基于DIC技术的复合材料疲劳分层的实验表征

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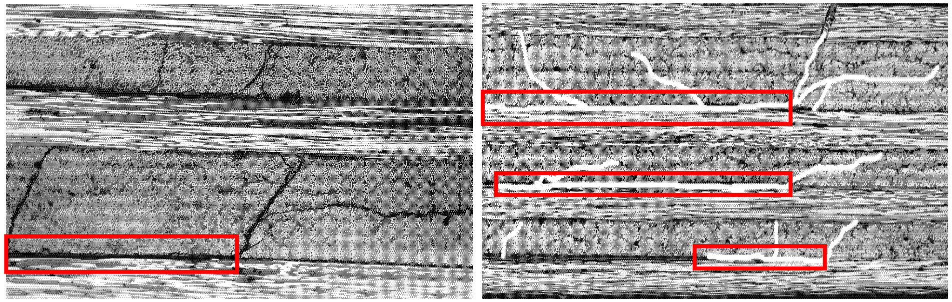
主要内容

- 研究背景
- 材料与实验
- 基于DIC的裂纹尖端识别算法
- 层间界面疲劳起始寿命确定
- 结果与讨论
- 结论

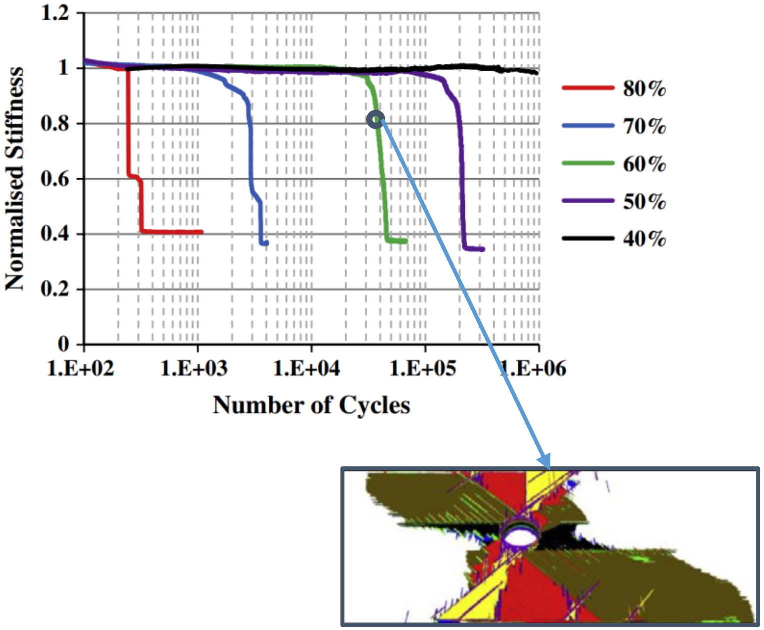
复合材料的疲劳分层现象

层间界面损伤



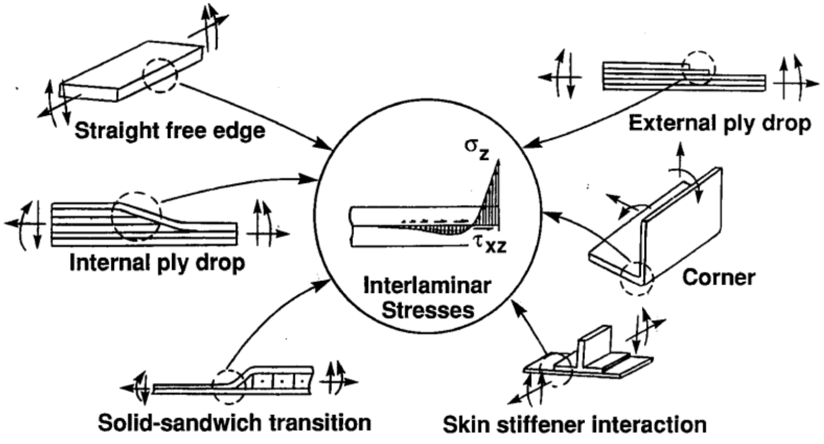
Tarpani J.R. et al.. Materials Research, 2006, 9(2): 121-130.

