A NEWLY-DEVELOPED FIXTURE AND TESTING METHOD FOR STRAIN RATE-DEPENDENT FLEXURAL PROPERTIES DETERMINATION OF CARBON/EPOXY COMPOSITES

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ABSTRACT

This study deals with a newly developed fixture to obtain strain rate-dependent properties of carbon fiber reinforced plastics (CFRP) under flexural loading. While the quasi-static method is mostly state of the art and covered in standards, the dynamic testing of CFRP is very demanding in terms of testing procedure, test rig and occurring failure mechanisms. In this context, unidirectional carbon fiber/epoxy prepreg under short-time dynamic flexural loading is investigated.

1 INTRODUCTION

Light weight structures have always had challenges in the design process of load bearing components (e.g. car body development in automotive industry). For automotive parts legal crash load cases are of major importance when it comes to defining wall thickness and fiber orientation. In order to ensure the vehicle crash performance finite element models are used. It is relevant to take into account strain rate properties of CFRP to obtain reliable simulation results. For quasi-static material properties, 3-point-bending (3PB) tests are normally performed to validate the material cards to be used in finite element models. Hence, for this reason it is important to have a reliable 3PB test setup that can be used to validate material cards that take into account CFRPs strain rate-dependent properties [1]. For this purpose a fixture for dynamic 3PB is developed, as shown in Fig. 1.

The quasi-static 3-point bending test is state of the art and international standards have been developed. Such standards – for example DIN EN ISO 14125 [2] – give guidelines regarding the optimal test setup in terms of specimen geometry, supports and impactor radius, support span, and loading rate.

For example, Mujika et al. [3] were able to obtain the tensile and compressive modulus for two UD carbon/epoxy materials from bending tests. They then checked the tensile modulus obtained with the one resulting from tensile tests on the same material. The two values were in agreement and differed by less than 5%. Van der Vossen [4] investigated the spatial variability of stiffness in fiber-reinforced composites, focusing on specimens used for short beam shear tests. Digital image correlation (DIC) combined with finite element (FE) analysis were used to characterise material properties. It has been shown that for tensile, compressive, and shear tests there are no standards for strain rate-dependent tests. The same is valid for bending tests. Strain rate-dependent 3-point bending test (also referred to dynamic

or impact 3-point bending) is under investigation in the research community. However, a limited amount of studies has been found in literature. One of the first studies was performed by Lifshitz et al. [5]. Low velocity impacts were performed using a drop tower on carbon/epoxy AS4/3502 specimens. Also Sánchez-Sáez et al. [6] performed 3-point bending impact tests using an instrumented drop weight tower on carbon/epoxy laminates. Test results at room temperature showed that the mechanical strength for dynamic tests was lower compared to the quasi-static values, for all layups tested. This behaviour was also observed by Lifshitz et al. [5]. In both studies the specimens failed initially on the tensile side of the specimen and the main failure mechanism was fiber breakage. Hallett [7] performed 3PB impact tests using a gas gun apparatus. Wiegand [8] performed impact bending tests using a gas gun apparatus similar to the one used be Hallett [7], recorded using digital photography. Specimens were cut from a 3 mm thick plate, which was manufactured using non-crimp carbon/epoxy T700/MTM44 fabric. Specimens were tested using a support span of 50 mm and 30 mm. All the specimens tested failed with compressive failure as the primary failure mode. The force and displacement at failure increase compared to quasi-static results. This behaviour was observed at both support spans tested. This behaviour differs from the one observed in other studies [5, 6, 11]. This could be due to the fact that the specimens tested by Wiegand failed first in compression, and not in tension.

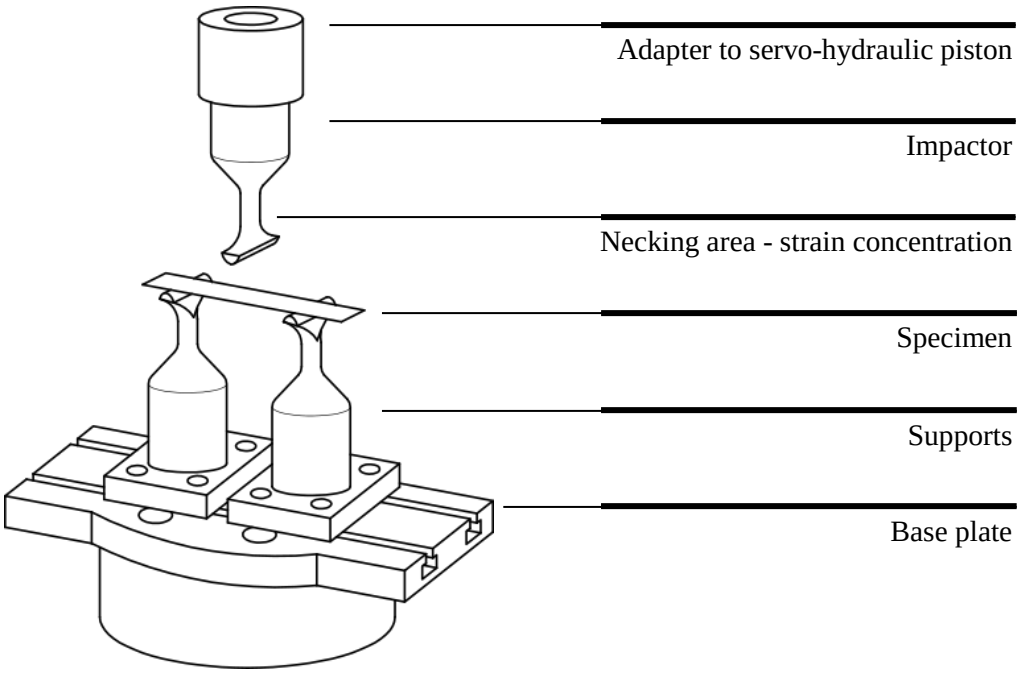


Figure 1: 3-point-bending test setup to derive strain rate-dependent flexural properties

This review corroborated that there is no accepted standard for rate-dependent testing of composites. There is, therefore, a need for the evaluation of tests like the 3-point bend test in order to determine the optimum parameters (specimen thickness and support span) such that reliable data can be measured from the test setup. This can then be used to validate a material card in the FE model which take into account strain rate-dependent material properties, so more accurate material cards are available for simulation of vehicle crash tests.

