods due to its no need to override phases, haloes, and waves. This method was introduced in 1982 at the University of South Carolina by Professor Sutton to obtain the displacement field [4]. Fiber-reinforced polymer base composites are usually produced under a process in which the resin is heated, the fibers are moistened, and curing operations are carried out at high temperatures. The need for high temperatures in curing operations will result in residual stress on the final composite layers. The main cause of these stresses is the thermal expansion mismatch in the composite materials and the chemical wrinkles of the polymers in the composite structure. Measuring the exact amount of these stresses is complex [1]. In this study, residual stresses in composites by combining central hole drilling and digital image correlation methods have been investigated.

2. Material and methods

In the Digital image correlation method, a speckle pattern is created on the surface of the piece. After sample preparation, before and after loading two images are taken from the surface pattern, and then by analyzing these two images in the correlation algorithm, the displacement and strain field can be obtained. A schematic of the correlation method equipment is shown in Figure 1 [4-7].

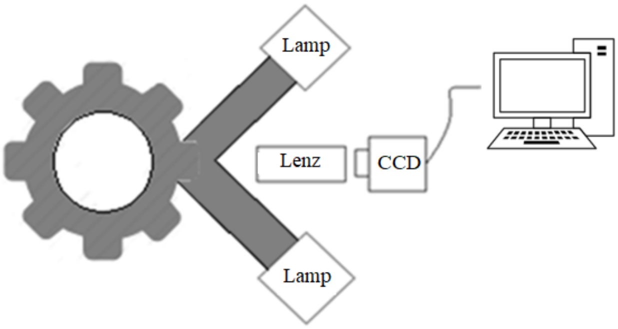


Figure 1. Schematic of DIC equipment

The main idea of this method is how to communicate between points before and after deformation in the piece. Digital image correlation does this by using subsections of the reference image, known as the subset, and determining their relative position. For each subset, the displacement and strain information is calculated during the transition to match the subset position in the current situation [4].

The final result of a network consists of displacement and strain information according to the reference configuration information. In the digital image correlation method, the light intensity of each image is estimated by a continuous polynomial function. In an article, Sutton et al. showed that the fifth-degree curve shows the best results. The correlation algorithm compares the light intensity function of two images subsets before and after loading with N × N pixels each time, and the deformed image subset that is most consistent with the reference image subset, considered as the deformed subset and will calculate its displacement and deformation (as shown in Figure 2). This process is performed for all subsets of the reference image and finally the total displacement field is obtained. To check the conformity of each pair of subsets, the correlation coefficient C is defined as Eq. 1, which can be a good criterion for understanding the correspondence value of the two intended subsets [4].

$$C(R)=\frac{\sum_{i=-m}^{i=m}\sum_{j=-m}^{j=m}(G_r(X_p,Y_p)-G_d(X_p',Y_p'))^2}{\sum_{i=-m}^{i=m}\sum_{j=-m}^{j=m}(G_r(X_p,Y_p))^2} \quad (1)$$

$$X_p=x_p+i \quad (2)$$

$$Y_p=y_p+j \quad (3)$$

$$X_p' = x_p + i + U_s(i,j) \quad (4)$$

$$Y_p' = y_p + j + V_s(i,j) \quad (5)$$

And R is the unknown vector as follows:

$$R=(X,Y,U,V,\frac{\partial u}{\partial x},\frac{\partial v}{\partial x},\frac{\partial u}{\partial y},\frac{\partial v}{\partial y}) \quad (6)$$

In Eqs. 2-6, U and V are displacement components G_r and G_d are continuous functions of light intensity interpolation before and after loading. (x, y) and (x', y') are points coordinates in subsets of reference and deformed images that relate to each other according to Eqs. 7 and 8 [4].

$$x'=x+U+\frac{\partial U}{\partial x}\Delta x+\frac{\partial U}{\partial y}\Delta y \quad (7)$$

$$y'=y+V+\frac{\partial V}{\partial x}\Delta x+\frac{\partial V}{\partial y}\Delta y \quad (8)$$

