FULLY REVERSED MODE-II FATIGUE TESTING

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Abstract

Composite structures for aerospace applications are constantly subjected to vibration loading from a variety of sources including aerodynamic loading and aero-engine vibration. This loading is by nature both cyclic and "fully reversed", i.e. the structure deforms both in the positive and negative senses. Fully reversed fatigue degradation needs to be better understood from a material point of view. This paper presents a novel test method for fully reversed mode-II delamination fatigue. The test has been used to study the material behaviour of laminated carbon fibre composites in fully reversed loading and its validity been investigated. First test results are presented and discussed which will help identify underlying material behaviour for future model development.

1. Introduction

Fatigue in composites has, relative to quasi-static loading, received much less attention in the open literature, and so its influence in structural failure is not well understood. Yet components that are subjected to rotational, cyclic and vibration loading can endure exceptionally high numbers of cycles, which can cause initially small amounts of damage to propagate and, if left unchecked, lead to ultimate failure. The fatigue damage can be represented on different scales ranging from molecular degradation to fibre scale mechanisms that cause composite fatigue. To ensure robust design in safety critical applications, fatigue mechanisms need to be fully understood and ultimately embedded in predictive numerical models. From a limited number of observations in the open literature [1] it has been noted that fully reversed fatigue cases are much more severe when compared to non reversed fatigue cases. Real life applications are subjected to greatly varying cases of fatigue loading [2] which is why different R-ratios and different mode mixities must be investigated. The main focus of the current work is mode-II shear delamination propagation as it is one of the more prominent cases for failure. A new test method has been developed and is presented in Section 3. Following this method different fatigue tests at different R-ratios and severity levels have been conducted.

2. Failure Mechanisms

The main objective of the tests presented here is to better understand the difference between fully reversed loading and the more standard testing at an R-ratio (trough/peak load ratio) of 0.1, and to identify differences in the material degradation mechanism. As mentioned in [3] shear loading of composites translates into tensile loading of the matrix. Fatigue and crack growth in polymer matrices then initiate

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at stress concentrations in the matrix [4]. Stress concentrations can be caused by the presence of reinforcements (e.g. fibres), particulates, contaminants or voids. These tensile stress concentrations will then lead to cavitation, which then creates a craze. These crazes expand orthogonally to the maximum principal stress. In mode-II loading the craze would expand diagonally through the thickness of the matrix as this is the path of maximum tensile stresses. If loading is reversed, any polymer bridging that might be present in the craze [4] is broken by a perpendicular load across the craze due to load reversal, which leads to a much faster material degradation than for positive R-ratios.

3. Fully Reversed Fatigue Testing

For the testing of delamination resistance in carbon fibre reinforced polymers (CFRP) two tests methods have been used, namely the End-Notch-Flexure (ENF) test [5] and the End-Loaded-Split (ELS) test [6]. The ENF test has been the main focus for the fatigue testing of composites as reported in the literature. The test setup of an ENF test is very similar to that of a three-point bending test, except that the specimen has a pre-determined delamination area at the mid plane at one end. There have been attempts to use a modified ENF fatigue test for fully reversed loading [1], but the setup used in these studies has been problematic, in particular the articulated supports used to load the specimen.

Other studies [7, 8] focussed instead on a variant of the ELS test for fatigue loading. The ELS test uses a very similar specimen as the ENF test, i.e. a unidirectional composite beam with a PTFE film inserted at its mid plane to provide an initial delamination area. The specimen is then clamped as a cantilever but sits on a ‘sled’ which is free to translate horizontally. The free end of the specimen containing the pre-crack is then loaded transversely which causes the delamination to propagate. The crack length is recorded either via imaging techniques or indirectly via a compliance calibration method [6].

In the present work the ELS test has been adapted for fully reversed loading by allowing the cantilever specimen to be bent in both directions. Both the support and the loading device have been modified. Instead of using a sled to compensate for the horizontal movement of the specimen, a fully fixed support is used and the horizontal movement is introduced via a specially designed loading device. The latter is a metal fork which surrounds the specimen as shown in Figure 1(a). This reduces the moving mass and hence inertia of the system in the dynamic loading regime. Loading blocks are glued to the top and bottom surfaces of the specimen. For the load transfer, two rods are inserted into the loading blocks on the specimen (Figure 1(b)). The load fork is designed to have a small clearance, which ensures that only one loading rod is engaged with the fork at any given time.