2 EXPERIMENTAL

Tests have been performed using specimens of different thicknesses – from 1.5 mm to 5.5 mm – and at different impactor velocities – from $0.0\overline{3}$ mm/s to 10 m/s. Furthermore, the influence of the support span has been assessed by testing with the support span of 80 mm and 60 mm. The specimen geometry is illustrated in Fig. 2. This parameter variation has been done to determine the best test setup that allows the determination of reliable test results at high velocities. A summary of the testing parameters for the two different configurations is shown in Table 1.

Testing configuration 1			Testing configuration 2		
Specimen geometry	Support span [mm]	Testing velocity [m/s]	Specimen geometry	Support span [mm]	Testing velocity [m/s]
		3.3×10^{-5}			3.3×10^{-5}
		0.1			0.1
		0.5			0.5
A	80	3	B	60	3
		5			5
		8			8
		10			10

Table 1: Testing configurations.

2.1 Materials selection and specimen preparation

A commercial high-modulus carbon fiber (T700, Toray) with a tensile strength of 4,900 MPa was used as a part of epoxy-based prepreg system (DT120, Delta-Tech, areal weight 150 g/m^2) [9,10]. Unidirectional laminates with different thicknesses (Table 2) were manufactured using the autoclave process. The curing of the laminates followed the suppliers recommendations for autoclave processing [9].

High quality of the manufactured laminates was required; therefore, several quality inspections were performed. The first step is the thickness measurement using a Kroeplin IP 67. The thickness is measured in nine different positions of each resulting plate. Furthermore, the fiber volume content is determined by a density measurement using an uplift scale (Mettler Toledo).

For sample preparation in the first step, the initial plates are cut in smaller rectangular coupons by waterjet cutting. The final cut of the desired width was achieved by means of a water-cooled diamond precision saw. Two different specimen geometries were manufactured.

Geometry A was chosen because it is the shape suggested for quasi-static tests for UD laminates. It was tested with a support span of 80 mm, which mostly eliminated shear-driven failures [6]. This type of specimens were expected to have a compressive failure. The smaller specimen geometry was tested with a support span of 60 mm. Such support span is the smallest that can be obtained with the designed fixture. It was decided to reduce the support span, because trial tests had shown oscillations in the force signal for tests at high piston velocities. This was mainly due to the successive separations of the specimen from the impactor during testing.

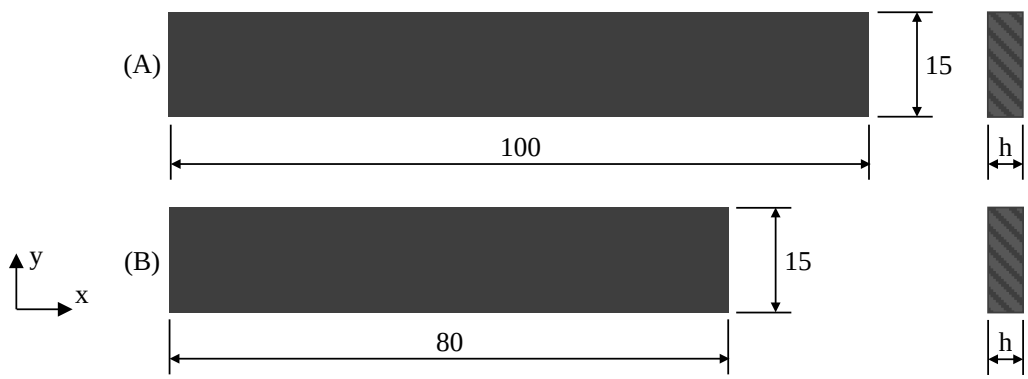


Figure 2: Specimen geometry tested with the support span of 80 mm (A) and 60 mm (B)

2.2 Testing machine and equipment

A servo-hydraulic testing machine is used for the characterization of dynamic material properties. A fixture, composed of the two supports and the impactor, has been designed adapting the recommendation given by DIN EN ISO 14125, which is used for quasi-static tests. The force applied on the specimen is measured through strain gauges bonded to the fixture. The method used for force measurement is shown in Fig. 3 and a characteristic force signal is shown in Fig. 5. To measure the specimen mid-point displacement and the impactor velocity the DIC method was used. The tests were recorded using two high-speed cameras (Photron SA-X), the specimens were painted using a gray-scale stochastic pattern, and the impactor was instrumented. The test results were analysed in terms of force and displacement when fiber kinking occurred; at this point the maximum load was reached. A total of three replicates were tested for each configuration. The pictures and the data coming from the strain gauges were combined together using the DIC software ARAMIS®, which also allowed computing the parameters of interest from the pictures.

To amplify the signal coming from the strain gauges a VISHAY signal conditioning amplifier [12] was used. Each fixture component was connected to a separate amplification unit. The amplification unit provides the connection to the ground and has a built-in Wheatstone bridge circuit, shown in Fig 3.

For all three fixture components the quarter Wheatstone bridge configuration was selected, it is shown in Fig. 3. Since the strain gauge had a resistance of 120 Ω, the bridge configuration with all resistors of equal resistance was selected. The amplification units provided the bridge excitation voltage U_{in} and the amplification factor A_{WB}.