引起材料承载能力急剧下降



O.J. Nixon-Pearson, S.R. Hallett Composites: Part A 69 (2015) 266–278

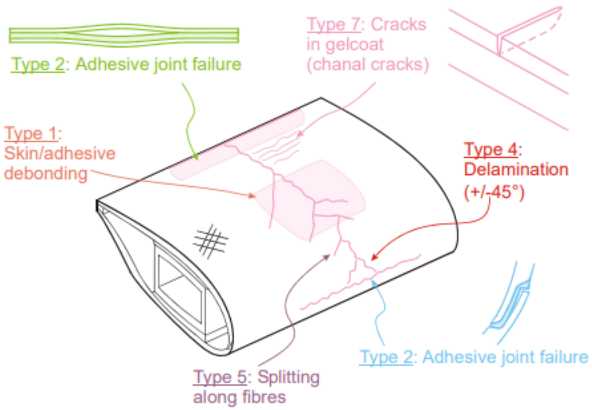
通常源于几何结构或材料性能不连续

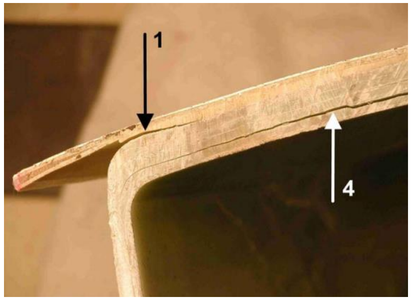


O'Brien T K. ICF10, Honolulu (USA) 2001.

工程中的复合材料疲劳分层现象

风电叶片





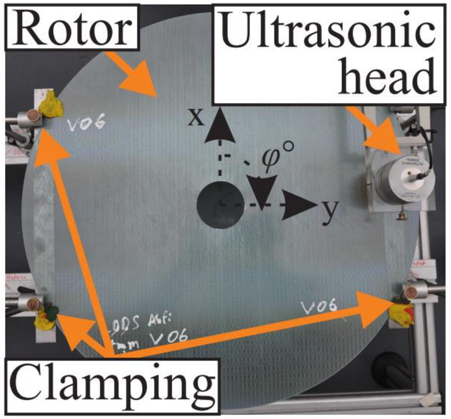
"interlaminar failure mode (delamination) is expected to be the most important failure mechanism"

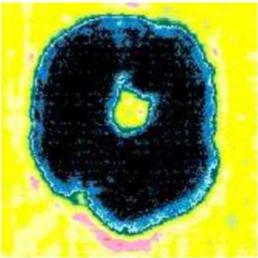
Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) - Summary Report, 2004

直升飞机桨叶

POLISH MARITIME RESEARCH, No 2/2017

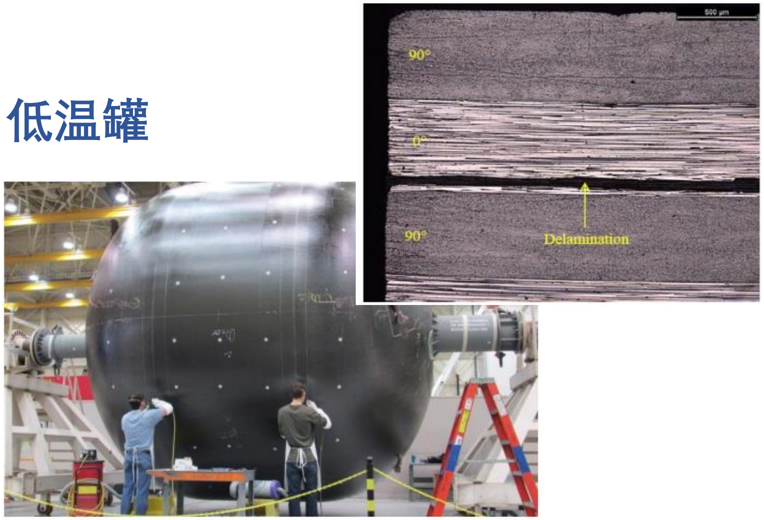
复合材料转子





Materials 2018, 11, 2421

低温罐



Damage and permeability in linerless composite cryogenic tanks, 2015

复合材料疲劳分层实验标准

公开发表的实验标准 -- Mode I 疲劳分层起始实验:

ASTM D6115 – Mode I Fatigue Delamination Growth Onset of Unidirectional Fiber-Reinforced Polymer Matrix Composites:

