Stress ratio dependence of fiber bridging significance in mode I fatigue delamination growth of composite laminates

Yao, Liaojun; Sun, Y.; Zhao, M; Alderliesten, Rene; Benedictus, Rinze

DOI
10.1016/j.compositesa.2016.11.030

Publication date
2017

Document Version
Proof

Published in
Composites Part A: Applied Science and Manufacturing

Stress ratio dependence of fibre bridging significance in mode I fatigue delamination growth of composite laminates

Liaojun Yao, Yi Sun, Meiying Zhao, R.C. Alderliesten, R. Benedictus

PII: S1359-835X(16)30424-9
DOI: http://dx.doi.org/10.1016/j.compositesa.2016.11.030
Reference: JCOMA 4502

To appear in: *Composites: Part A*

Received Date: 2 August 2016
Revised Date: 9 October 2016
Accepted Date: 27 November 2016

Stress ratio dependence of fibre bridging significance in mode I fatigue delamination growth of composite laminates

Liaojun Yao[a,b*], Yi Sun[a], Meiying Zhao[b], R.C. Alderliesten[c], R. Benedictus[c]

[a] Department of Astronautics Science and Mechanics, Harbin Institute of Technology, Harbin, P.R. China

[b] School of Aeronautics, Northwestern Polytechnical University, Xi'an, P.R. China

[c] Structural Integrity and Composites Group, Faculty of Aerospace Engineering, Delft University of Technology, the Netherlands

*Corresponding Author:

Email: L.Yao@hit.edu.cn;

Abstract:

This paper aims to investigate stress ratio effect on fibre bridging significance in mode I fatigue delamination growth of composite materials. Fatigue resistance curves (*R-curves*) of different stress ratios are determined and compared with the quasi-static *R-curve*. The fatigue *R-curve* of a high stress ratio is similar to the quasi-static results. However, fatigue resistance of a low stress ratio is smaller than quasi-static resistance. These indicate that fibre bridging significance is stress ratio dependent. More bridging fibres can be generated in delamination of a high stress ratio, as compared to that of a low stress ratio. This can lead to fatigue bridging laws are stress ratio dependent and fatigue delamination is block load sequence dependent.

Keywords: B. Fatigue; B. Delamination; Fibre bridging; A. Polymer-matrix

composites (PMCs)

1. Introduction:

Delamination is one of the most important damage in composite laminates or adhesively bonded structures. Scientific community has paid keen attention to this issue in the last several decades, due to increasing applications of advanced composite materials in aerospace engineering for the requirements of light-weight structures as well as fuel efficiency. Delamination is detrimental to composite structures. It can occur at a relatively low stress level and gradually propagate between adjacent layers under fatigue loading, making it difficult to have a real-time monitor on this kind of damage. In practice, two principles have been widely used in composite structural design, i.e. *no crack growth* or *damage tolerance philosophies*. Using the first principle will limit the weight saving potential and loading capacity of composite materials. Thus, more and more composite structural designs are in agreement with the *damage tolerance principle*, leading to urgent requirements of in-depth understanding of delamination behavior under fatigue loading and reliable prediction models.

Pascoe et al [1] provided a critical literature review on the prediction methods for fatigue delamination growth in composites. The Paris relation and its variations, based on fracture mechanics by correlating crack growth with stress intensity factor (*SIF*) or strain energy release rate (*SERR*), work well in determining fatigue crack behavior in metals and composites. However, there is no consensus on the selection of similitude parameter in these Paris relations for composite materials. People alternatively employed the maximum *SERR* G_{max} or the *SERR* range, i.e. $\Delta G = \left(\sqrt{G_{max}} - \sqrt{G_{min}}\right)^2$, in fatigue delamination studies [2-5]. According to these relations, various factors that can affect fatigue delamination behavior have been carefully examined via experimental or theoretical methods. These factors include, but not limited to, the stress ratio *R*, the mixed-mode ratio, the temperature, the moisture [2-9].

Amongst these factors, stress ratio is one of the most important governing parameters in determining fatigue delamination behavior in composite laminates. However, there is no agreement on its effect in fatigue delamination growth, as this effect seems to be similitude parameter dependent [2-6]. In case of using G_{max} to represent the similitude, fatigue crack growth can decrease with the increase of stress ratio, due to the decrease in ΔG of a high stress ratio. On the contrary, using ΔG as the similitude can result in accelerating fatigue crack growth with the increase of stress ratio, due to a higher G_{max} of a larger stress ratio. To solve this controversy, some people stressed that the *R*-ratio dependence of fatigue crack growth indeed resulted from the insufficient description of a fatigue loading. As a result, two-parameter Paris-type relations were proposed to characterize fatigue delamination behavior and to remove the *R*-ratio dependence [3,10]. Once these two-parameter models were applied in fatigue data reduction, a single master resistance curve can be obtained to determine fatigue delamination behavior under different stress ratios.

Fibre bridging is another significant phenomenon in delamination growth. This shielding mechanism can bridge fracture surfaces and retard crack propagation, consequently making interlaminar resistance increase. The *R-curv*e concept, in terms of fracture toughness against crack growth length, has been introduced to phenomenologically characterize the increase of resistance in quasi-static crack growth [11,12]. In the perspective of physics, bridging laws, in terms of bridging stress against crack opening displacement (*COD*), have been proposed and recommended to physically determine the fibre bridging phenomenon [11-14]. And corresponding prediction models have been successfully developed for quasi-static delamination with large-scale fibre bridging [13-15]. However, research work on fibre bridging is still very limited in fatigue crack growth. In the previous studies [16-17], people can only phenomenologically explain its effect, according to the experimental observation in fatigue delamination growth. This is far away from the requirements of in-depth understanding of this phenomenon. Therefore, Yao et al [18-20] systematically investigated the role of fibre bridging in fatigue delamination growth via both experimental and theoretical approaches. They not only drew conclusions that fibre bridging can significantly decrease fatigue crack growth, but also found there is a plateau state in fibre bridging development. According to the energy principles, they highlighted that bridging fibres can periodically stored and released strain energy in loading and unloading cycles. However, these fibres actually have no or negligible contribution to the *SERR* unless there is failure in them. In followed studies [21,22], they attempted to correlate curve-fitting parameters of the Paris relation and proposed Paris-type relations to determine fatigue crack growth with fibre bridging. Other people recently investigated the bridging phenomenon in fatigue crack growth using the bridging laws. Stutz [13] made a comparison on the significance of fibre bridging between quasi-static and fatigue delamination via the bridging laws determined with a semi-experimental method. The results clearly indicated that fibre bridging is more significant in fatigue delamination. In another study performed by Donough et al [23], an inverse method was applied to quantify the bridging laws in delamination. It was reported that the maximum bridging stress is similar in quasi-static and fatigue delamination, whereas fatigue bridging law decays even faster with *COD*, as compared to quasi-static bridging law.

According to about brief review and discussion, both stress ratio and fibre bridging can significantly affect delamination behavior under fatigue loading. Questions arise here as what the interactions between these two factors, i.e. what is the bridging effect on the stress ratio and what is the stress ratio effect on the bridging. The first question has been well answered in a study completed by Khan et al [6], via fatigue delamination tests with or without fibre bridging removal. They reported that fibre bridging has effect on the magnitude of G_{max}, G_{min} and ΔG, but has no or negligible effect on the stress ratio.

However, to the author's knowledge, no study has been performed to answer the second question. Thus, the objective of present work is to investigate stress ratio effect on fibre bridging significance in fatigue delamination growth.

2. Quasi-static and fatigue delamination experiments

2.1 Material and specimen geometry

Unidirectional double cantilever beam (DCB) specimens were manufactured and tested to investigate fatigue delamination behavior with fibre bridging. The composite laminates were produced by hand-lay-up of 32 thermosetting unidirectional carbon/epoxy prepreg layers of M30SC/DT120 with a nominal cured thickness of 5 mm. A 12.7μm Teflon film was inserted in the middle plane of these laminates during the hand-lay-up process to act as an initial delamination. The laminates were cured in vacuum in an autoclave at a pressure of 6 bars and curing temperature of 120℃ for 90 min. After curing, the laminates were C-scanned to detect potential imperfections. The plate was subsequently cut by a diamond saw into 25 mm width beams with 200 mm length, and only these samples were tested where the C-scan did not reveal any obvious imperfections. A pair of aluminum loading blocks, 25 mm width by 20 mm length with 6 mm thickness, was adhesively bonded onto the specimen at the side of the Teflon insert for load introduction.

