

# Prediction of Onset of Mode I Delamination Growth Under a Tensile Spectrum Load

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## Abstract

In this investigation, the onset of mode I delamination growth under a standard aircraft spectrum load sequence, mini-FALSTAFF truncated to contain only tension-tension fatigue cycles is predicted. The study was carried out on a standard Double Cantilever Beam (DCB) test specimen of Uni Directional (UD) layup Carbon Fiber Composite (CFC) IMA/M21. Finite element modeling and analysis was carried out using ABAQUS standard to determine Strain Energy Release Rate (SERR) by Virtual Crack Closure Technique (VCCT). Both two dimensional (2D) and three dimensional (3D) models were studied. Using the FE analysis results, an empirical equation was derived for SERR (G) and load (P) relationship. Further, the load cycles in the spectrum sequence were rain flow counted to separate individual cycles. For each of the counted cycle, the SERR was obtained and corresponding  $N_{\text{onset}}$  for that cycle was estimated from the Constant Onset Life Diagram (COLD) of the material. Linear damage accumulation law was used to predict the number of spectrum load blocks required for onset of mode I delamination growth. The prediction was carried out for various reference loads ( $P_{\text{ref}}$ ), and the corresponding reference SERR ( $G_{\text{ref}}$ ) of the spectrum sequence. Predicted results show that decreasing the reference stress increases the mode I delamination onset life under spectrum loads.

**Keywords:** DCB, Spectrum loads, FALSTAFF, SERR, VCCT, delamination, onset, FE modeling

## 1. Introduction

Carbon fiber reinforced polymer matrix composites are widely used in airframe structures. Mainly due to their high specific strength and stiffness, they are fast replacing metallic materials in primary and secondary structures. The structural composites are subjected to various types of static and variable amplitude fatigue loads in service. For a durable and safe structure, in addition to having high static strength and stiffness, the composites should possess high fatigue resistance and fracture toughness.

The fatigue properties of polymer composites have been studied by various investigators and the micro-mechanisms based observations on progressive failure mechanism in CFC has been well established (Talreja, 2000). The major fatigue damage mechanisms in composites are (i) matrix cracking (ii) debond or disbond (iii) delamination, and (iv) fiber breaks (Jones, 1998). These damage mechanisms have been observed in composites to occur either independently or as a consequence of evolution and growth of other type of damage during fatigue loads.

Damage tolerance evaluation of composites requires the knowledge of the behavior of micro-structural damages under external loads on the structures in service. Delamination, being one of the major types of damage in polymer composites, may initiate either during the fabrication or due to low/high velocity impact in service. It has been observed that delamination subjected to fatigue loads requires significant number of load cycles for onset of delamination growth (Brunner et al., 2008). This depends on various factors including the applied stress level and mode of loading. Regardless of the method by which delamination is created, it has two phases i.e., onset and growth. Hence, the knowledge of the onset and growth behavior of such damage under service loads would assist in safe design of composite structures. Knowledge of delamination onset provides significant inputs on the damage tolerant behaviour of composites.

Several studies on the delamination onset and growth have been carried out both by using finite element analysis and laboratory experiments. Mailliet et al. (2013) studied delamination onset and observed that increasing the frequency from 10 Hz to 100 Hz decreased the onset life at  $R = 0.1$  by over an order of magnitude. Argüelles et al. (2008) studied effect of  $R$  and observed that increasing the  $R$  from 0.2 to 0.5 increases onset life and also increases onset threshold. The effect of pre-crack shape such as sharp or blunt notch is investigated in mode I and mode II conditions (Stevanovic et al., 2000). The variation of specimen thickness from 3.9 to 19 mm in a GFRP specimen has been shown to have no significant effect on the onset behavior (Behzad et al., 2013). Effects of various parameters such as frequency, load ratio, notch shape etc. and various methods of modeling have been used to investigate the fatigue behavior of delamination (Abrate, 1998). The VCCT is generally used for the evaluation SERR in finite element analyses. Various numerical analyses have been performed by using this technique, many of them dealing with delamination growth initiations (Mukherjee et al., 1994) and others with growth evolution (Shen et al., 2001).

It may be noted that most of these studies have been limited to constant amplitude fatigue. Considering that the service loads are mostly spectrum in nature, it is necessary to understand the delamination behavior under spectrum load sequence and such efforts have been found to be limited in the past. Thus, the main aim of this study was finite element modeling and analysis of a standard DCB specimen and predict the onset of mode I delamination growth in a carbon fiber composite under a truncated standard spectrum load sequence.

