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Eliminating friction between flat specimens and an antibuckling support during cyclic tests using a simple sensor

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Abstract.

Friction between flat specimens and antibuckling supports during cyclic tests can change the shape of cyclic curves in the compressive direction. Therefore a simple sensor has been designed that can be attached to any pre-existing test rig so that the friction force exerted on a specimen can be measured independently from the stress and the strain. The stress signal obtained during an experimental run is then compared with the friction force signal, and the delay between the signals can be determined. Hence the stress due to the friction is subtracted from the stress signal measured on the test rig to obtain the real stress signal. The method has been validated using two metals: an aluminium alloy AlMgSi0.5 and a complex phase steel CP 800. For the aluminium alloy, a noticeable change in the compressive part of the cyclic curve is observed due to the friction whereas a minor influence of the friction is detected for the steel. However this friction component in the compressive direction can now be eliminated using the friction sensors to establish the true cyclic curves.

Keywords: fatigue, cyclic curve, cross correlation, antibuckling support, friction.
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1. Introduction

The stabilised behaviour of material subjected to dynamic mechanical loads in a low cycle fatigue (LCF) regime is represented by the stabilised cyclic stress-strain curve. This enables modelling of elastoplastic material behaviour during a random load history with cyclic phenomena, such as nonlinear kinematic hardening or Masing and memory rules [1, 2, 3, 4]. The stabilised cyclic stress-strain curve for a given material is determined experimentally using one of the following methods:

- LCF testing where numerous specimens are loaded at constant strain levels [2, 5, 6, 7, 8, 9, 10]
- Incremental step testing where a single specimen is loaded, but the strain range changes incrementally during the loading history between successive reversal points [5, 6, 7, 8, 11]
- Multiple step testing where a single specimen is loaded at a number of pre-set levels until saturation at each level has been observed [8]
- A tensile test of a specimen which is performed after a pre-set number of incremental or multiple step loadings [8]

The durability and load bearing capacity of parts, e.g. for the automotive industry, is often required to ensure such parts meet international safety standards [12]. These factors are derived from the stress-strain relation of the materials used to manufacture those parts, hence the ability to determine this relation for a material is extremely important. The automotive lightweight design focuses on reducing the weight by utilising advanced high-strength steels, aluminium alloys and magnesium alloys as sheet metals with a thickness of less than 3 mm [13, 14]. Lightweight design is used even for the most vital load bearing components such as the chassis and suspension [12]. The specimens cut from a particular sheet metal should therefore have approximately the same thickness and surface roughness as future manufactured components made from the same sheet metal to exclude the influence of surface effects on the stress-strain relation of the material. As the thickness of the high strength materials is less than 3 mm, it is difficult to perform cyclic tests with high load amplitude without buckling. Whilst two typical material representatives for the lightweight design have been chosen and tested i.e. an aluminium alloy AlMgSi0.5 and a complex phase steel CP 800 both in the form of a sheet metal with thickness 2 and 3 mm, no reliable low-cycle fatigue data could be found in the available literature. Data does exist for the aluminium alloy AlMgSi0.5 however it is usually presented for thicker or round specimens [15], whereas no cyclic data are available for the complex phase steel CP 800 to date. The thickness is however a crucial factor for a cold-rolled sheet metal therefore the data from the literature are not directly comparable for the tested materials if a sheet-metal of a different thickness has been tested. Furthermore, the scatter of the experimental data for the cyclic curves and the hysteresis branches is typically not provided in the literature although it is a crucial piece of information for reliability predictions which are based on the measured stress-strain relation. Low-cycle fatigue tests for more conventional materials have been previously carried out by the authors, [16, 17, 18] and the results correlated with data available in the literature [19]. This expertise has now been extended to flat specimens of smaller thickness in the low-cycle and ultra low-cycle fatigue area.

Any external influence that appears during experimental testing, e.g. friction between the specimen and the antibuckling support, should be detected and not considered as part of the stress-strain response of the material under investigation. For example, durability predictions based on accumulated energy criterion consider the area

within the hysteresis loop as the basis upon which durability predictions are made. If an external influence is considered as part of the material response, erroneous durability assessments may be obtained as can be seen in Fig. 1. Although the contribution of the friction between the specimen and the antibuckling support might be modest, identification and measurement of the magnitude of the friction force is still important in order to numerically evaluate its influence on the test results at any instant in time. Moreover, the ability to evaluate friction is more important than the magnitude of the friction measurement itself. In the case of distorted measurement signals or scarcer sampling frequencies, the robustness of the method is of greatest importance to be able to couple the stress-strain and friction measurements.

