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FROM MEASUREMENTS ERRORS TO A NEW STRAIN GAUGE DESIGN FOR COMPOSITE MATERIALS

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ABSTRACT

Significant over-prediction of the material stiffness in the order of 1-10% for polymer based composites has been experimentally observed and numerical determined when using strain gauges for strain measurements instead of non-contact methods such as digital image correlation or less stiff methods such as clip-on extensometers. In the present work, this has been quantified through a numerical study for three different strain gauges. In addition, a significant effect of a thin polymer coating or biaxial layer in the erroneous using strain gauges has been observed. An erroneous which can be significantly decreased using an enhanced grid design of the measuring grid.

1 INTRODUCTION

Determining the material stiffness require a precise strain measurement. Due to the price and ease of using, strain gauges are often used as the deformation measurement testing composites. Strain gauges are measuring the strain in the underlying material through an electrically resistance change in a measuring grid. A resistance change which are related to a strain value through a gauge factor supplied by the strain gauge manufacture together with the specific strain gauge batch. Nevertheless, used on composite materials with a material stiffness in the range of 3-35 GPa, a uni-directional strain gauge has been found to over-predicting the material stiffness with 1-9 %, see [1]. Based on finite element studies and digital image correlation measurements, this over-predictions are identified to be caused by a strain inhomogeneity introduced by a stiffness mismatch between the measurements grid on E=180GPa and the testing material. Despite a thickness of the measurements grid on only 5 microns, the strain inhomogeneity is found to significantly influence the strain in the measurement grid. Inspired by the finite element simulations, this strain inhomogeneity in the strain gauge grid is suggested to be removed by adding a stiff material at the end of the measuring part [2]. During this, it is possible to lower the erroneous of the material stiffness determination to below 1% in the full, for the composites materials, relevant stiffness range. The improvements are only based on an alternation of the shape of the measurement grid and will therefore only cause a negligible higher manufacturing cost of the strain gauges. The improvements does not only relates to unidirectional strain gauges. As it is shown in the figure, the finite element predictions shows that using the new strain gauge design in the case of a +-45 degree strain gauges, it is possible to improve the accuracy of the experimentally shear module determination significantly. In addition to this, the improved strain gauges design is found to also to lower the dependency of the stain gauge measurements on the occurrence of low stiffness outer layer such as a resin rich layer or by applying a top ply of woven or chopped fibers. In the following, the erroneous of conventional strain gauges are numerically validated. The results from the improved strain gauges design will not be presented in the proceedings paper but will be presented to ICCM20.

2 NUMERICAL MODEL

A uniaxial tensile test specimen with the length of 100 mm, the width of 30 mm and a thickness of either 2, 4 or 30 mm are modelled as a linear elastic isotropic material with a material stiffness in the range of $E \in [1;\ 200] GPa$ and a Poisson's ratio on $\nu = 0.3$. The uni-axial test specimen is mounted with a strain gauge on both sides but due to symmetry, only one quarter of the specimen in the width and the thickness direction is modelled, see figure 1. The strain gauge is modelled as an E=180 GPa stiff linear elastic constantan alloy grid (red part in figure 1) mounted on a 45μm thick polymer film (yellow part in figure 1). Three different gauge length, $L_{grid} = 1.5mm$, $L_{grid} = 3.0mm$ or $L_{grid} = 10mm$ are investigated with the corresponding grid spacing $W_{gap} = 30\mu m$ for the two first and $W_{gap} = 100\mu m$ for the last one and a corresponding wire width on $W_{wire} = 20\mu m$, $W_{wire} = 30\mu m$ or $W_{wire} = 80\mu m$, respectively. For all cases, the grid thickness is given by $t_{wire} = 5\mu m$. The strain gauges geometry is chosen to mimic the HBM [3] strain gauges series, 1-LY11-1.5, 1-LY11-3/120 and 1-LY11-10/120, respectively but could as well be chosen to mimic one of the other strain gauges on the market. The mesh is concentrated near the strain gauges with smallest element size given by the wire width.