## 2. Finite Element Analysis

A standard DCB specimen of a twenty layered unidirectional IMA/M21 CFC specimen was considered for the study. Both 2D and 3D models were created for the study to determine the SERR. A schematic diagram of the DCB specimen and the mechanical properties of the composite used are shown in Figure 1 and Table 1, respectively.

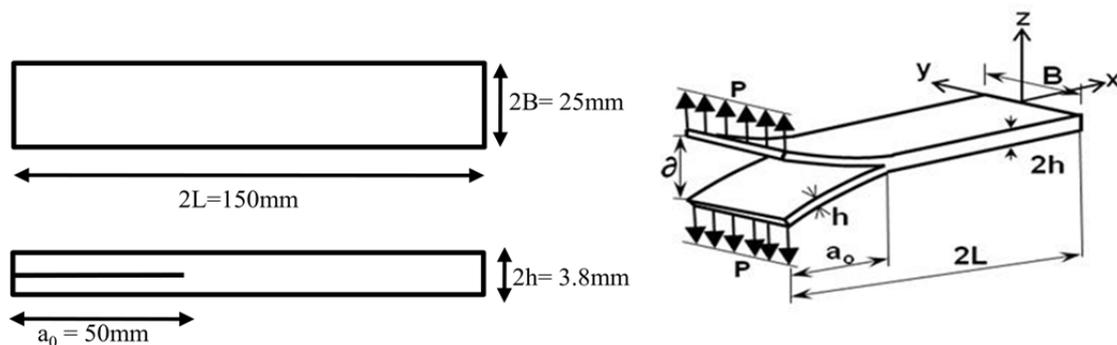


Figure 1. Schematic diagram showing the dimensions of the double cantilever beam (DCB) specimen

Table 1. Mechanical properties of the CFC investigated

Modulus(GPa)	$E_{11} = 128$ $E_{22} = 10$ $E_{33} = 10$
Strength(MPa)	$\sigma_{UTS} = 920$ $\sigma_{UCS} = 640$
Toughness ( $J/m^2$ )	$G_{IC} = 212$ $G_{IIC} = 480$ $G_{IIIC} = 480$
Poisson's ratio	$\nu_{12} = 0.31$ $\nu_{23} = 0.52$ $\nu_{13} = 0.31$

Shear (GPa)	$G_{12} = 4.80$
	$G_{23} = 4.80$
	$G_{13} = 3.20$

### 2.1 Two-Dimensional Model

A typical 2D finite element model of DCB specimen is shown in Figure 2. The specimen was modeled with solid plain strain elements (CPE4I) in ABAQUS standard 6.11 (Abaqus Analysis Users Manual, 2011). The DCB specimen was modeled with six elements through the specimen thickness ( $2h$ ). Along the length of the specimen ( $2L$ ), from the delamination front, mesh was refined at the center with an elemental length of 0.50 mm otherwise the element size was kept approximately 2mm. Across the width ( $B$ ), uniform mesh was used to avoid potential problems at the transition between a coarse and fine mesh (Krueger, 2007) (Krueger, 2008). The plane of the delamination, was modeled as a discrete discontinuity in the center of the specimen i.e., between the tenth and eleventh layer (Abaqus Analysis Users Manual, 2011). For the analysis with ABAQUS standard, the models were created as separate meshes for the upper and lower part of the specimen with identical nodal point coordinates in the plane of delamination. Two surfaces (top and bottom surface) were defined to identify the contact area in the plane of delamination as shown in Figure 2. Additionally, a node set was created to define the contact (bonded nodes) region. The VCCT approach was used to calculate SERR.