Figure 1: Difference in durability assessments (damage accumulation) based on the accumulated energy calculation if an external influence is erroneously considered as part of the material response during a cyclic test.

Regardless of the method for the determination of the stabilised cyclic stress-strain curve, the testing can be carried out on either round or flat specimens. Standards such as ASTM E606 provide details on the shape of the specimens, test procedure, strain control, calibration, data acquisition and post-processing of LCF testing for standard specimens [9]. Non-standard specimens can also be used for the determination of the cyclic curve, especially if measuring equipment such as the extensometer requires a specific gauge length of the specimen to mount the extensometer arms [20]. Tensile, bending or torsional tests are all possible although tensile tests are the most common as most rupture hypotheses are based on equivalent stresses which require uniaxial tensile test results. However, as the testing using any of the methods for the determination of the stabilised cyclic curve must be performed under alternating strain, i.e. the dynamic ratio R_ϵ must be equal to -1, flat specimens in particular can undergo buckling if

Figure 2: Experimental set-up for the determination of a cyclic curve with flat specimens.

the applied compressive load is higher than the limit buckling load of the specimen (Fig. 2). Moreover, non-standard specimens can buckle under even smaller loads if their slenderness is increased. Furthermore, buckling can occur even before the yield strain of the material, in which case determination of the cyclic curve for sizeable strains becomes impossible.

To overcome the buckling problem of flat specimens subjected to compressive loads, antibuckling supports or fixtures using sliding guides are usually mounted (Fig. 2). However, the increased stability of the specimen is accompanied by friction between the antibuckling support and the specimen which can affect the determination of the cyclic curve. Alternative methods using magnetic guides or roller guides could be utilised to prevent buckling [21, 22]. However, the magnetic guides cannot be used for cyclic tests of non-magnetic materials whereas the roller guides only change the effective length of the specimen as it is not supported on the whole length [22]. Similarly, design guidelines based on stiffness calculations require considerable safety factors due to the theoretical assumptions of buckling and therefore result in oversized thickness of the specimen, which is not suitable for use in lightweight design. Several antibuckling supports have been proposed [23, 24, 25, 26, 27, 28, 29, 30, 31, 32]. They all handle buckling and friction in a specific way. Feraboli [23] developed a support for crush energy absorption testing where knife-edges are finger-tightened directly onto the specimen. It has been concluded that tightening of knife-edges can influence the experimental result [23], however no numerical data exists regarding the knife-edge support as the friction between the support and the specimen has not been measured. Khan reports on the use of a non-standard specimen shape to minimise buckling and application of an antibuckling support with a PTFE foil of 0.5 mm thickness, but does not measure the

friction force [28]. Instead, half of the cycle with the highest amplitude was compared with the monotonic curve to detect the friction influence. Dietrich et al. designed an antibuckling support suitable for cyclic tensile-compressive tests of sheet metals [26, 29]. The design allows the side-supporting blocks to move with the actuator during the test and enables the connection of a friction force transducer with the measurement amplifier of the testing machine controller. This then allows the recording of the friction force signal with the same frequency as the other measured quantities, e.g. strain and force. The pressure of supporting blocks is determined by screws which are tightened gradually using a torque wrench. Knoerr et al. created an antibuckling support from two sets of plates which apply a force to the specimen by preloaded springs [25]. Performing a monotonic tensile test with and without the antibuckling support, the friction force can be estimated and applied to cyclic tests. Antibuckling supports can also be supplied by the test rig producers [24] which provide both wing and hex nuts to connect the supports. Hex nuts allow the use of a torque wrench to set the exact bolt torques whereas wing nuts enable a more rapid set-up procedure [24]. Libura et al. report on the successful use of antibuckling supports for cyclic tests of DP690 steel [29]. Similarly, Kowalewski et al. report on the use of antibuckling supports for cyclic tests of CW508L brass [30].

