National Physical Laboratory

NPL REPORT MAT 109

INTERMEDIATE STRAIN RATE TESTING – A CAPABILITY STUDY USING A HYDRAULIC TEST MACHINE AND HIGH-SPEED CAMERAS

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MARCH 2022

Department for Business, Energy & Industrial Strategy

FUNDED BY BEIS

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ISSN 1754-2979

DOI: https://doi.org/10.47120/npl.MAT109

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This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the UK's National Measurement System programmes.

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1 INTRODUCTION

Fibre-reinforced polymer (FRP) composites are increasingly used across a wide variety of applications, due in part to the desirability of their in-plane properties relative to their weight. However, some polymer-based composites, such as glass-fibre reinforced polymer composites (GFRPs), can be strain-rate dependent and this may influence their ability to function in the desired application. As such, for effective component design, an understanding of the material behaviour under a range of loading conditions is required, including the influence of loading rate.

Pemberton et al [1] examined the current status of FRP composite test methods for the characterisation of mechanical properties at different strain rates. The report focused on the use of high-speed servo-hydraulic testing machines that can load materials at 'intermediate' strain rates, i.e., 0.1 to 100 s^{-1} (Figure 1). From this report it was shown that, at present, there are no test standards, and little guidance available for measuring mechanical properties of composite materials at strain rates considered intermediate (or higher). It is worth noting that for metals, ISO 26203-1 [2] and ISO 26203-2 [3] cover tensile testing at intermediate and high strain rates using the split Hopkinson bar (SHB) method and hydraulic test machines, respectively. While the approaches used in these methods have been adapted for use with composite materials, they have not been thoroughly evaluated and therefore it is not clear if these are directly applicable.

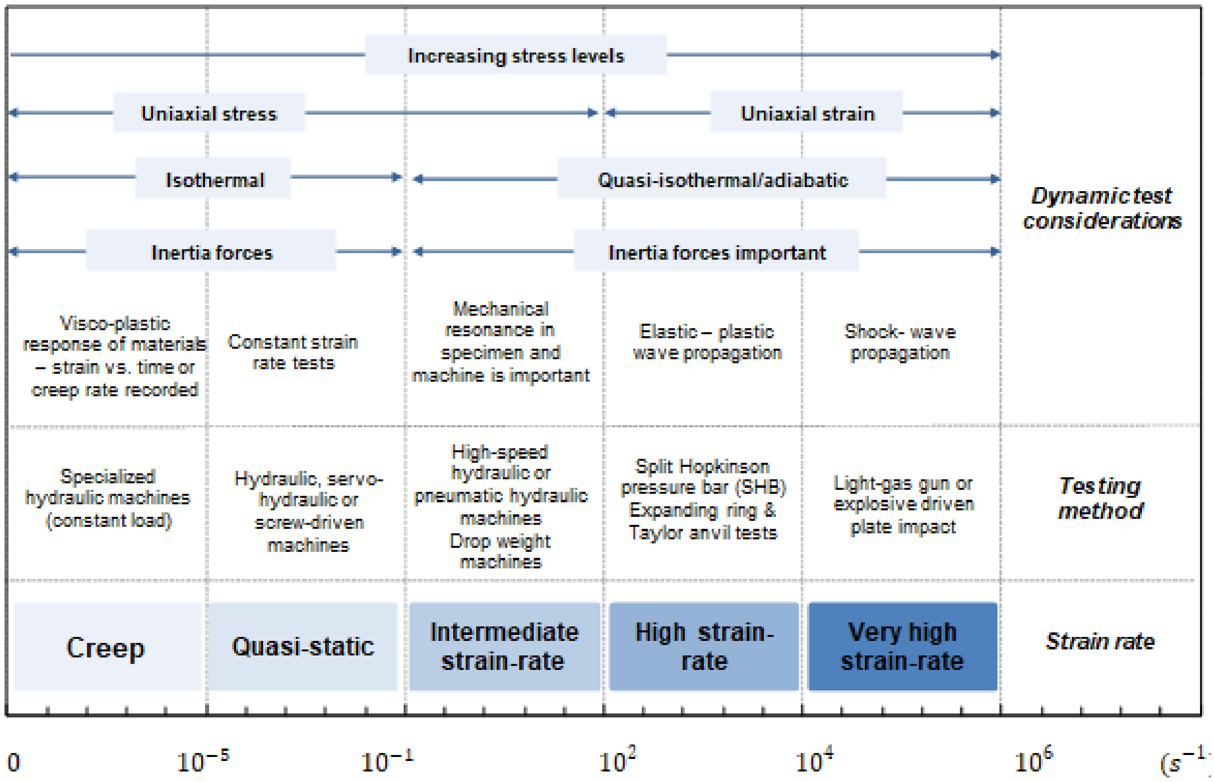


Figure 1: Strain rate regimes with associated testing systems and dynamic considerations [1]

The aim of the work detailed in this report is to develop and validate test methodologies for intermediate strain rate characterisation of polymer composites with a view to providing industry with guidance and work towards future standards. The work was undertaken within the Polymer Composites Metrology in Support of Regulations, Codes and Standards (RCS) Infrastructure project as part of the 2021-2022 Advanced Manufacturing Sector (Materials Metrology) National Measurement System Programme, funded by the Department for Business, Energy and Industrial Strategy (BEIS).

This report details initial capability development utilising a high-speed servo-hydraulic test machine (Instron VHS) in conjunction with high-speed cameras (Photron Fastcam Nova S16) and digital image correlation (DIC) software for measurement of full-field strain distributions.

2 EXPERIMENTAL SETUP

2.1 TEST MACHINE

Intermediate strain rate testing was conducted using an Instron VHS 160/100 -20 test machine (Figure 2). The Instron VHS is a hydraulically driven test machine that can be operated from speeds of less than 1 mm/s to as high as 20m/s and has a static and dynamic loading capability of 160 kN and 100 kN, respectively. In addition, the maximum stroke of the actuator is 300 mm, and the frame separation (distance between T-slotted base and crosshead) is 1500 mm. Load is measured using a Kistler piezoelectric load washer which is highly sensitive to changes in load, making it suitable for dynamic loading measurements. Attached to the Kistler load sensor is a static grip body that can accommodate specimens up to a thickness of approximately 3-3.5 mm.

Compared to screw-driven quasi-static and hydraulic dynamic fatigue test machines, where specimens generally experience load from the moment the test has started, the Instron VHS only applies load to a specimen once the actuator has achieved the desired test speed. At low test speeds, the time and travel needed for the actuator to reach the chosen loading rate is low and as such the specimen experiences the required test speed for the vast majority of the test duration. Under the same conditions, but at high test speeds, test specimens in the Instron VHS may fail before the correct loading rate is achieved. While the actuator can accelerate very quickly to the chosen test speed, its travel will not be negligible compared to that needed to permanently damage or fail the test specimen. To avoid premature failure, specimen loading on the Instron VHS does not occur until the desired loading rate is reached. For tensile testing this is done using a fast jaw gripping system, whereby knockout wedges keep the grip faces apart, releasing only when the actuator is at the correct speed and thus loading the specimen. The test machine can run in either a tensile or compressive loading mode and various test fixtures can be attached to the frame in order to accommodate different test types.

Due to the testing speeds available and the potential for explosive failures, the test machine is secured behind a protective enclosure constructed from aluminium frame with Perspex windows. In addition, the doors on the enclosure have an interlock that will disengage the test machine and put it in a lower powered state to reduce any potential for user harm.

Currently, only one side of the Instron VHS provides access for cameras. There is a window that can be opened or closed depending on the user’s choice. Ideally the window remains open during testing to limit interference from window reflections on the captured images. However, for particularly explosive testing, where both user safety and protection of cameras or ancillary equipment are essential, this window can be closed. For image capture on more than one face/edge of a test specimen, either an opening needs to be created in the Perspex, the camera placed outside the Perspex enclosure, or camera placed within the frame.

Depending on the type of testing being conducted, the chosen test speed and the material being tested, test times can be very short, as low as 3 ms. As such, high data acquisition rates are required to capture a sufficient number of data points for analysis. The Instron VHS can acquire at rates up to 60 MHz.

Note 1: At the top end of the data acquisition rate, the data files will be GBs in size. The choice of acquisition rate should be based on the type of material being tested. The more brittle the material, the greater the acquisition rate is required to be to ensure sufficient data capture over the test duration. This consideration is also required when testing at higher test speeds and strain rates. Typical acquisition rates for some different materials are:

- Polymers: 10-20 kHz
- Metals: up to 1 MHz
- Composites: up to 5 MHz
- Ceramics: up to 5 MHz

The test machine uses analysis software that is designed to align digital image correlation (DIC) strain measurements with load and displacement data acquired from the machine. This software takes both sets of data and synchronises them based on the point at which both the load and strain data begin to increase in magnitude. Since DIC strain measurements made using high-speed cameras are likely to be acquired at a slower rate than is used by the dynamic test machine for data acquisition, interpolation is used to create new DIC data points to match the machine acquisition rate. Both sets of data can then be used in the calculation of properties such as yield strength and modulus.