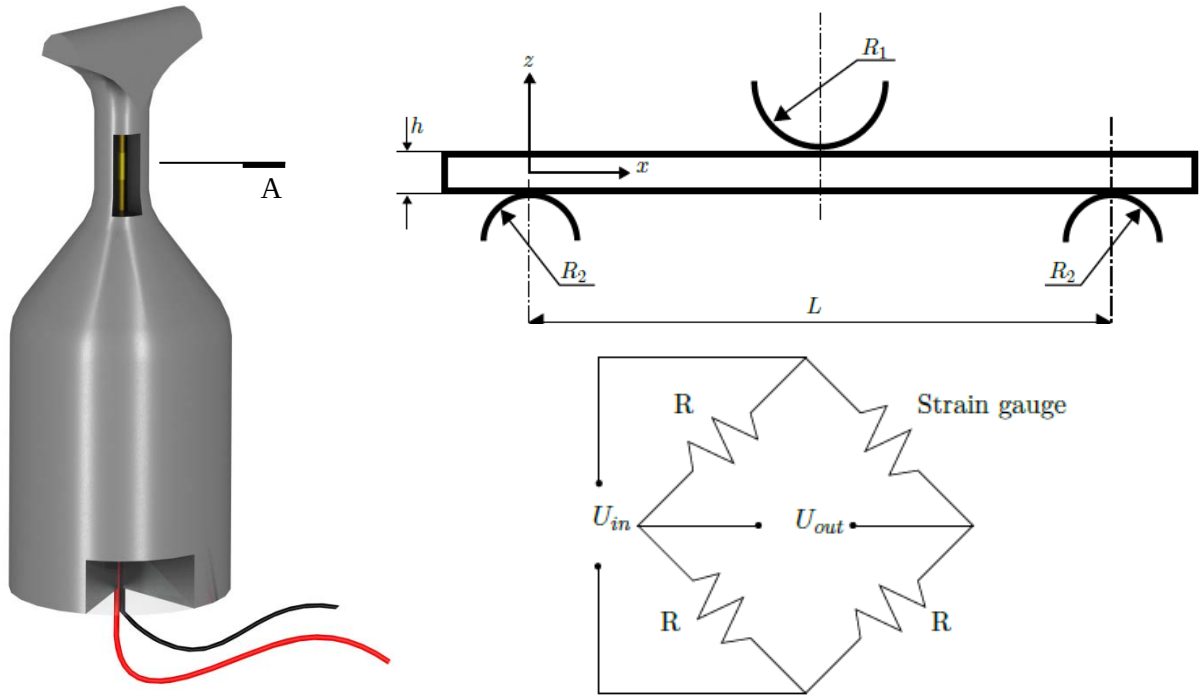


Figure 3: Basic procedure for force measurement used for the impactor and supports. 3-point bending setup and the corresponding quarter Wheatstone bridge for every strain gauge.
Detail A - Strain gauge bonded to central hole.

Through the Wheatstone bridge theory it was possible to convert the measured voltage into the applied load. The output voltage is defined by the equation

$$U_{out} = \frac{1}{4}\, U_{in}\, A_{WB}\, k\, B\, \varepsilon \tag{1}$$

where k is the gauge factor, B is the bridge factor (which is equal to 1 for the quarter bridge configuration), and ε is the strain in the necking area. The strain ε is the only unknown variable in the equation, as the output voltage is the quantity measured during testing. The strain is related to the applied stress σ through the modulus of elasticity E, according to Hooke's law for isotropic material. Steel was used in this case. The applied stress is therefore obtained as

$$\sigma = E\,\varepsilon \rightarrow \sigma = \frac{4\,U_{out}\,E}{U_{in}\,A_{WB}\,k\,B} \tag{2}$$

knowing the reference area A of the necking region the applied load is found:

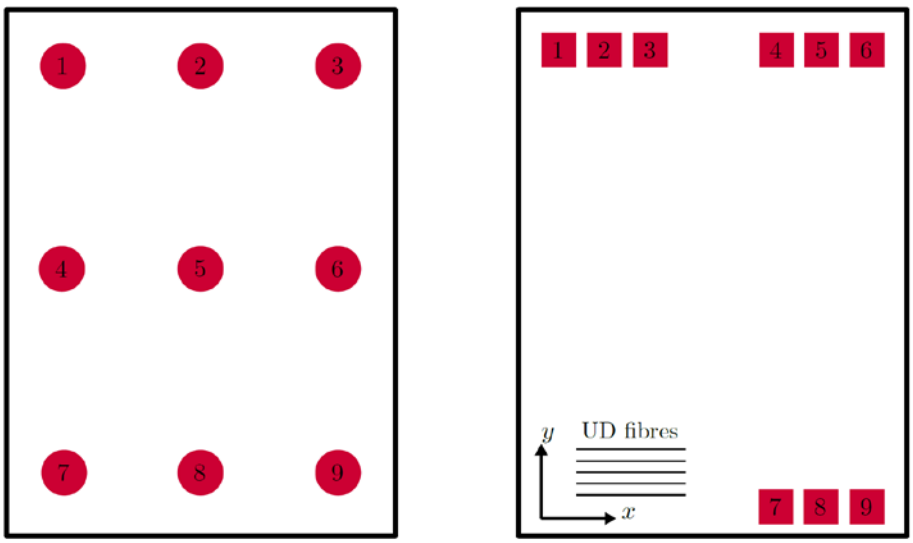
$$F = \sigma\,A \rightarrow F = \frac{4\,E\,A}{U_{in}\,A_{WB}\,k\,B}\,U_{out} = S\,U_{out} \tag{3}$$

where S is a constant for a given setup and is the conversion factor that allows computing the applied load from the measured output voltage. S was used as initial conversion factor, before starting the test program the impactor and the support were calibrated to obtain a more reliable conversion factor. The calibration process followed the standard ISO 7500-1 [13], which defines how to calibrate the force-measuring system for uniaxial testing machines.

3 RESULTS AND DISCUSSION

3.1 Quality assurance

To investigate the thickness effect on the force signal, plates of different thicknesses were manufactured. All the plates were manufactured using the hand layup to stack the UD plies. The stacked prepreg plates were then cured in an autoclave using the vacuum bag method.