Data logging systems of test rigs for mechanical tests have a limited number of input signals. There are four input signals available on the test rig used during this study which are used for the displacement, force, strain and temperature measurements. If another quantity is to be measured, one of the input signals has to be detached in order to measure the new quantity. In this case, a friction sensor designed for measurements of the friction force between the specimen and the antibuckling support is attached to the data logging system and the use of the correlation function is superfluous as the signals for the stress and the friction force are already synchronised. On the contrary, if the input signals to the data logging system of the test rig remain unchanged and there is no option for an additional input signal, the friction measurements on the test rig during cyclic tests are possible using one of the following options:

- An extension of the data logging system is provided which enables additional inputs. This option enables synchronised measurements for the extended range of input signal but incurs additional experimental costs.
- A more affordable independent parallel system is used which measures only the new quantity at its own starting point and its own sampling frequency. However, this option requires correlation of the signals in order to be able to apply a mathematical relation between them.

The objective of this paper addresses the latter option. The antibuckling support has been designed for testing with an arbitrary load amplitude, so the number of cycles to failure can vary between several dozens (ultra low-cycle fatigue [33]) to hundreds of millions (ultra high-cycle fatigue [34]). In order to provide a consistent evaluation of the friction force between the antibuckling support and the specimen, the antibuckling

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Figure 3: An independent parallel data logging system is added to the original data logging system to collect friction measurements.

support is mounted regardless of the load amplitude. Although initially other shapes of the antibuckling support were considered, a flat contact area was selected since the friction force exerted on the specimen does not depend on the size of the surface area. Furthermore during the search for the optimal shape, an antibuckling support was designed with a thinner vertical part and hence a smaller contact area with the specimen. This shape however turned out to act rather as a stiffener than a side support, i.e. local buckling modes could occur during the cyclic test [35]. Hence it was decided to maximise the contact area between the antibuckling support and the specimen in order to prevent any buckling modes during the cyclic tests. Fig. 3 presents how the input data are collected using two independent data logging systems. We propose that a simple sensor is added to an existing test rig which enables measurement of the friction force between the antibuckling support and the specimen using any of the four methods for determination of the stabilised cyclic stress-strain curve. The motivation for this work was therefore an improvement of the friction measurement by adding a numerical value to the friction that occurs between the specimen and the antibuckling support at any time during the test, regardless of the size of the friction force. As the data acquisition frequencies between the test rig and the friction sensors differ, a cross-correlation function [36, 37, 38, 39, 40] is utilised which enables alignment of the two signals and extraction of the true compressive stress-strain curve. The use of cross-correlation is common practice in measurement science and has a broad applicability. Vorburger et al. [36] used the cross-correlation function to quantify the similarity of 2D surface profiles or of 3D areal surface topography images. Chen

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Figure 4: a) Geometry of specimen, b) placement of PTFE foil and antibuckling support, c) placement of friction sensors, d) mounting between the test grips and e) placement of extensometer.

and Koenders [37] applied the cross-correlation method to nanometer metrology and measurement. Marzano et al. [38] utilised the cross-correlation method for spectrum analysis of low frequency resistance fluctuations in graphene samples. Costa-Junior et al. [39] studied the measuring uncertainty of ultrasonic longitudinal phase velocity estimation by the use of the cross-correlation function and Kiselev et al. [40] employed it to study the white light interferometry. Hence, in the case of two independent data logging systems, the cross-correlation function enables extraction of the true stress signal from the recorded stress-strain signal from the test rig using the friction force recorded by the friction sensors. This procedure can be performed on any test rig as the friction sensors are simply disengaged from one test rig and moved to another.

Figure 5: Forces and displacements of a) the specimen and b) the antibuckling support.

2. Method

2.1. Working principle

A test specimen of gauge length l and rectangular cross-section $a \times b$ is mounted between the test grips as shown in Fig. 4. The antibuckling support is mounted around the specimen and placed onto two friction force sensors. It is then secured by springs so it cannot move during the test. Its shape is represented by two strengthened I-profiles held together by 4 bolts. During assembly however, the bolts are only tightened modestly so that a zero or negligible friction force occurs between the specimen and the antibuckling support. Furthermore, to reduce the friction force between the specimen and the antibuckling support, a polytetrafluoroethylene (PTFE) foil of 0.1 mm thickness is placed between the specimen and the support (Fig. 4). The holes in the support allow strain measurements using an extensometer. Strain measurements are necessary as tests to determine the cyclic curve must be strain controlled.