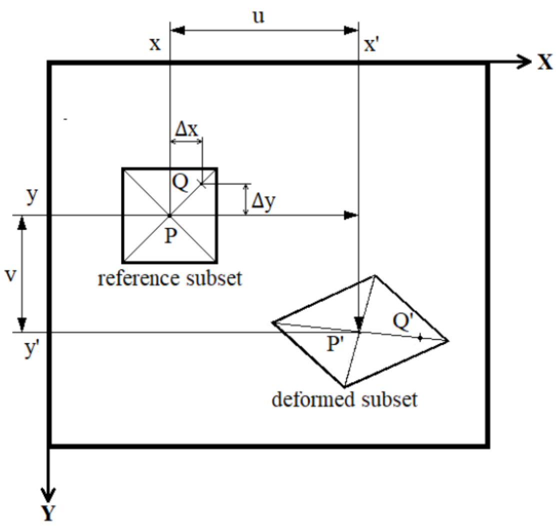


Figure 2. Reference and deformed subsets

In Eqs. 2 and 3, Δx and Δy are horizontal and vertical distances of the point (x, y) from the subset center. In correlation relation, the amount of light intensity at each point of the reference image subset is compared with the same subset in the image after loading and their difference is obtained. Then the square of their difference is divided by the square of light intensity of that point in the reference image. The obtained number is a measure of the relative error at that point. To calculate the sum of total error in a subset, the error values of the points are added together, when the correlation coefficient is zero the error function in the whole subset is zero, and this indicates a complete match. The best solution is obtained when the coefficient C(R) in Eq. 1 is minimized. In other words, interpolation functions are slightly different before and after loading anywhere. According to Eq. 9, to minimize C, its gradient must be zero.

$$\nabla C = \left(\frac{\partial C}{\partial R_k}\right)_{k=1,13} \tag{9}$$

Newton-Raphson method is used to solve Eq. 4 and obtain its roots. This method uses an approximate initial value to find the root of the equations and repeats until the error is less than a certain value. Since the correlation coefficient is a function of the displacement components and their gradients, these unknowns can be obtained by searching for a category of these components that minimize the correlation coefficient. In the correlation method algorithm, the search process for calculating the unknown displacements and displacement gradients is started with long steps. In this process, the displacement gradients are initially considered zero, the algorithm searches for the 1-pixel steps in the interest area , and the pixel that minimizes the correlation coefficient is considered the initial solution. Then, using the Newton-Raphson method, their displacements and gradients are accurately obtained with a fraction of pixel size. The results of this step are used as initial values in the Newton-Raphson algorithm for the next subset [3]. In this method, by performing general calculations, finally, the strains in different directions are calculated as Eqs. 10-12:

$$\varepsilon_{XX}=\frac{1}{2}\left(\left(\frac{du}{dx}\right)^2+\left(\frac{dv}{dx}\right)^2+\left(\frac{dw}{dx}\right)^2\right)+\left(\frac{du}{dx}\right) \tag{10}$$

$$\varepsilon_{yy}=\frac{1}{2}\left(\left(\frac{du}{dy}\right)^2+\left(\frac{dv}{dy}\right)^2\right)+\left(\frac{dv}{dy}\right) \quad (11)$$

$$\varepsilon_{zz}=\frac{1}{2}\left(\left(\frac{du}{dy}\right)+\left(\frac{dv}{dx}\right)\right)+\frac{1}{2}\left(\frac{du}{dx}\frac{du}{dy}+\frac{dv}{dx}\frac{dv}{dy}\right) \quad (12)$$

3. Central hole drilling

In the central drilling method, a rosette strain gauge is first attached to the part surface with residual stress. In the rosette strain gauge, the optimum strain gauges points are observed. Then a small hole, a little deeper than the diameter of the hole, is created at the center of the rosette strain gauge. This hole locally releases stresses around the hole and the strains released are measured by three strain gauges on the rosette as shown in Figure 3 [8].