One side of each DCB specimen was coated with thin typewriter correlation fluid to enhance visibility of the delamination front during the test. A strip of grid paper was pasted on the specimen coated side to aid in measuring the delamination propagation length.

2.2 Experiment procedures

Quasi-static experiments were conducted on a 20KN tensile-compression Zwick machine according to the ASTM D5528. All tests were performed under displacement control with an applied displacement rate 1mm/min in ambient conditions. A computer controlled high resolution digital camera system was applied to monitor the delamination growth by automatically recording an image of specimen coated side every 5 seconds during the entire test.

Fatigue experiments were performed on a 10KN MTS machine under displacement control at a frequency of 5Hz with stress ratio R=0.1 and R=0.5 in ambient conditions. The aforementioned digital camera system was employed to monitor the crack growth at the maximum displacement with pre-defined intervals during the test. The load, displacement and number of cycles were automatically stored in an Excel file every 100 cycles enabling data evaluation after the test.

To determine fatigue delamination behavior with different amounts of fibre bridging, DCB specimens were repeatedly tested for several times with different applied displacements, but keeping stress ratio the same. Fatigue test was manually terminated in case of crack retardation. After each fatigue test, DCB specimen with a given fatigue delamination length, equivalent to a certain amount of fibre bridging, was quasi-statically loaded until the load-displacement curve became nonlinear. According to this monotonic load procedure, the maximum and minimum displacements for the subsequent fatigue test can be evaluated. Additionally, delamination resistance with a certain amount of fibre bridging can be calculated at the nonlinear point. It is worth noting that it is really difficult to prevent crack re-growth during the quasi-static load procedure and visual crack growth was observed in some cases. Strictly speaking, the crack re-growth can lead to fatigue damage state be destroyed. However, in present study, it postulated here that the damage state change is negligible, as the visual crack is relatively small. In this condition, the delamination resistance related to crack growth was calculated.

The Modified Compliance Calibration (MCC) Method recommended in the ASTM

D5528, see Eq.(1), was used to calculate the *SERR* in quasi-static and fatigue delamination growth.

$$G_I = \frac{3P^2C^{(2/3)}}{2A_1Bh} \quad (1)$$

where C is the compliance of the DCB specimen; B is the specimen width and h is the thickness of the specimen; A_1 is the slope of the curve in the graph where a/B is plotted against $C^{1/3}$.

The 7-point Incremental Polynomial Method, recommended in the ASTM E647, was employed to determine the fatigue crack growth rate *da/dN*.

3. The Paris curve distribution with fibre bridging

At a given stress ratio, two DCB specimens were repeatedly fatigue tested to provide sufficient information for the investigation on delamination growth with different amounts of fibre bridging. All results are illustrated Fig.1 and Fig.2, in terms of *da/dN* against *SERR* range. For both stress ratios, the Paris resistance curves will significantly shift from left to right with fibre bridging development and finally converge into a single curve representing fibre bridging saturation.

There may be a range of reasons for length scale dependence of fatigue crack growth in different materials [18,19,24]. Incorporating with the previous studies [18,19,21,22], fibre bridging is proposed as the main reason for the decrease shift in fatigue crack growth in composite laminates. Even more significant bridging fibres can be present in a long delamination, contributing to a large portion of strain energy periodically stored and released in these fibres under fatigue loading. And only a small portion of strain energy is actually applied to the delamination front, acting as the effective crack driving force. It is worth noting that there is an up limit of fibre bridging. Once crack propagation exceeds a certain value, fibre bridging can become saturation, resulting in the Paris curves finally converge into a single curve.

The results illustrated in Fig.1 and Fig.2 clearly demonstrated that fibre bridging has important effect on fatigue delamination behavior in composite laminates. Bridging can significantly retard crack growth and affect the Paris curve distribution, invalidating the use of a single Paris resistance curve to represent fatigue crack growth. It is, therefore, imperative to have an insight into this phenomenon. This can benefit future studies on fatigue delamination growth with fibre bridging.

4. Quasi-static and fatigue delamination *R-curves*

Fibre bridging can enhance interlaminar resistance by bridging fracture surfaces and releasing stress concentration around the crack front. As a result, delamination resistance in quasi-static crack growth is not constant, but depends on the significance of fibre bridging. The *R-curve* concept was usually introduced to phenomenologically determine resistance increase because of bridging or other toughening mechanisms in quasi-static crack growth. This method was implemented in present study to quantify the resistance increase in fatigue delamination as well.

Two DCB specimens were monotonically loaded to determine the quasi-static *R-curve*. Fig.3 illustrates the increase of interlaminar resistance with crack propagation. No obvious scatter is observed in the resultant data from different specimens, indicating the repeatability of the tests. Resistance increase is also observed in fatigue delamination. However, obvious difference is observed in the magnitude of resistance between quasi-static and fatigue delamination of *R*=0.1, as shown in Fig.3(a). Fatigue resistance is much lower than that of quasi-static. This difference becomes negligible as stress ratio increase. The fatigue *R-curve* of *R*=0.5 is similar to the quasi-static results, as shown in Fig.3(b).

In the author's opinion, fibre bridging is still the main reason for resistance increase in fatigue delamination growth. A higher increase of resistance indicates more fibre bridging generation, and vice versa. Taking the quasi-static *R-curve* as a reference, one can make a conclusion that stress ratio has effect on fibre bridging significance in fatigue delamination growth. More bridging fibres seem to be present in fatigue delamination of a high stress ratio, as compared to that of a low stress ratio. Furthermore, this dependence can cause fatigue bridging law to be stress ratio dependent. Thus, it is invalid to use a single bridging stress distribution to physically represent fibre bridging in fatigue delamination.

The results illustrated in Fig.3 also provide important information for the discussion of stress ratio effect on the differences and similarities of damage states between quasi-static and fatigue delamination. Clear resistance difference illustrated in Fig.3(a) indicates the damage states are not the same. The same or similar resistance illustrated in Fig.3(b) implies the damage states are the same or at least similar. Thus, one can conclude that the damage states are stress ratio dependent significantly and there seems a correlation between quasi-static and fatigue delamination resistance of a high stress ratio. This finding is really important for the validation of normalization in fatigue data analysis.

The differences and similarities of damage states can be physically explained by crack closure and fractography analysis. In a previous study, it was reported that crack closure can occur at low stress ratios, i.e. $R<0.3$ [6]. This shielding mechanism can cause bridging fibres damage and degrade fibre bridging significance. However, no crack closure was reported in fatigue delamination with high stress ratios. As a result, no or negligible bridging fibre will be damaged in the unloading cycles. Thus, crack closure is one reason for the difference in the significance of fibre bridging, constituting different fatigue *R-curves* and damage states.

Fractography study indicates that fibre prints and cusps are two dominant micro-features on fatigue fracture surfaces, and no obvious plasticity deformation is observed, as shown in Fig.4. The scale of cusps is stress ratio dependent. It becomes more significant with increasing stress ratio. It is worth keeping in mind that this micro-feature is generated by the debonding between fibres and matrix. The increasing severity of cusps provides evidence on the significance of fibres pulled out from matrix. Larger dimension of cusps in delamination of a high stress ratio means more bridging fibres can be created. This is indeed consistent with the fatigue *R-curves* of different stress ratios. The presence of more fibre bridging can cause a higher fatigue *R-curve*.

5. Threshold increase with fibre bridging

According to the above discussion, there is solid and sufficient evidence that fibre bridging has important effect on fatigue crack behavior and can enhance interlaminar resistance significantly. Threshold, under which no crack propagation is assumed to occur, is another important property in fatigue crack growth study. It plays a really critical role in the application of *no crack growth principle* in composite structural design. However, it is really long duration and expensive to experimentally determine the threshold. In practice, it can be conveniently calculated at a relatively low crack growth rate, for example da/dN=1×10^{-10} m/Cycle recommended in the ASTM E647.