The test rig has the force sensor placed above the top grip, the top grip standing still during the test. So the bottom grip moves towards the top grip during the compression part of the load cycle by a displacement f until the pre-set strain has been reached.

If the tensile-compressive loading of the specimen remains below the critical buckling load, friction-free tests are expected and the obtained cyclic curve is true in both the tensile and compressive direction. The friction force between the specimen and the antibuckling support occurs when the compressive load exceeds the critical buckling load of the specimen (Fig. 2). As the I-profiles are bolted together with no clearance, only minimal buckling can occur due to the deformation of the PTFE foil, I-profiles and bolts. When the specimen buckles a normal force F_N occurs between the specimen and one of the I-profiles. On the other I-profile, two components of the normal force $\frac{F_N}{2}$ occur as the reaction to the buckling (Fig. 5a). As the antibuckling support rests on the friction force sensors on the bottom grip and is not restrained on the top, the displacement of any point on the support is equal to the displacement of the bottom grip. The displacement of the specimen changes linearly from the highest displacement on the bottom grip to a value of zero on the top grip. Therefore at all the points of contact between the specimen and the antibuckling support, the displacement of the specimen during the compression part of the loading cycle is smaller than the displacement of the antibuckling support. The resultant friction force works downwards on the antibuckling support and upwards on the specimen.

Equilibrium of forces on the specimen yields

$$\sum_{i=1}^n F_{yi} = 0; F_{BG} + 2F_N\mu_f - F_{TG} = 0 \longrightarrow F_{TG} = F_{BG} + 2F_N\mu_f. \quad (1)$$

As the force in the specimen is measured on the top grip, one can see from Fig. 5a that the measured force F_{TG} is increased by friction forces $2F_f = 2F_N \cdot \mu_f$ as compared to the applied force F_{BG} where μ_f represents the friction coefficient between the specimen and the PTFE foil. Furthermore, by positioning the friction force sensor between the antibuckling support and the bottom grip (Fig. 5b), it follows from the equilibrium of the forces in the vertical direction that both the sum of the friction forces $2F_f$ and the spring forces $2F_S$ can be measured as one force F_{FS} on the sensors during the compressive part of the loading cycle,

$$\sum_{i=1}^n F_{yi} = 0; 2\frac{F_{FS}}{2} - 2F_N\mu - 2F_S = 0 \longrightarrow F_{FS} = 2F_N\mu + 2F_S. \quad (2)$$

During the tensile part of the loading cycle the friction force equals 0, as there should be no contact between the antibuckling support and the specimen. However a very small, negligible friction force is detected if the bolts of the antibuckling device are overtightened during assembly. The only detectable force F_{FS} represents the spring forces $2F_S$ which remain approximately constant throughout the test. After the test has been accomplished, three time series are available, σ_i^* , ε_i ; $i = 1, \dots, n_\sigma$ and μ_j ; $j = 1, \dots, n_\mu$. The first two series represent the measurements of the stress $\sigma^* = \frac{F_{TG}}{A_0}$ and the strain ε where F_{TG} represents the force measured on the test rig and $A_0 = ab$ is the initial cross-section of the specimen. The friction force measurements F_{FS} are represented by μ . As the time series are sampled with different frequencies ν_σ and ν_μ , their lengths n_σ and n_μ are not the same. Therefore, the time series must first be

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resampled so as to ensure the same length of the time series n . An interpolation can be used to resample σ_k^* and ε_k ; $k = 1, \dots, n$ for chosen resampling frequency ν as

$$\sigma_k^* = \sum_{i=\lfloor x \rfloor}^{\lfloor x \rfloor + l} \sigma_i^* \prod_{\substack{m=\lfloor x \rfloor \\ m \neq i}}^{\lfloor x \rfloor + l} \frac{x - m}{i - m} \quad (3)$$

and

$$\varepsilon_k = \sum_{i=\lfloor x \rfloor}^{\lfloor x \rfloor + l} \varepsilon_i \prod_{\substack{m=\lfloor x \rfloor \\ m \neq i}}^{\lfloor x \rfloor + l} \frac{x - m}{i - m} \quad (4)$$

where l equals 1 for linear interpolation, $\lfloor \cdot \rfloor$ represents the floor function and x is calculated as