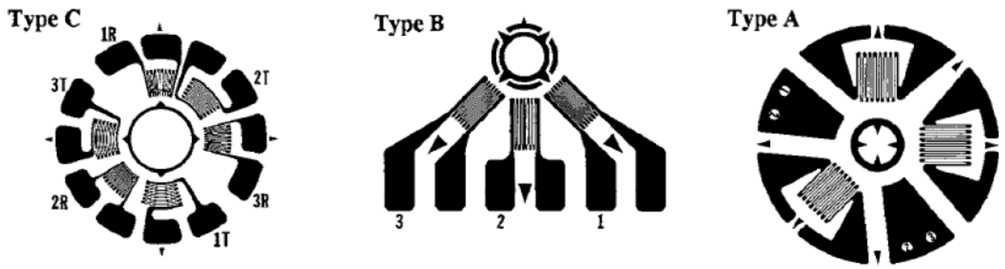


Figure 3. Strain gauge location in central hole drilling method [8]

In this regard, Schajer and Yang have identified nine calibration coefficients to relate the residual stress and strain released, which can be obtained by theoretical, numerical, and experimental methods [9]. With an analytical solution, they calculated the values of the calibration coefficient for a suitable range of different mechanical properties of orthotropic materials. They used the matrix as shown in Eq. 13:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix}=\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} \quad (13)$$

In Eq. 8 softness or calibration coefficients C_{11} - C_{33} are dependent on the elastic properties of the specimen, diameter, depth of the hole, and strain gauge geometry. To solve these coefficients, an analytical solution, reference to a standard, and finite element simulation can be used [10]. In this study, to calculate the calibration coefficients, simulation was used in ANSYS 19.2 software.

Eqs. 14-22 can be used to measure the stress around the created hole. The following strain values must be used to calculate the following constants as shown in Eqs. 14-16 [8].

$$p = \frac{(\varepsilon_3 + \varepsilon_1)}{2} \quad (14)$$

$$q = \frac{(\varepsilon_3 - \varepsilon_1)}{2} \quad (15)$$

$$t = \frac{(\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)}{2} \quad (16)$$

As stated, there are different methods for calculating calibration coefficients and after calculating these coefficients their values are put in Eqs. 17-19 [8].

$$P=\frac{(\sigma_y+\sigma_x)}{2}=\frac{Ep}{\bar{a}(1+\vartheta)} \quad (17)$$

$$Q=\frac{(\sigma_y-\sigma_x)}{2}=-\frac{Eq}{\bar{b}} \quad (18)$$

$$T=\tau_{xy}=-\frac{Et}{\bar{b}} \quad (19)$$

After calculating relationships, the values of plate stresses can be calculated through Eqs. 20-22 [8].

$$\sigma_x=P-Q \quad (20)$$

$$\sigma_y=P+Q \quad (21)$$

$$\tau_{xy}=T \quad (22)$$

The maximum and minimum stresses can also be calculated by Eq. 23. The maximum tensile (or minimum compressive) principal stress, σ_{max} is at the angular position β in the clockwise direction relative to the strain gauge position 1 shown in Figure 3. In the same way, minimum tensile (or maximum compressive) principal stress, σ_{min} is at the angular position β in the clockwise direction relative to the strain gauge 3 shown in Figure 3. The angle β can be calculated by the Eq. 24[8].

$$\sigma_{max},\sigma_{min}=P\pm\sqrt{Q^2+T^2} \quad (23)$$

$$\beta=\frac{1}{2}\tan^{-1}(T/Q) \quad (24)$$

4. Experimental

4.1 Preparation of composite specimen

There are various methods for producing composites, which hand layup process is the oldest and most basic method. This method was designed to produce small parts but now is used for mass production.