This configuration leaves the specimen briefly unloaded at the zero displacement position between each half cycle (due to the tolerance of the loading fork). Engagement of the load fork with the rods at the change from positive to negative displacements induce unwanted dynamic loading onto the specimen which might contribute to the material degradation. Extensive testing and modelling of the specimen response have been conducted and counter measures have been taken. As a mechanical solution rubber dampers have been introduced onto the load rods. These damp the disengagement and re-engagement of the load fork and significantly reduce any unwanted oscillations.

Furthermore, modified load curves have been proposed. In a perfectly sinusoidal load curve the actuator is moving with greatest velocity as the rod engages with the load fork, which will then cause large oscillations. The load curve has been modified so that the re-engagement velocity of the load fork is reduced. Two options were investigated, namely (i) the use of a sine-squared function (inverted during the second half-cycle) and (ii) the use of a linear gradient (fixed-velocity) portion in the region of load reversal. Both options are shown on the left-hand column of Figure 2.

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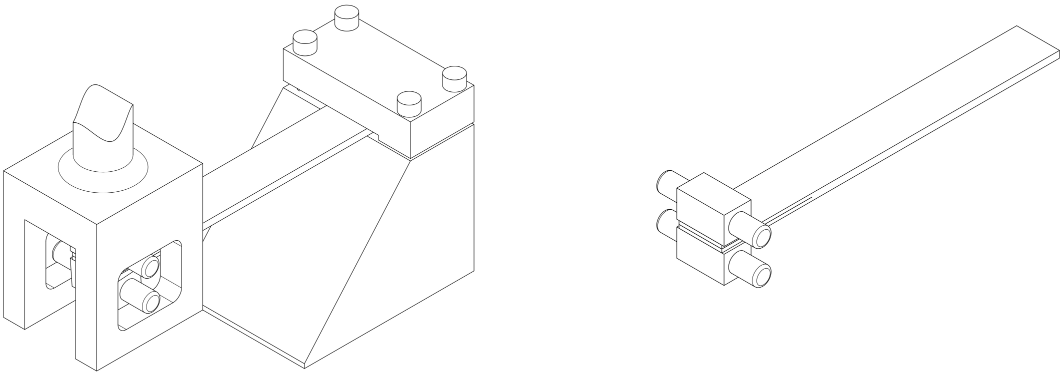

(a) Test Setup (b) Specimen Setup

Figure 1. The test configuration for the fully reversed fatigue test.

The specimen response was studied for the three different load curves. In the short unloaded interval between the load fork engagement, the specimen is free to oscillate at its eigenfrequency. This problem has been investigated both via experiments and Finite Element (FE) analysis using the software Abaqus/Explicit. It was observed that the length of time between the disengagement and re-engagement of the load fork in fact determined the intensity of the free oscillations of the specimen, instead of the engagement velocity as initially thought. In Figures 2(b), 2(d) and 2(f) it can be seen that the higher amplitudes led to higher velocities of the load fork in between the load extremes. Lower velocities allowed up to two periods of oscillation whereas higher velocities only allowed one period of oscillation at the eigenfrequency. The input frequency was constant at 3 Hz in all cases.

The correlation between the input load curves and the output specimen response can be seen in Figure 2. Despite its simplicity, the sinusoidal load curve resulted in the smallest oscillations between the three curves and is currently the option of choice for future testing. The amplitude of the free oscillation was only 1.3% of the applied displacement amplitude which is believed to have negligible effects on the material degradation.