$$x = k \cdot \frac{\nu_\sigma}{\nu}; k = 1, \dots, n. \quad (5)$$

The length of the resampled time series n can be determined either as

$$n = \frac{\nu}{\nu_\mu} \cdot n_\mu \quad (6)$$

or

$$n = \frac{\nu}{\nu_\sigma} \cdot n_\sigma. \quad (7)$$

Similarly, μ_k ; $k = 1, \dots, n$ can be resampled as

$$\mu_k = \sum_{j=\lfloor y \rfloor}^{\lfloor y \rfloor + l} \mu_j \prod_{\substack{m=\lfloor y \rfloor \\ m \neq j}}^{\lfloor y \rfloor + l} \frac{y - m}{j - m} \quad (8)$$

where l equals 1 for linear interpolation and y is calculated as

$$y = k \cdot \frac{\nu_\mu}{\nu}; k = 1, \dots, n. \quad (9)$$

The delay τ between the time series can then be searched for in order to achieve optimal alignment of the two curves. It is determined by the cross-correlation function as

$$\tau = \underset{i}{\operatorname{argmin}} (\sigma^* \star \mu)_i \stackrel{\text{def}}{=} \underset{i}{\operatorname{argmin}} \left(\sum_k \sigma_k^* \mu_{k+i} \right); k = 1, \dots, n. \quad (10)$$

Frequency ν can stand for either of the sampling frequencies ν_σ and ν_μ or it can be arbitrarily chosen. Its choice however affects the size of the discretisation step i in Eq. 10 and hence also influences the precision of the delay determination between the time series. The use of the *argmin* instead of the *argmax* function in Eq. 10 considers the increase of friction force measurements whilst the specimen is being compressed, i.e. the measured stress σ^* on the test rig is negative. The true stress σ_k can now be calculated by subtracting the shifted friction force $\mu_{k+\tau}$ over the initial cross-section $A_0 = ab$ from the measured stress σ_k^* as

$$\sigma_k = \sigma_k^* - \frac{\langle \mu_{k+\tau} \rangle}{A_0}; k = 1, \dots, n \quad (11)$$

where $\langle \cdot \rangle$ represent Macaulay brackets. A true cyclic stress-strain curve is obtained when the points $(\varepsilon_k, \sigma_k)$; $k = 1, \dots, n$ are connected by a continuous curve.

Table 1: Chemical composition in %-weight for aluminium alloy AlMgSi0.5 [41].

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.3—0.6	0.1—0.3	0.1	0.1	0.35—0.6	0.05	0.15	0.1	rest

2.2. Mechanical sensor

A simple mechanical sensor has been designed based on the principle of measuring bending strains (Fig. 6). It enables measurements of axial loads whilst compensating for any variations in temperature or shear load. A single point load input on the top side of the sensor is in contact with the antibuckling support and bends the gauge area which rests on a two point support in contact with the bottom test grip. A simulation in Fig. 6a shows the strain field that emerges after the sensor has been loaded with a force of 100 N. Four strain gauges are placed on the lower side of the gauge area as shown in Fig. 6b. They are connected into a full Wheatstone bridge circuit and via an input module to a computer. The limiter depicted in Fig. 6a serves for protection of the gauge length. If the load is increased such that the sensor reaches its deflection limit, the limiter leans on the bottom test grip and prevents further deflection. Two such mechanical sensors are placed between the bottom test grip and the antibuckling support as shown in Fig. 4c. Prior to first use they were calibrated as shown in Fig. 6c. If the sensors get damaged and are then repaired or replaced, a new calibration is mandatory.

3. Cyclic curve determination

The multiple step testing method has been chosen for determination of the stabilised cyclic stress-strain curves of an aluminium alloy AlMgSi0.5 and a complex phase steel CP 800. Typical chemical compositions of these two metals can be found in Tables 1 and 2. The specimens were mounted between the test grips and then loaded at room temperature with controlled strain histories until rupture as shown in Fig. 7. Twenty cycles were chosen at each level of strain as a stabilised hysteresis loop is observed after this number of repetitions. The following strain amplitudes were chosen: ± 0.0005 , ± 0.001 , ± 0.0025 , ± 0.0050 , ± 0.0075 , ± 0.0100 , ± 0.0125 , ± 0.0150 and ± 0.0175 . The loading frequencies for the aluminium alloy were set at 1 Hz for the first two levels, 0.5 Hz until 1 % of strain amplitude, 0.2 Hz until 1.5 % of strain amplitude and 0.1 Hz for 1.75 % of strain amplitude (Fig. 7a). The loading frequencies for the steel were set at 0.5 Hz until 1 % of strain amplitude, 0.2 Hz until 1.5 % of strain amplitude and 0.1 Hz for 1.75 % of strain amplitude (Fig. 7b). Six specimens in total were tested, three for each material.