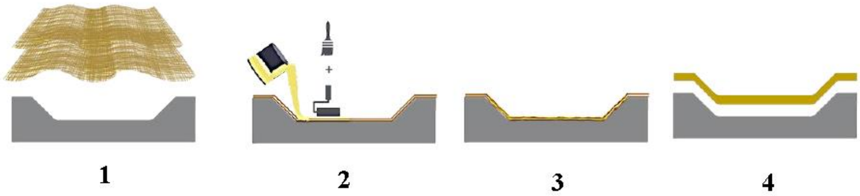


Figure 4. Composite fabrication by hand layup method

The composite used in this study is proposed as a part of a car with more desirable properties and higher strength that has polyester resin and glass fiber. Properties of resins and fibers have been shown in Table 1.

Table 1. Mechanical properties of composite components

Properties \ Material	Polyester	Glass fiber
Young's Modulus (GPa)	3.5	72
Poisson's Ratio	0.35	0.2
Weight Percent	0.65	0.35

The Equivalent Properties Law will be used to evaluate the equivalent properties of the composite. This rule will define the equivalent property for a composite based on the property of each component and its weight percentage. This rule will be defined as Eq. 25 to evaluate the equivalent Young's modulus value.

$$E_c = F_f \times E_f + F_m \times E_m \qquad (25)$$

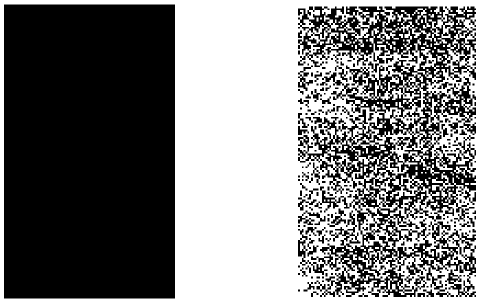
In Eq. 25, E and F are Young's modulus and the weight percent of each composite component, respectively. By performing the required calculations based on Eq. 25, the equivalent Young's modulus value E_c will be obtained for the composite. Using Eq. 25, the equivalent Young's modulus E_c is 27.5 GPa and the equivalent Poisson's ratio is 0.3.

The construction steps are a form of wax molding, separator film application, gel coat layer application (to improve quality, and protection against moisture), Apply Tisho Fiber Layer to strengthen the gel coat layer, apply a resin and apply layers as needed. After waxing and separating and drying, the gel was applied to the mold. Gel coat is a polyester resin made of thixotropic materials. After 17 to 20 minutes, the gel layer is manually placed at angles and surfaces using glass needle fibers. If the piece is thick, the matte fiber of 225 to 450 grams can be used which is denser. Figure 5 shows the composite fabrication steps.

Figure 5. Steps composite production

4.2. Hole Drilling – Digital Image Correlation process

A device performing drilling and imaging operations has been designed to evaluate the residual stress in composite components. Due to the digital image correlation method, a speckle pattern on the piece must first be created as Figure 6. Because the base surface of the piece is black, this speckle pattern will be created white by spraying on the sample.



(a) (b)

Figure 6. Surface (a) without (b) with speckle pattern

After creating a speckle pattern on the piece, the workpiece will be clamped under the setup. At this step, an image of the workpiece surface will be taken by the camera and saved as a reference image. Then drill edge will be tangent to the workpiece and then the drilling operation will be performed following standard values. After the operation, the drill will be pulled out of the piece and the next image will be taken. The same procedure will be repeated in as many steps as possible for imaging.

Figure 7. Designed setup for residual stress measurement

5. Simulation

Composite specimens were made and drilling operations were modeled with the same conditions in ANSYS software as shown in Figure 8. The installation of strain gauges with the required size and diameter has carefully meshed. Also, the drilling location and dimensions of the plate have carefully meshed. The number of elements used in the simulation is 3951 elements and 192 elements are used for each strain gauge.

