Substitution of Strain Gauges by Optical Strain Measurement for Standard Test Methods of Composite Specimens and Introduction of a New Biaxial Test-Fixture

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Abstract. Composite parts have a high potential in weight saving for aerospace as well as automotive applications. In the research project RICA, which is funded by the German Federal Ministry for Economic Affairs and Energy, the Universität der Bundeswehr München, the test house BKW Applus+, the composite material manufacturer Teijin and the aircraft manufacturer Boeing are working closely together to enhance material values and allowable by improving material tests to gain more precise values from testing. The project also includes Altair for numerical simulation methods, Vorwerk Autotec for automotive applications, the material manufacturer Henkel and the small and medium enterprise Eckerle for tooling design and manufacturing. Expensive strain measurements will be discussed and modifications to reduce waste and CO_2 in standard testing will be proposed. Complete stress–strain curves are necessary to use advanced failure criteria and material models in simulation to reduce weight in structural parts. However, measurements with the use of strain gauges often cannot provide these complete strain curves until failure, therefore optical strain measurement is investigated for standard test methods. Standard tests were used as baseline and are modified to get more value out of a single test specimen. Additional values needed for modern failure criteria will be discussed and a new Boeing owned bi-axial test-fixture will be presented.

Keywords: Strain measurement · Strain gauge · Optical strain measurement · Digital Image Correlation · Material characterization · Failure criteria · Composite

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1 Introduction

Material values and allowable are used in todays linear calculations. For more advanced predictions of the load carrying behavior until failure, progressive failure analysis in finite element simulation are used more commonly now. Complete stress–strain curves are needed in all main manufacturing but also loading directions like tension, compression and shear. Strain gauges are used to measure the complete stress–strain curves. In Fig. 1 [1] the distribution of the costs for a complete material card as input for structural calculation is shown. The most expensive part with 58% of the complete costs is related to the strain gauges coming from procurement, installation and cabling. Part of the project is to find a more advanced, cheaper and sustainable method to measure strains in standard tests.

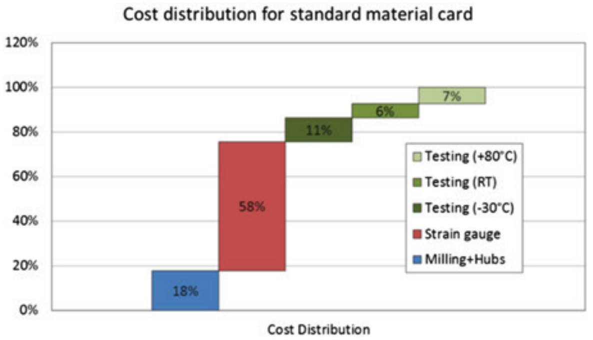

Fig. 1. Cost Distribution for standard material test [1]

In Table 1 a comparison is done with each advantages and challenges for the different systems like: Strain gauges, 1D mechanical measurement, 1D optical measurement, 2D optical measurement (1 camera) and 3D optical measurement (2+ cameras).

Table 1. Comparison of different strain measurement methods

	Strain Gauges	1D Mechanical	1D Optical	2D Optical	3D Optical
Advantage	– more than one direction possible – well known – small	– well known	– no surface preparation, marker required – no damage at failure	– 2D strain distribution – all strains over the complete specimen	– 3D strain distribution – all strains over the complete specimen
Challenge	– expensive – time consuming application – surface preparation	– only one direction – needs space – maybe damages at failure – slipping possible	– only one direction – may not be able to be used at different temperatures	– large amount of data – surface preparation – needs space	– large amount of data – surface preparation – needs space

2 Testing

2.1 Specimen Manufacturing

Composite plates with unidirectional plain carbon fibers and woven glass fibers with an epoxy resin system were used (RTM6/G1157). The composite plates were cut and adhesively bonded with quasi isotropic glass fiber tabs. After curing of the tabs, specimens were cut according to ASTM D3039 [2] with a length of 250 mm, and 25 mm and 15 mm in width. A linear strain gauge in a 3-wire circuit has been applied to the center of each specimen. For strain measurement with Digital Image Correlation (DIC), the surface of the specimens was painted with white acrylic spray. A stochastic speckle-pattern of black dots was sprayed with a paint gun afterwards. The final specimens are shown in Fig. 2a).