The best-fit Paris relation of each experimental data set was used to determine the threshold at the recommended crack growth rate. The calculated limits are illustrated in Fig.5 in terms of $G_{max,th}$ against crack extension a-a_0. The magnitude of threshold significantly depends on the crack extension. It increases with crack growth and eventually keeps constant as fibre bridging becomes saturation. The model proposed by Bao [25] in the characterization of delamination resistance increase because of bridging was employed here to determine the threshold increase. This increase is comparable with the Paris curve distribution shown in Fig.1. The decrease shift of crack growth rate can lead to the required G_{max} at a given da/dN increase obviously. The converge of the most right resistance curves into a single Paris curve indicates that there is a plateau of G_{max} at a fixed da/dN. In agreement with the resistance difference observed in Fig.3, the increase of threshold is proportional to the stress ratio. It is more significant for R=0.5 than that for R=0.1 at the same crack extension. This is consistent with the conclusion that more fibre bridging can be generated in fatigue delamination of a high stress ratio.

From the data illustrated in Fig.5, fatigue threshold is not constant. Its magnitude is not only dependent on the stress ratio R, but also related to the crack extension a-a_0.

These two factors should be carefully taken into account in composite structural design in accordance with the *no crack growth principle*. Particularly, the use of the initial value of the threshold in engineering can result in really conservative results, whereas, the application of the plateau value cannot guarantee safety. Thus, the values located in-between must be carefully evaluated and employed in engineering. And the threshold *R-curve* proposed in present study seems a reasonable and convenient approach to evaluate the magnitude of threshold with fibre bridging.

6. Fatigue delamination behavior under block loading

Shielding mechanism of plasticity deformation around the crack tip plays a dominant role in load sequence effect on fatigue crack growth in metals. This mechanism can lead to fatigue crack behavior in a HI-LO block loading differs from that in a LO-HI block loading. Fibre bridging, acting as the counterpart in composite materials, should have the similar effect on fatigue delamination growth. According to the discussion on stress ratio dependence of fibre bridging significance, more bridging fibres can be generated in fatigue delamination with a high stress ratio, making the shielding mechanism even more significant. It is, therefore, reasonable to postulate that fatigue delamination growth is load sequence dependent in composite materials. Particularly, delamination growth retardation of a HI-HI block loading should be more obvious than that of a LO-HI block loading.

To verify this idea, two DCB specimens were fatigue tested with different load sequences, i.e. HI-HI (R=0.5 and R=0.5) and LO-HI (R=0.0 and R=0.5). The first time fatigue tests on the specimens were manually terminated until crack propagated

11.6mm under different stress ratios, i.e. R=0.5 and R=0.0. These specimens were subsequently tested for the second time under the same high stress ratio R=0.5 until there was no obvious crack growth. By comparing the delamination data of the second time tests, load sequence effect on fatigue crack growth behavior can be analyzed and discussed.

Fig.6 provides resultant data sets for the second time fatigue tests of HI-HI and LO-HI block loadings. The results can be described very well using the Paris relation ($R^2 \geq 0.965$). Clear difference is observed in the resistance graph, where the results for HI-HI block loading locate on the right side of the data for LO-HI block loading. Consequently, at a given *SERR* range, crack growth behavior is not the same. It is almost one order of magnitude faster in the LO-HI block loading, as compared to that in the HI-HI block loading. This difference clearly consolidates the hypothesis that there is load sequence effect on fatigue delamination growth in composite materials. More significant crack retardation is observed in the HI-HI block loading. In the author's opinion, fibre bridging is the main reason for the load sequence effect on fatigue delamination growth in composite materials.

7. Energy balance analysis on fatigue delamination growth

Crack growth is an energy dissipation process obeying the physics laws on energy conservation. In the previous studies [19,20], energy balance principles have been applied to analyze fatigue delamination growth behavior in composite materials, expressed in terms of energy dissipation rate dU/dN against crack growth rate da/dN. This analysis takes advantage of clear physics background by directly correlating fatigue delamination growth with the amount of strain energy release actually used in crack increment. It can provide detail information related to delamination growth, instead of using only curve-fitting approaches to interpret the experimental results phenomenologically. To have better understanding of bridging effect on fatigue delamination in block loadings, the experimental data sets shown in Fig.6 were re-analyzed using the energy principles.

It is worth noting that fatigue crack growth will decrease as delamination propagates in a displacement controlled fatigue test. Fig.7 shows the resultant data interpretation in accordance with the energy principles. At the beginning of delamination, the amount of energy for the same crack growth is not the same. More energy is needed for the LO-HI block loading. This difference becomes negligible after the crack growth rate below $da/dN=2\times10^{-7}$ m/Cycle, indicating the same amount of energy release for the same crack growth.

It has demonstrated that a steady state exists in fatigue delamination growth [20]. This can be applied here to explain the differences and similarities illustrated in Fig.7. In the steady state, all energy release concentrates to the damage evolution around the delamination front, constituting the same energy dissipation of the same crack increment. However, the situation at the beginning of crack propagation is much more complicated. Energy dissipation is not only related to crack advance, but also relevant to fibre bridging. A certain amount of energy is indeed dissipated because of bridging fibre pullout or failure. It should be stressed here that the fibre damage severity is stress ratio or mean stress dependent. Particularly, bridging fibres may not be fully pulled out from matrix in the first time fatigue test in the specimen with a low stress ratio R=0.0. These fibres need to be further pulled out at the beginning of a followed fatigue test with an increasing stress ratio R=0.5. This phenomenon, however, may be not so obvious in fatigue delamination of the HI-HI block loading. As a result, more energy dissipation can occur at the beginning of fatigue delamination in the LO-HI block loading, as compared to that in the HI-HI block loading.

8. Discussion on damage states in quasi-static and fatigue delamination

For the application of the Paris laws in the interpretation of fatigue crack growth in metals, the exponent approximately ranges from 1.8 to 4.0 [24]. However, it is much higher for composite materials, especially in mode I fatigue delamination growth [26,27]. This means fatigue crack growth is really sensitive to the magnitude of applied *SERR*. A small uncertainty in the *SERR* can cause obvious error in the crack growth evaluation.

Normalization has been widely applied to fatigue data analysis in order to reduce the exponent magnitude as well as data scatter. This method is based on the principle of relative crack driving force [28]. In practice, the maximum *SERR* or *SERR* range is usually normalized by the quasi-static delamination resistance. Furthermore, normalization was also used in total fatigue model development, which was based on a phenomenological description of the sigmoidal shape of *da/dN* against *SERR* in a log-log graph [29]. Pascoe et al [1] proposed a brief discussion on the validity of using normalization in fatigue delamination study in composite materials. It has been stressed that normalization was lack of physical or mechanical support, as there was no evidence to correlate quasi-static and fatigue delamination resistance. This method is valid unless the damage states between quasi-static and fatigue crack growth are the same or at least similar, equivalent to the resistance between quasi-static and fatigue delamination is comparable. In present study, it has clearly demonstrated that the fatigue resistance is stress ratio dependent. The fatigue resistance of a high stress ratio is comparable to quasi-static, supporting by the similar quasi-static and fatigue *R-curves* shown in Fig.3(b). However, this is not true for fatigue delamination with a low stress ratio, as obvious difference is observed in the *R-curves* shown in Fig.3(a).

In previous studies [18,19], it has reported that the Paris curves for fatigue tests with the same quasi-static and fatigue pre-crack are different, even at the same stress ratio R=0.5. This seems to disagree with the results of present study, i.e. the same quasi-static and fatigue delamination resistance illustrated in Fig.3(b). In the author's understanding, this can be reasonably explained by the load level difference in quasi-static and fatigue crack growth. Crack propagation occurs at the high critical quasi-static loading. In this condition, bridging fibres can be fully stretched and pulled out from matrix. In a subsequent fatigue test, these fibres are, therefore, not completely tensioned at a sub-critical loading, leading to less strain energy periodically stored and released in fibre bridging or permanently dissipated due to fibre damage. However, crack growth can occur at a sub-critical loading in fatigue delamination. Most bridging fibres, in this condition, are not fully stretched or pulled out. Thus, these bridging fibres can be further tensioned and pulled out in a subsequent fatigue test with increasing displacements. Consequently, more strain energy can be periodically stored and released under fatigue loading or permanently released because of damage in bridging fibres. This is the reason for the difference observed in the Paris curves in previous studies [18,19].

