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A Method for Measuring Normal and Shear Stiffness of Laminate Stacks of Electric Motors

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Abstract

Structural simulations of electric motors require precise material models. Laminate stacks that are made of several identical steel sheets are particularly challenging to simulate using FEA. The structural stiffness of laminate stacks usually follows transversal isotropic behavior. Measuring a complete laminate stack used in passenger cars is challenging due to its size and the high testing load needed to reach real loads experienced while in operation. A new method capable of performing such measurements is presented in this article, with the help of equipment normally used for testing structures used in civil engineering. Two sets of exemplary results are presented utilizing this measurement procedure, that were performed on a real automotive rotor laminate stack: axial compression stiffness from a cyclic test, and shear stiffness at various axial preload levels. In the axial compression load case, the loading and unloading curves form a hysteresis, that changes in every test cycle. Shear stiffness shows high dependance on the axial compression preload. After loading and unloading the stack with shear loads, significant plastic deformations remain.

Keywords

laminate stacks, stiffness, transversal isotropic, electric motor, measurement, cyclic test

1 Introduction

Electromobility is gaining popularity nowadays, with various companies offering better Battery Electric Vehicles (BEVs) every year. Building and testing prototypes can be a rather time consuming and costly procedure. Prototypes usually have high manufacturing costs, and testing requires costly equipment and know-how. In order to achieve optimal designs, while minimizing costs virtual testing can be utilized. Simulation is a key procedure nowadays in the development process of such motors.

The fidelity of simulation models has a strong correlation with the quality of inputs and assumptions used to build it. Measurements are required to validate a model, or to derive material or contact stiffness properties.

Laminate stacks are important parts of electric motors, used in the rotors and the stators. The stiffness of laminate stacks of electric machines can be assumed to behave in a transversal isotropic way for simulation purposes [1]. When subjected to pure radial loads in the planar direction of the sheets (Fig. 1 load case 1, the structure will behave as a solid steel block, as the sheets deform synchronously together.

This is the case for pure rotational load cases, when no axial prestress or load exists. An example for this load case is rotating the steel stack around the axis, which induces centrifugal loads on the part. For this load condition, the behavior of the stack can be described as linear elastic, while for higher loads elastoplastic in the plane of the sheets. The stress field can be calculated analytically, using the formula for rotating discs [2].

For pure axial compression loads (Fig. 1 load case 2), the initial stiffness of the laminate stack is low. In this case, it can be deformed by applying a manual load on it. The sheets are not always bonded together, for some specimens they can be separated from each other (Fig. 2).

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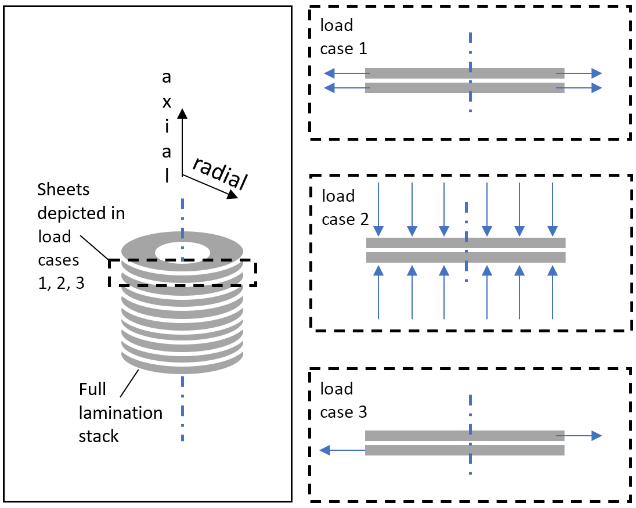

Fig. 1 Main load cases for the transversal isotropic loading of a steel stack: load case 1 – pure radial, load case 2 – pure axial compression, load case 3 – shear