2.2 Test-Setup

The specimens were tensile-tested with a ZwickRoell Z150 testing machine with hydraulic clamps. A 150 kN load cell was used. Tests were driven position-controlled with 1 mm/min until specimens' failure. Strain was measured using the following three methods: strain gauge, Digital Image Correlation (DIC) and extensometer. An extensometer (digiclip kurz, ZwickRoell) was used to measure strains up to 0.3% strain and was clamped off above this value to prevent possible destruction of it. Because of the strain gauge and DIC-region of interest, the extensometer had to be clipped above the specimen's center, see Fig. 2b). The strain gauges were connected to a data acquisition device (MGCplus, HBM). Strain measurement with strain gauge and DIC was performed on the same specimen side to avoid different strain values caused by potentially occurred bending moment in the specimen. Through this, a direct comparison between the two methods can be made.

DIC Test-Setup. A Digital Image Correlation system (Q400, Limess GmbH,) with two cameras was used for the optical strain measurement method. The cameras were equipped with macro lenses including spacers, so that the image area was about 35 mm wide and 25 mm high to record the full specimen's width. After focusing the cameras to the specimens' surface, the relative position of one camera to the other was calibrated with a special calibration target. A reference image was recorded of the specimen, clamped one-sided. This image is set as the unloaded condition of the specimen. Also, strain gauges were tare at this moment. A frequency of 1 Hz was used for recording acquisition of the DIC.

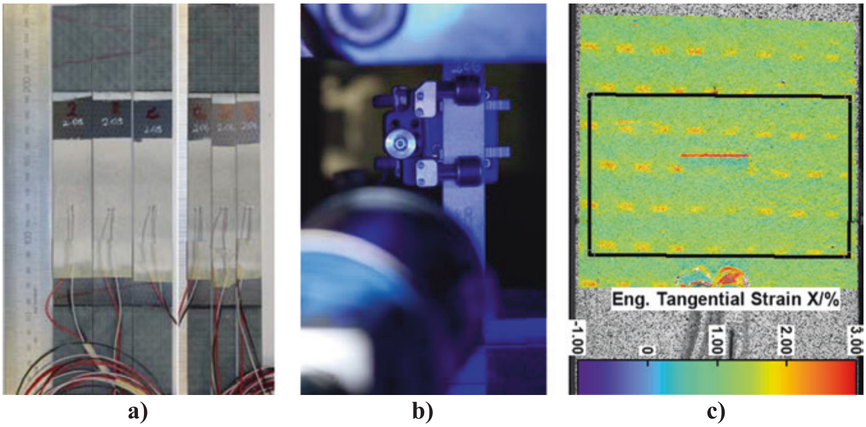

Fig. 2. Test-Setup: a) specimens; b) backside view with extensometer, strain gauge and speckle-pattern; c) DIC-Evaluation field on specimen surface

2.3 Test Results

Evaluation of Strains Using DIC. A coordinate system was set to define the x-direction as the loading direction and the y-direction perpendicular on the specimen's surface to it. For evaluating the strains, an area of the surface was defined, in which the strain is averaged for each time step. This area nearly contains the full specimen width. Figure 2c) shows the evaluation field (black frame) of a specimen.

Stress Strain Curves. The strain measurements of extensometer (Ext), strain gauge (DMS) and DIC are shown in Fig. 3 to compare the different measurement methods on all specimens.

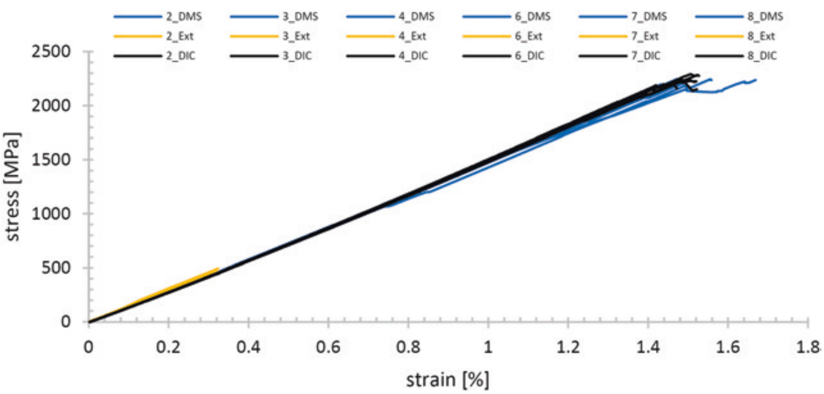

Fig. 3. Stress–strain curves with different strain measurement methods

2.4 Evaluation and Comparison of Strain Measurement Methods

DIC Measurement Scatter. To compare the different strain measurement methods, it is of importance to evaluate the scatter of the DIC measurement. Therefore, the strain in x-direction of a one-sided clamped and unloaded specimen was measured for approximately one minute. Figure 4 shows the calculated strain by the DIC with a computed uncertainty added/subtracted from the actual calculated value. The calculated values show a scatter of about 0.001% strain (in x-direction). Adding and subtracting the uncertainty to/from the actual value (dashed upper/lower line), shows a total scatter of about 0.002% strain (20 microstrains) which is equal to strain measurement requirement in DIN EN ISO 527-1 for Young's modulus estimation based on strain gauges [3].

