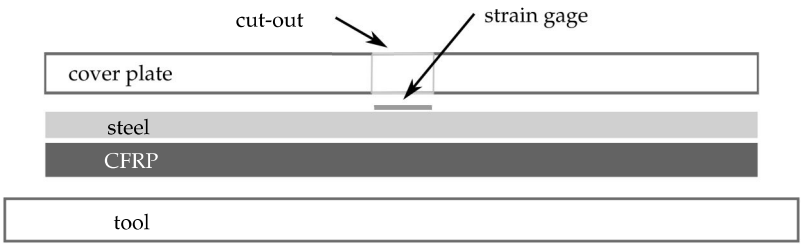

Figure 7. Manufacturing setup for specimen equipped with strain gauge.

2.4. Analytical Correlation between Curvature and Stress-Free Temperature

Several analytical models to describe the curvature of asymmetric laminates after manufacturing are found in the literature [42–44]. The analytical approaches mainly originate from bimetal applications where two different metallic layers are joined together to produce a thermomechanical bending transducer. The most comprehensive analytical description to calculate the radius r of such bi-materials dependent on a reference temperature is given by Timoshenko [44]:

$$r = \frac{h(3(1+m)^2 + (1+m\cdot n)(m^2 + \frac{1}{m\cdot n}))}{6\cdot(\alpha_2 - \alpha_1)(T_{sf} - T_r)(1+m)^2} \quad (1)$$

where h is the specimen thickness, α_1 and α_2 are the coefficients of thermal expansion for the two materials, T_r is the reference temperature, and T_{sf} is the stress-free temperature. Here, $m = {}^{t_1}/_{t_2}$ represents the ratio of the thicknesses (t_1 and t_2) of the two constituents (FRP and steel), whereas $n = {}^{E_1}/_{E_2}$ indicates the ratio of the elastic moduli of the two constituents (FRP and steel), respectively.

This equation is widely used in the literature for the description of curvatures of asymmetric CFRP laminates [17,42] and FML [23] and will therefore also be used in this work to correlate the radius and stress-free temperature of different asymmetric laminates with each other. The applicability of the analytical description in the context of this work will be discussed in the results section.

2.5. Numerical Correlation Between Curvature And Stress-Free Temperature

In addition to the analytical curvature calculation, finite element analysis is also used for the validation. In the FEA, the experiment to determine the stress-free temperature based on a given curvature as described in Section 2.3 is modeled using the FEA software Abaqus.

A curved specimen is created using a shell section and given the radius derived from the GOM ATOS measurements. The laminate layup and the respective material properties are assigned to the shell section, and the part is meshed using quadrilateral shell elements with reduced integration (type S8R). Subsequently, the specimen is placed on a flat surface consisting of rigid body elements. Because of the large deformations, a non-linear calculation is pursued. A temperature step is included in the model to achieve the deformation by heating the specimen from room temperature to a higher temperature level. Using a Python script, the temperature at which the curved specimen transitions into its flat state is determined iteratively. The flat state is defined when the nodes at the short specimen edges have identical Y-coordinates compared to the center nodes as shown in Figure 8. Consequently, the resulting temperature is defined as the stress-free temperature of the investigated specimen.

In the results section, the numerical outcomes are compared to the experiments and analytical calculations.

However, the influence of warpage needs to be considered to avoid false assumptions. While warpage mainly affects laminates with thicknesses below 1 mm, thick laminates are not affected [26]. The asymmetric laminates in this work are all in the range of 0.5–1 mm, and the tool material shows to be a significant contributor to the residual stress state in the specimens. However, for a thicker laminate, this does not necessarily need to hold true. Therefore, it is assumed that by keeping the influence of the tool within the asymmetric specimens to a minimum by using compliant tool CTEs, the accuracy of the proposed method is increased.

The use of asymmetric samples for process monitoring and in particular for residual stress quantification is shown schematically in the form of a flowchart in Figure 16. The boxes framed with thick lines in the figure indicate the focus of this work.

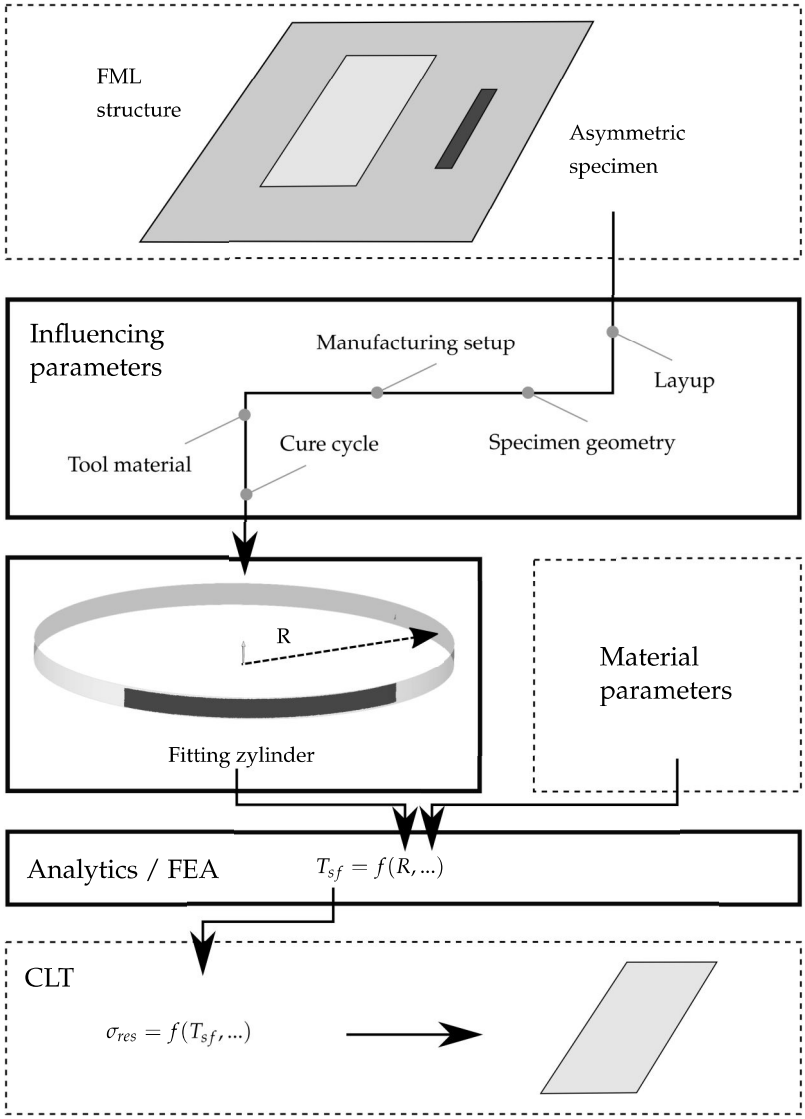

Figure 16. Proposed workflow to use asymmetric specimens for residual stress quantification of FML structures. The focus of this paper is indicated by the boxes framed with thick lines.

It was shown that the curvature and stress-free temperature of asymmetric laminates can be accurately determined using experimental methods. However, curvature measurement using a 3-dimensional scanning head seems to be the most accurate method compared to the T_{sf}-determination or other curvature measurement techniques and is, therefore, to be preferred. During curvature measurements, it is important to also determine the ambient temperature because it is needed as a reference temperature during subsequent calculations.

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