(a) (b)

Figure 4: Positions for thickness (a) and fiber volume (b) measurements.

High quality-manufactured plates were required. In order to obtain smooth surfaces the stacked prepregs were placed between two carbon fiber mould plates, during the curing process. After the autoclave process, several quality inspections were performed. The thickness of all plates was measured using a Kroeplin IP 67 at nine different positions, as shown in Fig. 4a. The fiber volume was measured using specimens taken from the nine positions shown in Fig. 4b. The results are summarised in Table 2.

The average fiber volume of all plates was 54.09% and all the plates show a very similar fiber

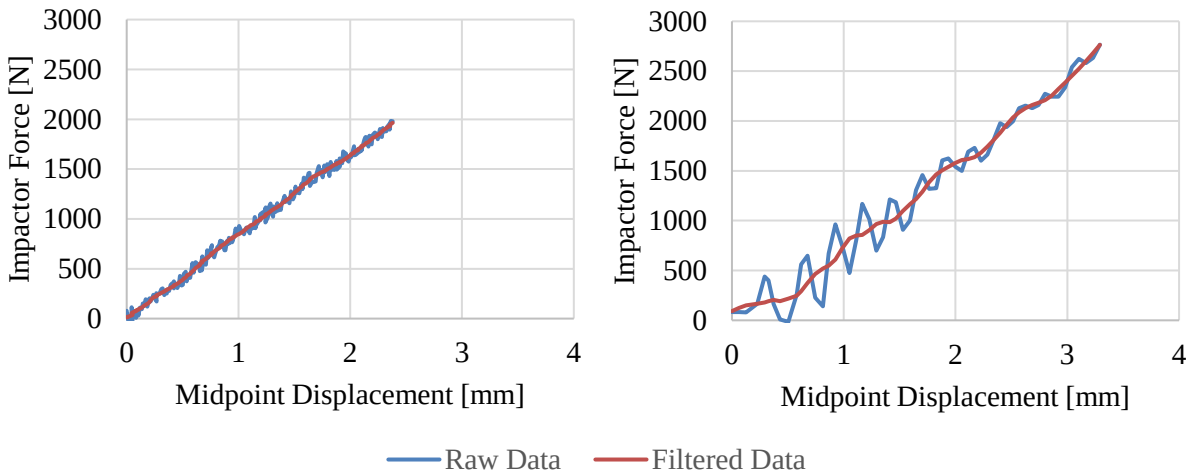
volume. This was an important requirement, as specimens with different thicknesses were tested, and the fiber volume should not affect the results obtained.

Number of UD plies	Plate thickness [mm]	Fiber volume content [%]
10	1.49	54.29
13	1.96	54.56
17	2.54	53.52
20	2.99	53.96
23	3.41	54.44
27	4.00	54.56
30	4.50	53.83
33	4.90	54.18
37	5.52	53.45

Table 2: Quality assurance by thickness measurement and microwave incineration.

3.2 Force signal

The output signal coming from the strain gauges showed some fluctuations. One source of oscillation in the signal was the noise induced by the testing equipment and the setup. This resulted in small fluctuations in the signal, as shown in Fig. 5a. The other source was due to vibrations of the specimen. When the impactor hits the specimen, it slightly bounces and contact is lost between the specimen and the impactor. This behaviour induces the signal oscillations visible in Fig. 5b. The force-displacement curves (Fig. 5) were cut off at the failure point, as after initial failure a drop in the load was observed. It was therefore decided to filter the signal using a LOESS filter. The LOESS filter allows to define a smooth curve that fits the force signal. For this particular application a span of 25% was the one that best fitted the data at all testing velocities.



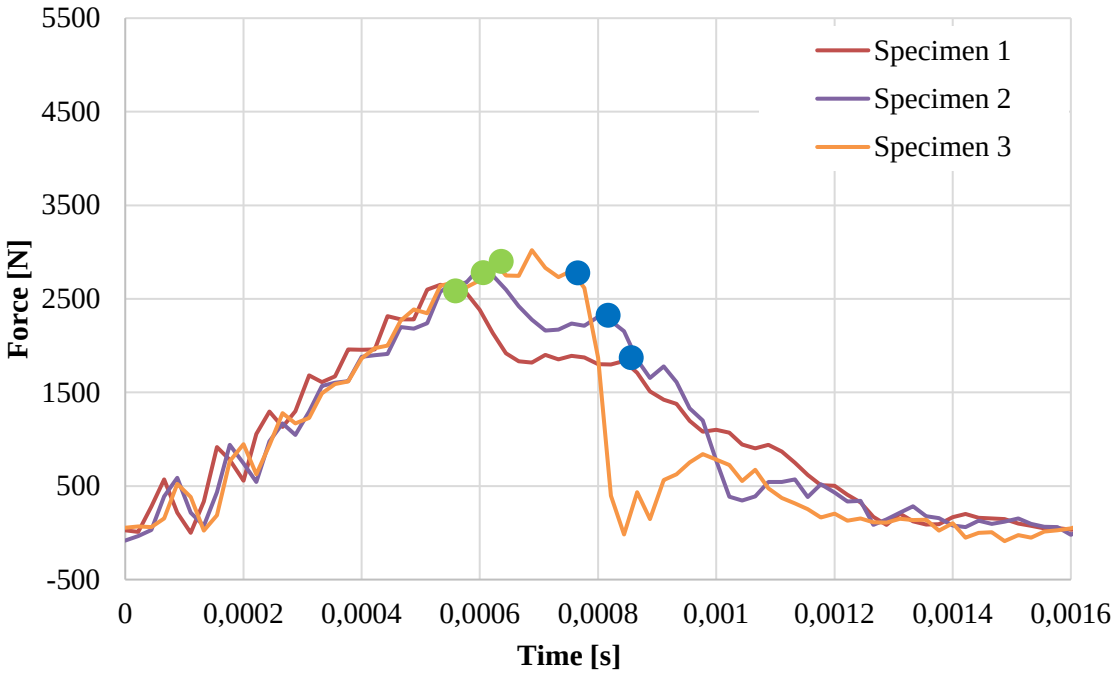
(a) (b)