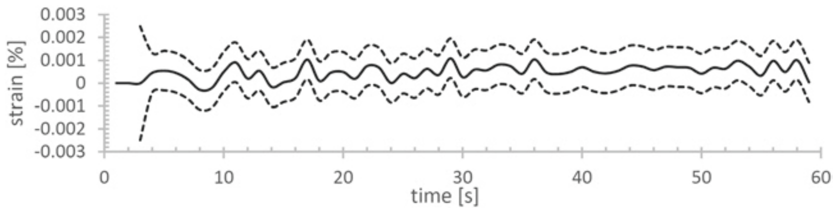

Fig. 4. DIC measurement's scatter of an unloaded specimen

Comparison of DIC and Strain Gauge Values. The calculated strains (in loading direction x) are now compared to the measured strains of the strain gauges of each specimen. Therefore, the absolute deviation was calculated by the difference of gauge strain and DIC strain, following Eq. 1:

$$\Delta\varepsilon = \varepsilon_{DMS} - \varepsilon_{DIC} \quad (1)$$

Figure 5 shows the absolute strain deviation based on strain gauge measurement for every specimen.

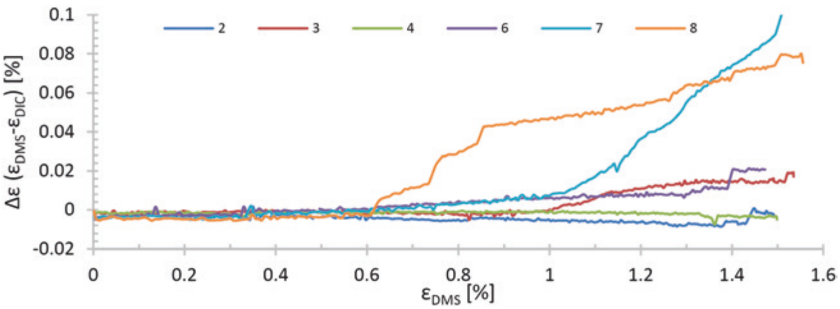

Fig. 5. Absolute deviation [% strain] of measured and calculated strain between strain gauge (DMS) and DIC

Up to a strain of $\varepsilon_{DMS} = 0.6\%$, a maximum absolute deviation of about $\Delta\varepsilon = 0.005\%$ strain is observed for all specimens. The deviation of specimen 8 increases from $\varepsilon_{DMS} > 0.6\%$ strain on, while the other specimens show a smaller increase of deviation up to $\varepsilon_{DMS} = 1\%$ strain, which is about a maximum deviation of $\Delta\varepsilon = 0.008\%$ strain or less. High and sudden deviations (specimens 7 and 8) are assumed to be damages in the strain gauge, or its soldered point.

Comparison of Young's Moduli by Different Strain Methods. Typically, Young's modulus estimation is performed by the difference quotient of stress and strain between 0.1% and 0.3% strain (Eq. 2), according to [2]:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_{x,2} - \varepsilon_{x,1}} \tag{2}$$

Especially in measurement data of the DIC, the selection of the measurement points can lead to different results. Therefore, every measuring point between 0.1% and 0.3% is taken into account by generating a linear regression, whose slope corresponds to the Young's modulus. Figure 6 shows a detail of the Young's modulus estimation based on the DIC-measurement. Here, some data points do not fit perfectly with the linear regression, which would lead to different results in a difference quotient.