The axial force was measured during the test and the stress σ^* calculated as the measured axial force per nominal cross-section area is given in Fig. 8. The friction force F_{FS} was measured using two mechanical sensors throughout the multiple step tests.

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Figure 6: A simple mechanical sensor enables measurements of the friction force. a) Strain field in the mechanical sensor after a force of 100 N has been applied to the single-point input. b) A full Wheatstone bridge circuit enables measurements of the axial force. c) Calibration of mechanical sensors.

Table 2: Chemical composition in %-weight for complex phase steel CP 800 [42].

C	Si	Mn+Cr+Mo	P	Fe
0.140	0.14	~ 2.5	0.011	rest

The sampling frequency was set to 2000 Hz. The measurements of both sensors were multiplied by calibration constants (Fig. 6c) and added together which results in the friction force μ shown in Fig. 9.

Figure 7: Load histories with strain as controlled variable for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800.

Figure 8: Stress σ^* measurements during multiple step tests for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800.

Figure 9: Friction force μ measurements during multiple step tests for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800.

To exclude the contribution of the friction force from the stress-strain response of

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the material, a strain level of the test is chosen, e.g. ± 0.0150 as indicated in Figs. 7, 8 and 9 and enlarged in Fig. 10.

Figure 10: Stress and friction force measurements for the chosen strain level of ± 0.0150 before shifting for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800.

Figure 11: Stress and friction force measurements for the chosen strain level of ± 0.0150 after shifting for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800.

After resampling the measured signals with resampling frequency $\nu = 200$ Hz using Eqs. 3, 4 and 8, the time delay can be determined by the cross-correlation function in Eq. 10. Afterwards, the friction force signal is shifted by the calculated time delay (Fig. 11) and it is then possible to obtain the true stress σ using Eq. 11. It is also evident from Figs. 10 and 11 that the *argmin* function rather than the *argmax* function must be

used in Eq. 10 due to the reciprocal changing of stress and friction force measurements. Finally, hysteresis loops for the chosen strain level of ± 0.0150 are presented in Fig. 12. A stabilised cyclic curve is observed by connecting the reversal points of the stabilised hysteresis loops.

Figure 12: Hysteresis loops for the chosen strain level of ± 0.0150 with and without friction for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800. Blue curves represent measured stress signals, red curves represent true stress signals.

The stabilised hysteresis loops for all loading conditions are shown in Fig. 13 and the stabilised cyclic curve is presented in Fig. 14.

4. Robustness of the method

The robustness of the method is evaluated as follows. For the stress and the friction force measurements, discrete Fourier analyses are performed to determine the amplitude spectra of both signals and then the average values of the amplitude spectra are calculated. Next, the threshold values of two, five and ten times the average values of amplitude spectra are chosen. For the frequencies, whose amplitudes lie below the threshold values, the real and imaginary parts are replaced by random values uniformly distributed between zero and half the threshold value in both positive and negative directions. This way a distortion is introduced to the signals. Finally, inverse discrete Fourier analyses are performed to obtain distorted time series and then the delay between these signals is determined (Fig. 15).

The influence of the time discretisation on the determination of the time delay is evaluated next. The resampling frequency ν varies between 2 and 2000 Hz and the

Figure 13: Stabilised hysteresis loops for all loading conditions with and without friction contribution for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800. The measured stress signal is shown in blue and the true stress signal is shown in black. The stabilised cyclic curve is shown in red.

Figure 14: Stabilised cyclic stress-strain curve with and without the friction contribution for a) aluminium alloy AlMgSi0.5 and b) complex phase steel CP 800. Compressive curves are plotted using absolute values.

corresponding delay has been calculated. The sensitivity analysis of the calculated delay

is shown in Fig. 16.

Figure 15: Calculation of the delay for various levels of distorted signals of stress and friction force measurements for a strain level of ± 0.0150 on aluminium alloy AlMgSi0.5.