Figure 5: Filtered force signal for a 4 mm thick specimen with geometry A tested in (a) quasi-static quasi-static conditions and (b) at 3m/s

3.3 Fracture mechanism

All the specimens tested had a compressive failure. The initial failure was fiber kinking on the compression side of the specimens, in correspondence of the contact area with the impactor. Initial failure on the compressive side of the specimen was also reported by Wiegand [8]. This is because the

region of the specimen below the impactor is the one where the material is subject to the highest stresses and strains. Moreover, being UD carbon/epoxy composites anisotropic material with lower compressive properties compared to the tensile ones [3], compressive failure was expected. For the specimens with thicknesses of 1.5 and 2 mm, once fiber kinking occurred the specimen nearly instantaneously split in two parts. Specimens with thickness of 2.5, 3 and 3.5 mm tested with both support spans and specimens with thickness of 4 mm tested with a support span of 60 mm showed a fiber tensile final failure, see example in Fig. 6. After the initial fiber kinking the fracture propagates through the specimen thickness. This event results in a reduction in the applied load or in a plateau where the applied load remains constant. Once the tensile failure strain is reached on the tensile surface of specimen, tensile fiber breakage occurs. The result is a sharper decrease in the load signal.



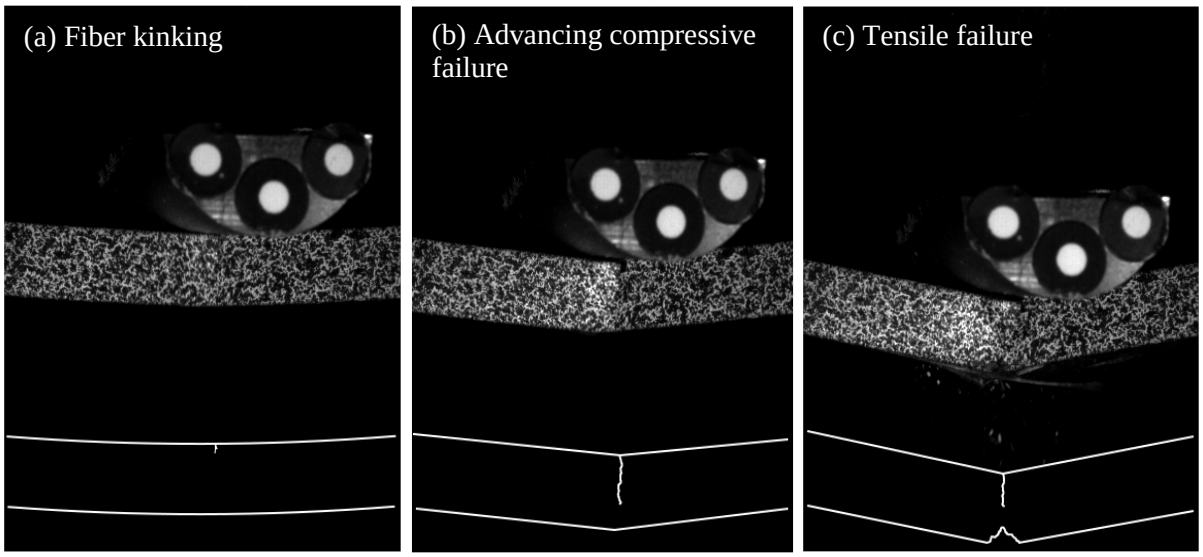
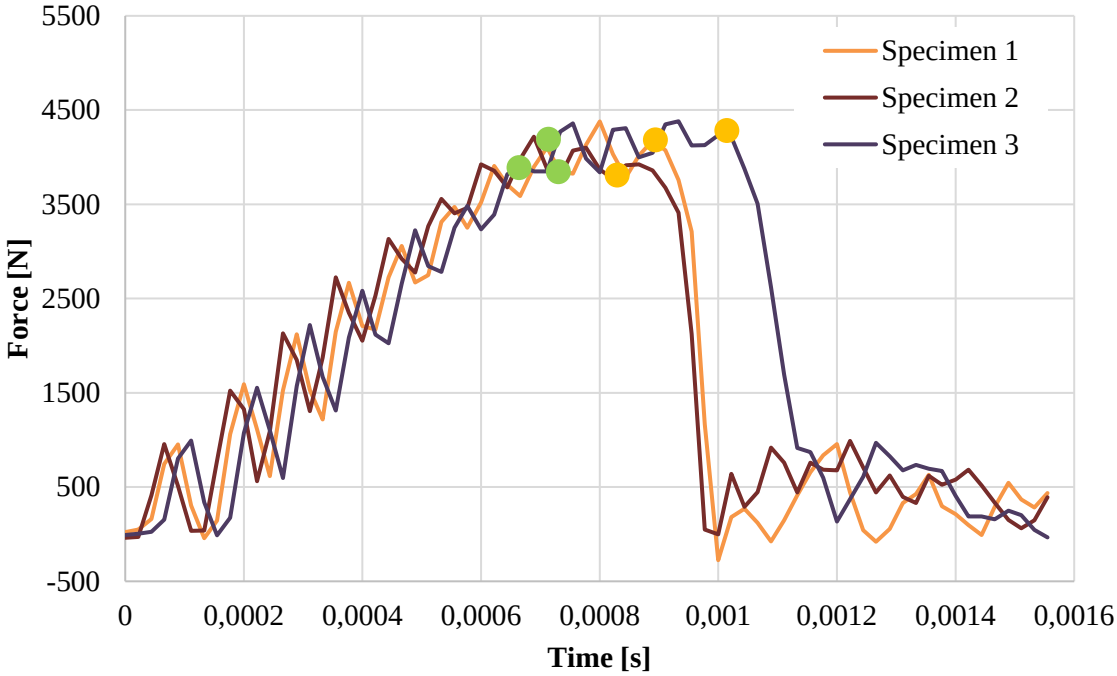


Figure 6: Failure mechanism of 3.5 mm thick specimen. Support span of 80 mm at a velocity of 5 m/s.