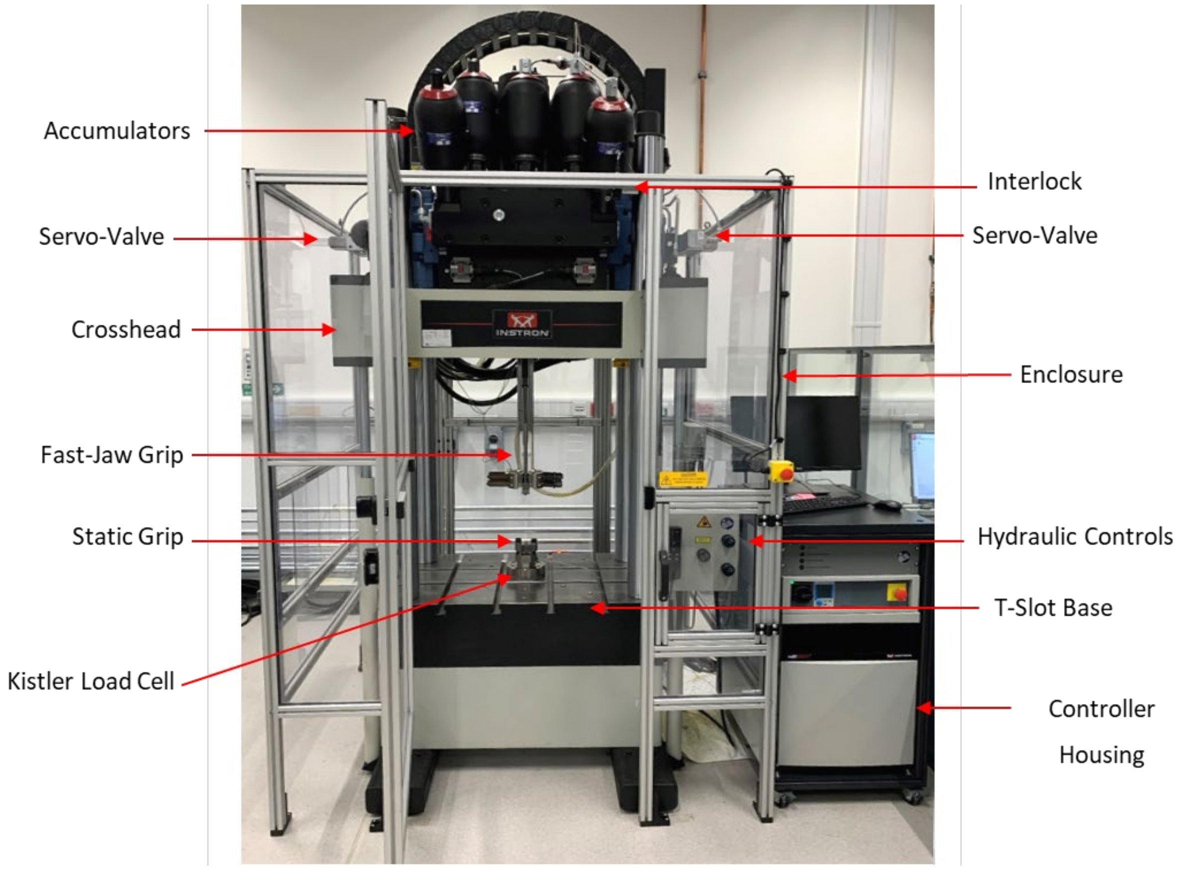


Figure 2: Instron VHS 160/100 – 20 test machine.

2.2 TEST SPECIMEN GEOMETRY

Due to the use of the fast jaw gripping system, the test speed has a direct influence on the overall length of the test specimen. The travel required for the actuator to accelerate over increases as the test speed increases. It is recommended that there is a minimum of 10-20 mm of specimen protruding above the fast jaw grips once they have engaged the test specimen. The required length of test specimen depends on the distance between the crosshead and the

T-slot base, and the desired actuator speed. When running the machine at 20 m/s and using the fast jaw gripping system, the shortest specimen length is approximately 350 mm.

In addition to specimen length, the choice of gauge length determines the strain rate that is achievable. The maximum strain rate is a function of the gauge length and maximum test speed available as indicated in equation (1). By reducing the gauge length, the maximum strain rate is increased. For example, at 20 m/s, gauge lengths of 100 mm and 20 mm give strain rates of 200 s^{-1} and 1000 s^{-1}, respectively.

$$v = L_g \dot{\varepsilon} \tag{1}$$

$v = test\ speed$
$L_g = gauge\ length$
$\dot{\varepsilon} = strain\ rate$

2.2.1 Metallic test specimens

BS EN ISO 26203-2 2011 [3] is a standard for high (and intermediate) strain rate testing of metallic specimens using servo-hydraulic test machines. While the standard does not restrict the choice of test specimen geometry and dimensions, it does provide recommendations for how best to determine suitable dimensions based on the test speed and desired strain rate. Figure 3 shows an example of a metal test specimen which fulfils the recommended criteria of ISO 26203-2. In this case the specimen is steel and has a parallel-sided gauge section of length 50 mm, giving a maximum strain rate of 400 s^{-1} at a displacement rate of 20 m/s. These particular specimens have a thickness of approximately 1.4 mm.

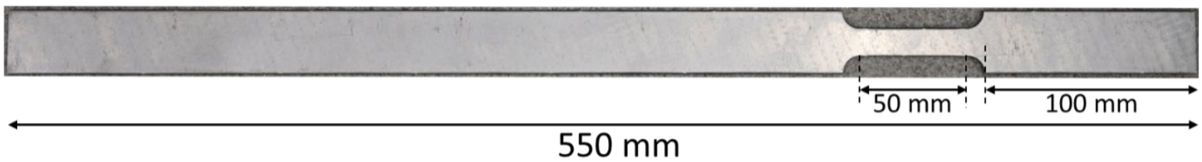


Figure 3: A metallic test specimen that can be used for tensile testing at intermediate strain rates when using fast jaw grips on hydraulic test frames

2.2.2 FRP test specimens

For quasi-static tensile testing, as per ISO 527-4 [4], the choice of test specimen geometry is dependent on the material format. There are typically two main types of geometry for tensile specimens, these are waisted (dog-bone) and straight-sided. Waisted specimens are generally not recommended for use with unidirectional (UD) or multidirectional (MD) continuous-fibre composites due to the predominance of longitudinal splitting in radiused regions of the specimen. As such, straight-sided specimens tend be used for composites of UD and MD formats. Whilst at intermediate strain rates the use of straight-sided specimens is fine, the location of failure can occur anywhere along their length. As such, when used in conjunction with high-speed cameras for strain measurement, this can severely limit the maximum acquisition rate, since the entire length of the specimen needs to be monitored; see section 2.3.2 for more information on the limitations of high-speed cameras. In addition, the use of straight-sided specimens with fast jaw grips limits the maximum strain rate achievable since the minimum ungripped specimen length is limited to approximately 230 mm when the machine is run at 20 m/s. Especially for the former limitation, waisted specimens are seen as more desirable as they ensure failure occurs within a predefined region, which enables higher acquisition rates to be achieved by the high-speed cameras.

In the most recent revision of ISO 527-4 [4], a new specimen geometry (Type 4) is prescribed which has a slight waist defined by a Bezier curve. The Type 4 specimen is recommended for multidirectional composite formats with a thermoplastic matrix. The specimens are 300 mm long, 28 mm wide and are waisted to a parallel-sided gauge section of 25 x 25 mm. Due to both the initial width and fine waist of these test specimens, the geometry of the Type 4 specimen may be suitable for intermediate strain rate testing as it focuses failure on the centre of the specimen. When used with a fast jaw gripping system, the length of the specimens will need to be increased. In the current machine configuration, a length of 550 mm and set out as shown in Figure 4 may be suitable. The material used for the specimen shown in Figure 4 is 2 mm thick Tufnol® 10G/40 with a 0/90° fibre orientation. This is a glass fibre epoxy woven composite.

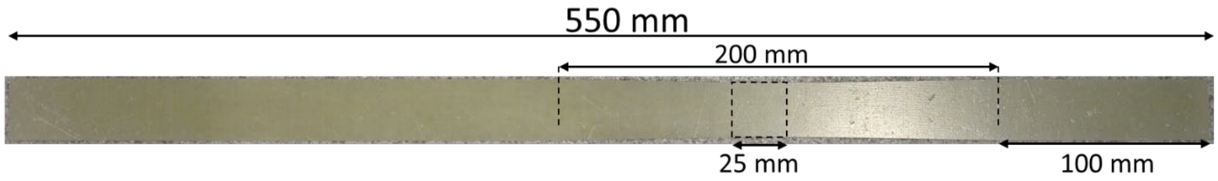


Figure 4: An example of a composite test specimen that could be used for tensile testing at intermediate strain rates using a hydraulically drive test frame and quick release fast jaw grips. Specimen dimensions modified from those of a Type 4 specimen from ISO 527-4

2.3 HIGH SPEED CAMERAS

Two Photron Fastcam Nova S16 high-speed cameras were utilised to capture images of test specimens loaded at high strain rates (Figure 5). These cameras have a 1-Megapixel (Mpx) CMOS image sensor that is capable of capturing 16,000 frames per second (fps) at full sensor resolution. The 1-Mpx sensor is a square sensor containing 1024 pixels along the horizontal and vertical directions.

2.3.1 General operation

When recording using a high-speed camera, all images are initially stored within the memory of the camera before being saved. As such, the camera data storage determines the length of image capture time available. Both high-speed cameras utilised here have a memory capacity of 64 GB. Although only a relatively minimal number of images are saved when conducting an intermediate strain rate test, the storage space of the cameras can be used as a buffer to ensure that failure is not missed. A memory capacity of 8 or 16 GB would likely be sufficient for use with the high strain rate testing, however having a larger amount of memory provides freedom for the cameras to be used for other applications where longer image capture periods are needed. The maximum number of images that can be captured depends on the image size (in pixels), whereas the maximum capture time depends on the camera frame rate.

Lenses used with high-speed cameras are Nikon-style F-mount and G-mount lenses. These types of lenses are the same as those used on most Nikon DSLR cameras and are large enough to ensure that light hits the whole sensor when capturing images. At present, there are three pairs of lenses that are available for use with the NPL high-speed cameras; these are:

- VST 200 mm marco lens
- Sigma 105 mm macro lens
- VST 50 mm macro lens

Note 2: The main difference between F-mount and G-mount lenses is the ability to control the aperture from the lens. F-mount lenses have an aperture dial on the lens itself, whereas G-mount lenses do not. For aperture control on G-mount lenses special adapters are required that connect between the lens and the camera.

Note 3: To protect the optics at the front of the lens from debris from a test, clear protection filters can be used. These filters are designed to protect lenses from dirt and scratches, while unaltering the images captured through the lenses.

When recording images at high frame rates, it is important to ensure that adequate lighting is used. As frame rate increases, the exposure time of the sensor needs to be decreased so that the images remain sharp, with no motion blur during capture. For high-speed cameras, the exposure time required can often be 1 µs or less depending on the speed of capture and the motion of the object being captured. To capture high quality images at very low exposure times, the light sensitivity of the camera needs to be high. High-speed cameras are generally equipped with large image sensors, with each sensor pixel of the order of 20 µm. The large size of each pixel allows for greater light sensitivity, which increases the signal-to-noise ratio allowing for high fidelity images to be produced. By decreasing the exposure time, less light is able to reach the camera sensor. Therefore, to capture images with a reasonable image intensity, high powered lighting is required. In addition, opening of the aperture on the camera lens will increase the amount of light that hits the image sensor.

Note 4: The lens aperture controls the image depth of field. Reducing the size of the aperture (increasing the aperture f-stop number) causes less light to reach the sensor but increases the overall depth of field of the image. Depending on the test piece being monitored, this value should be adjusted accordingly. Typically for intermediate rate materials testing it is recommended that the aperture is toward, if not at, its most open in order to let as much light in as possible.