On the contrary, delamination resistance for specimen with a given fatigue crack length was measured at the critical loading or a loading really close to the critical in present study. In this condition, all bridging fibres can be completely tensioned, making negligible difference between quasi-static and fatigue *R-curves* shown in Fig.3(b). Therefore, delamination resistance should be carefully measured to investigate the resistance or damage state difference in quasi-static and fatigue delamination.

9. Conclusions

This paper provides an insight into fibre bridging in fatigue delamination growth under different stress ratios. It apparently demonstrated that fibre bridging has significant effect on fatigue delamination behavior in composite materials. The presence of fibre bridging can lead to a clear decrease shift in fatigue crack growth.

The significance of fibre bridging is stress ratio dependent in fatigue crack growth. More bridging fibres can be present in fatigue delamination of a high stress ratio, as compared to that of a low stress ratio. The first reason for this dependence is the crack closure mechanism, as this shielding mechanism can cause bridging fibres damage in the unloading cycle. The second reason is related to stress ratio or mean stress. More bridging fibres seem to be pulled out from matrix in delamination of a high stress ratio. The stress ratio dependence of fibre bridging significance can cause fatigue bridging law stress ratio dependent. Thus, it is inappropriate to use a unique bridging stress distribution to represent fibre bridging in fatigue delamination.

The differences and similarities of damage states between quasi-static and fatigue delamination is stress ratio dependent. Fatigue *R-curve* of a high stress ratio is similar to that of quasi-static *R-curve*, indicating the same or at least similar damage state. However, fatigue resistance of a low stress ratio with crack closure is much smaller than that of quasi-static crack growth, indicating the difference in damage states. As a result, stress ratio effect on the damage state must be carefully taken into account, in case of using normalization in fatigue data analysis or model developments.

Fibre bridging, acting as the shielding mechanism in delamination of composites, can play a dominant role in the block load sequence effect on fatigue crack growth. The fatigue delamination behavior of a HI-HI block loading differs from that of a LO-HI block loading. Crack growth is much faster in a LO-HI load sequence, as more fibre bridging can be generated in fatigue delamination of a high stress ratio.

Acknowledgements:

The authors gratefully acknowledge financial support from the International Postdoctoral Exchange Fellowship Program, Harbin Institute of Technology, P.R. China.

References:

[1] J.A. Pascoe, R.C. Alderliesten, R. Benedictus. Methods for the prediction of fatigue delamination growth in composites and adhesive bonds-A critical review. Engineering Fracture Mechanics 2013. 112-113:72-96

[2] S. Mall, G. Ramamurthy, M.A. Rezaizdeh. Stress ratio effect on cyclic debonding in adhesively bonded composite joints. Composite Structures. 1987 (8): 31-45

[3] M. Hojo, K. Tanaka, C. G. Gustafson, R. Hayashi. Effect of stress ratio on near-threshold propagation of delamination fatigue cracks in unidirectional CFRP. Composites Science and Technology. 1987(29): 273-292

[4] M. Shahverdi, A.P. Vassilopoulos, T. Keller. Experimental investigation of R-ratio effects on fatigue crack growth of adhesively-bonded pultruded GFRP DCB joints under CA loading. Composites Part A: Applied Science and Manufacturing. 2012(43): 1689-1697

[5] C. Rans, R. Alderliesten, R. Benedictus. Misinterpreting the results: how similitude can improve our understanding of fatigue delamination growth. Composites Science and Technology. 2011(71): 230-238

[6] R. Khan, R. Alderliesten, L. Yao, R. Benedictus. Crack closure and fibre bridging during delamination growth in carbon fibre/epoxy laminates under mode I fatigue loading. Composites Part A: Applied Science and Manufacturing 2014. 67: 201-211

[7] N. Blanco, E.K. Gamstedt, L.E. Asp, J. Costa. Mixed-mode delamination growth in carbon-fibre composite laminates under cyclic loading. International Journal of Solids and Structures. 2004(41): 4219-4235

[8] G. Charalambous, G. Allegri, S.R. Hallett. Temperature effect on mixed mode I/II delamination under quasi-static and fatigue loading of a carbon/epoxy composite. Composites Part A: Applied Science and Manufacturing. 2015(77): 75-86

[9] B. Landry, G. LaPlante, L. R. Leblanc. Environmental effects on mode II fatigue delamination growth in an aerospace grade carbon/epoxy composite. Composites Part A: Applied Science and Manufacturing. 2012(43): 475-485

[10] D.R. Atodaria, S.K. Putatunda, P.K. Mallick. A fatigue crack growth model for random fiber composites. Journal of Composite Materials. 1997(31): 1838-1855

[11] B.F. Sorensen, T.K. Jacobsen. Large-scale bridging in composites: R-curves and bridging laws. Composites Part A: Applied Science and Manufacturing 1998. 29:

1443-1451

[12] T.K. Jacobsen, B.F. Sorensen. Mode I intra-laminar crack growth in composites-modelling of R-curves from measured bridging laws. Composites Part A: Applied Science and Manufacturing 2001. 32: 1-11

[13] S.Stutz, J. Cugnoni, J. Botsis. Studies of mode I delamination in monotonic and fatigue loading using FBG wavelength multiplexing and numerical analysis. Composites Science and Technology 2011. 71: 443-449

[14] E.F. Ashitiani, J. Cugnoni, J.Botsis. Specimen thickness dependence of large scale fiber bridging in mode I interlaminar fracture of carbon epoxy composite. International Journal of Solids and Structures 2015. 55: 58-65

[15] C.G. Dávila, C.A. Rose, P.P. Camanho. A procedure for superposing linear cohesive laws to represent multiple damage mechanisms in the fracture of composites. International Journal of Fracture 2009. 158: 211-223

[16] W. Hwang, K.S. Han. Interlaminar fracture behavior and fibre bridging of glass-epoxy composite under mode I static and cyclic loadings. Journal of Composite Materials 1989. 23: 396-430

[17] M. Hojo, T. Ando, M. Tanaka, et al. Mode I and II interlaminar fracture toughness and fatigue delamination of CF/epoxy laminates with self-same epoxy interleaf. International Journal of Fatigue 2006. 28: 1154-1165

[18] L.Yao, R. Alderliesten, M. Zhao, R. Benedictus. Bridging effect on mode I fatigue delamination behavior in composite laminates. Composites Part A: Applied Science and Manufacturing 2014. 63: 103-109

[19] L.Yao, R. Alderliesten, M. Zhao, R. Benedictus. Discussion on the use of strain energy release rate for fatigue delamination characterization. Composites Part A: Applied Science and Manufacturing 2014. 66: 65-72

[20] L.Yao, R. Alderliesten, R. Benedictus. Interpreting the stress ratio effect on delamination growth in composite laminates using the concept of fatigue fracture toughness. Composites Part A: Applied Science and Manufacturing 2015. 78: 135-142

[21] L.Yao, R. Alderliesten, R. Benedictus. The effect of fibre bridging on the Paris relation for mode I fatigue delamination growth in composites. Composite Structures 2016. 140: 125-135

[22] L. Yao, Y. Sun, R.C. Alderliesten, R. Benedictus, M. Zhao. Fibre bridging effect on the Paris relation for mode I fatigue delamination growth in composites with consideration of interface configuration. Composite Structures 2017. 159: 471-478

[23] M.J. Donough, A.J. Gunnion, A.C. Orifici, C.H. Wang. Scaling parameter for fatigue delamination growth in composites under vary loading ratios. Composites Science and Technology 2015. 120: 39-48

[24] R. Jones. Fatigue crack growth and damage tolerance. Fatigue & Fracture of Engineering Materials & Structures 2014. 37:463-483

[25] G. Bao, Z. Suo. Remarks on crack-bridging concepts. Applied Mechanics Reviews 1992. 45: 355-366

[26] R. Jones, S. Pitt, A.J. Bunner, D. Hui. Application of the Hartman-Schijve equation to represent mode I and mode II fatigue delamination growth in composites. Composite Structures 2012. 94: 1343-1351