Specimen with thickness of 4.5, 5.0 and 5.5 mm tested with both support spans and specimens with thickness of 4 mm tested with a support span of 80 mm showed delamination as final failure mode. An example is shown in Fig. 7. Once fiber kinking occurs on the compression side, the applied load remains constant while the fracture propagates through the thickness. At the occurrence of delamination the load

signal goes instantaneously to zero as the specimen is split in two parts. This behaviour is due to the fact that, as the ratio between specimen thickness and support span decreases, the influence of shear stresses increases [6, 11].



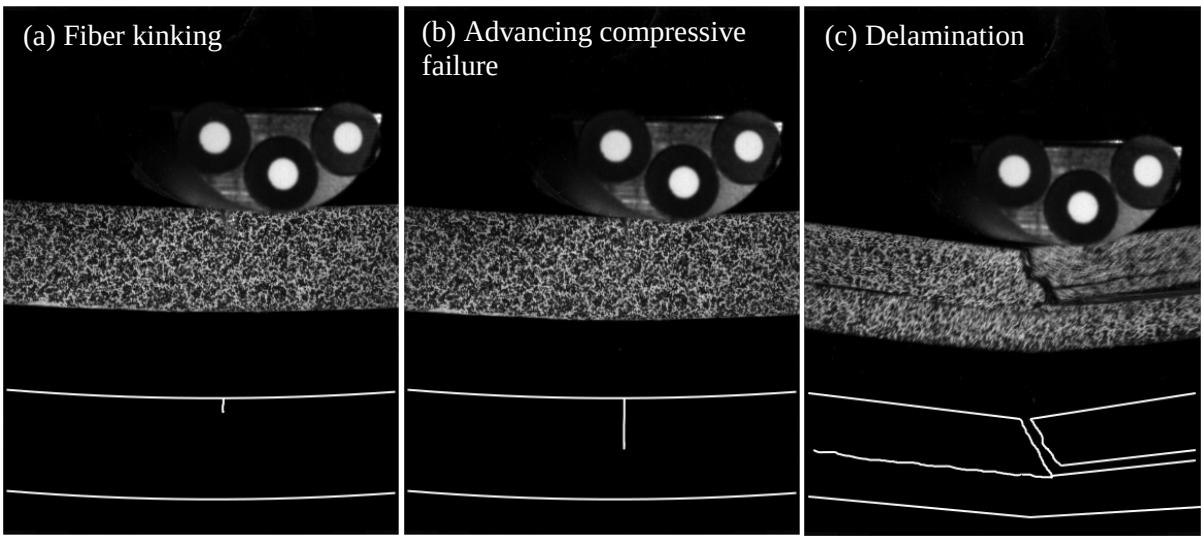


Figure 7: Failure mechanism of 5 mm thick specimen. Support span of 80 mm at a velocity of 5 m/s.

3.4 Maximum force

The maximum force coming from the smoothed force signal for the tests performed is summarised in Fig. 8. For each specimen thickness, the bar plots display the maximum load reached at every velocity tested. As three replicates were performed, the displayed value is the average of the three tests and the error is given as the standard deviation. Even though the designed fixture is not suitable to test thin laminates, specimens with thickness from 1.5 to 3 mm were tested because this thickness range is the most used for standard material characterisation of structural components. These specimens are the ones which show high variation in maximum force and there is no delineated trend in the maximum force as the testing velocity increases. This is mainly observed for tests with the larger support span. As general trend, specimens with a thickness higher that ≥ 3 mm show an increase of maximum load with increasing testing velocity.