When high-speed cameras are used to capture images of a specimen under test conditions, they can either be attached to tripods or a heavy-duty frame, such as that seen in Figure 5.

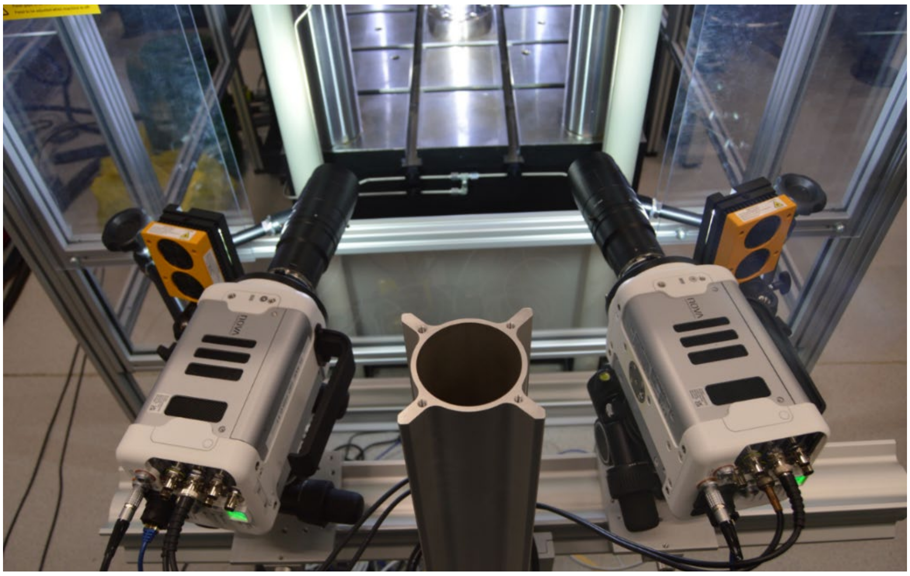


Figure 5: Example of a high-speed camera set up for use in capturing material test data at intermediate test rates.

2.3.2 Limits of high-speed cameras

As the test rate increases, it becomes increasingly important to consider the limits that the test equipment impose on the measurements to be made. With test speed, the acquisition rate of data needs to be increased to ensure that the measurement resolution remains sufficient. Test machines for intermediate rate testing tend to be able to acquire data at very high rates, of the order of the 10's of MHz (here it is 60 MHz), and as such should be sufficient for most materials. In contrast, high-speed cameras are far more limited due to the interconnection between frame (acquisition) rate and image resolution.

To determine the most suitable acquisition rate when using high-speed cameras, factors such as test speed, strain rate, and specimen geometry also need to be considered. Test geometry influences the maximum strain rate achievable during a test. For instance, at 10 m/s with a 100 mm gauge length, the maximum strain rate is only 100 s^{-1}, whereas with a 10 mm gauge length this test speed can give a strain rate of 1000 s^{-1}. However, as the example below shows, reducing the gauge length also reduces the ultimate amount of extension. Therefore, for a chosen strain rate, the acquisition rate is proportional to the specimen gauge length.

Example: A composite specimen needs to be tested at a strain rate of 100 s^{-1}. The test specimen has a gauge length of 100 mm and is expected to fail at around 2% strain

From the test criteria, the test speed required is:

$$100\ mm \times 100\ s^{-1} = 10{,}000\ mm\ s^{-1} = 10\ m\ s^{-1}$$

Assuming failure occurs at 2% strain, the expected specimen elongation in mm is:

$$0.02 \times 100\ mm = 2\ mm$$

At 10 m/s:

$$10{,}000\ fps = 10{,}000\ mm\ s^{-1}\ \therefore 1\ frame\ mm^{-1}; so\ 2\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 1\ mm$$

$$100{,}000\ fps = 100{,}000\ mm\ s^{-1} \therefore 10\ frames\ mm^{-1}; so\ 20\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 0.1\ mm$$

$$1{,}000{,}000\ fps = 1{,}000{,}000\ mm\ s^{-1} \therefore 100\ frames\ mm^{-1}; so\ 200\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 0.01\ mm$$

Alternatively, if the gauge length was 10 mm then the test speed would be:

$$10\ mm \times 100\ s^{-1} = 1{,}000\ mm\ s^{-1} = 1\ m\ s^{-1}$$

And the elongation in mm at 2% strain:

$$0.02 \times 10\ mm = 0.2\ mm$$

Therefore:

$$1{,}000\ fps = 1{,}000\ mm\ s^{-1}\ \therefore 1\ frame\ mm^{-1}; so\ 0\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 1\ mm$$

$$10{,}000\ fps = 10{,}000\ mm\ s^{-1} \therefore 10\ frame\ mm^{-1}; so\ 2\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 0.1\ mm$$

$$100{,}000\ fps = 100{,}000\ mm\ s^{-1} \therefore 100\ frame\ mm^{-1}; so\ 20\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 0.01\ mm$$

$$1{,}000{,}000\ fps = 1{,}000{,}000\ mm\ s^{-1} \therefore 1000\ frame\ mm^{-1}; so\ 200\ images\ per\ test$$
$$Displacement\ resolution\ per\ image = 0.001\ mm$$

To increase the acquisition rate of a camera, the sensor size has to be cropped. For the Photron Fastcam Nova S16 cameras, full resolution only allows a maximum of 16,000 fps but, when cropped to the minimum allowable, can achieve 1.1 million fps, which corresponds to a cropped sensor size of 128 x 16 pixels, providing a very narrow image band as indicated in Figure 6. Table 1 provides some example frame rates that can be achieved. Reducing the image resolution to increase the acquisition rate and displacement resolution has the added disadvantage of limiting the number of pixels available to accurately observe those changes in displacement. For instance, when cropped to 128 x 16 pixels, it will likely be difficult to obtain any meaningful data relating to transverse displacements, even at slower test speeds, due to the limited pixel resolution.

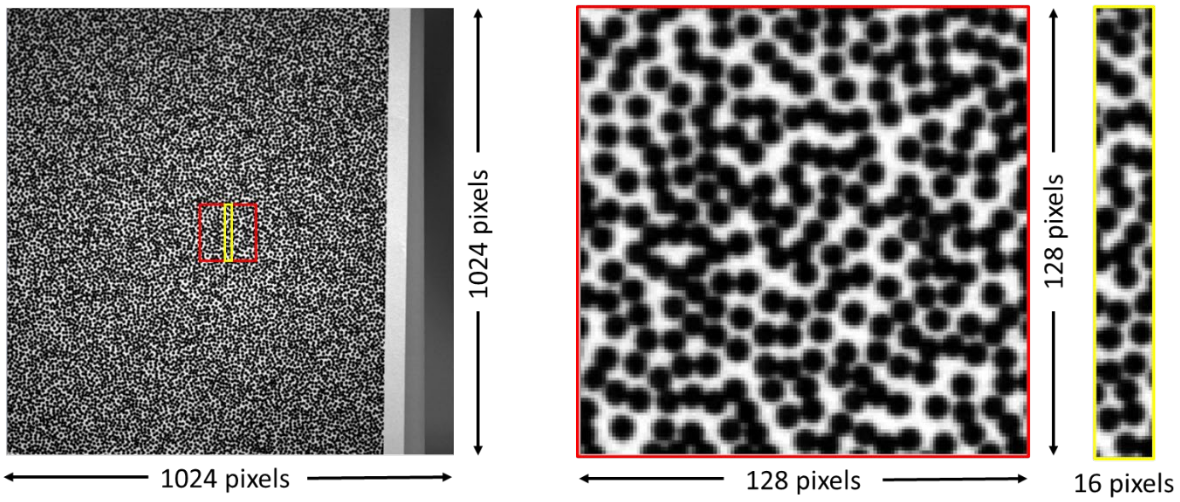


Figure 6: Comparison of cropped sensor image sizes

Table 1: Examples of frame rates at different image sensor resolutions for the Photron Fastcam Nova S16 high-speed cameras

Resolution (h x v pixels)	Frame rate (fps)
1024 x 1024	16,000
640 x 640	36,000
512 x 512	52,800
384 x 256	100,000
256 x 256	144,000
128 x 128	330,000
128 x 64	600,000
128 x 16	1,100,000

Tip 1: Due to the greater number of minimum pixels available when cropping horizontally; when using the cameras to monitor tests such as tension, where the specimen gauge length is usually much greater than its width, it is recommended that the camera is set on its side.

2.4 DIGITAL IMAGE CORRELATION (DIC)

DIC is a non-contract optical technique that uses cameras to capture and track changes between images. It can be used for a wide variety of applications but is most often used to measure full-field displacements and strains. Due to the test speeds employed in high strain rate testing, optical techniques such as DIC are extremely valuable measurement tools. The main requirement of DIC is optical access to, and sufficient illumination of, the area of interest, with some form of speckle pattern to enable effective correlation of the test piece to produce measurements of displacement and strain.

2.4.1 2D and 3D DIC

There are two types of DIC, 2D and 3D, with typical setups depicted in Figure 7. 2D DIC relies on the use of a single camera orientated perpendicular to the planar axis of the test piece. When using a single camera, only measurements relative to the 2D plane of the camera sensor can be calculated, with no depth information available. This setup is best used with flat planar test specimens. While no direct depth related information can be produced using 2D DIC, by placing a camera on either side of the test specimen, similar to back-to-back extensometers or strain gauges, it is possible to determine the amount of bending present in uniaxial test specimens.

When using 2D DIC, any out-of-plane motion, will lead to measurement errors. Small errors can be minimised by ensuring the test piece remains planar relative to the cameras throughout the test and by using telecentric lenses. Alternatively, using long focal length lenses, which increase the working distance, can minimise the effect of out-of-plane motion and thus reduce the out-of-plane motion related errors [3]. However, for this set up, any large out-of-plane motions will still cause measurement errors.

3D DIC, also known as stereo DIC, uses at least two cameras to observe and image a test piece to produce a full three-dimensional rendering of its motion through space. The use of 3D DIC is recommended over 2D DIC where possible as the accuracy of all measurements through 3D space is improved. The stereo angle between cameras is typically 15° to 30°, with the former providing better in-plane measurement accuracy and the latter giving better out-of-plane measurement accuracy. Like 2D DIC, using a back-to-back 3D DIC setup is recommended not only for full-field measurement on each surface of the specimen, but also for determination of the amount of bending present during loading.

Unlike 2D DIC, the full optical system of a 3D DIC setup requires calibration to correct for lens distortions, and to enable the position and orientation of all cameras with respect to each other and the test piece to be known. Calibration is achieved using targets with features of precisely known positions that can be detected through the chosen DIC software.