4. Test Results

The previously described test procedure has been used to test different loading amplitudes at an R-ratio of -1. Test specimens were manufactured from Hexcel$^{\text{TM}}$ IM7/8552 pre-preg material. The results have been plotted in modified Paris curves which relate the *crack growth rate*, $\mathrm{d}a/\mathrm{d}N$, to the normalised applied *peak strain energy release rate*, $G_{\mathrm{II\,max}}/G_{\mathrm{IIC}}$, as shown in Figure 3. The tests were run in displacement control to ensure a monitoring of the load degradation for the specimen when subjected to cyclic loading. The initial amplitudes were chosen to represent a load of 50% of G_{IIC} for specimens 3_2, 3_3 and 3_4, and 30% of G_{IIC} for specimens 3_6, 3_7 and 3_8.

The first tests were conducted at a higher amplitude which caused high interlaminar crack growth rates over the whole specimen. Because of the limited specimen length the high amplitude test could not be continued for a wider range in $G_{\mathrm{II\,max}}$. When compared to a Paris curve from the literature [9] for $R = 0.1$, it can be clearly seen that for both tested amplitudes the crack growth rate is much higher than for a non reversed fatigue case for equivalent energy release rates (normalised by G_{IIC}). It should be

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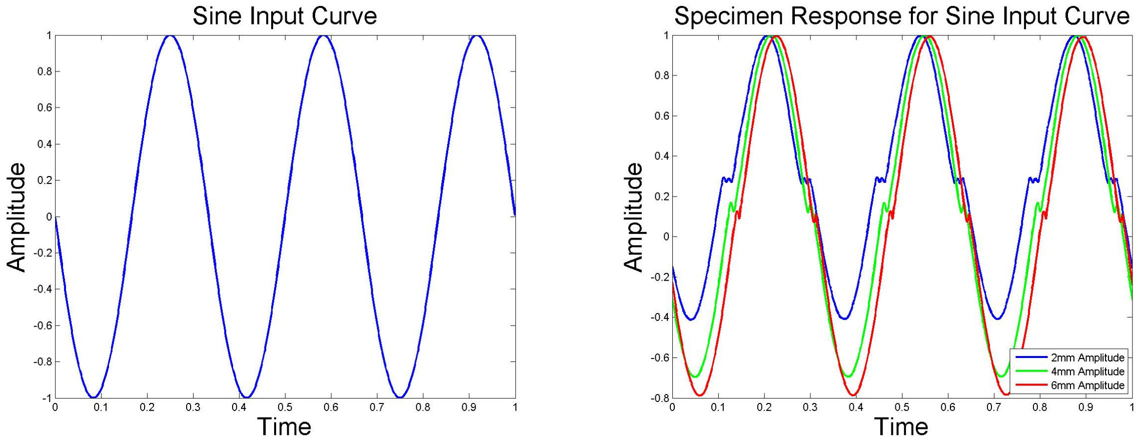
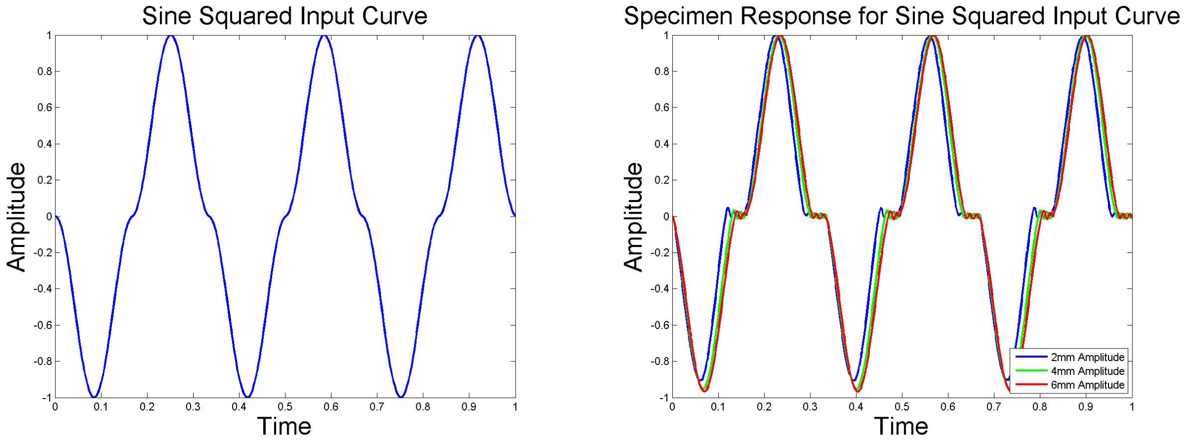