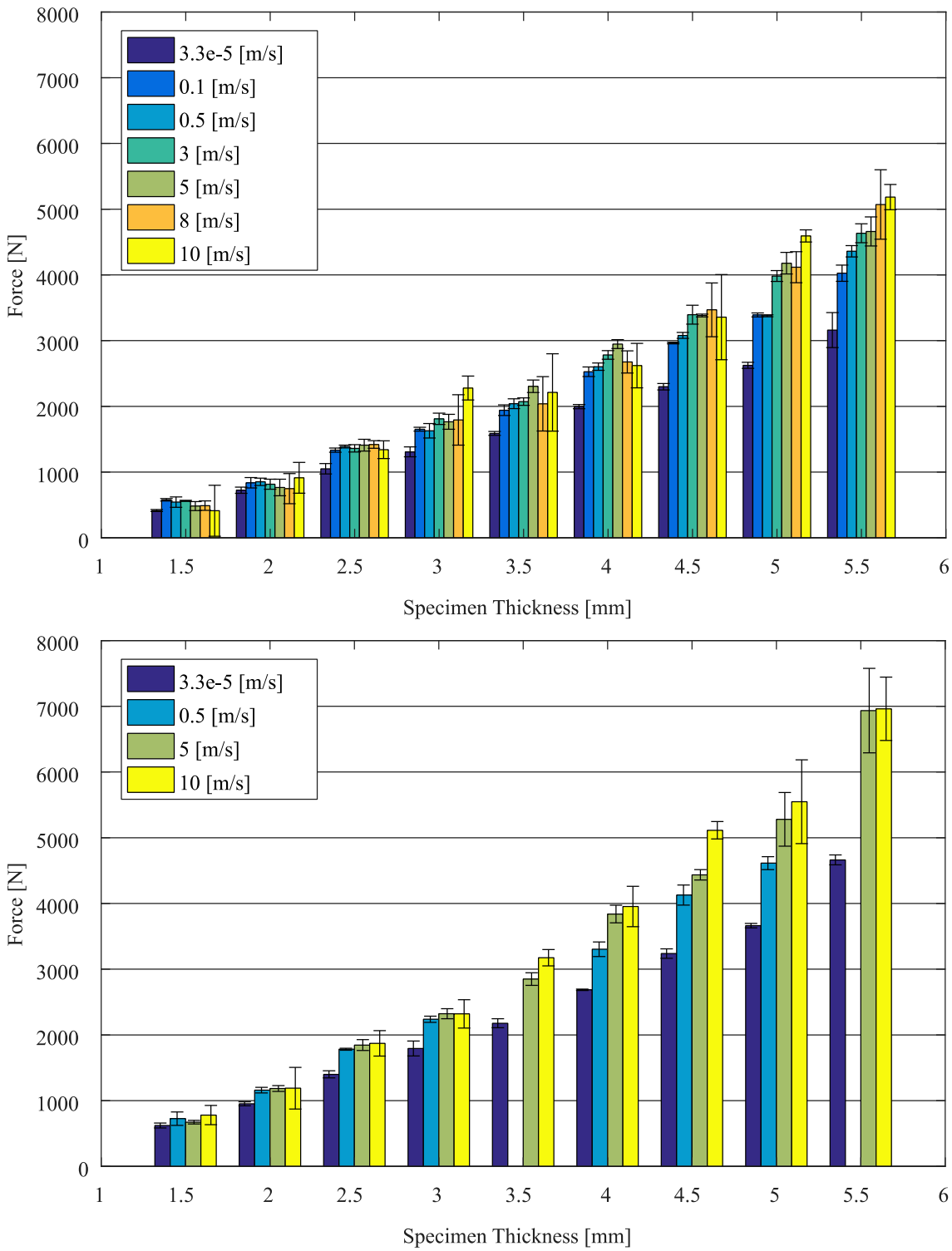


Figure 8: Maximum force at failure. Support span 80 mm (top) and 60 mm (bottom)

When the support span is 80 mm, this is true up to testing velocities of 5 m/s. For example, for the specimens with thickness of 4 mm and 3.5 mm, at high velocities the maximum force decreases compared to the one obtained at 5 m/s. Another outcome is that high deviation in the results is observed, as for specimen with thickness of 4.5 mm and 5.5 mm. This behaviour could be due to specimen vibrations during testing. Results obtained with the smaller support span show a more homogeneous increasing behaviour.

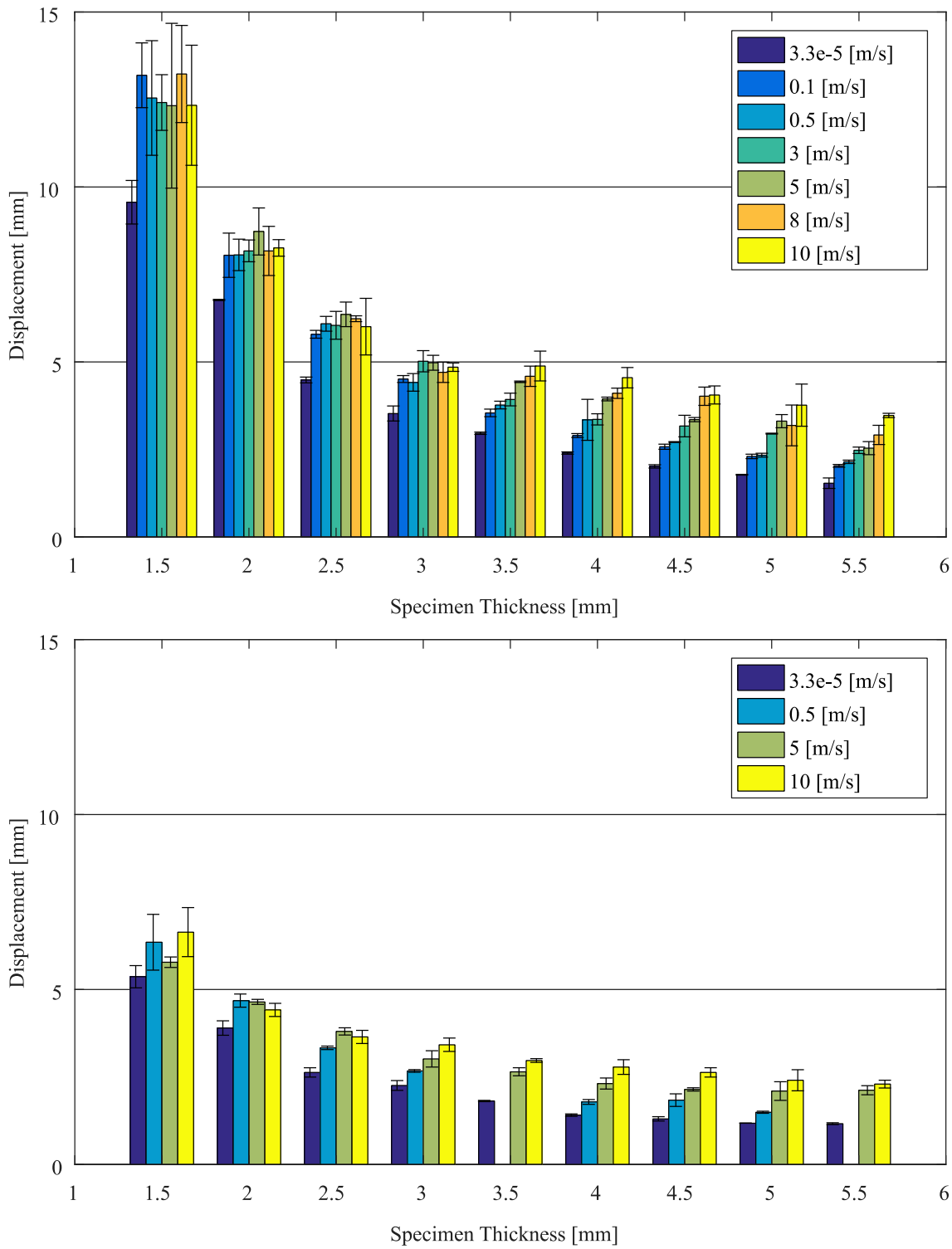


Figure 9: Maximum midpoint displacement at failure. Support span 80 mm (top) and 60 mm (bottom)