Note 5: It is important to ensure the light intensity of each image is even and uniform across the test specimen. Uneven lighting and saturated regions (often due to reflections) can lead to errors within measurements produced via correlation and therefore should be eliminated where possible.

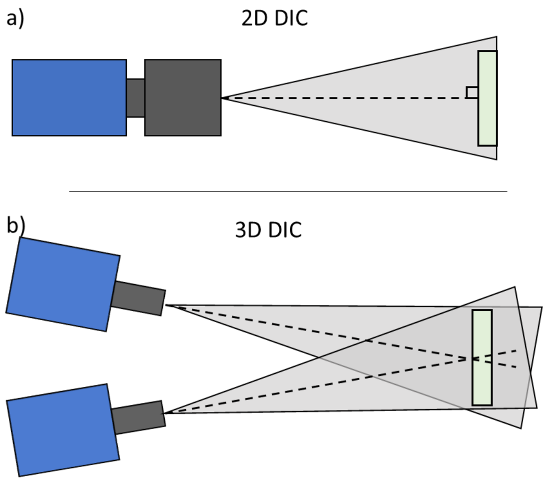


Figure 7: Schematic indicating the differences in setup between a) 2D DIC and b) 3D DIC

2.4.2 Speckle pattern

To conduct DIC, some form of randomised speckle pattern is required that can be used to correlate and map the changes in strain across the area of interest on a test specimen. There are many different methods of speckling a test specimen but for the purpose of this report only three will be examined: spray paint, printing on tattoo paper and manual drawing. Figure 8 shows some examples of the different methods of speckle application.

- Spray paint — This is typically done with either an aerosol can or an air brush. An undercoat of either white or black matte paint is initially applied as a thin base layer. On top of this, fine speckles of either black or white (of the order of 10s-100s of μm), depending on the undercoat colour, are applied. This is a common and quick method of applying a speckle pattern, often used with low-speed testing applications where (1) the camera resolution is usually greater than that of high-speed cameras (5MPx or above) and (2) the area of interest is small and cover a large portion of the image sensor, which can be used to ensure a sufficient number of pixels per speckle feature (see Note 6). However, for high-speed image applications, the speckles may be too fine, especially when trying to maximise the camera capture rate by cropping the image sensor, for effective correlation. In addition, the paint, once dried, can flake from the test specimen at high test speeds, increasing measurement errors and making correlation harder.

- Printing — Another method of applying a speckle pattern is to print onto tattoo paper and adhere to the specimen. This method allows the size and density of speckles to be designed by the user and printed using a standard laser or inkjet printer. When compared to other speckling methods, printed patterns can be used to ensure that the speckles are of a uniform size and randomly, distributed across the entire area of interest. Unfortunately, only the black speckle pattern can be printed and therefore a white base layer is still required. The print needs to be in full contact with the specimen surface, so it is important to ensure no air pockets are produced during application. One current downside to this method is that tattoo transfers are glossy and not matte, meaning it can be difficult to completely remove all unwanted reflections of light from captured images without using polarising filters for both the lenses and light source used.

- Manual speckle — Compared to the other two methods, this is the most time consuming and is limited to coarse speckle patterns. In this case, the minimum size of a speckle feature is approximately of the order of 0.5-0.7mm depending on the speckle application. Here, a white paint pen was used to apply a pattern onto a black background. For high-speed applications, larger speckles are preferred, especially when minimising the image window for greater capture rates. Like spray painting speckles, the size of each speckle is not consistent, depending heavily on the user. Unfortunately, like printing to tattoo paper, reflections can still be present.

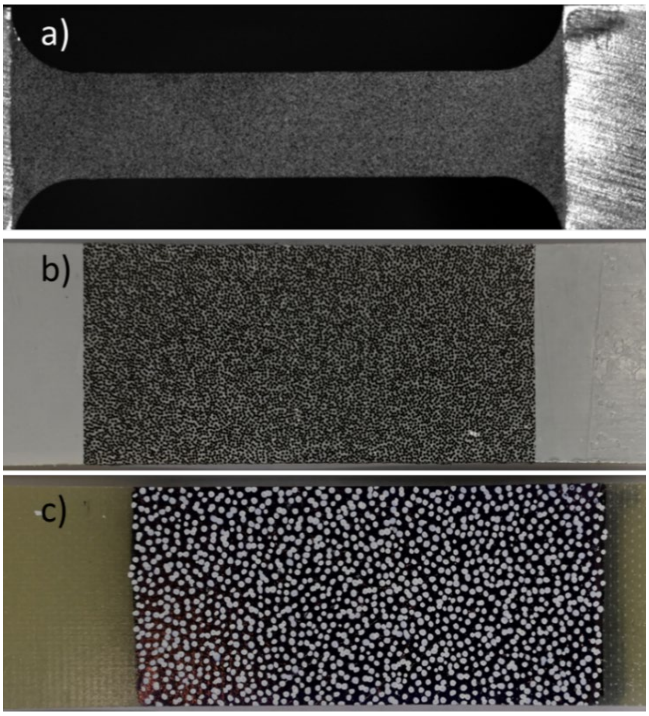


Figure 8: Different methods of producing a speckle pattern; a) spray paint; b) printing to tattoo paper; (c) manual speckling using pens

> **Note 6:** The international Digital Image Correlation Soceity's (iDICs) good practice guide [5] suggests that speckles should be a minimum of 3-5 pixels in size. Speckles smaller than this can potentially lead to increased error in the DIC measurements. The error is more noticeable for small displacements.

3 EXPERIMENTAL TESTING

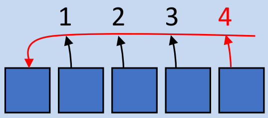
3.1 DIC

3.1.1 Metal specimens - steel

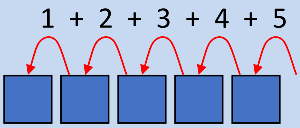
Three steel specimens were tested at a test speed of 5 m/s. The high-speed cameras were placed in a stereo array as shown in Figure 5 and calibrated for 3D DIC measurements. Both cameras used a 200 mm macro lens with a wide open aperture (f-stop of 4 on this lens). Each specimen was speckled using a different method with Figures 9, 10 and 11 showing spray paint-speckled, printed speckle transfer, and manual speckled specimens, respectively; included here are the original high-speed camera captured images and the DIC strain measurements at various stages of loading. It is worth noting that all metal specimens were correlated using the sum of differential function on DaVis, see Note 7 for more information.

Note 7: There are generally two types of image correlation that can be undertaken to produce strain measurements:

- Relative to first*: Takes any image in a set and compares it to the initial image. This works best for small deformations.



- Sum of differential* - Compares an image with the previous image and sums all the differential changes of the previous images. Useful with large deformation changes where the shape of speckle does not reflect the start of the test. Unfortunately, calculation error sums up with measured deformation and thus produces lower precision in measurements.



* terminology used by LaVision in the correlation software DaVis

Typically, when undertaking DIC measurements a balance must be found between how much the image sensor is filled by the test specimen and how much deformation is expected. Ideally the specimen will fill the entire sensor field to optimise and improve the precision of the measurements being made. However, it is important to ensure that none of the test goes out of frame. When using a high-speed camera there is the added complexity of having to crop the sensor to increase the maximum frame rate achievable. To achieve a balance between all these conditions, the working distance between the cameras and the test piece may need to be increased. As such, the number of pixels that cover the test piece can reduce, meaning that the speckle size becomes an important consideration.

For the specimen with spray painted speckles (Figure 9), the speckle size is considered very fine, such that a single speckle is smaller than a single pixel. While spray painted speckle patterns are often sufficient for testing at slower test speeds, this is often because the DIC setup is usually closer to the test piece and can therefore fill a much larger portion of the image sensor. As well as the fineness of the speckle pattern, it can also be seen in Figure 9 that test speeds of 5 m/s cause the paint to flake off. This shows that at during intermediate strain rates loading conditions, the paint does not adhere well to the surface of the material. Despite this, the images were able to be correlated to produce strain measurements, though there will be a degree of uncertainty in the strain measurements due to the flaking of the paint. Methods of improving adhesion may include abrading the surface of the material and/or testing shortly after application of the speckle and before it has had a chance to fully dry, though the latter may be difficult to achieve due time taken to set up each test. In principle, while the paint is still ‘wet’, it should be able to deform more easily with the underlying material without cracking and flaking off.