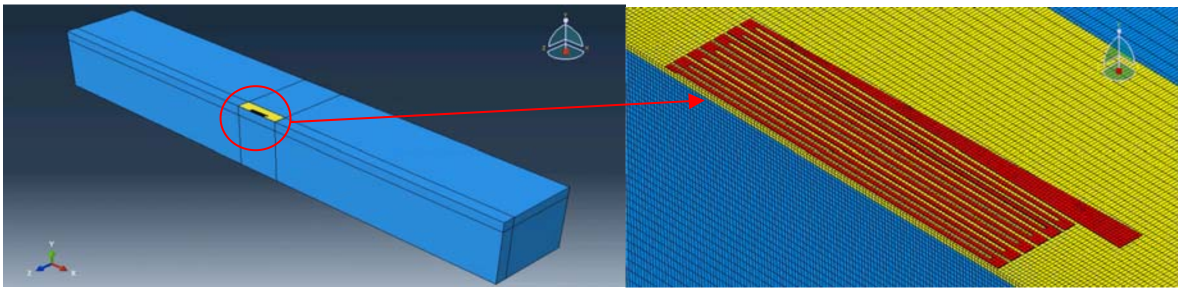

Figure 1: Finite element model of strain gauges

As the model is linear, the load level doesn't matter. Nevertheless, as the standard for testing fibre reinforced polymers [4] prescribe that the stiffness shall be taken in the range of $\varepsilon \in [0.05;\ 0.25]\%$ strain the specimen is elongated to an overall 0.25% strain. A physically strain gauges relate the resistance change with the strain in the substrate through a gauge factor provide by the strain gauge manufacture from a calibration on a 200 GPa stiff material. In the finite element model, the average straining of the wire in the measuring grid can be considered analog to a resistance change and the gauge factor is found relating this strain gauge wire averaging strain with the straining in the underlying substrate with a numerical gage factor found by performing the analysis for a 200 GPa substrate. Of this reason, all results found for 200 GPa has a defined error on 0%.

3 RESULTS

In the following, a numerical study has been performed predicting the measurement error of the strain gauge determining the strain and thereby the material stiffness of the substrate. A positive error corresponds to an underestimate of the strain and therefore an overestimate of the material stiffness.

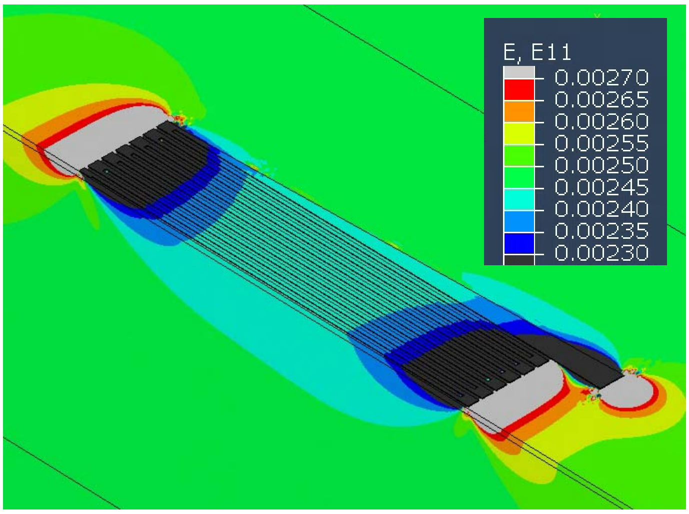

Figure 2: The non-uniform strain around a 3 mm strain gauge mounted on an E = 10 GPa stiff substrate.

Figure 2 show the variation of the axial strain around a conventional 3 mm strain gauge mounted on a thick 10 GPa stiff substrate which e.g. could corresponds to a biaxial reinforced polymer composite. The substrate is deformed to an axial strain on $\varepsilon = 0.25\%$ during a uniaxial elongation which corresponds to the green colour. Despite that small thickness of the constantan wire in the strain gauge grid, the higher stiffness of the wire is seen to results in a rather spread-out non-uniform strain field. The contours' going from blue to red represents axial strain in the range $\varepsilon \in [0.23; 0.27]\%$ while the grey and black contours corresponds to values below and above those values, respectively. Due to the thickness, the overall stiffness of the substrate is not affected by the strain gauges. Therefore, the smaller axial strain just below and in the grid must be accompanied by larger strain in the substrate material just outside the strain gauge.