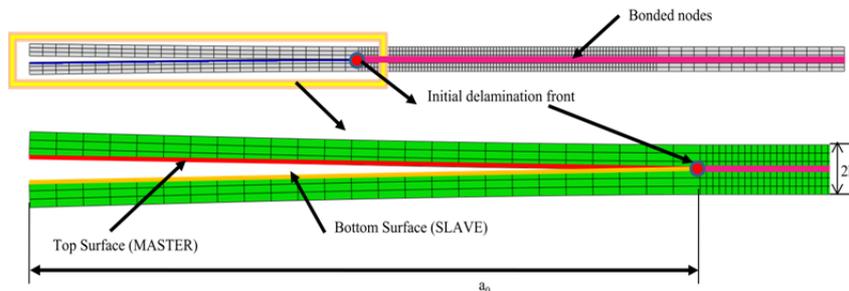


Figure 2. Two dimensional finite element model of a DCB specimen

### 2.2 Three-Dimensional Model

A typical 3D finite element model of DCB specimen is shown in Figure 3. The specimen was modeled with solid brick elements (C3D8I), in ABAQUS standard 6.11 (Abaqus Analysis Users Manual, 2011). Through the specimen thickness ( $2h$ ), four elements were used. Along the length of the specimen the mesh was refined after the delamination front with elemental length of 0.50 mm and at other places the elemental length of 2mm was maintained. The plane of the delamination, was modeled in the similar way as explained in the two dimensional modeling in the previous paragraph.

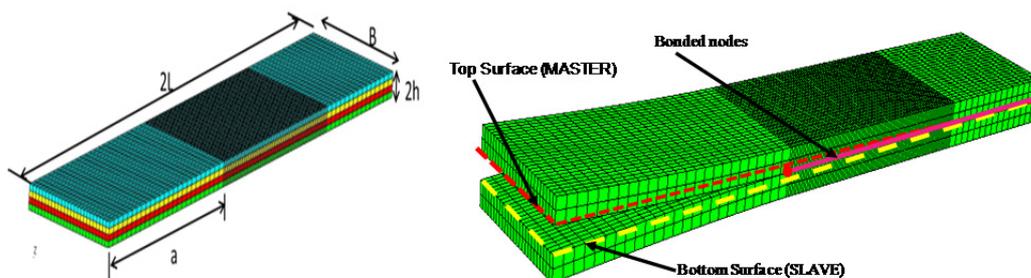
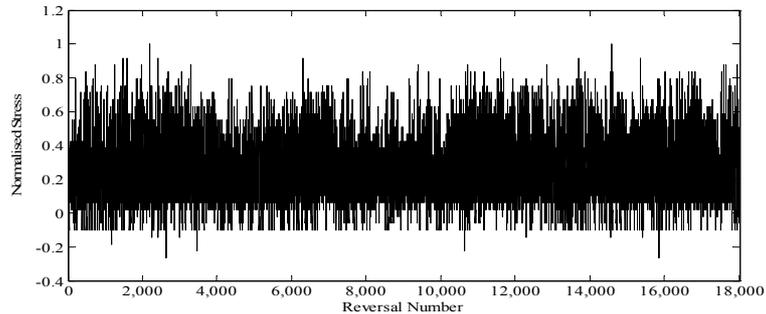


Figure 3. Three dimensional finite element model of a DCB specimen

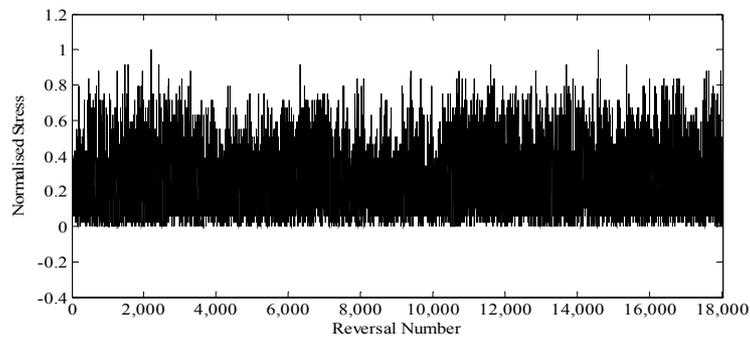
## 3. Spectrum Load Sequence

A standard spectrum load sequence, known as Fighter Aircraft Loading STandard For Fatigue evaluation;

mini-FALSTAFF (Van Dijk et al., 1975) was used in the present study. A short version of standard FALSTAFF load spectrum, which was a standardized variable-amplitude test load sequence developed for the fatigue analysis of materials used for fighter aircrafts is shown in Figure 4a. Y-axis is a normalized value of load or stress and is plotted against peak/trough points of load sequence. One block of this load sequence consists of 18,012 reversals at 32 different stress levels and represents loading equivalent of 200 flights. For the purpose of present investigation, the load sequence was truncated below zero so that it has only positive loads. All the negative values were set to zero and the resulting truncated mini-FALSTAFF load sequence is shown in Figure 4b. The onset of delamination was predicted under this load sequence. The actual load sequence was obtained by multiplying with a constant reference load value,  $P_{ref}$  for all the peak/trough points in the entire block.