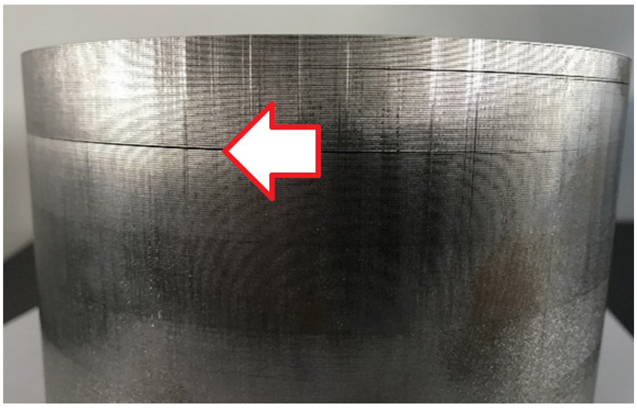

Fig. 2 Side view of a laminate stack with a gap, as the sheets are separated

As pure axial compression load is applied on the upper surface of the stack, it will gain stiffness following a progressive characteristic, converging to the stiffness of a solid steel block (Fig. 3). This stiffening is due to the following properties of the laminate stack:

- Imperfect planar shape – waviness – of the sheets. As the normal load increases, the area of contact between the sheets will steadily increase. The planar imperfections of the sheets will get flattened, which leads to a more homogeneous macroscopic structure. According to Luchscheider et al. [3] this phenomenon has a small influence on the overall stiffness of the stack.
- Sharp/deformed edges on the cut surfaces of the sheets [4]. The method used to manufacture the sheets can have influence on the smoothness of the cutting edges, and ultimately, on its stiffness. Sheets obtained using laser cutting have smoother edges compared to the ones made by stamping. Smoother edges can result in a stiffer initial loading characteristic, by improving the contact between the sheets. The authors have not found any studies proving this theory.
- Resin coating of the plates [5]. The reason laminate stacks are made of separate sheets is to reduce eddy currents in the rotor and the stator of electric machines [6]. In order to improve the isolation between the sheets, resin coating is widely used. The structural behavior of resin can be approximated as linear elastic for small displacements – Young moduli are readily available [7–11]. In order to model it more precisely, viscous material models are required in the FEA model, which can simulate creep and relaxation [5].
- Surface roughness. The smoother the surface, the higher the initial stiffness, as the whole structure is approximating the stiffness of a steel block by having a greater overall contact area, and more homogeneity [3].

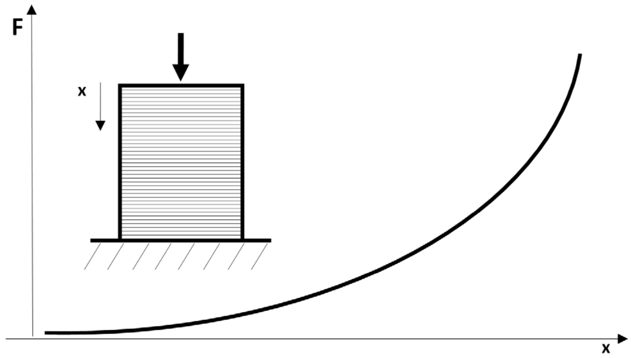

Fig. 3 The progressive nonlinear stiffness curve of a laminate stack for pure axial compression loading

For shear radial loads (Fig. 1 load case 3), the behavior is different as the individual sheets are able to slide one on another. The influencing factors are generally the same, as for the pure axial compression load case: surface geometric properties, resin coating, surface roughness, and most importantly, the magnitude of the pure axial compression prestress. Increasing this prestress will cause the stiffness of the structure to increase.

Another important factor influencing this stiffness is the procedure, how the stacks are joined during assembly. There are several joining methods used in the industry at this style of the manufacturing process. The sheets can either be glued together or welded together on the side or joined mechanically. An extensive review about joining techniques was made by Xia et al. [12]. An example for mechanical joining is shown in Fig. 4.