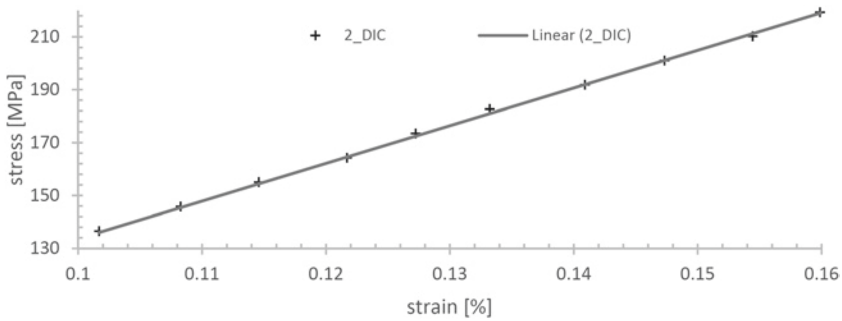

Fig. 6. Stress–strain-curve with linear regression of DIC measurement for Young's modulus estimation

Figure 7 shows the calculated values for Young's modulus based on the different strain measuring methods. It is seen, that the values are comparable. Figure 8 shows the mean values with the standard deviation, where the DIC measurement has a comparable standard deviation (986.1 MPa) compared to strain gauge measurement (1229.8 MPa). The measurement with extensometer shows the highest standard deviation (4891.7 MPa), supposed to be caused by slipping of the extensometer in specimens 2 and 8 (see Fig. 7).

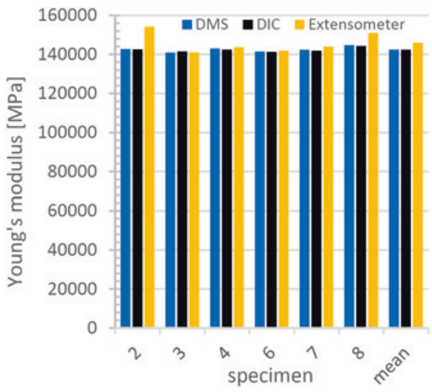

Fig. 7. Calculated Young's moduli by different strain measurement methods for all specimens and mean values

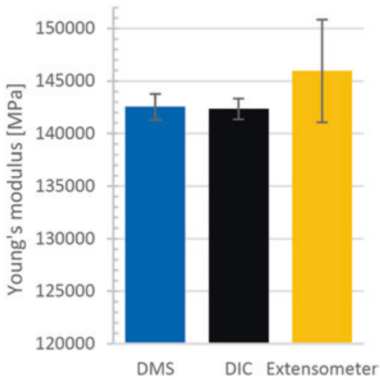

Fig. 8. Mean values and standard deviation of calculated Young's moduli by different strain measurement methods

Beside the evaluated strains in loading (x-) direction, the DIC measurement also offers (y-) strains perpendicular to the loading direction. With these strains, the estimation of the Poisson's ratio is possible, which could not be provided by 1D linear strain gauges. The Poisson's ratio was calculated using Eq. 3 at two measuring points (0.1% and 0.3% strain in loading direction). Figure 9 shows the calculated Poisson's ratio of each specimen and their mean value.

$$\nu = -\frac{\Delta\varepsilon_y}{\Delta\varepsilon_x} = -\frac{\varepsilon_{y,2} - \varepsilon_{y,1}}{\varepsilon_{x,2} - \varepsilon_{x,1}} \tag{3}$$

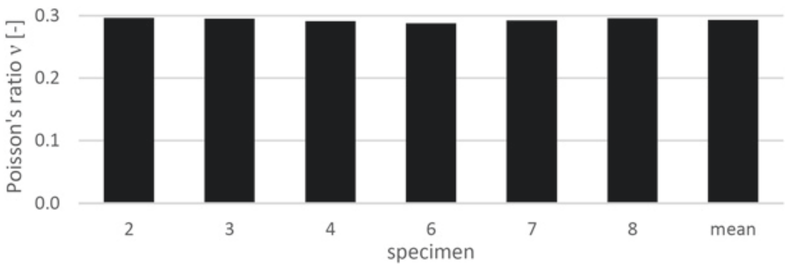

Fig. 9. Calculated Poisson's ratio of specimens and mean value using DIC

2.5 Conclusion

Different strain measurement methods were compared in tensile tests of composite specimens. Uncertainties in the DIC measurement were monitored by conducting a strain measurement with DIC of an unloaded specimen, which showed acceptable results concerning the measurement scatter of about 0.002% strain (with calculation uncertainties).

The comparison of strain values by DIC and strain gauge showed a low deviation until about 0.6% strain. Possibly due to strain gauge rupture, deviation in strain increases for some specimens. Increasing temperature due to lighting of the DIC could also have led to an increasing difference of strain values for strain gauges and DIC.

Comparing the calculated values for Young's modulus, methods based on strain gauges and DIC showed similar values. Here, the approach was to calculate the modulus by linear regression between 0.1 and 0.3% strain to not underly the effect that the selection of the measuring point influences the result. Young's moduli estimation based on values of the extensometer shows higher standard deviation, probably due to extensometer slipping on two specimens.