(a) Original mini-FALSTAFF load sequence (Van Dijk et al., 1975)



(b) Truncated mini-FALSTAFF load sequence

Figure 4. Standard spectrum load sequence used in this investigation

#### 4. Onset Life Prediction

The delamination onset under truncated mini-FALSTAFF load sequence has been predicted using the following procedure schematically shown in Figure 5.

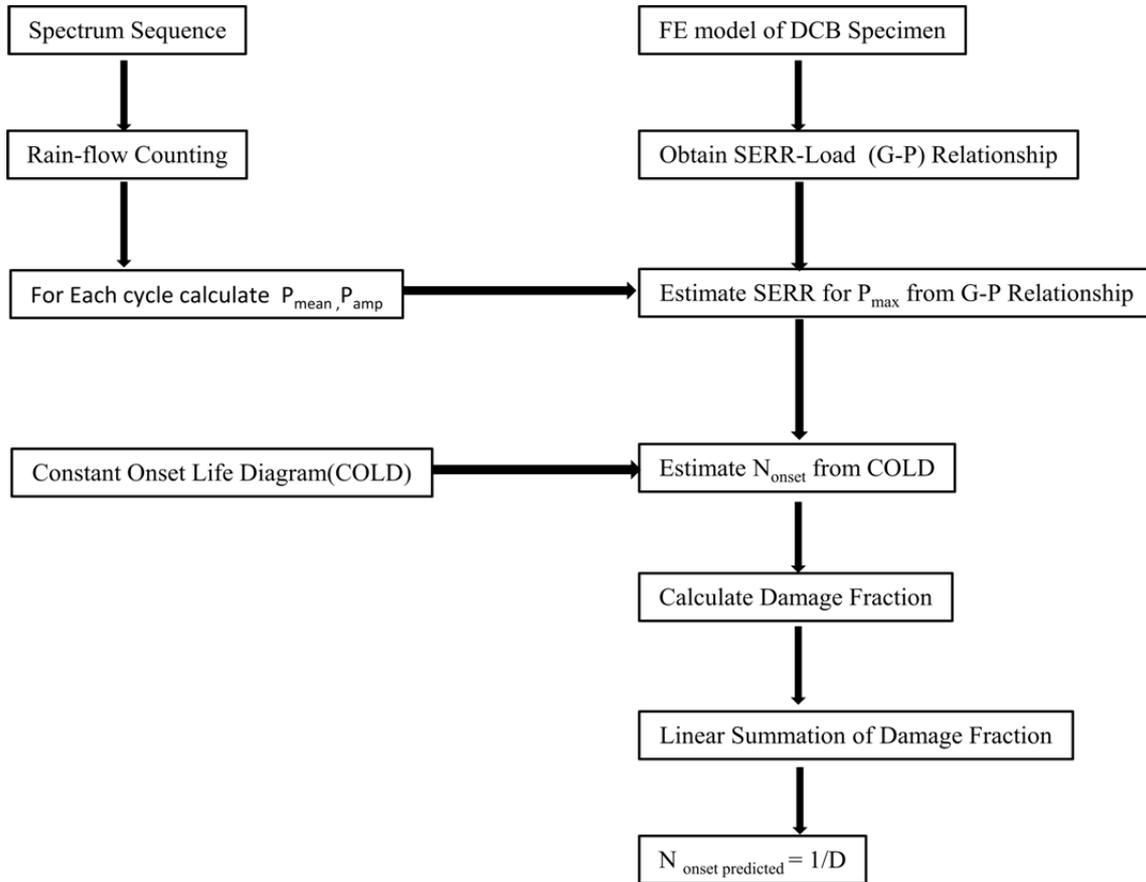


Figure 5. Flow chart showing the methodology used for onset life prediction

## 5. Results and Discussion

In order to derive the SERR-Load ( $G_{\max}$ - $P$ ) relation for the material, the SERR was computed from FE analysis of DCB specimen for various loads. The maximum load value used was about 95% of the load corresponding to  $G_{IC}$  of the material. The variation of  $G_{\max}$  as a function of  $P$  is shown in Figure 6. 3D model results were closer than 2D results, when compared to analytical calculations. Hence, the data from 3D model was least square fit to obtain the  $G_{\max}$ - $P$  relation as