5. Results and discussion

The limit buckling load can easily be obtained from a comparison of the measured and corrected curves as they start to differ noticeably in the compressive branch of the hysteresis loop (Fig. 14). It is more pronounced for the aluminium alloy than for the steel as the values of the stress due to friction are comparable whereas the values of the true stress for the steel are almost three times greater than the values of the true stress for the aluminium alloy. The same observation applies to the difference between the measured stress and the true stress signals (Fig. 12). The friction force in the compressive part of the cycle increases with the increasing load (Fig. 9). This occurs according to the model in Fig. 5 when the specimen buckles and leans onto the antibuckling support which causes both a normal force and a friction force. As axial stress increases with increasing strain, the friction force also appears to increase (Figs. 9, 10 and 11). It is interesting

Figure 16: Calculation of the delay for various values of the resampling frequency ν for a strain level of ± 0.0150 on aluminium alloy AlMgSi0.5.

that the values of the friction force of both the materials do not differ by more than a factor of two even though the axial loadings applied to the steel are approximately five times higher than those applied to the aluminium alloy. This similarity is most probably a consequence of different friction coefficients, different cross-sections and the stiffness of the two metals. Furthermore, the friction force noticeably changes the compressive part of both the cyclic stress-strain curve and the hysteresis loops for the aluminium alloy whereas it can be hardly seen for the steel. So whilst the values of the stress due to friction are similar for the two materials, the influence is relatively negligible for the steel whereas it does affect the shape of the curves for the aluminium alloy (Figs. 13 and 14). As aluminium alloy AlMgSi0.5 specimens of 2 mm thickness and CP 800 steel specimens of 3 mm thickness were used (Fig. 4), higher compressive loads were necessary to reach the critical buckling force for the steel specimens. Furthermore given a compressive strain, lower compressive forces were necessary to achieve this strain for the aluminium alloy as the elastic modulus of 70 GPa is approximately three times lower than the elastic modulus of 210 GPa for the steel. Once the specimens reached the critical buckling force and leant against the antibuckling support, further increasing of the compressive force caused pressing of the antibuckling support onto the friction sensors via the friction force (Fig. 5b). Although the friction force was smaller in the case of the aluminium alloy due to the smaller compressive force, similar values of the stress due to friction were observed as the cross-section area was smaller for the aluminium specimens. Furthermore, as the absolute stress values in case of the aluminium specimens were lower as compared to the absolute stress values in case of the steel specimens, a more pronounced friction offset of the cyclic curve was detected for the aluminium specimens. The difference in the cyclic stress-strain curve and the hysteresis loops as a percentage of the peak stress can therefore be considered as the most relevant impact of the friction. Although

higher absolute values of the friction force for complex phase steel CP 800 are observed (Fig. 9b), it causes a smaller impact in terms of the cyclic curve (Fig. 14b) as the peak values for complex phase steel CP 800 and aluminium alloy AlMgSi0.5 (Figs. 9a and 14a) differ by more than a factor of three. It could be concluded that the friction evaluation is especially important for materials with lower load-bearing capabilities where the impact of the friction force is higher in terms of the percentage of the peak stress. Although the differences might not be considerable, their size still needs to be evaluated numerically in order to separate the true material stress-strain behaviour and the influence of the test environment. The difference between the cyclic curves scales as a function of the coefficient of friction and the critical buckling force. For slender specimens, the critical buckling force is lower and hence the influence of the friction is higher. The influence of the coefficient of friction depends on the pair of materials in contact. Whilst the influence of the specimen slenderness can be estimated by the equations of mechanics, the coefficient of friction can only be determined experimentally.

Detailed measurements are presented here for only one specimen of each material. However similar values of the friction forces are observed for repeated measurements. For example, at a strain level of ± 0.0075 , mean peak values of 62 N and 90 N with standard deviations of 25 N and 5 N were observed for the aluminium alloy and steel, respectively. Whilst the number of repeated experiments is small the data suggest the results are reproducible.