3.5 Maximum midpoint displacement

The specimen displacement was obtained from the analysis of the pictures taken with the high-speed cameras. The results are shown in Fig. 9. As expected, the midpoint displacement decreases with the increase in specimen thickness. This is due to an increase in the beam stiffness. As a result, increasing the testing velocity gives an increase in maximum displacement. For thicknesses higher than 3.5 mm

the maximum displacement for tests performed at 10 m/s is in all cases nearly twice the displacement measured in quasi-static conditions. This behaviour is observed regardless of the support span.

In Fig. 10 the relationship between the specimen midpoint displacement and the testing velocity is shown. The general trend is an increase in displacement with increasing testing velocity. In all tests performed the results show a high increase in specimen displacement between the quasi-static velocity and low testing velocity of 0.5 m/s for support span of 60 mm. The increase between the other testing velocities is not as steep, and the curves have a tendency to flatten. This behaviour suggests a logarithmic relationship between the specimen midpoint displacement at failure and the testing velocity.

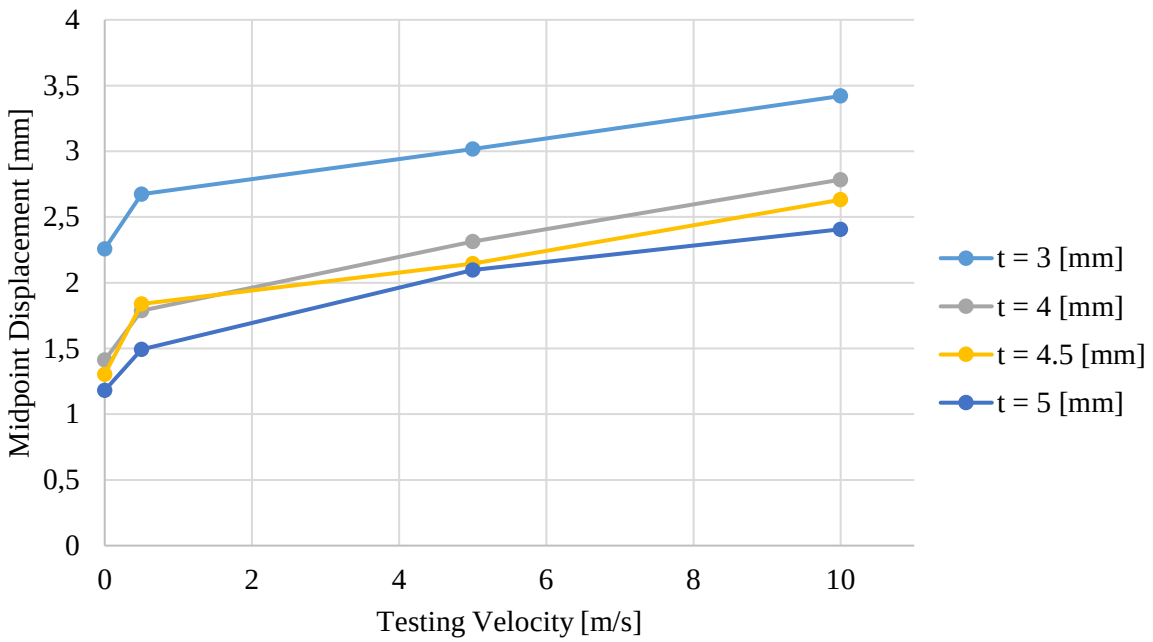


Figure 10: Specimen displacement vs. testing velocity. Support span 60 mm

3 CONCLUSIONS

The designed fixture allowed correctly measuring the load applied by the impactor on the specimen at every testing speed. It was necessary to filter the output signal, as it showed oscillations due to noise in the setup. The use of high-speed cameras, combined with DIC software, allowed to easily obtain the specimen midpoint displacement and the impactor displacement and velocity. Thanks to this data it was possible to notice that after the initial impact the contact is lost between specimen and impactor. This induced vibrations on the specimen. In order to reduce this effect it is possible to increase the specimen thickness or to reduce the support span. The latter solution is the most effective, because it increases the specimen global stiffness. As a result, the detachment between specimen and impactor, and the specimen vibrations are reduced.

All specimens tested failed starting with fiber kinking on the compression side of the specimen. The location is in the area of contact with the impactor, as it is the region of the specimen where the highest strains are reached. Depending on the specimen thickness, the final failure can be tensile fiber failure or delamination. Generally, there is no increase in load after initial fiber kinking, therefore this point was chosen as specimen failure; maximum load and displacement are the ones measured when fiber kinking occurs.

Both the maximum load at failure and the specimen midpoint displacement at failure increase at every testing velocity compared to the values obtained at quasi-static tests. The increase in the maximum load for every combination of specimen thickness and support span compared to the relative quasi-static

one is always above 20%. The general trend is the increasing maximum load at failure for increasing testing speed. This behaviour is especially observed in tests performed with the support span of 60 mm, which minimises the specimen detachment from the impactor and therefore the specimen vibrations. The reason is due to the fact that, if the specimen is considered as a simply supported beam, with the lower support span the beam stiffness increases if compared to the larger support span. The specimen midpoint displacement at failure always increased with increasing testing speed. It was found that the midpoint displacement showed an increase when plotted versus the testing velocity.

ACKNOWLEDGEMENTS

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