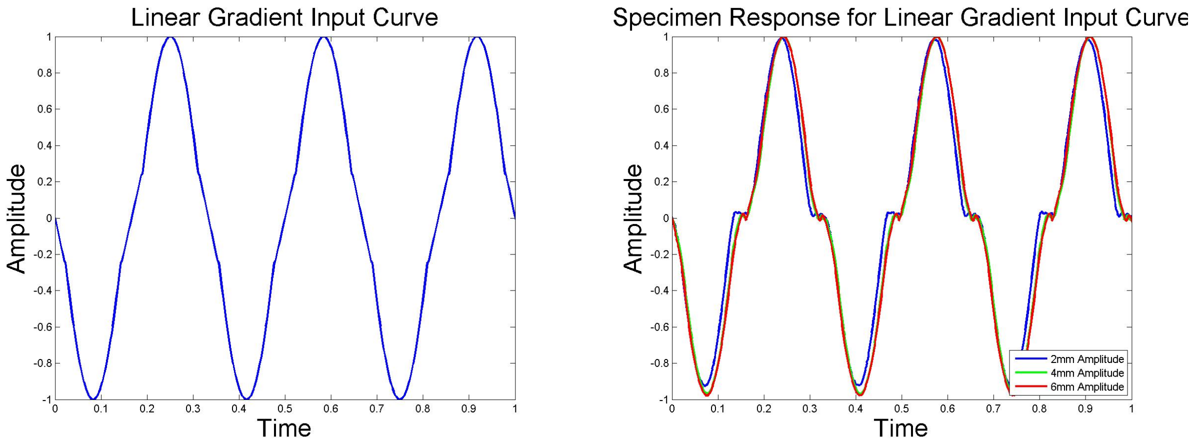
(a) Sine Curve Input

(b) Sine Curve Output



(c) Sine Squared Curve Input

(d) Sine Squared Curve Output



(e) Linear Gradient Curve Input

(f) Linear Gradient Curve Output

Figure 2. The tested input curves and their corresponding specimen response.

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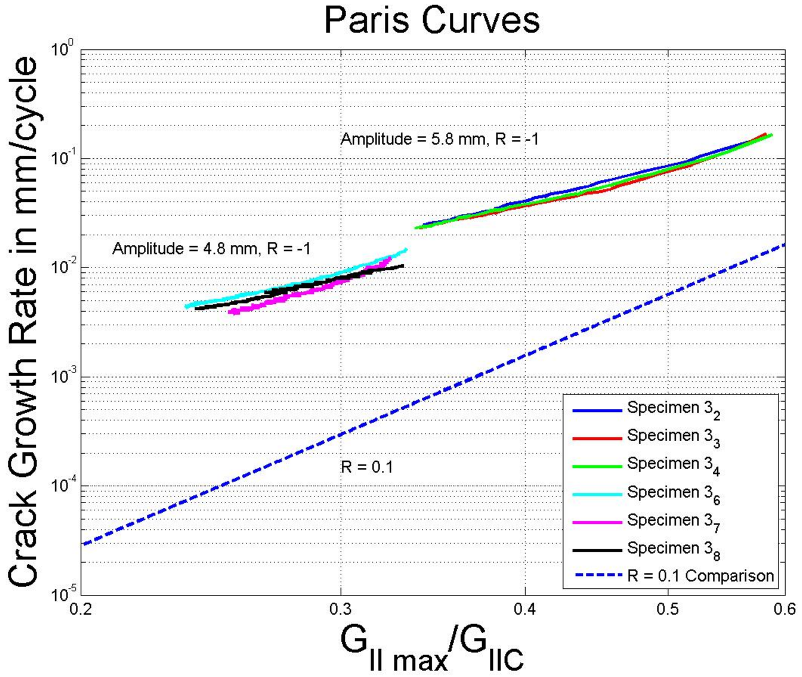

Figure 3. Paris curves at $R = -1$ compared to literature data for $R = 0.1$ after [9].

noted that the specimens from both test groups, the high amplitude and the low amplitude loading, were manufactured from different plates, which may explain the slight discontinuity in the Paris curve at their meeting point.