[27] R. Jones, S. Stelzer, A.J. Brunner, Mode I, II and mixed mode I/II delamination growth in composites. Composite Structures 2014. 110: 317-324

[28] A. Wang, M. Slomiana, R. Bucinell. Delamination growth in composite laminates. In: W Johnson, editor. Delamination and debonding of materials. ASTM STP 876. Philadelphia: American Society for Testing and Materials 1985. 135-167[29] M. Shahverdi, A.P. Vassilopoulos, T. Keller. A total fatigue life model for the prediction of R-ratio effects on fatigue crack growth of adhesively-bonded pultruded GFRP DCB joints. Composites Part A: Applied Science and Manufacturing 2012. 43: 1783-1790

List of figure captions

Fig.1 Paris curve distribution under stress ratio *R*=0.1

Fig.2 Paris curve distribution under stress ratio *R*=0.5

Fig.3 Quasi-static and fatige *R-curves*

Fig.4 The SEM observation on fracture surfaces

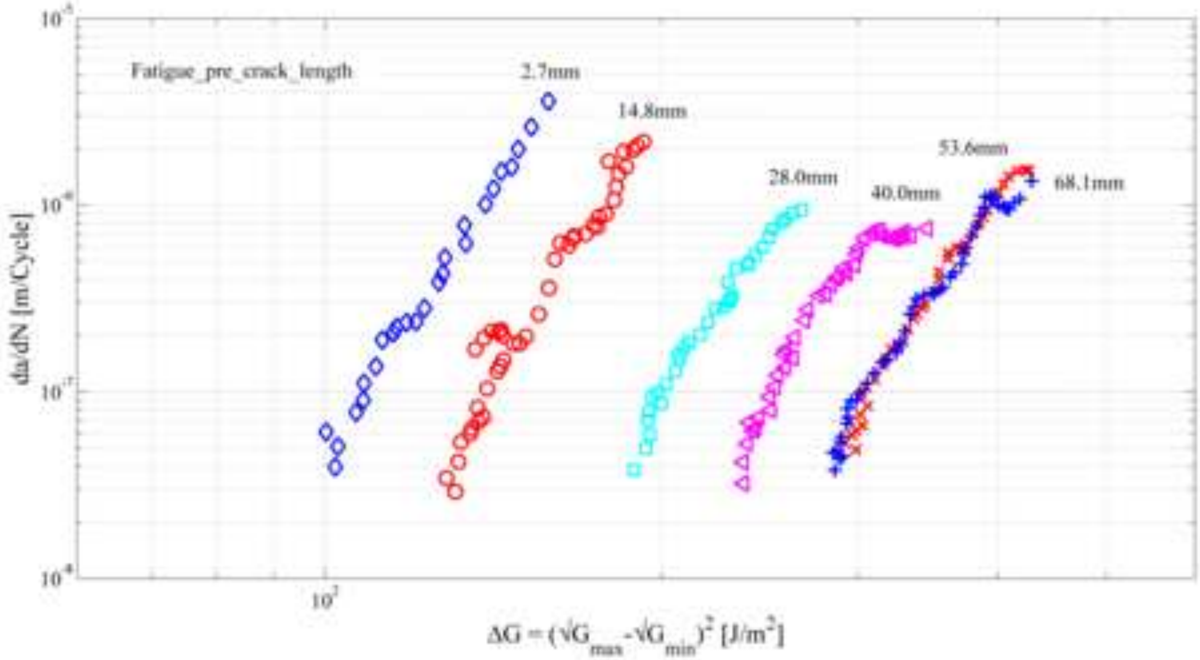
(a) *R*=0.1; (b) *R*=0.5

Fig.5 Threshold increase with delamination growth under different stress ratios

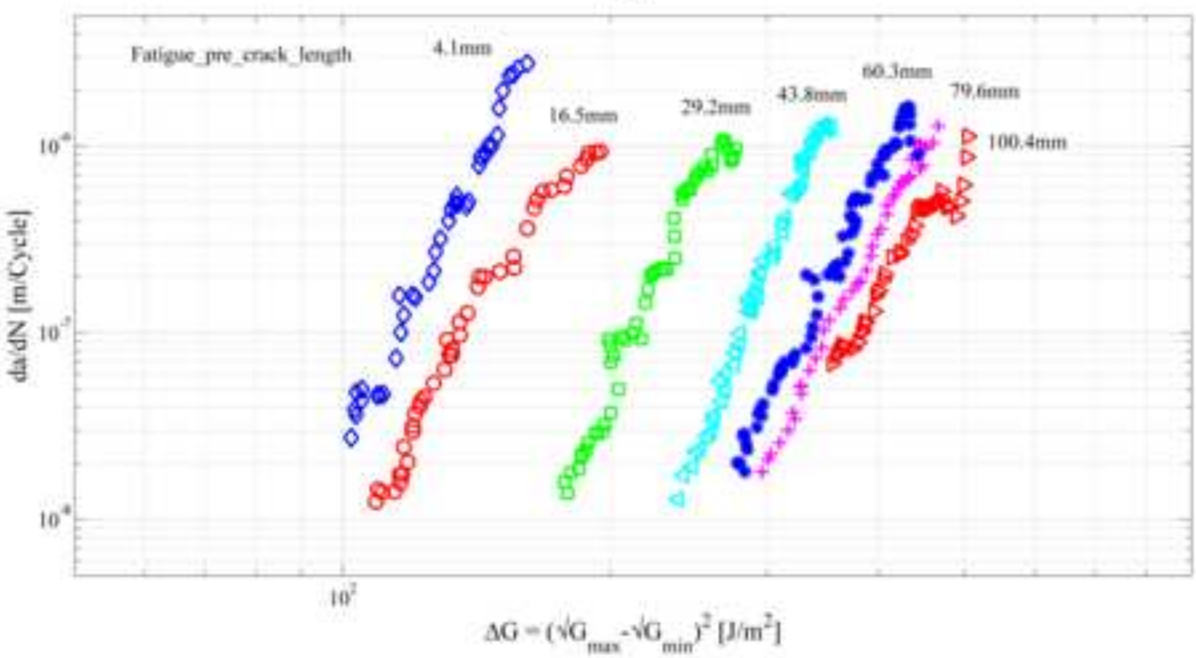
Fig.6 Fatigue delamination behavior in different bolck loadings

Fig.7 Energy dissipation in HI-HI and LO-HI block loadings

Figure(s)

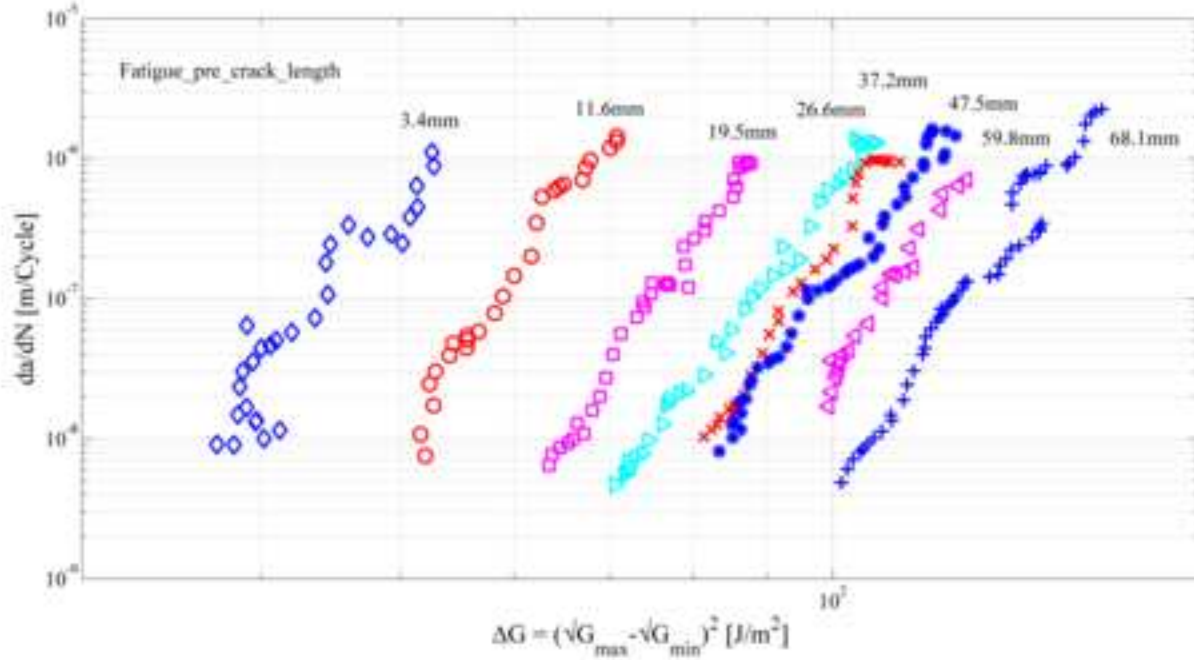


(a)