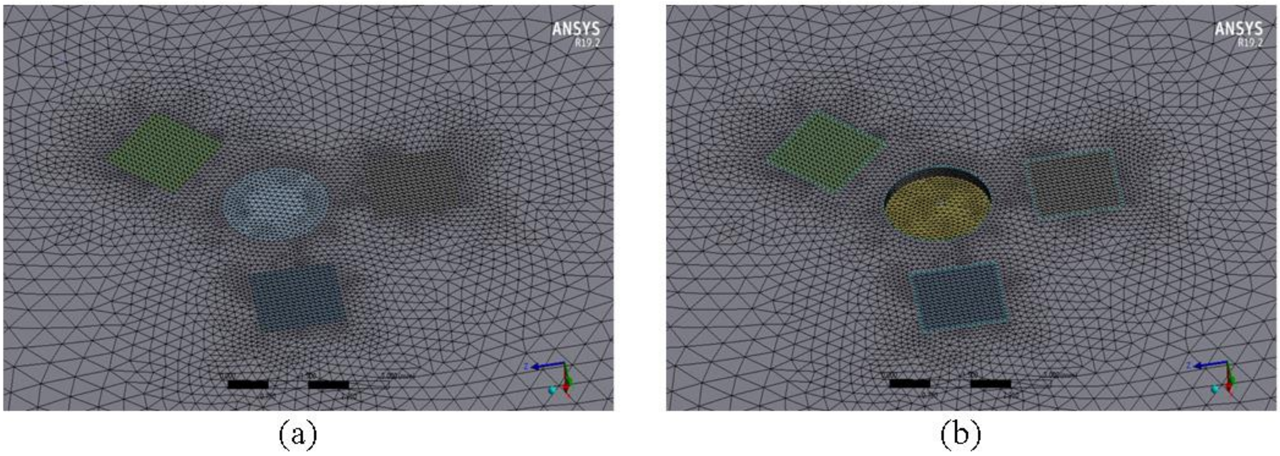


Figure 8. Simulation of drilling operations in Ansys software (a) before drilling (b) after drilling

To calculate the residual stress values generated in the specimen, the calibration coefficients should be calculated by software simulation. To calculate the calibration coefficients, they must be loaded in three standard conditions, as shown in Figure 9, and calculated by extracting the strain values and placing them in the stress-value equations.

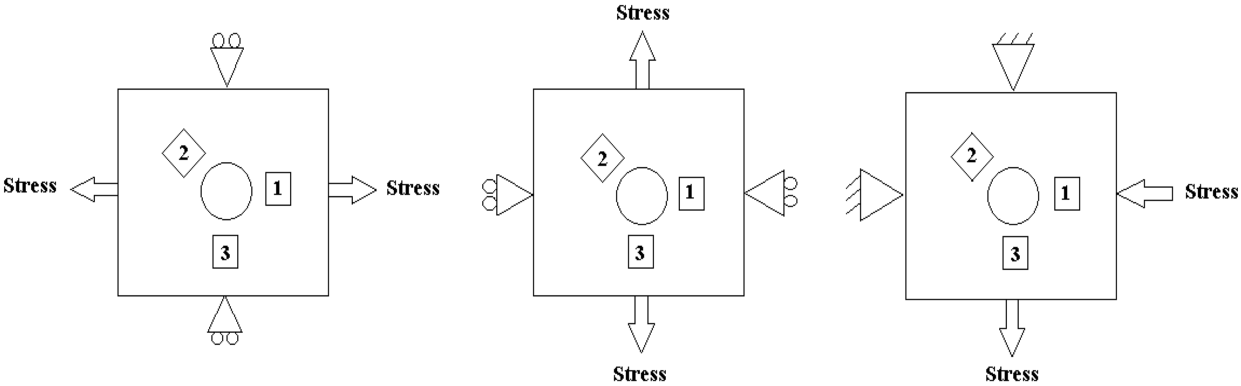


Figure 9. Standard loading condition for calibration coefficient calculation

Composite specimens were drilled by the drilling machine and digital imaging was performed during the operation. All the recorded images are then analyzed in GOM Correlate software. After importing the images before and after deformation into the software, the areas required for analysis will be selected and the displacement and strain fields will be calculated at these regions. With the use of strain output and the use of calibration coefficients, stress parameters can be achieved. The sample image in the software is shown in Figure 10. The directions shown in Figure 10 are selected according to the standard and the strain values will be calculated in these directions.