5. Fractography

For an improved understanding of the damage and fracture mechanisms involved in the tests, the fracture surfaces of the specimens were observed under a high-magnification optical microscope. Figure 4 shows typical fracture surfaces for non-reversed ($R = 0.1$) and reversed ($R = -1$) loading. The horizontal lines seen in both cases are fibre filaments exposed on the fracture surface. Areas of interest where the matrix material is shown more clearly are identified by arrows. It can be seen that the crack surface for reversed loading (Figure 4(b)) is considerably rougher, with higher peaks and deeper troughs of resin material when compared with the non-reversed load case (Figure 4(a)). This suggests that the damage mechanisms observed in the polymer matrix are considerably different between reversed and non-reversed loading, as discussed briefly in Section 2. This correlates well with the much higher crack growth rate observed for $R = -1$, as shown in the Paris curve in Figure 3. For a more detailed investigation of the different damage mechanisms, Scanning Electron Microscopy (SEM) will be used to analyse specimens subjected to different load amplitudes and R-ratios.

6. Discussion

The proposed test method will be further used to identify the fatigue mechanisms in the composite under a mode-II fatigue loading with different R-ratios. The purpose of the test is to gather data for the development and verification of numerical fatigue models. A future modelling approach will be based on the fatigue mechanism that underlies the observed material degradation. Identifying the mechanism will

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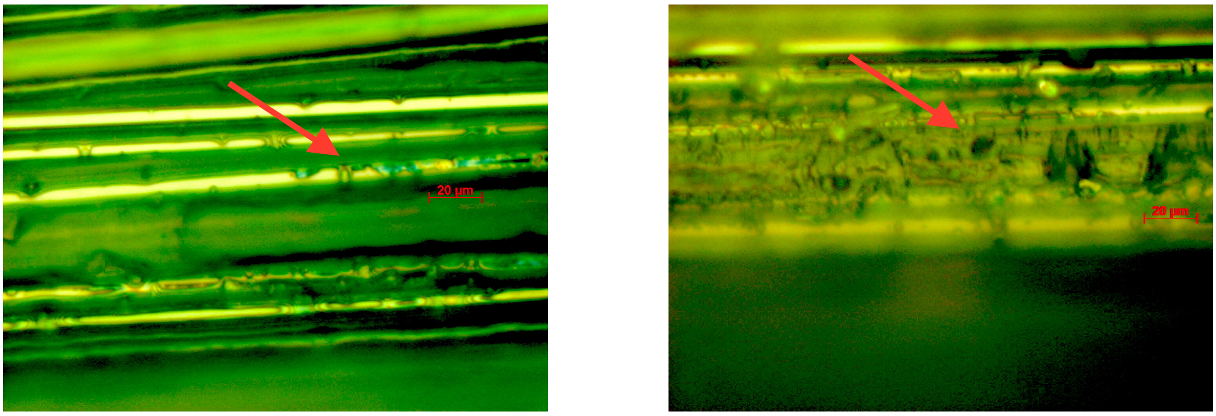

(a) Fracture surface for $R = 0.1$ (b) Fracture surface for $R = -1$

Figure 4. Fracture surfaces of specimens tested under different R-ratios (regions of interest marked by arrows).

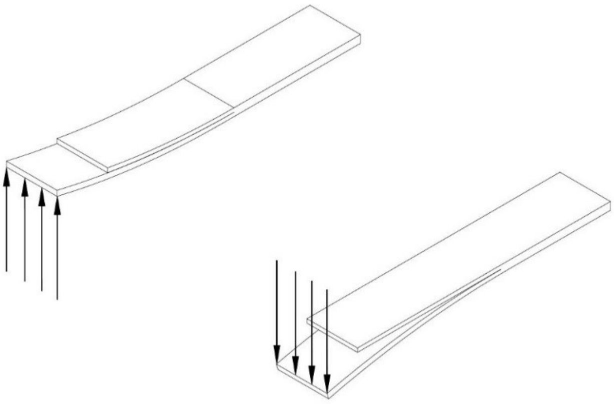

Figure 5. Proposed mixed mode testing for realistic fatigue scenarios.

help in building a robust routine and finding a link between material degradation and the load parameters.