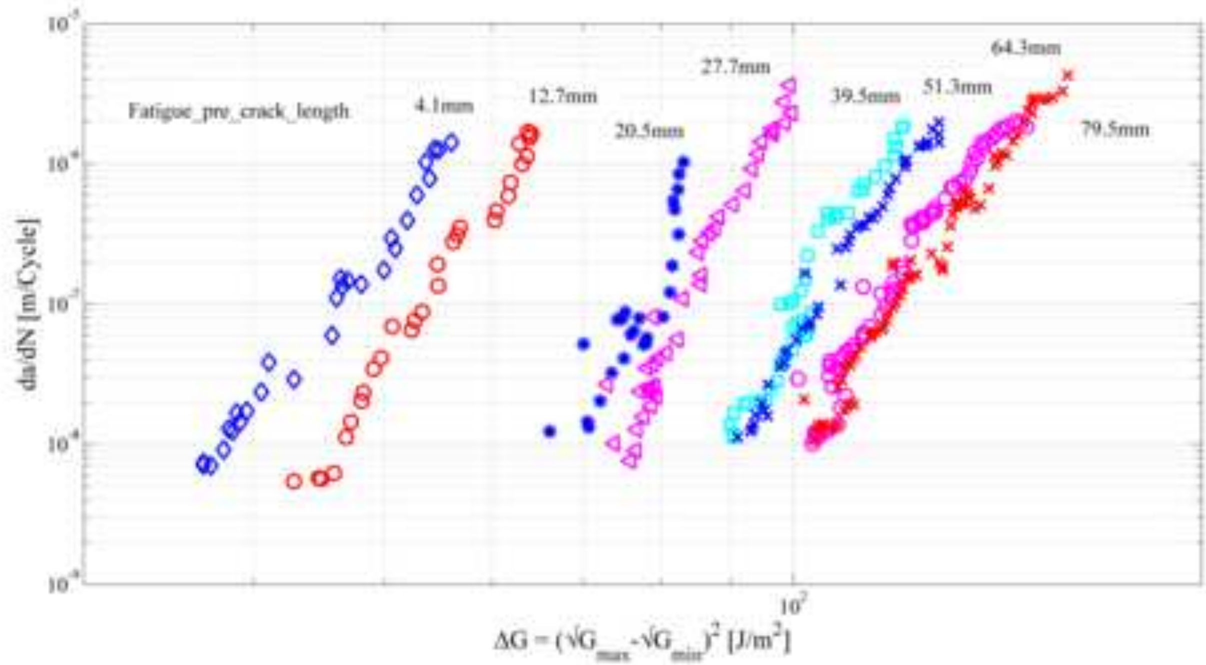


(b)

Figure 1


Fatigue_pre_crack_length
3.4mm
11.6mm
19.5mm
26.6mm
37.2mm
47.5mm
59.8mm
68.1mm
da/dN [m/Cycle]
ΔG = (√G_max -√G_min)^2 [J/m^2]

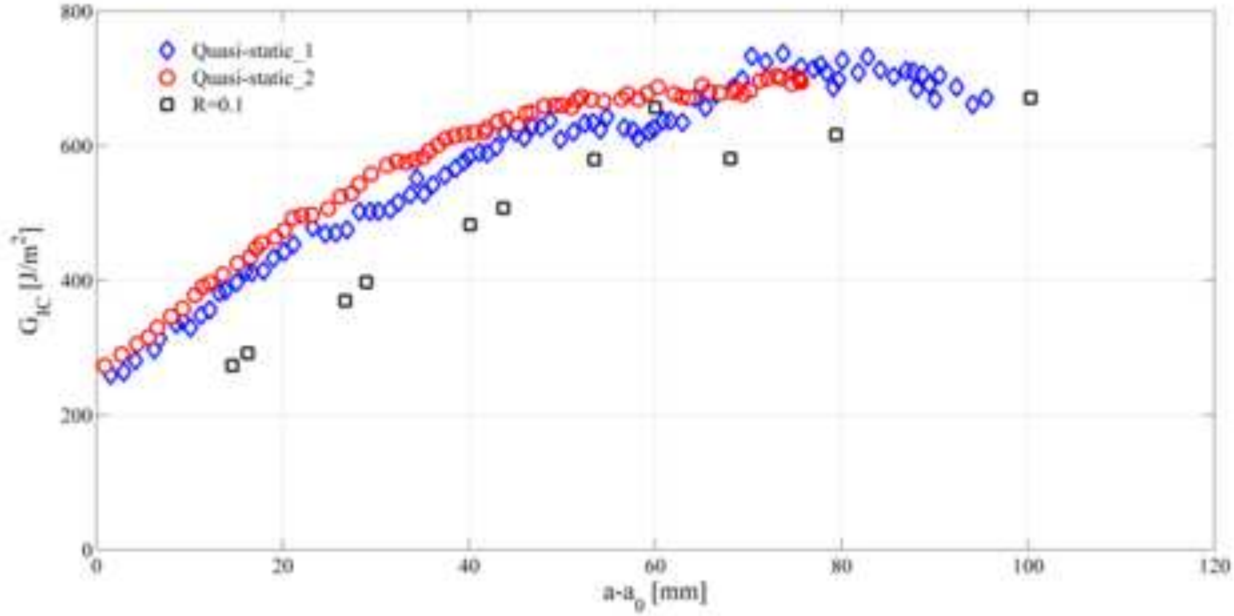
(a)


Fatigue_pre_crack_length
4.1mm
12.7mm
20.5mm
27.7mm
39.5mm
51.3mm
64.3mm
79.5mm
da/dN [m/Cycle]
ΔG = (√G_max -√G_min)^2 [J/m^2]

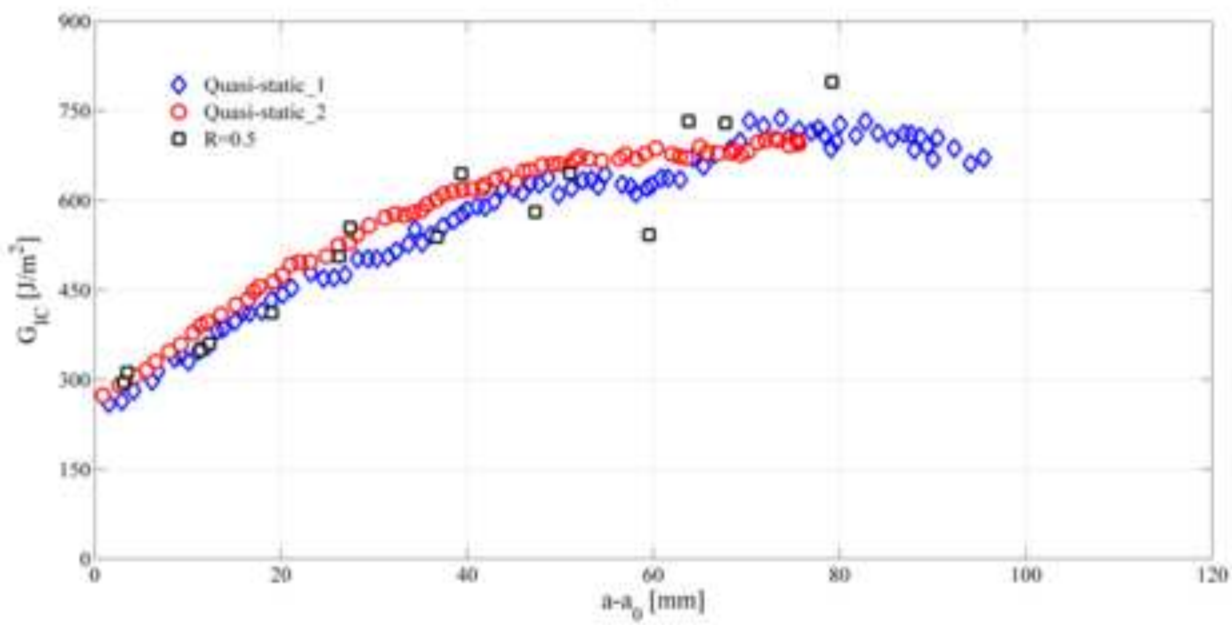
(b)