Before the start of the cyclic measurements, the elastic modulus in the compressive load direction for each material is determined. The peak prior to the cyclic measurements shown in Fig. 9 shows the point in time in the experiment for which the modulus is calculated. If the measured value of the elastic modulus differs significantly from the expected value for a particular material this is a clear indicator that the bolts on the antibuckling support are overtightened and need to be loosened. However, as exactly zero clearance between the specimen and the antibuckling support is hard to achieve, some friction between the PTFE foil and the specimen will still occur. This is evident from the small negative values of the friction force after reaching the compressive reversal points whilst the specimen is still in contact with the antibuckling support due to contraction in the direction perpendicular to tensile loading. This effect is noticed even at the smallest load levels and varies between zero and 25 N. The negative sign of this force follows from the initial conditions of the friction force measurement. The measurement on the friction force sensors is started after the test setup has been completed, which also includes the installation of the springs for maintaining the position of the antibuckling support. As installation of the springs causes the support to compress the sensors, the sensors are zeroed to remove the compressional effects of the springs. However, once a specimen in the rig buckles under a compressive load, the successive applied tensile load then pulls the support away from the sensors which causes an apparent negative reading on the sensors.

It can be seen from Fig. 8 that the cyclic hardening of the aluminium alloy is present mostly at strain levels of ± 0.0050 and ± 0.0075 whereas at ± 0.0150 the material does

not show any cyclic hardening or softening behaviour (Figs. 10, 11 and 12). Therefore the hysteresis loops do not differ significantly at ± 0.0150 (Fig. 12a). On the contrary, cyclic softening is present in the complex phase steel CP 800 from ± 0.0050 until rupture (Fig. 8). Cyclic softening at ± 0.0150 is more pronounced in the tensile region whereas it is subdued in the compressive region (Fig. 12b). As the steel specimen ruptured before reaching the stabilised state at ± 0.0175 , the last point in the stabilised cyclic curve deviates from the curve trend (Figs. 13b and 14b).

Although there exists relative motion between the specimen and the antibuckling support, the PTFE foil does not show any signs of damage after the test. With a PTFE foil friction coefficient of 0.07 (value provided by the manufacturer which is in accordance with the literature, e.g. [43]), it can be calculated according to the model in Eq. 2 that the normal force F_N (Fig. 5) could increase up to 1300 N where the specimen and the antibuckling support touch (Fig. 5).

As the test is stopped after the completion of the loadings at the chosen level, the stress and strain signals differ from the continuous friction force measurement. The cross-correlation function must therefore be applied to each load level in order to correlate the signals correctly. If both signals were taken in one step, an erroneous time delay would be calculated. The correlation of both signals for all tested levels in one step is therefore only possible if multiple step testing is performed without pauses between the levels.

The analysis of the robustness of the method presented in Fig. 15 shows that the calculated delay between the signals varies insignificantly. This variation is between zero and 1.2 % for the chosen example as compared to the period of the cycle although severe distortions of both measured signals have been introduced. The calculation of the delay between the signals therefore enables a credible determination of the true stress during the cyclic test. It can be noticed from Fig. 16 that by decreasing the resampling frequency by a factor of 20 (from 2000 Hz to 100 Hz), a negligible variation of 0.5 % of the delay calculation can be observed. However further decreasing of the resampling frequency by a factor of 50 (from 100 Hz to 2 Hz) starts to increasingly affect the delay calculation. In the case of 2 Hz, the calculated delay varies by 50 % as compared to the value observed at 2000 Hz. As the loading frequency for the test example given in Fig. 15 is 0.2 Hz, only 10 notably inadequate discretisation steps per load cycle would have been considered for the resampling frequency of 2 Hz. For a sufficiently high resampling frequency of the measured signals, the calculation of the delay can therefore be determined accurately.

6. Conclusion

The method presented in the paper enables the determination of a cyclic curve without the influence of friction. Simple mechanical friction sensors have been designed which can be placed on any pre-existing test rig using antibuckling supports. They enable measurements of the friction force independently from the force and strain measurements

on the test rig. The method then equalises the data acquisition frequencies of the test rig and the friction sensors. Finally, the two signals are aligned using the cross-correlation function and the true compressive stress-strain curve can be determined.

Two metals were used to verify the method, an aluminium alloy AlMgSi0.5 and a complex phase steel CP 800. The effect of the friction force is a higher stress signal measured on the test rig and is more noticeable on the aluminium alloy rather than the steel. It is seen by a change of the stabilised cyclic stress-strain curve in the compressive part of the diagram and could have implications for material response modelling if the frictional component is not removed from the measured stress signal.

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