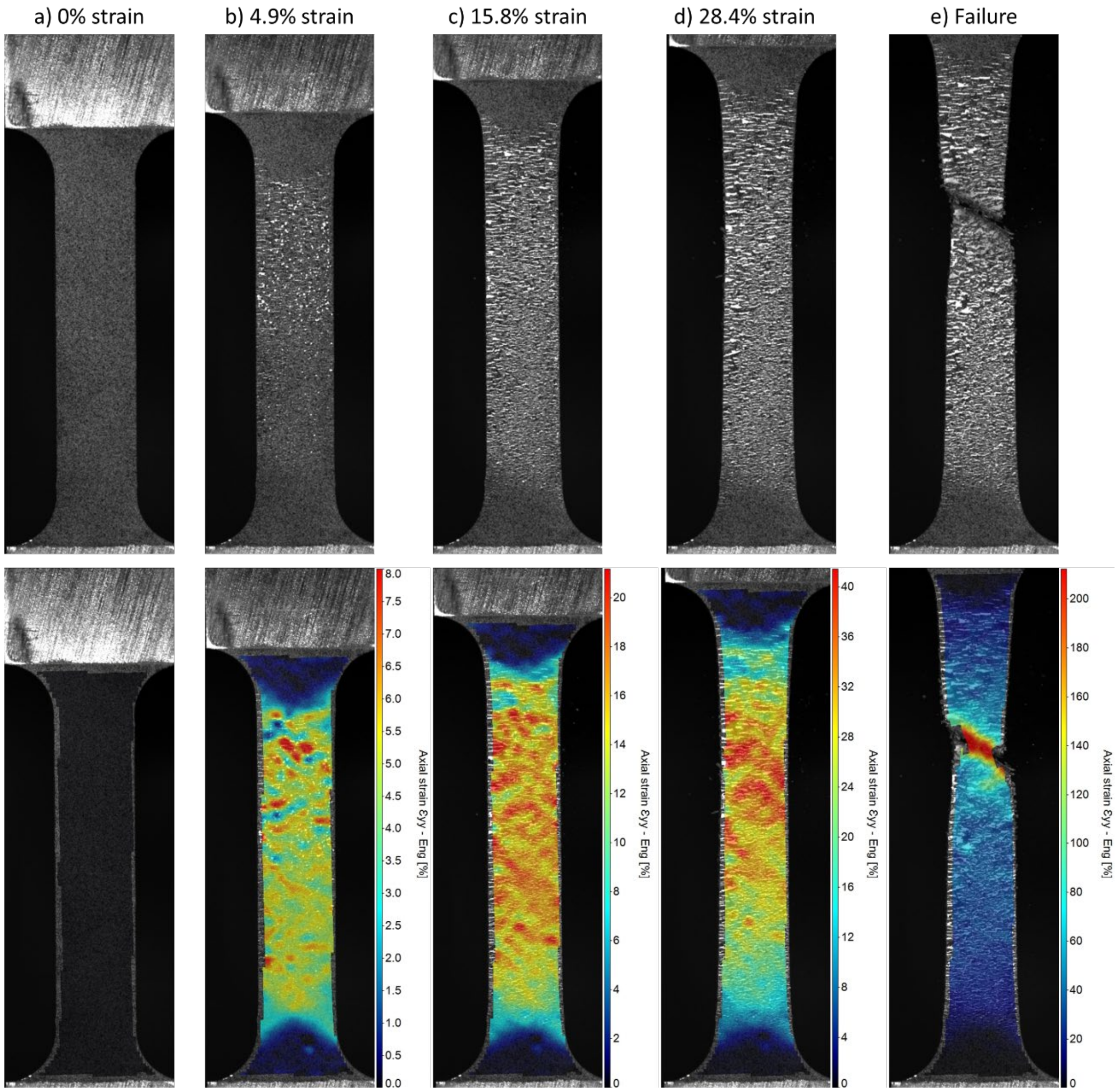


Figure 9: Spray paint-speckled steel test specimen at different stages of loading. The top line of images is those captured directly on the high-speed cameras at a frame rate of 46.25 kHz and cropped sensor size of 336 x 1024 pixels. The bottom line of images is the same as the top line but includes an overlay of the strain measurements produced using DIC.

Unlike spray painted speckles, printed patterns can be chosen based on the required camera setup. Different patterns and speckle sizes can be printed and placed in front of the camera at distances equivalent to that of the test specimen to determine the optimal speckle size and density. Figure 10 shows a specimen with printed speckle pattern, adhered to the surface via tattoo transfer paper. Since only the black speckles could be printed, a white matte base layer was sprayed onto the surface before adhering the speckle pattern. As mentioned in section 2.4.2, tattoo transfers have a glossy surface finish, which is not ideal for DIC measurements. In addition, the transfer on the specimen in Figure 10 contained air pockets, resulting in the pattern not being flat on the surface of the material. Both the glossy surface and the air pockets made it difficult to minimise regions of image saturation due to reflections. Removal of saturated regions can be achieved by reducing the exposure time and/or closing the aperture. However, this can lead to underexposed regions of the image and may lead to increases in noise and error in the measurements produced. Ideally lighting should be of uniform intensity across the entire area of measurement. Alternatively, polarising filters on both the lenses and light source can be used to remove most reflections, however these also have the added effect of making images darker similar to closing the aperture which is not ideal.

During loading, the printed transfer was observed to split in two regions along the gauge length and separate from the surface as the specimen began to neck. Failure of the transfer can lead to errors and artifacts in the correlated strain measurements. It is worth noting that the splits in the transfer did not appear until more than 4% strain. As such, the transfer may be more suitable for use with more brittle materials such as composites and is an area that needs further investigation.

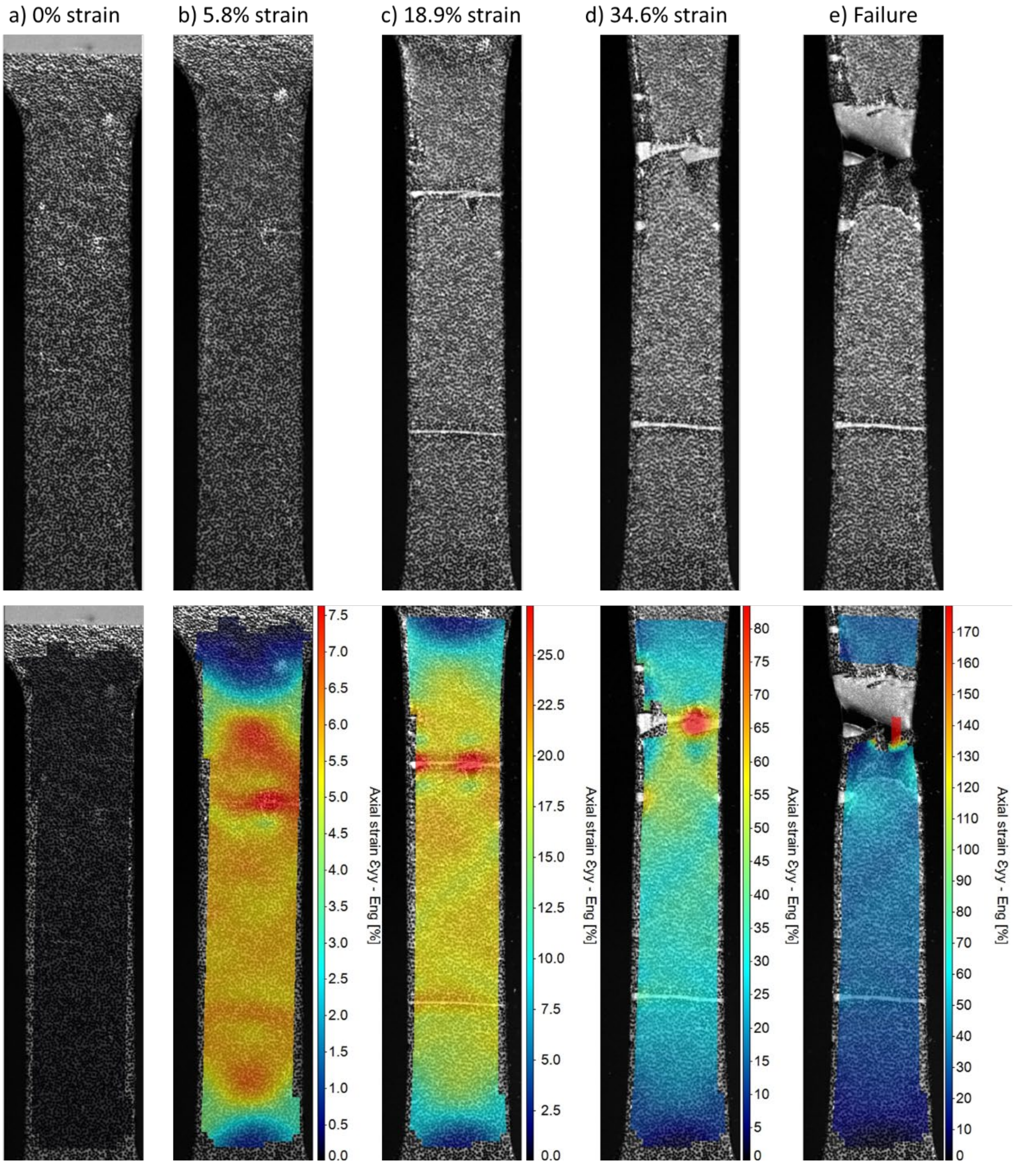


Figure 10: Printed speckle via tattoo transfer on steel test specimen at different stages of loading. The top line of images is those captured directly on high-speed cameras at a frame rate of 47.98 kHz and cropped sensor size of 192 x 768 pixels. The bottom line of images is the same as the top line but includes an overlay of the strain measurements produced using DIC

Compared to the other speckling methods examined, manual application produces very coarse speckles, with their size dependent on the choice of marker tip and the user; here speckles of approximately 0.7 mm were produced. In addition, applying speckles manually to a test specimen is far more time consuming. However, as illustrated in Figure 11, the speckles adhered well to the surface, deforming with the test specimen as expected. Compared to the other methods of speckling, this method performed the best, and therefore it is worth exploring options of direct to substrate printing such as UV printing or using convention inkjet/ laser printing heads.

Despite the speckles being coarse, a reasonably uniform strain map was produced across the material surface. Although the images correlated well, it was observed during setup that the surface was still reasonably reflective in some small regions. To remove these regions of saturation, much of the image may become underexposed and this could increase the uncertainty of the correlation measurements.