Fig. 4 Laminate stack joined using stamping

The behavior of laminate stacks in this direction is assumed to be linear in acoustic studies [7–11]. For structural strength FEA applications, a nonlinear description is required, that can be achieved either using a special anisotropic material model, or as a contact law in static measurements [3, 5]. Very little data was found by the authors regarding this behavior.

Tests are usually performed on smaller specimens that are obtained from real motor components [3, 11, 13]. However, cutting out smaller specimens from larger parts can influence their mechanical behavior significantly. Surface waviness changes, cut edges are modified, mechanical joint locations are modified or excluded.

Real automotive electric drive rotors are large in size. The order of magnitude of the loads required for testing the stiffness of such a part can reach several hundred kilonewtons and require powerful testing equipment – similar to those used in civil engineering. The question arises: how do real laminate stacks from real rotors behave, without any modifications in the geometry or in the production processes?

2 State of the art measurement methods

The available methods found by the authors to measure the stiffness of laminate stacks are based on two principles: derivation of elastic material properties from dynamic measurements, and direct static force-displacement characterization. The methods shown in this article do not include methods based on deriving global material properties from the properties of the composing materials (for example, homogenization [1]).

2.1 Derivation of elastic material properties (*E*, *G*, *γ*) from dynamic analyses

This procedure is based on a modal analysis performed on the specimen with the objective of determining its eigenfrequencies and eigenmodes. This methodology is capable of supplying material properties for all of the load cases shown on Fig. 1, but with strong limitations: the stiffnesses obtained will be linear and results valid for a single prestress state only.

An example for this method is an FEM model, used to reproduce the modal dynamic response of the specimen. The procedure starts by measuring the dynamic response of a test specimen using dynamic measurement methods, such as laser vibrometer [14, 15], a shaker [13], or free excitation using a hammer. In the latter case, for example, the specimen can be hung on springs with low spring coefficients. The results obtained from this experiment are the first n eigenfrequencies and eigenmodes. In the next step, the experiment is recreated virtually using FEA. The specimen can be modeled using solid elements, and a linear transversal isotropic material model, with approximated starting material stiffness coefficients (E_{ij}, G_{ij}, γ_{ij}, where i and j correspond the directions of the local material coordinate system). Using an FEM modal dynamic analysis, the first virtual testing yields a starter output of eigenmodes and eigenfrequencies. An optimization software can be used to determine the best material input to reproduce the results from the physical experiment. As the material behavior is drastically simplified when using linear material properties, and the solid element substitute of the sheets adds artificial geometrical stiffness to the model, the accuracy of the results decreases. Such a method is described by Millithaler et al. [7]. A different approach using contacts is described in [8] and [9].

2.2 Direct measurement using bolts for pretension

This method uses threaded bolts, displacement and pressure sensors to measure a force-displacement curve (Fig. 5).

It is capable of measuring the pure axial compression characteristic of the stack (Fig. 1 load case 2), in its full nonlinearity (Fig. 3). The specimen is positioned between two rigid steel plates, which are connected through threaded bolts. Displacement sensors are arranged around

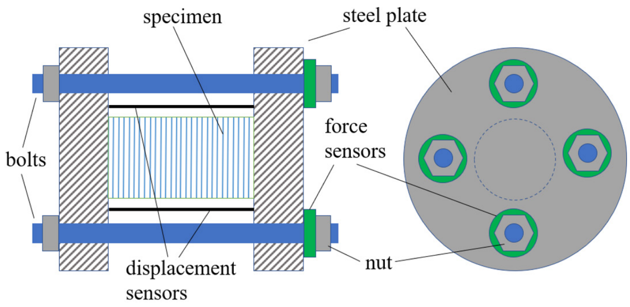

Fig. 5 Static measuring of the normal stiffness using bolts to apply pretension

the specimen, in order to record the distance between the steel plate, and to ensure that the steel plates stay parallel during the test. The nuts are gradually tightened on the bolts in small increments, carefully one after another, thus achieving a high axial compression load on the specimen. The actual magnitude of the load is recorded using force sensors under the nuts.