Figure 2

Figure(s)



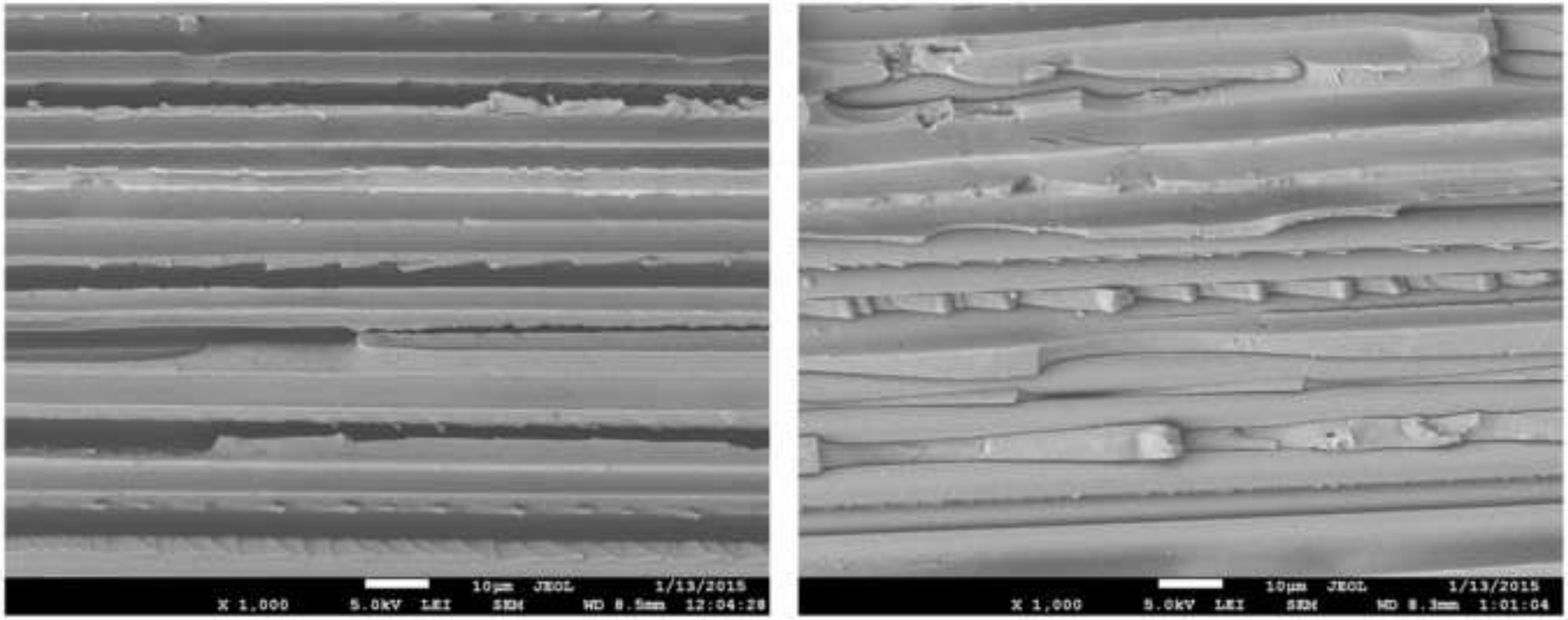
(a)



(b)

Figure 3

Figure(s)



(a) (b)

Figure 4

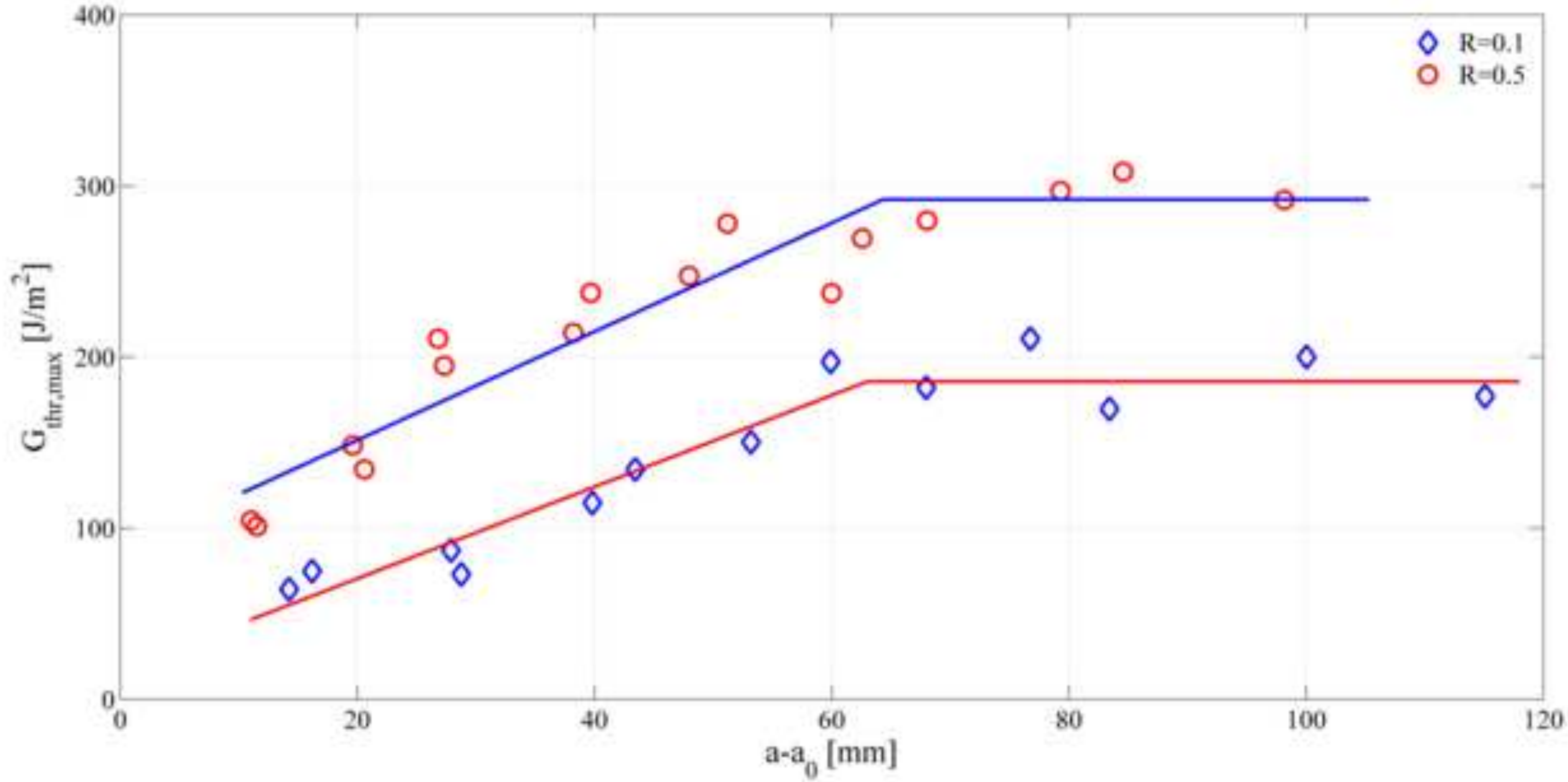
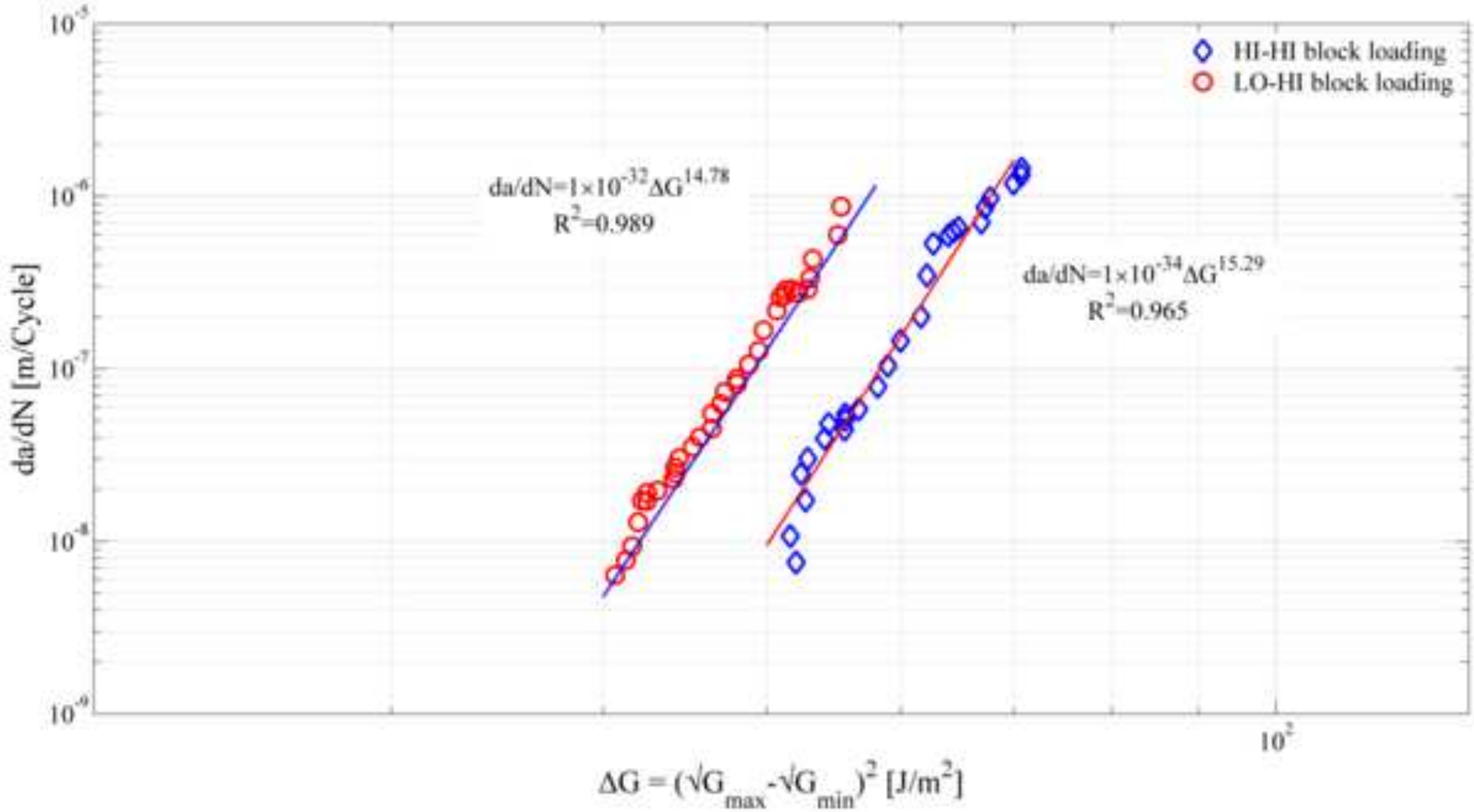