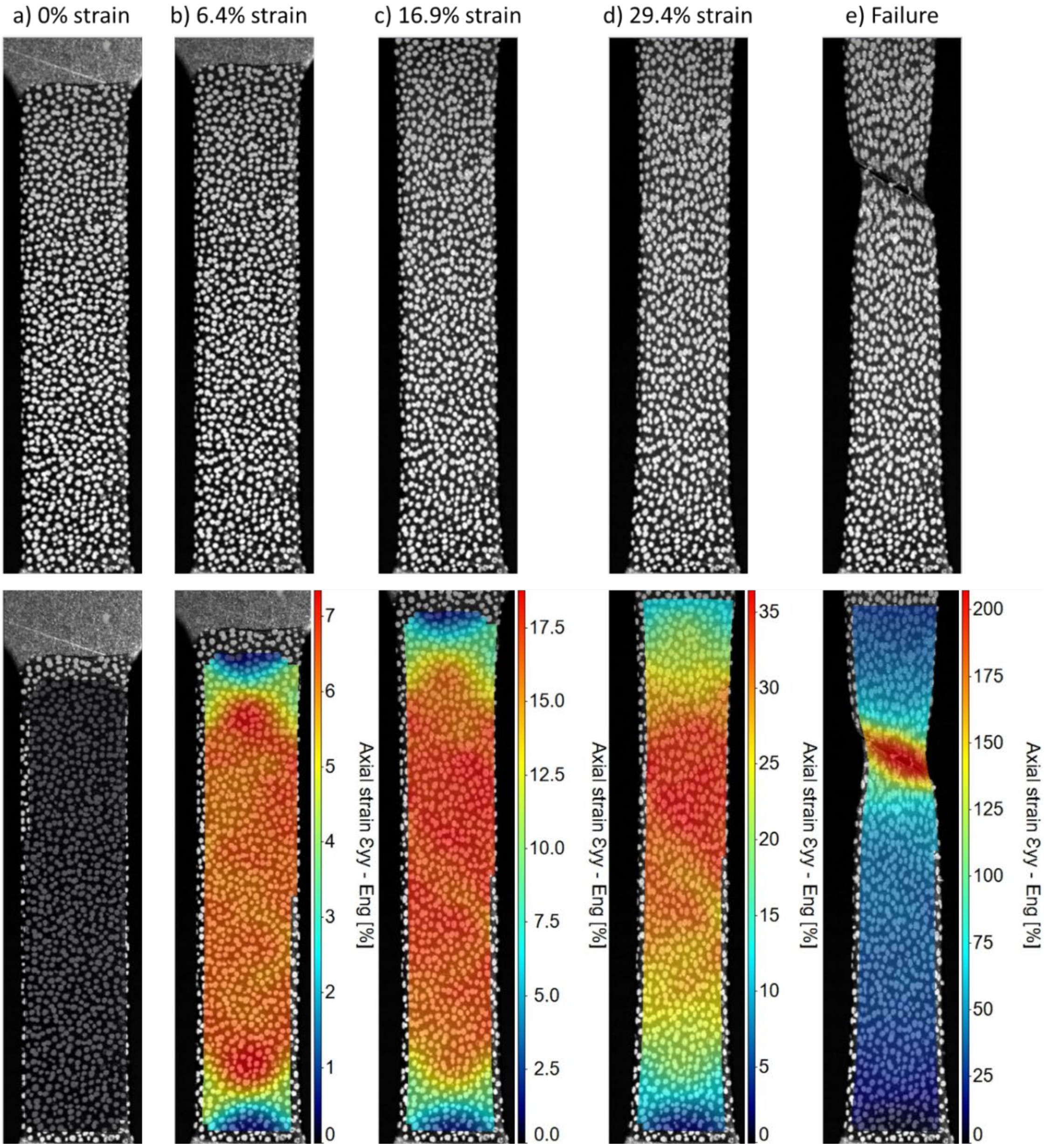


Figure 11: Manual applied speckle using black marker and white paint marker on steel test specimen at different stages of loading. The top line of images is those captured directly on the high-speed cameras at a frame rate of 47.98 kHz and cropped sensor size of 192 x 768 pixels. The bottom line of images is the same as the top line but includes an overlay of the strain measurements produced using DIC

Figure 12a shows the load traces of each of the steel test specimens acquired via the Instron VHS. The load traces are generally similar for each test specimen. The general trend consists of each specimen loading to a peak before dropping to a plateau as the specimen plastically deforms. The noise in the load data is due to the natural oscillations of the specimen and frame becoming superposed over the load signal measured by the piezoelectric load cell. These oscillations occur from the high amplitude stress waves that occur as the specimen is engaged and loaded. This is an unfortunate effect of loading at increased strain rates and produce values that are not representative of the true mechanical response of the material. When data is collected in this way, filtering is required to remove the oscillations/noise in the data at certain frequencies. The method of filtering and interpretation of data to provide accurate measurements is user dependent, and as such care must be taken not to lose information through over-filtering/dampening of the load response. However, it must be noted that at these loading rates, even after filtering, the peak loads are likely incorrect. These load values are amplified due to effects of inertia through the system and while filtering will move the peak closer to the true value, without the removal of all external influences on the load trace, the exact value cannot be determined. This can also make it difficult to provide an estimate of the uncertainty. The deviation from the true value increases with increasing test speed. As such, one method to see how much variation can occur and determine some of the influence of the test frame is to test the material incrementally at different test speeds from quasi-static to intermediate rates and observe how much the peak value changes as a result of noise.

Figure 12b shows the measurements of strain as determined using DIC. Here, the strain traces are an average of the correlated strain across the length of the gauge section. As for the load traces, each of the strain traces follow similar trends, despite the different performances observed with each method of speckling.

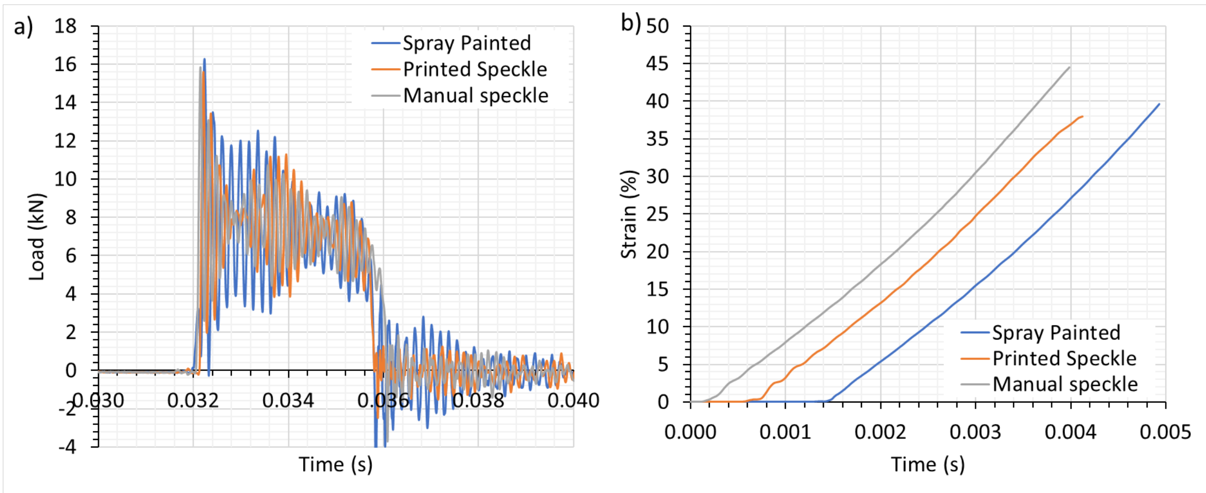


Figure 12: Comparative plots of Load vs. Time and Strain vs. Time for each of the different speckle methods. Load traces were taken directly from the Instron VHS and strain through DIC in DaVis 10.2.

3.1.2 GFRP

GFRP specimens were tested at a rate of 5 m/s, with images captured through a 200 mm macro lens attached to the high-speed cameras. Since the gauge length of these specimens is 25 mm, and assuming a failure strain of approximately 3%, it was estimated that the specimen displacement at failure should be approximately 0.75 mm. With the current camera setup, the sensor was cropped to 304 x 256 pixels, providing a maximum frame rate of 126 kHz; this sensor size contains the specimen width and approximately 20 mm of the gauge length. At this frame rate there should have been around 20 images for the expected displacement, however approximately 320 images were actually captured.

The number of captured images indicates that the specimen displacement was far greater than expected based on the specimen geometry. Looking at the correlated strain map in Figure 13 and the average strain plot in Figure 14b, the strain at failure was observed to be approximately 3%, which was as expected. However, the strain rate derived from DIC measurements did not coincide with the expected strain rate based on the length of the gauge section and the speed of the test. At 5 m/s and a 25 mm gauge length, the strain rate should be 200 s^{-1}, but the measured strain rate was approximately 12.5 s^{-1}, which is 1/16 of the expected value and accounts for the increased number of images captured. The difference between the expected and true strain rate can be determined by considering the entire length of the ungripped material. For the specimens tested here, free length of material when the fast jaw grips engaged the specimen is approximately 375 mm. Using this gauge length and 5 m/s, the strain rate should be 13.3 s^{-1}, which is much closer to the measured strain rate. This suggests that 25 mm x 25 mm gauge section does not influence the strain rate much different to using a straight-sided specimen. This strain rate was not expected and suggests that the modified test specimen based on the ISO 527-4 Type 4 geometry would not be suitable when trying to achieve a strain rate of 200 s^{-1} at a test speed of 5 m/s. Even at 20 m/s, the highest strain rate achievable may be at most 50-55 s^{-1}.

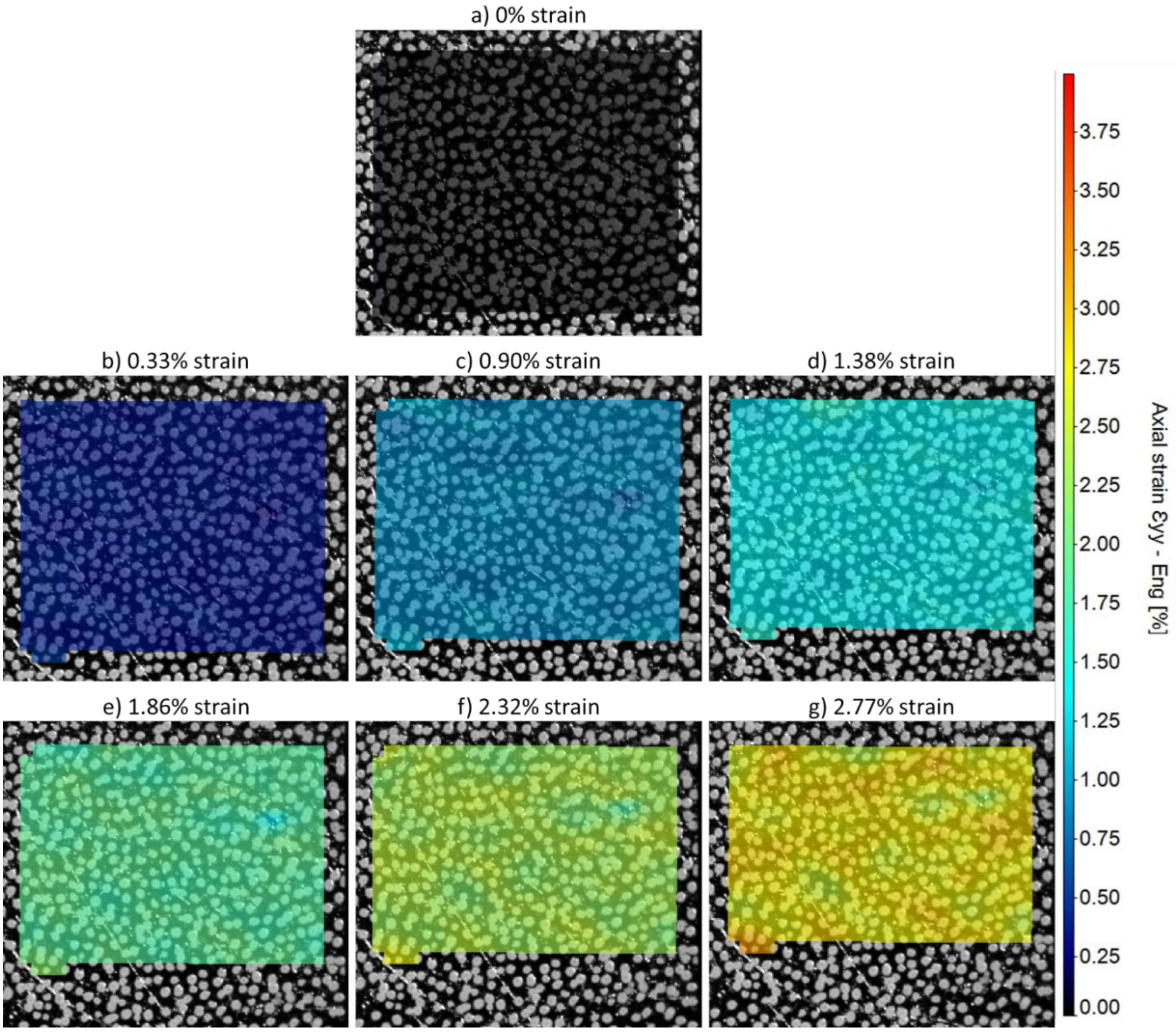


Figure 13: Manually applied speckle using black marker and white paint marker on GFRP composite specimen at different stages of loading. The specimen was loaded at a rate of 5 m/s. Images were captured on the high-speed cameras at a frame rate of 126.10 kHz and cropped sensor size of 304 x 256 pixels. These images are overlayed with strain maps produced by DIC.