This method allows a precise measurement of the normal stiffness, and the setup can be relatively inexpensive to build. It even enables to perform modal dynamic measurements in different prestressed states. As for the disadvantages, it is time consuming, and requires a high amount of manual work. These properties render it inappropriate for cyclic tests, but it does allow to perform dynamic analyses on the whole assembly. A similar method is used in [11], or in [16].

2.3 Direct measurement using a hydraulic press

In this case, the specimens are compressed using a press, and the deformation is measured using displacement sensors. Generally, only the pure axial compression characteristic of the stack is measured (Fig. 1 load case 2). Implementing this procedure can be more costly, than the method using bolts, because of the machinery involved, but enables quick testing of multiple specimens and performing many load cycles. Publications about cyclic tests of laminate stacks of electric motors are infrequent. The only study found by the authors was published by Luchscheider et al. [3] and Luchscheider [13]. Their experiment was conducted on a smaller specimen cut out of a real electric rotor laminate stack, not a whole undamaged laminate stack used in an electric motor and was only done in the axial compression load case (Fig. 1 load case 2).

This principle is used in the experiment described in this paper, with the addition of measuring the shear (Fig. 1 load case 3) stiffness of real electric motor rotor laminate stacks at different axial compression preload states.

3 Direct measurement method for complete assemblies – axial compression loading

The load necessary to test the stiffness of such a laminate stack is in the order of magnitude of several 100 kilonewtons, and the dimensions of a typical specimen are considerably larger as those of a material test specimen. For this reason, the measurements were performed in the Structural Engineering Laboratory of Széchenyi István University, using equipment normally used for tests performed for civil engineering research.

The specimen was placed between two rigid steel plates. The load was applied centrally using the hydraulic cylinder on the top. The loading force was measured using a load measurement cell, mounted between the hydraulic cylinder and the support frame (setup on Fig. 6 and image on Fig. 7). In order to ensure, that the load on the specimen is uniform, and the plates stay parallel during the test, the vertical displacements were measured at 4 different locations around the axis of the specimen. The data acquired from the displacement sensors was later examined and averaged during postprocessing. The resolution of the displacement sensors was 0.001 mm (class 2 precision), and the force sensor had a precision of 1 N. Specifications of the equipment used is listed in Tables 1–5.

4 Direct measurement method for complete assemblies – shear loading

Shear loading is visually explained in Fig. 1 load case 3. The forces acting on the sheets are perpendicular to the rotational axis of the laminate stack, and work towards sliding the sheets tangentially relative to each other.

The shear stiffness experiment setup (Fig. 8 and Fig. 9) was similar to the axial compression stiffness experiment setup, with some differences. The upper steel plate had an additional hydraulic cylinder connected to it

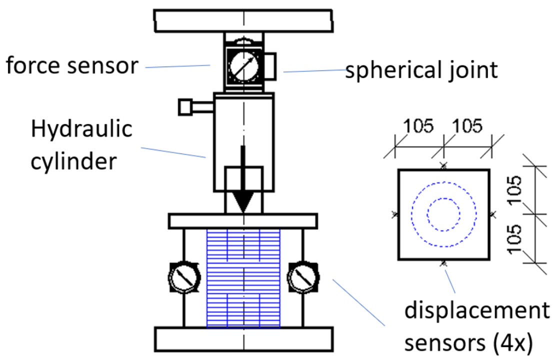

Fig. 6 Experiment setup for axial compression loads

Fig. 7 Image of an axial compression loading test

Table 1 Hydraulic cylinder specs

Type	Max. load [kN]	Loading length [mm]	Diameter [mm]	Max pressure [bar]
Hi-Force HSS 256	250	150	84.14	700
Hi-Force HSS 256	500	102	127	700