Due to the nature of a fully reversed fatigue test, the specimen is subjected to two load maxima per cycle. This is not regarded in the Paris curves, because it would introduce a factor of two in the crack growth rate, which would have a negligible effect on the crack growth rate in a log scale notation. Even if this factor were introduced to the Paris curves in Figure 3 the crack growth rate would still be significantly higher for $R = -1$ than in the non reversed fatigue case. This difference is consistent with data from other material systems [8].

The tests have been conducted as closely to the standard as possible to minimise any potential sources of error. The standard demands pre-cracking the specimen which creates a natural crack front and will also reduce the resistance to crack initiation. For a non pre-cracked specimen the major part of the fatigue life is invested in the crack initiation [10]. As only the crack propagation is studied in this test method, the results from this work cannot be applied directly to cases without an initial crack. Therefore, applying the results of this test directly to a model and to a real life application will result in overly conservative results.

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7. Conclusions

A novel test method based on the End-Loaded-Split (ELS) standard has been proposed in this paper. The method allows for fatigue testing under full load reversal. As means of improvement different load curves were tested and the curve producing the lowest unwanted oscillations has been found. As an additional measure rubber dampers were introduced which further reduced specimen oscillations. The outcomes of the method development are described in detail in Section 3. The new method was then applied in the testing of Hexcel$^{\text{TM}}$ IM7/8552 laminates under various load severities and R-ratios. The results will be used to identify the dominant failure mechanisms in composite materials subjected to fully reversed fatigue loading. Initial fractography analyses revealed clear differences in the topology of the fracture surfaces between non-reversed and reversed loading. Scanning Electron Microscopy will be used for more detailed investigations. From the gathered data and observed failure mechanisms a fatigue evolution model will be derived and applied to predict the material degradation in real life components. Work is ongoing also on mixed-mode reversed fatigue loading such as combined mode-I and mode-II cycles as shown in Figure 5. The objective is to test more realistic loading scenarios as observed in real life components.

8. Acknowledgements

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References

[1] G. Matsubara; H. Ono; K. Tanaka. Mode ii fatigue crack growth from delamination in unidirectional tape and satin-woven fabric laminates of high strength gfrp. *International Journal of Fatigue*, 28:1177–1186, 2006.

[2] B.A. Cowles. High cycle fatigue in aircraft gas turbines - an industry perpective. *International Journal of Fracture*, 80:147–163, 1996.

[3] K. T. O'Brien. Composite interlaminar shear fracture toughness, g_{IIC}: Shear measurement or sheer myth. *Composite Materials: Fatigue and Fracture*, 7:3–18, 1998.

[4] J. I. Kroschwitz; H. F. Mark. *Encyclopedia of Polymer Science and Technology*, volume 6. Wiley, 2004.

[5] Standard test method for determination of the mode ii interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites. Technical Report D7905/D7905M 14, ASTM, 2014.

[6] Fibre-reinforced plastic composites – determination of the mode ii fracture resistance for unidirectionally reinforced materials using the calibrated end-loaded split (c-els) test and an effective crack length approach. Technical Report ISO 15114:2014, International Organization for Standardization (ISO), 2014.

[7] A. J. Russell; K. N. Street. The effect of matrix toughness on delamination: Static and fatigue fracture under mode ii shear loading of graphite fiber composites. *Toughened Composites*, pages 275–294, 1987.

[8] K. Tanaka; H. Tanaka. Stress-ratio effect on mode ii propagation of interlaminar fatigue cracks in graphite/epoxy composites. *Composite Materials: Fatigue and Fracture*, 6:126–142, 1997.

[9] G. Allegri; M.I. Jones; M.R. Wisnom; S.R. Hallett. A new semi-empirical model for stress ratio effect on mode ii fatigue delamination growth. *Composites: Part A*, 2011.

[10] M. L. Benzeggagh; M. Kenane. Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus. *Composites Science and Technology*, 56:439–449, 1995.

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