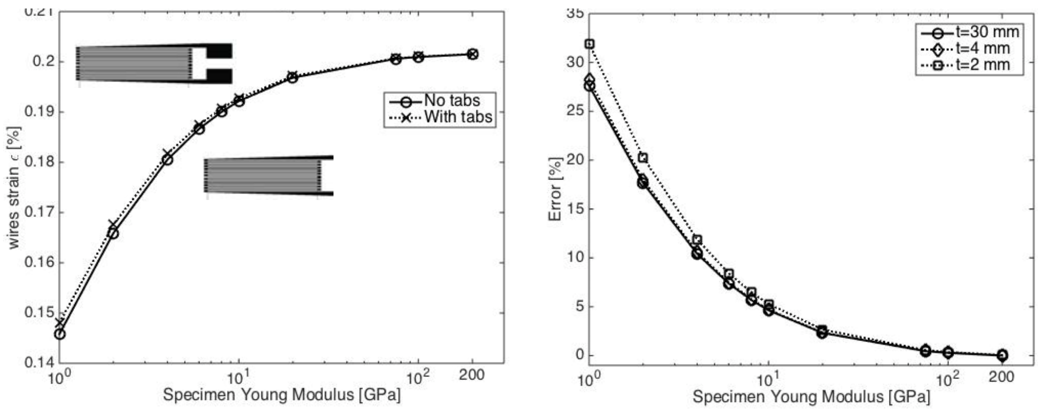

Figure 3: Effect of the soldering tabs (a) and of the thickness of the substrate (b) on the measurement error of the strain gauges with a 3 mm gauges section.

From the two nearly coinciding curves on Figure 3a, it can be seen that the effect of the soldering tabs of a conventional strain gauges on the strain measurements of the strain gauges can be neglected. Nevertheless from Figure 3b, a small increase in the measurement error is is found mounting the strain gauges on thinner materials. It is a symmetric model so the 2, 4 and 30 mm thick specimen mounted with strain gauges on both sides corresponds to a symmetric finite element model with the thickness of 1, 2 and 15 mm, respectively. The increases in the measurements error for the thinner specimens are due to the fact that the strain gauges for the thinner case will contribute slightly to the overall stiffness of the test sample. A comparison of the strain field for the 2 and 4 mm case are shown in figure 4. The contours level used are the same as the one used for the thick case in figure 2.

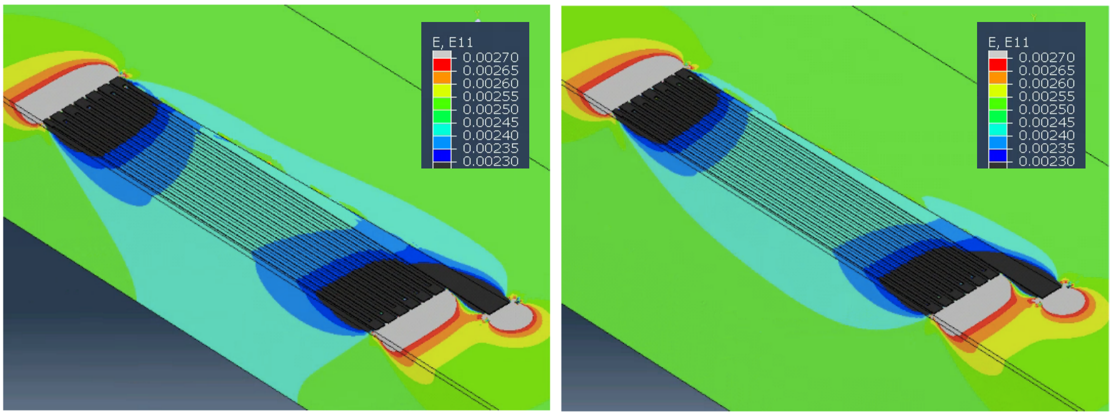

Figure 4: Non-uniform strain around a 3 mm strain gauge mounted on an E = 10 GPa stiff substrate for the 2 and 4 mm thick substrate case.

From the contour plots in figure 2 and figure 4 the reinforcement effect can be seen to concentrate around the ends of strain gauges and the size are not expected to scale the grid as also found in [1]. Therefore, the measurements error is expected to be smaller using a longer measuring grid. In figure 5, the measurements errors are found for strain gauges with a gauge length on 1.5, 3 and 10 mm, respectively. As expected, the measurement error is found degrees with increasing grid length but for all cases, there are still significant measurements error in the for glass fibre composite relevant stiffness range of $E \in [5;45]GPa$.