$$G = 0.074 P^2 + 0.022 P - 0.088 \quad (1)$$

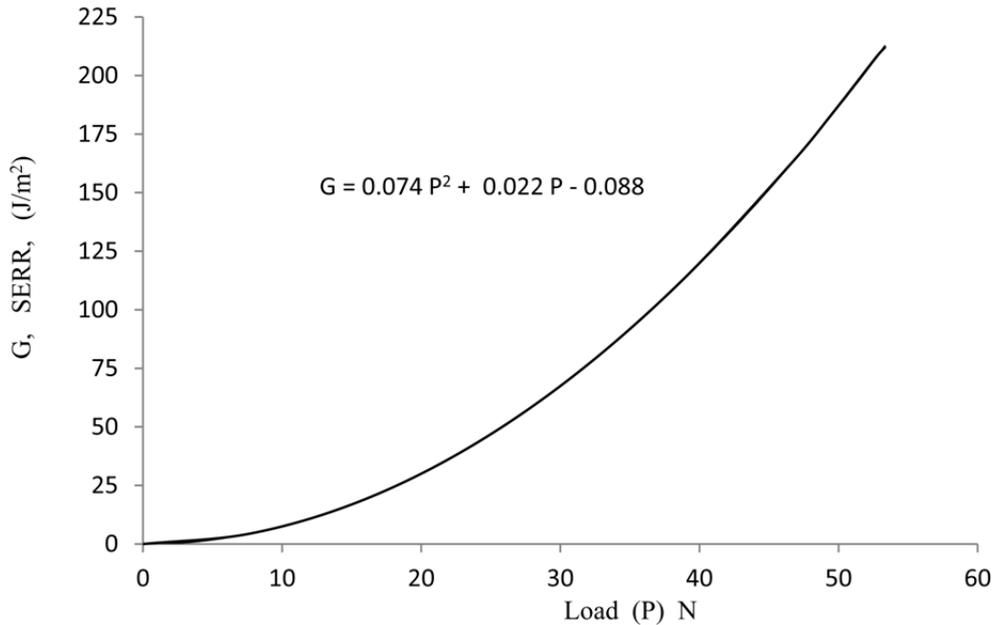


Figure 6. The G - P relationship derived for IMA/M21 Carbon Fiber Composite- DCB specimen

The onset of mode I delamination under truncated mini-FALSTAFF load sequence was predicted at various reference stresses following the procedure explained earlier. The COLD for the IMA/M21 composite material (Jagannathan et al., 2013) is shown in Figure 7. COLD is a two dimensional plot of  $G_{amp}$  vs  $G_{mean}$ . The radial lines emanating from origin represents the specific stress ratio (R). For any given rain flow counted cycle the onset life can be obtained from this figure. The rain flow-counted load cycles will be of various load amplitudes and mean stresses, it is necessary to interpolate and determine  $N_{onset}$  for all these load cycles using the COLD. Various interpolation techniques have been developed for determination of  $N_f$  from the Constant Life Diagram (CLD) for any given load cycle (Post et al., 2008; Vasilopoulos et al., 2010). However, Vasilopolous et al. (2010) have shown that the simple piecewise linear formulation compares favourably to other more sophisticated and complicated schemes. They also observed that, for most of the cases studied, the S-N predictions based on the piecewise linear CLD are the most accurate ones. Hence, the piecewise linear technique was employed for interpolation during this investigation. Several different damage accumulation models have been proposed for fatigue life estimation in composites (Post et al., 2008). In the present investigation, the simple Palmgren-Miner (PM) (Vasilopolous et al., 2010) linear damage accumulation mode was used

$$D = \sum (n_i / N_{i \text{ onset}}) \quad (2)$$

Where D is the damage fraction,  $n_i$  is the cycle count and  $N_{i \text{ onset}}$  is the cycles to failure for a given load cycle amplitude. From the COLD diagram, the number of spectrum load blocks required for onset was predicted following the procedure shown in Figure 5 and is plotted in Figure 8. As expected, decreasing the reference stress, increase the required number of load blocks for the delamination onset.