This work shows the potential using Digital Image Correlation for standard testing. The substitution of strain gauges would lead to less specimen preparation, cost and CO_2 savings, regarding its application and usage. Furthermore, complete stress–strain curves can be recorded, which could be a challenge while using strain gauges because of possible strain gauge rupture during testing.

3 Biaxial Test-Fixture

Interaction values in normal-normal loading are necessary for progressive failure analysis to support testing. They are used in various failure criteria like:

- Composites – unidirectional, woven and non-crimped fabric
  - CUNTZE-BOLD UD & WOVEN Fig. 10 a), b)
  - Tsai-Wu

- non-metallic – resin systems or adhesives
  - von-Mises Yield Criteria Fig. 10 c)
  - CUNTZE-BOLD Adhesives
- metal materials – like titanium, aluminum or steel
  - von-Mises Yield Criteria Fig. 10 c)
  - new CUNTZE-BOLD AM for additive manufactured materials Fig. 10 d)

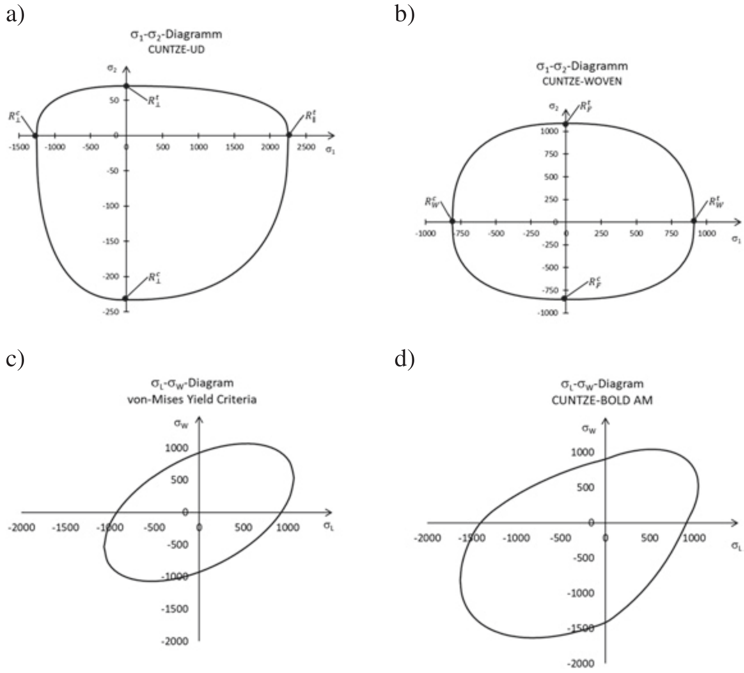

Fig. 10. Different failure criteria envelopes for a) CUNTZE UD, b) CUNTZE WOVEN, c) von-Mises Yield Criteria, d) new CUNTZE-BOLD AM

A new bi-axial test using an uni-axial standard test machine was developed from the design idea (Fig. 11 a), through a digital twin (Fig. 11 b) and the evaluation of the stresses (Fig. 11 c) to the design digital twin (Fig. 11 d) resulting in the real twin (Fig. 11 e).

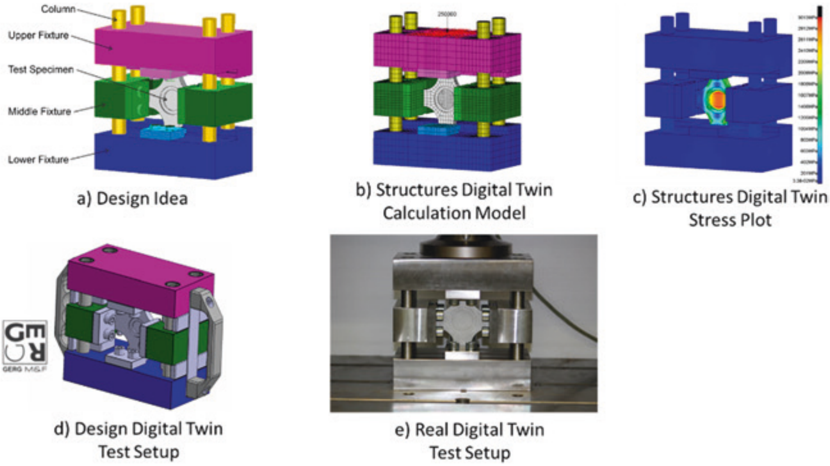

Fig. 11. Bi-axial test setup using a uni-axial test machine (Boeing intellectual property)

The strains were measured using Digital Image Correlation and evaluated in the center of the specimen on the complete area (circle 1) and only in the inner most area (circle 2) as shown in Fig. 12.