Table 2 Load sensor specs

Type	Max. load [kN]	Sensitivity [mV/V]	Accuracy	Length [mm]
MOM-Kaliber 7924	200	1 ± 0.1%	0.10%	110
MOM-Kaliber 7924	50	1 ± 0.1%	0.10%	81

Table 3 Displacement sensor specs

Type	Measuring range [mm]	Output signal [mV/V]	Accuracy	Length [mm]
HBM W5TK	±5	80	±1.0%	110
HBM W5TK	±5	80	±1.0%	110
HBM WA100	100	80	±1.0%	181.6
HBM WA100	100	80	±1.0%	181.6
HBM WA100	100	80	±1.0%	181.6
HBM WA100	100	80	±1.0%	181.6

Table 4 Measurement amplifier specs

Manufacturer	Sampling speed	Operating temperature	Accuracy class
HBM Quantum X	40 kS/s	−20 – +65 °C	0.05%

Table 5 Measurement data acquisition software

Manufacturer	Data collection speed	Display
HBM catman Easy DAQ	12 MS/s; 100 MB/s	Real time

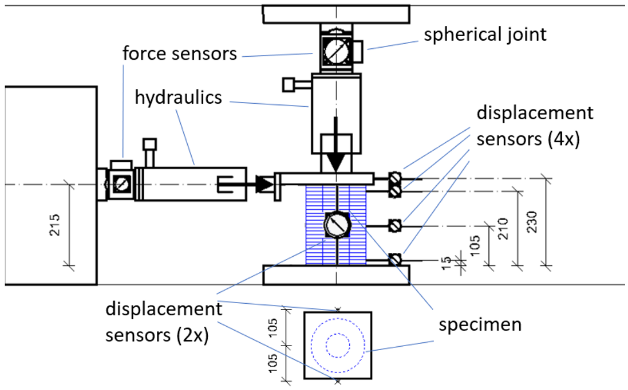

Fig. 8 Experiment setup modified to measure the shear stiffness of a laminate stack

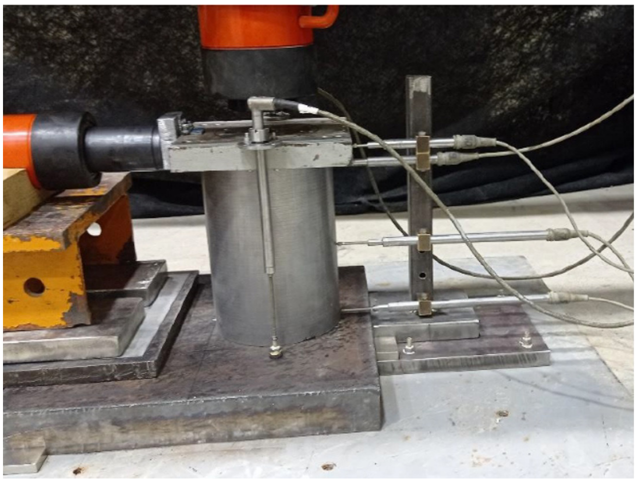

Fig. 9 Image of the shear measurement

horizontally, that enabled the application of a force perpendicular to the rotational axis of the specimen. The axial compression preload was applied through the vertical hydraulic cylinder. The spherical joint built into the measurement chain allowed for horizontal displacement of the upper steel plate, with simultaneous minimal rotation of the plate. Those factors need to be taken into account in the careful postprocessing of the measurement results.

This test system enables to test specimens with different geometries at different load levels in a time efficient way without the need to generally modify the measurement setup.

5 Measurement results

In this example, the specimen tested was the one depicted on Fig. 10. It had a diameter of 158 mm, and a length of 215 mm, and consisted of 614 sheets.

5.1 Axial compression loads

20 load cycles were performed at load levels ranging from 2 kN to F_{test}. The desired magnitude of the axial compression load was provided using force control. The load change rate was held at the order of magnitude of 1 kN/s, in order to avoid the influence of dynamic or viscous phenomena (Fig. 11).