Figure 14a shows the load-time trace as captured by the Instron VHS. Compared to the load-time traces for the metallic specimens (Figure 12a), the load-time trace of the composite specimen is typical of a brittle specimen failure where loading is reasonably linear until a peak load is reached, after which the load suddenly drops off.

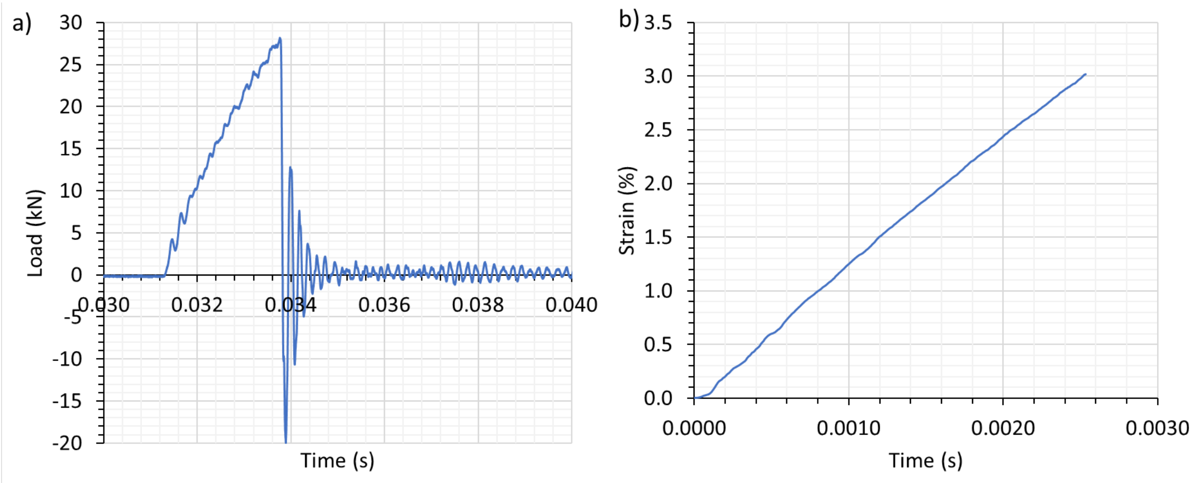


Figure 14: Plots of Load vs. Time and Strain vs. Time for a GFRP composite specimen tested at a rate of 5 m/s. Load traces were taken directly from the Instron VHS and strain through DIC in DaVis 10.2.

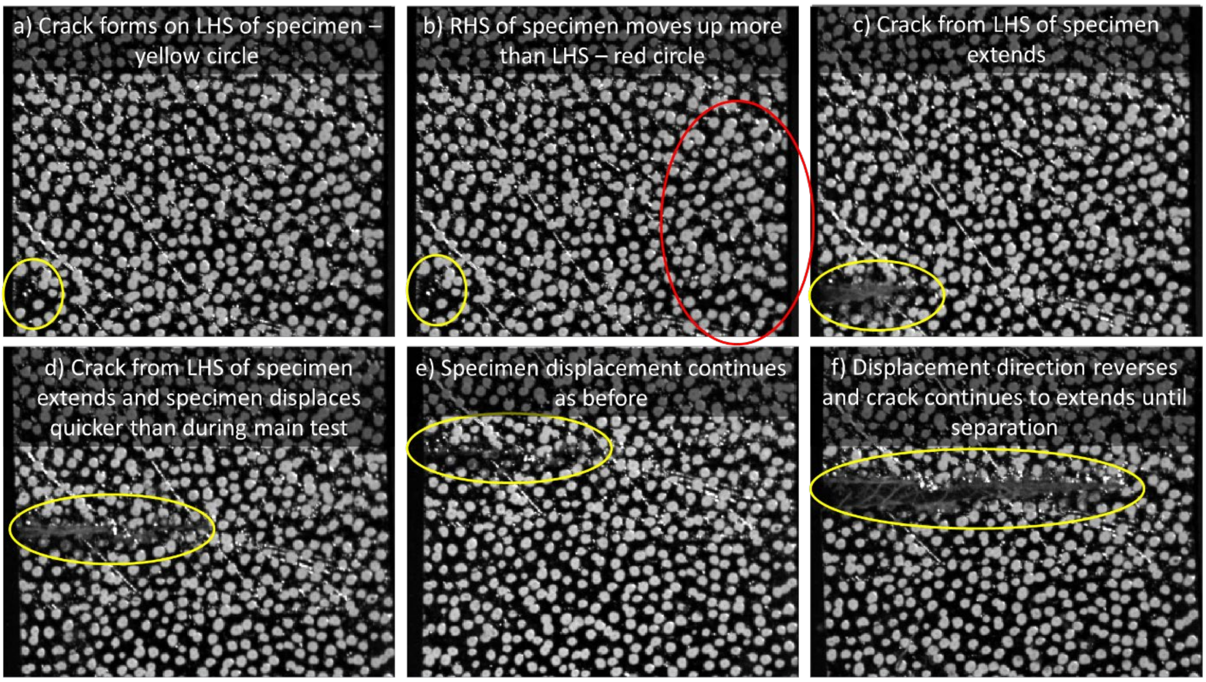


Figure 15: Failure of a GFRP composite test specimen tested at a rate of 5 m/s as captured by the high-speed camera. Images show the development of the crack and displacement of the test specimen. (Note: LHS – Left Hand Side)

Figure 15 shows the development of failure in the GFRP test specimen. It should be noted that the images in Figure 15 were not used in the strain correlation as the specimen displacement rate at this stage was much quicker than during the rest of the test, suggesting that this was not the initial failure location. From Figure 16 it can be seen that the specimen failed and separated into eight pieces of varying lengths. Due to the cropped sensor size only a limited view of the specimen could be seen and therefore it is unknown where failure initiated. Ideally failure would initiate in the reduced gauge section, but this is unclear from the captured images.

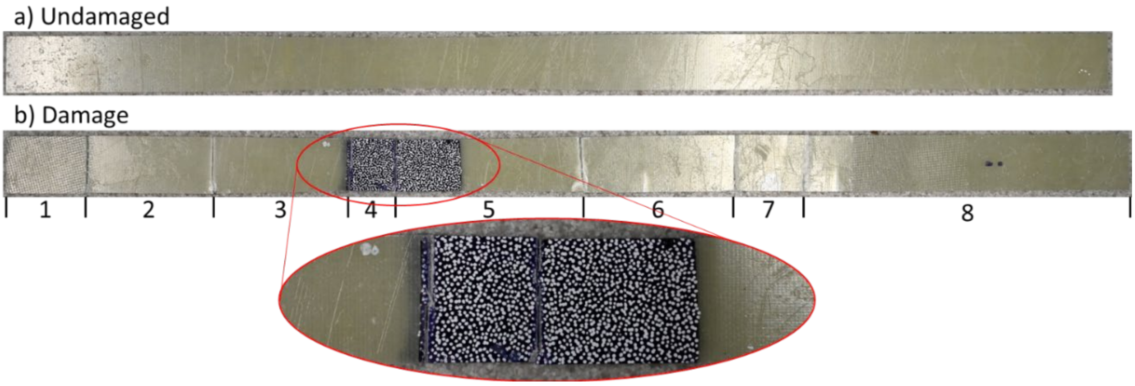


Figure 16: Image of a failed GFRP test specimen. The specimen was loaded at a rate of 5 m/s and split into eight individual pieces of various lengths.

A second GFRP specimen was tested at a displacement rate of 10 m/s. Images were captured using a 50 mm macro lens on the high-speed cameras to capture the majority of the specimen length. With this setup the image sensor was cropped to 80 x 1024 pixels, giving a maximum frame rate of 171 kHz. At 10 m/s the number of images captured during loading were, as expected, approximately half, and the strain rate double, that captured from the 5 m/s test. Observations from this test confirm that the specimen geometry cannot be treated much differently to a straight-sided specimens; with the use of specimens with this geometric configuration limited in strain rates they can be used at. For strain rate testing close and above 100 s^{-1}, different specimen geometries will be required.

Figure 17 shows the correlated strain map where it is evident that failure occurred within the gauge length of the test specimen. Looking across the whole length of the test specimen, Figure 18 shows that for this specimen failure initiated in the gauge section, with a secondary failure occurring near the fast jaw grips. The specimen split into four parts as shown in Figure 19.