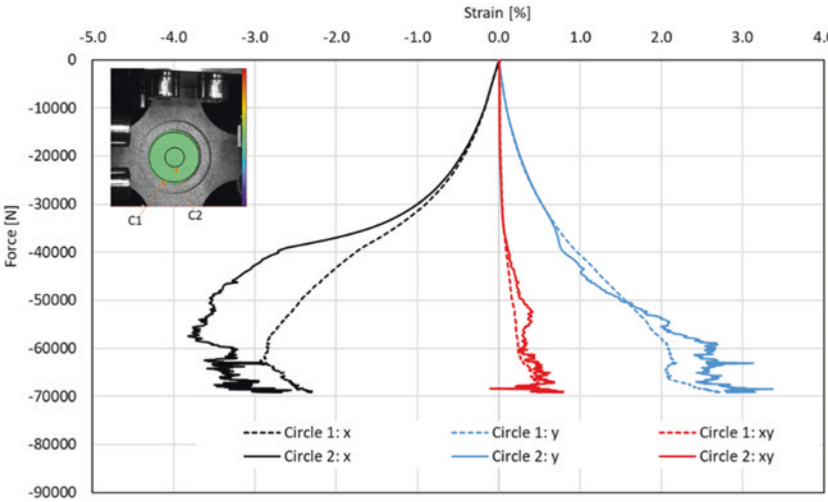

Fig. 12 Strain evaluation using digital image correlation for bi-axial test setup using a uni-axial test machine

The measured strains of the complete test area (C2) were used and the corresponding stiffness was calculated using a bi-linear approach for the non-linear, anisotropic material behavior in the loading direction. These were used to calculate the stresses based on a plane stress state (Eq. 4).

$$\begin{pmatrix} \sigma_W \\ \sigma_T \\ \tau_{WT} \end{pmatrix} = \begin{bmatrix} \frac{E_w(\varepsilon_W)}{1-\nu^2} & \frac{\nu E_W(\varepsilon_W)}{1-\nu^2} & 0 \\ \frac{\nu E_T(\varepsilon_T)}{1-\nu^2} & \frac{E_T(\varepsilon_T)}{1-\nu^2} & 0 \\ 0 & 0 & G_{WT} \end{bmatrix} \begin{pmatrix} \varepsilon_W \\ \varepsilon_T \\ \gamma_{WT} \end{pmatrix} \tag{4}$$

The efforts were calculated and are shown in Fig. 13 a). While the effort for von-Mises yield criteria would predict a value above 1, the new CUNTZE-BOLD AM will lead to an effort around 1. The normal-normal stress is posted in Fig. 13 b) and is very close to the new CUNTZE-BOLD AM non-linear material model and failure criteria envelope.

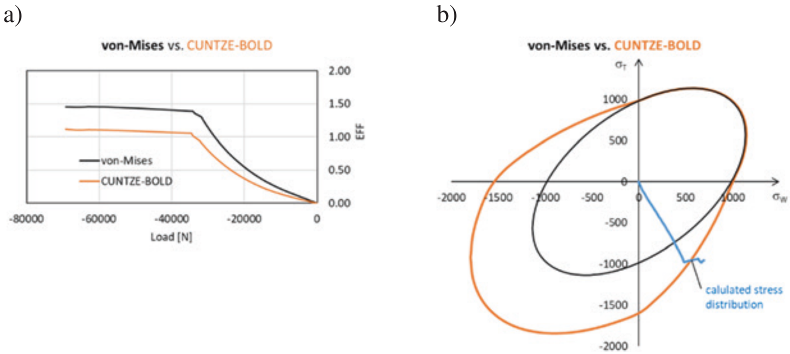

Fig. 13. a) Calculated effort for von-Mises yield criteria and CUNTZE-BOLD AM, b) normal-normal stress posted in failure envelope for von-Mises yield criteria and CUNTZE-BOLD AM

From Fig. 13 one can draw the conclusion that Von-Mises yield criteria would indicate an earlier failure while CUNTZE-BOLD AM is confirmed.

4 Summary and Outlook

The new Boeing owned bi-axial test setup using a uni-axial test machine can be used to evaluate the interaction factor. Further tests with tension loading and different materials are planned.

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