Fig. 12 shows the results of the cyclic test, with the load magnitude normalized to the maximum F_{test} force applied in each cycle. The first loading cycle results in higher forces needed to achieve a similar displacement, compared to subsequent cycles. Unloading curves generally result in lower force values for the same displacement, resulting in a hysteresis. The displacement data from the following cycles (cycle 2 to 20) show a similar behavior. The resulting load-displacement curves obtained in every cycle are slightly different compared to the previous cycles, and the difference decreases in magnitude from cycle to cycle.

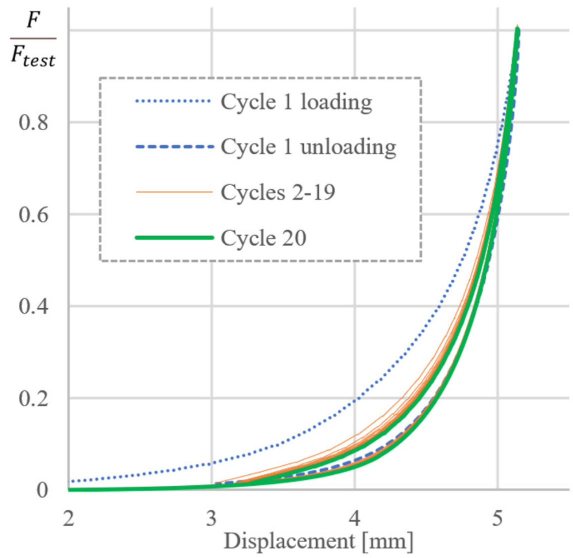

Fig. 12 Resulting stiffness curves for axial compression loads

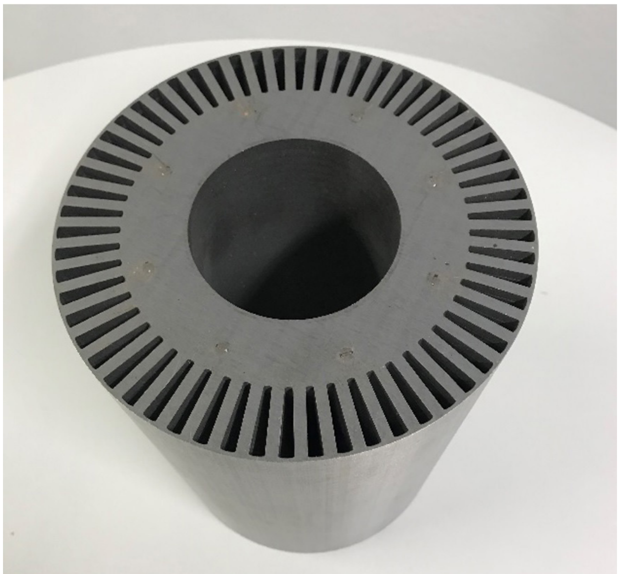

Fig. 10 The specimen tested in this example

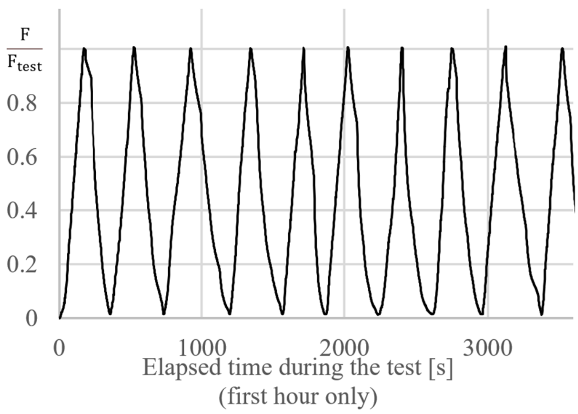

Fig. 11 Time distribution of load cycles during the first hour of an experiment

Based on Fig. 12, it can be concluded, that the hysteresis of the curves stabilizes itself after it is subjected to a high number of cycles.