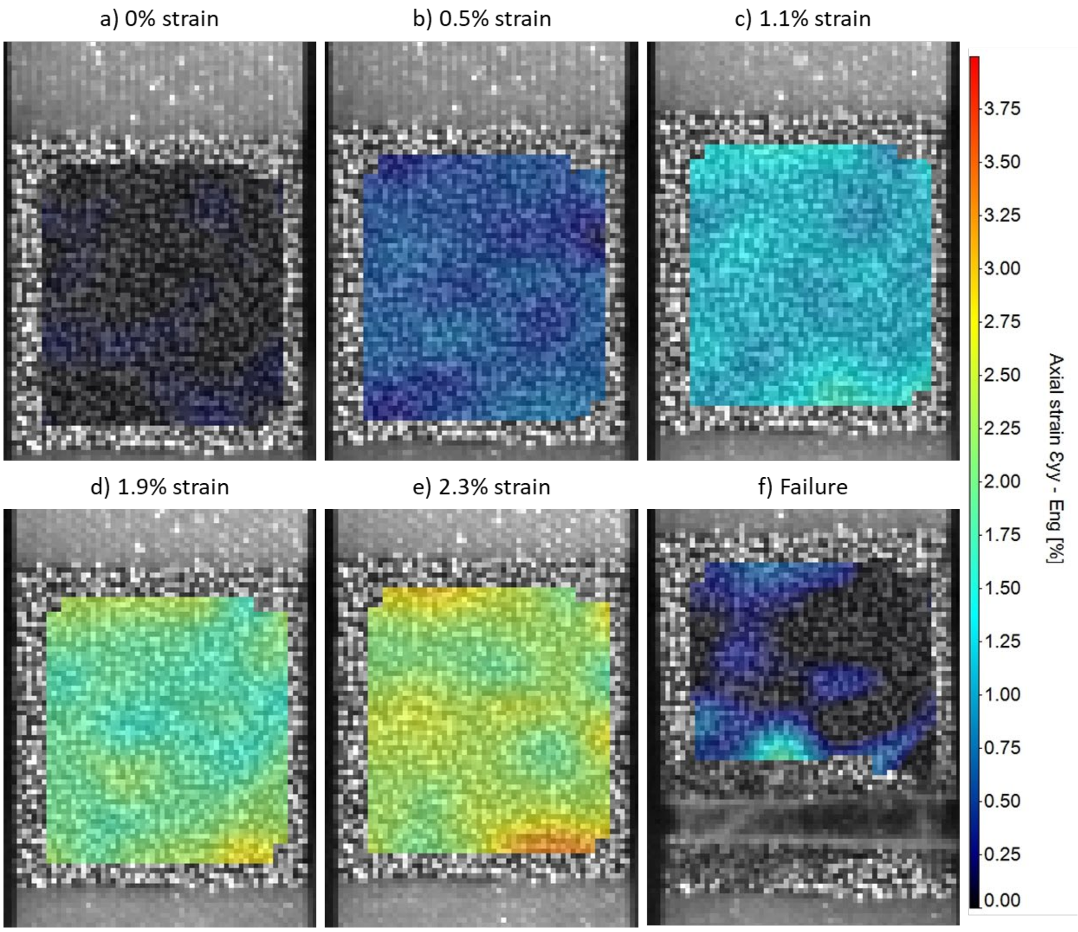


Figure 17: Manually applied speckle using black marker and white paint marker on GFRP composite specimen at different stages of loading. The specimen was loaded at a rate of 10 m/s. Images were captured on the high-speed cameras at a frame rate of 171.23 kHz and cropped sensor size of 80 x 1024 pixels. These images are overlayed with strain maps produced by DIC.

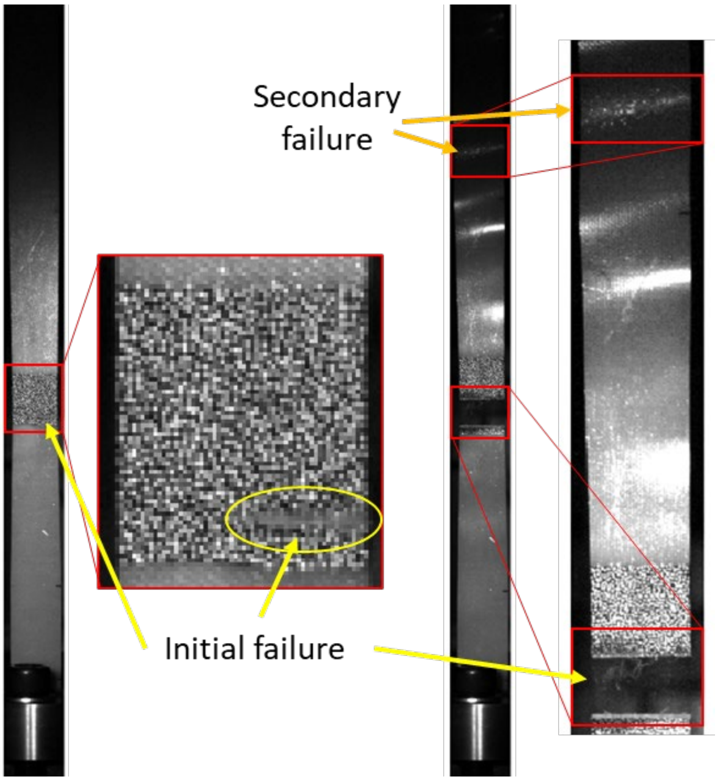


Figure 18: Initial and secondary locations of failure of a GFRP composite specimen as captured by the high-speed camera. Images captured using a 50 mm macro lens, which allowed the sensor to be cropped to a size of 80 x 1024 pixels.

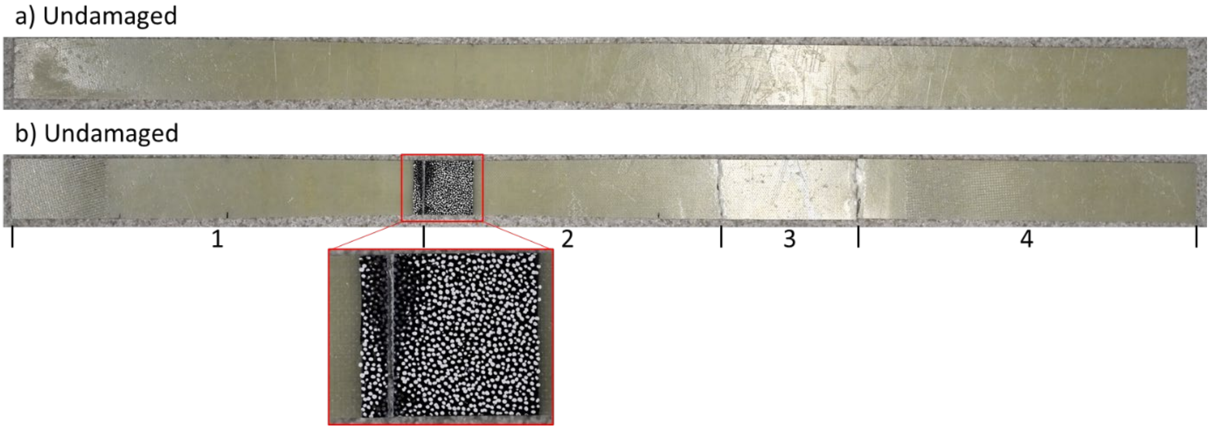


Figure 19: Image of a failed GFRP test specimen. The specimen was loaded at a rate of 10 m/s and split into four individual pieces of various lengths.

The load-time trace from the Instron VHS is shown in Figure 20a. Compared to the specimen run at 5 m/s there are two noticeable differences in the trace other than the reduced time to failure: (1) there is more noise in the load trace during actual loading of the test specimen, and (2) there is more noise upon failure. For the latter, the signal immediately after failure is extremely noisy with the signal almost doubling that recorded during loading. The noise in Figure 20a will likely be due to failure creating resonance and system ringing in the system that influences the signal generated in the Kistler load cell.

In Figure 20b the average strain-time plot taken from the correlated images can be seen. Compared to the 5 m/s test, the strain plot for the 10 m/s test is noisier due to their being fewer pixels available in each image available for correlation. With fewer pixels available, strain measurements become coarser as small changes in each loaded image become harder to notice. The speckle pattern for both composite specimens was the same and is not as clear for the 10 m/s test (Figure 18) compared to the 5 m/s (Figure 15) due to the use of different lenses and fields of view. However, it is interesting to note that the magnitude of the strain at failure is similar for both tests despite the differences in captured images and test speed.

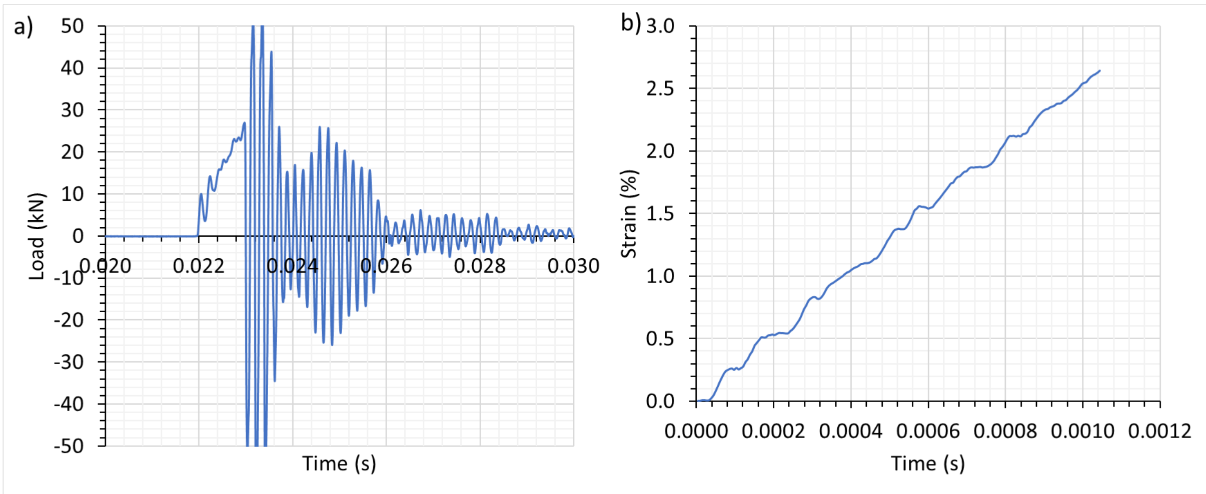


Figure 20: Plots of Load vs. Time and Strain vs. Time for a GFRP composite specimen tested at a rate of 10 m/s. Load traces were taken directly from the Instron VHS and strain through DIC in DaVis 10.2.

4 FURTHER WORK

From the work presented in this report, it is clear that there are a few areas that need to be explored further, namely:

1) Improve the speckle patterns used or determine more suitable methods of speckling. Current speckle patterns either do not adhere well enough to the surface throughout testing or produce too much reflection from the surface being glossy.

2) Suitable test specimen geometries for composite materials under tensile loading at various rates of loading as it is clear the current geometry used is unsuitable. The test specimen geometries need to be capable of reaching at least 100 s^{-1}.

3) Suitable and robust methods for processing data to ensure reliable property measurements can be achieved. Focus here will likely be toward the processing of load data captured by the test machine. However, as the speed increases, the number of data that can be captured by the high-speed cameras will also reduce and will lead to a coarser and more noisy strain response that may also need some smoothing.

In addition to the points above, work is needed to begin looking at developing test methods for other loading cases, i.e., compression, shear, flexure, fracture toughness etc. Limitations of measurements using the current equipment, especially when running the test machine at its highest loading rate of 20 m/s.

5 REFERENCES

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