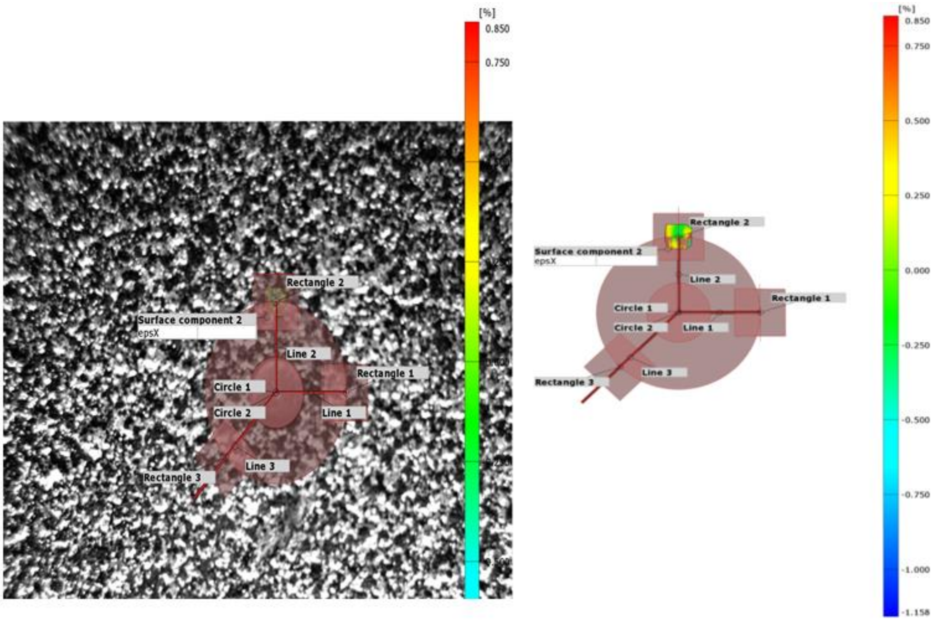


Figure 10. Experimental investigation of strain by drilling-correlation method

6. Residual stress

To investigate the residual stresses in produced composite components, three-point bending loading was applied to the piece. A Schematic of how the load is applied to the desired segment is shown in Figure 11.

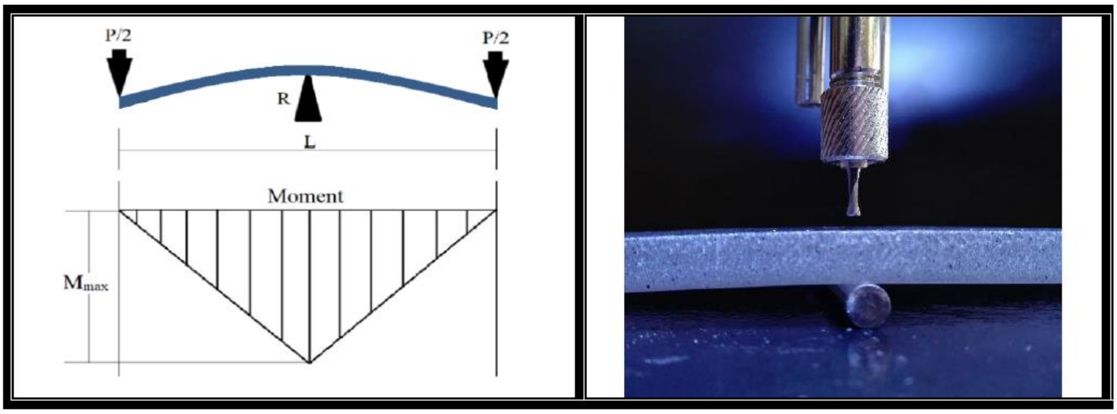


Figure 11. Apply a three-point bending load on the piece

In this test, due to the geometrical symmetry of the parts, a simple beam with a central load is considered and the bending stress applied to the components is calculated by Eq. 26:

$$\sigma_{bend} = \frac{Mc}{I} \quad (26)$$

In Eq. 26, M is the bending moment, c is the distance to the neutral line, and I is the cross-section moment. The amount of bending moment applied to the components is obtained by Eq. 27:

$$M = \frac{PL}{4} \quad (27)$$

The force that gives rise to this torque in the components can also be obtained by the displacement value expressed in Eq. 28:

$$\Delta_{max} = \frac{PL^3}{48\,EI} \quad (28)$$

After calculating the stress values by analytical solution and drilling-correlation method, these values are compared with each other. GOM software can obtain strain values in all directions. These values will then be converted to stress using the equations and calibration coefficients obtained from the simulation. The difference between the values obtained from the analytical stresses and the experimental tests and simulations will be equal to the values of residual stresses in the segment. These values are presented in tables 2 and 3.

Table 2. The amount of residual stress σ_x in different bending conditions

Bending amount (mm) \ Method	Central hole drilling-DIC stress (MPa)	Residual Stress (MPa)
3	10.81	3.91
5	15.51	4.01
6	18.19	4.39

Table 3. The amount of residual stress σ_y in different bending conditions

Bending amount (mm) \ Method	Central hole drilling-DIC stress (MPa)	Residual Stress (MPa)
3	9.61	3.01
5	14.42	3.22
6	17.23	3.73

7. Conclusion

In this study, a new method for measuring residual stress is presented. Due to the limitations of the central hole drilling method in strain gauge installation and its related parameters, the use of an optical method can increase the capabilities of this method. The digital image correlation method allows the user to calculate the residual stress in all directions at a very high speed. Finally, by comparing the values obtained for residual stresses, it has been found that the hole drilling-DIC method has good speed and accuracy and its results are in good agreement with the analytical solution results.

8. References

[1] Shokrieh, M. 2014. Residual stresses in composite materials. Woodhead publishing, Sawston, United Kingdom.

[2] Mathar, J. 1934. Determination of initial stresses by measuring the deformation around drilled holes. Trans. ASME. 56(4): 249-254.

[3] Schajer, G. S. 2010. Advances in hole-drilling residual stress measurements. Experimental mechanics. 50(2): 159-168.

[4] Sutton, M. A., Wolters, W. J., Peters, W. H., Ranson, W. F. and McNeill, S. R. 1983. Determination of displacements using an improved digital correlation method. Image and vision computing. 1(3): 133-139.

[5] Hild, F., Roux, S. 2012. Digital image correlation. Optical methods for solid mechanics. A full-field approach. 367: 183-228.
[6] Bartlett, J. L., Croom, B. P., Burdick, J., Henkel, D., and Li, X. 2018. Revealing mechanisms of residual stress development in additive manufacturing via digital image correlation. Additive Manufacturing. 22: 1-12.
[7] Ghasemi Tamami, P. and Akbari, D. 2017. Study on defect detection of industrial parts with Digital Image Correlation method. 25th Annual Conference of Mechanical Engineering. Tehran, Iran.
[8] Standard, A. S. T. M. 2008. E837-08 Standard test method for determining residual stresses by the hole-drilling strain-gage method. ASMT international, West Conshohocken, PA.
[9] Schajer, G. S. and Yang, L. 1994. Residual-stress measurement in orthotropic materials using the hole-drilling method. Experimental Mechanics. 34(4): 324-333.
[10] Shokrieh, M. M. and Ghasemi K, A. R. 2007. Determination of calibration factors of the hole drilling method for orthotropic composites using an exact solution. Journal of Composite materials. 41(19): 2293-2311.