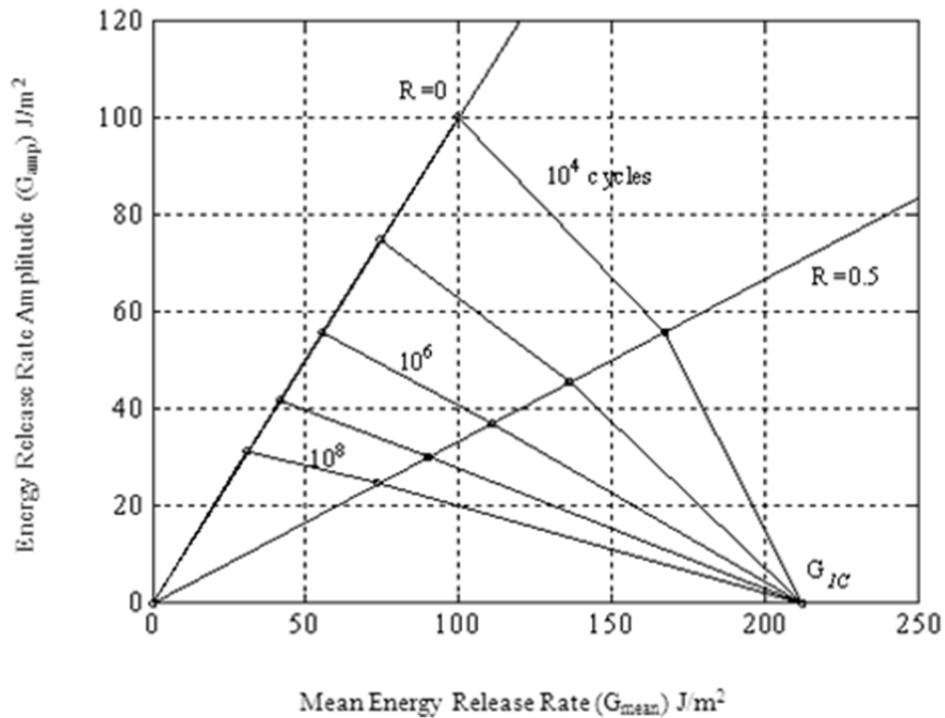


Figure 7. Constant onset life diagram (COLD) of IMA/M21 composite (Jagannath et al., 2013)

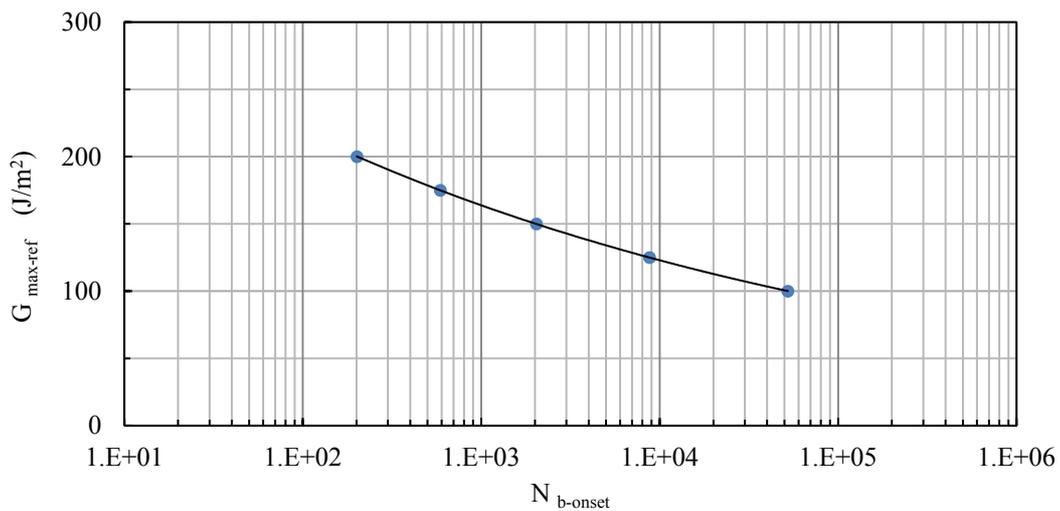


Figure 8. Predicted onset life for Mode I delamination under spectrum load sequence

**6. Conclusions**

An attempt is made to predict the onset of mode I delamination growth in a DCB specimen of a carbon fiber composite under a tensile spectrum load sequence. The procedure involved estimation of driving force, SERR from FE analysis for each of the rain flow counted fatigue cycles and then estimating the fatigue damage per cycle to determine the onset life. The prediction is made for a truncated mini-FALSTAFF load sequence and it is observed that decreasing the reference load, increase the onset life.

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