Figure 5



HI-HI block loading
LO-HI block loading
da/dN=1×10^-32ΔG^14.78
R^2=0.989
da/dN=1×10^-34ΔG^15.29
R^2=0.965
da/dN [m/Cycle]
ΔG = (√G_max-√G_min)^2 [J/m^2]
10^-5
10^-6
10^-7
10^-8
10^-9
10^2

Figure 6

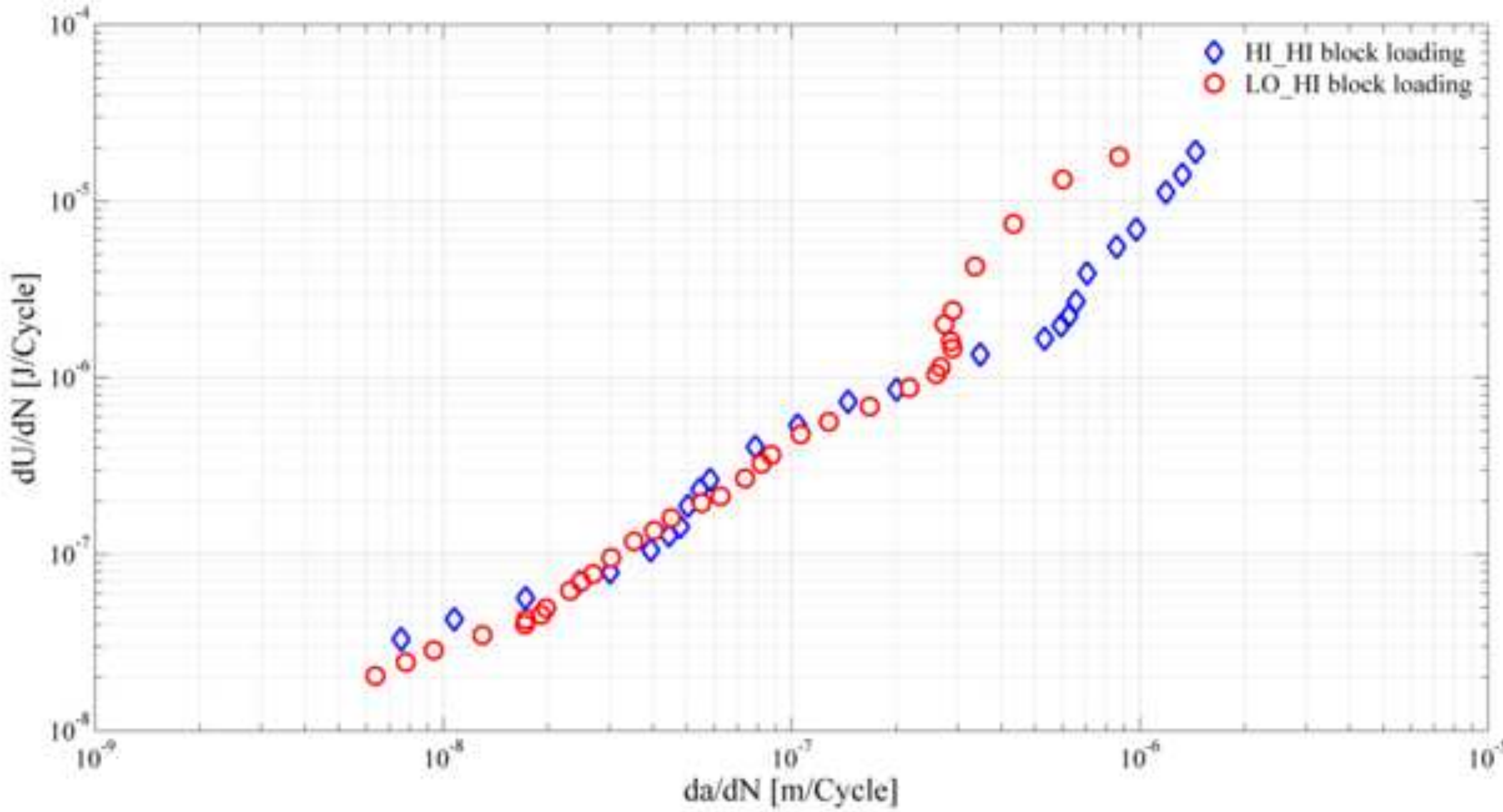

HI_HI block loading
LO_HI block loading
dU/dN [J/Cycle]
da/dN [m/Cycle]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}

Figure 7