5.2 Shear loads

After performing the cyclic axial compression test, the shear stiffness of the stack was measured. Using the same F_{test} as for the axial compression test, the specimen was put under axial preload. At the next step, the shear load was slowly applied, with a peak of $F_{test}/7.2$ (Fig. 13).

The same test was performed with a normal preload of $F_{test}/3$, and a lower shear load $F_{test}/20$. The resulting displacements are shown in Fig. 14. The displacement sensor data was reset to 0 mm at a 1 N load, to exclude initial adjustment displacement values, and to be able to compare the curves. The laminate stack in the higher axial prestress loading test case showed a considerably stiffer behavior, compared to the test performed at lower axial prestress. The deformation in case of lower prestress is considerably higher, even for lower shear loads. The plastic deformation observed is in the order of magnitude of half of the total deformation at these load levels.

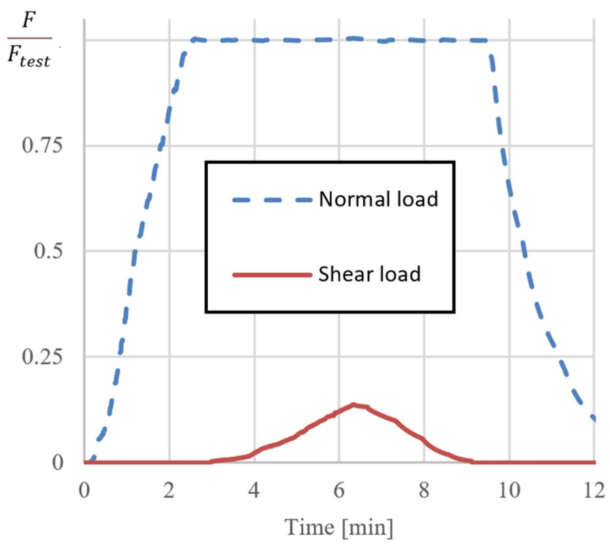

Fig. 13 Time history of preload and shear loads

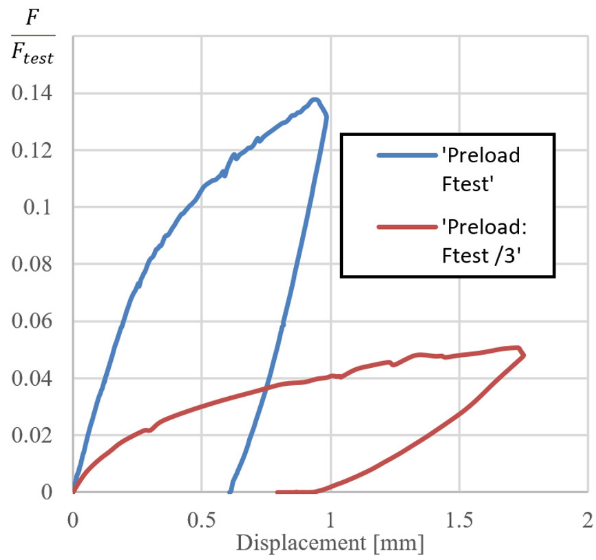

Fig. 14 Transverse displacement induced by shear loading at different axial compression preload states

6 Conclusion

The direct measurement of the axial compression and shear stiffness of the laminate stack of real electric machines is possible using the method shown in this article. The resulting stiffness curves from the axial compression cyclic analyses show a difference with every cycle, that decreases with every cycle performed.

Test results with shear loads confirm, that increasing the axial compression prestress of the structure increases the transversal stiffness. During shear testing, high plastic deformation of the stack was observed.

The next steps planned in this research are analysis of other similar specimens and geometries, approximation of the loading/unloading curves, analysis of tangential behavior and modelling in FEM, with the ultimate goal of understanding and being able to model these phenomena efficiently and precisely.

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