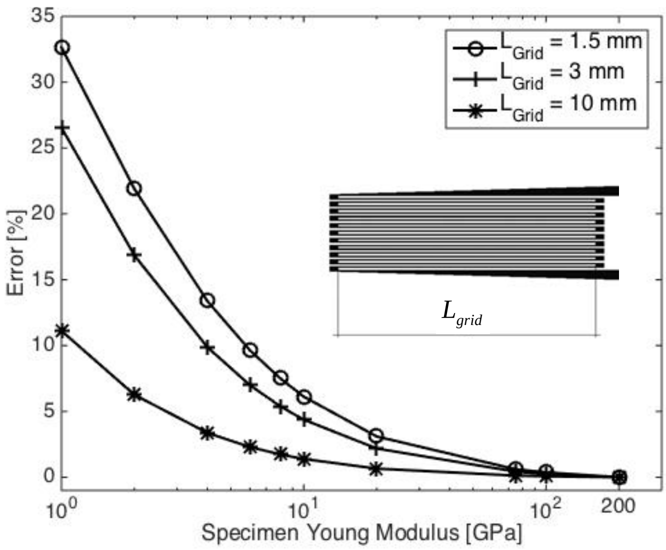

Figure 5: Predicted measurements error on the material stiffness using a 1.5, 3 and 10 mm strain gauges, respectively.

Unidirectional composite materials have often a protecting biaxial or randomly oriented ply on the outer layer. In addition, the present of a resin rich layer or a gelcoat can also be present. In figure 5, the measurement error for a uni-directional glass fiber composite can be found correspond to 2% using a 3 mm strain gauges. In figure 6, the effect of the present of a softer outer layer on the strain gauges measurements is investigated.

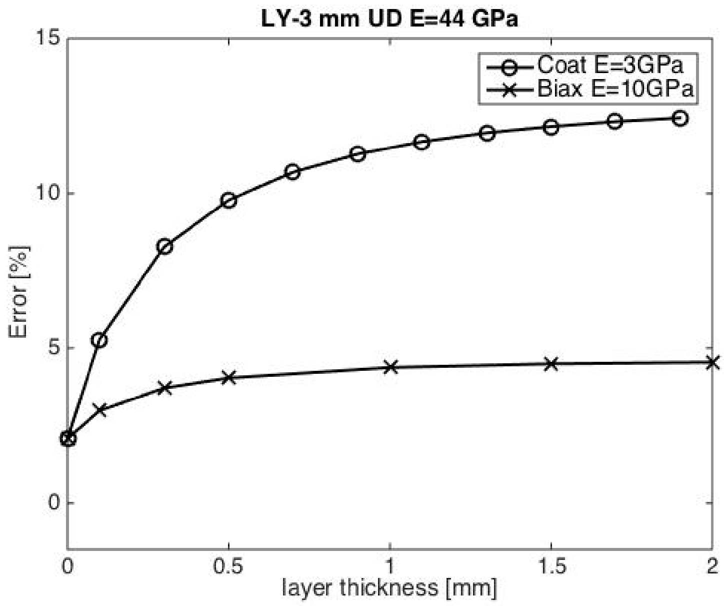

Figure 6: Effect on the measurement error of a gelcoat or biaxial composite layer between a 3 mm strain gauges and a thick uni-directional glass fiber composite substrate with E=44GPa.

Figure 6 show that increasing the layer thickness up-to approximately 1 mm will increase the overestimate of the material stiffness quite significant and e.g. increase the measurement up to above 10 % in the present of a gel-coat. Even for a thin resin rich layer on only 100 µm can be seen to increase the error with more than a factor of 2 to more than 5%. A factor needed to be taken into consideration when making precise experimental stiffness determination of compliant materials such as fiber reinforced polymer-based composites using strain gauges.

9 CONCLUSIONS

A linear numerical finite element model has been used in order to validate experimental observed over-estimation of the material stiffness using strain gauges. The numerical predictions have been used to quantify this over-estimation. In addition, the effect on the erroneous of the strain gauges when a thin soft layer such as a gel-coat or a biaxial layer is present in-between the composite and the measuring strain gauges. Predictions, which show the need for well-defined testing procedures comparing experimental determined material stiffness's.

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