□ 人为观察

– 操作依赖性

□ 1% 或 5% 试样结构柔度增加

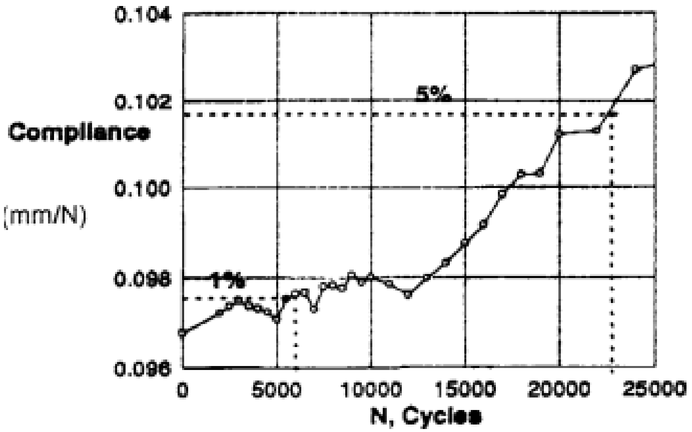
– 结构依赖性

尚无关于疲劳分层扩展的实验标准:

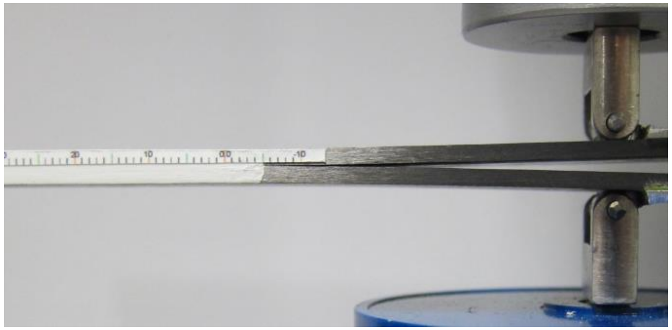
□ 根据疲劳分层起始实验经验，测试得到疲劳分层扩展Paris’ law

□ 通过实验中的照片或录像人为确定裂纹扩展

– 精度有待确定、费时费力



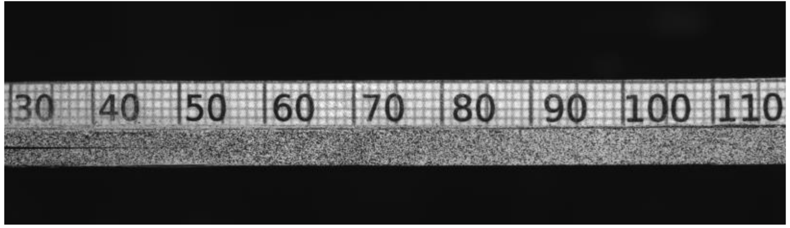
ASTM D6115



G.B. Murri, NASA report, 2013

材料与实验

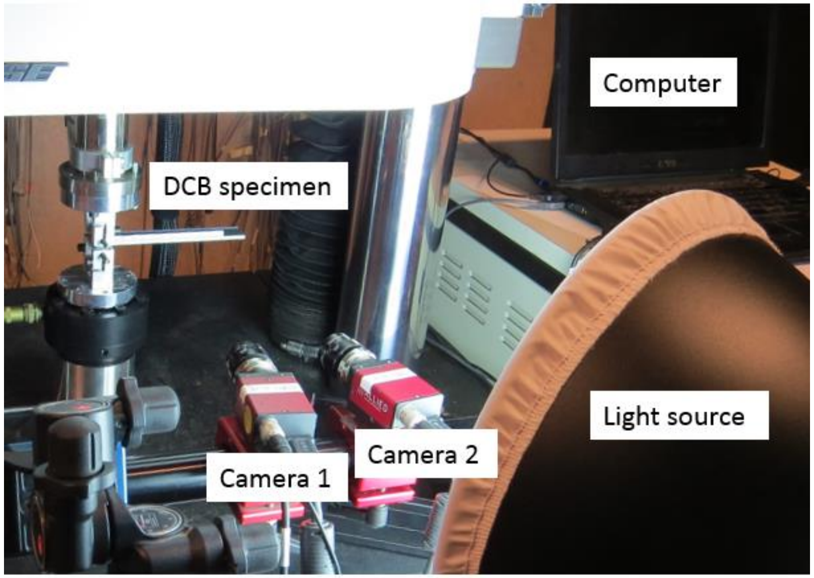
- **材料&试件**
  - 碳纤维/环氧树脂: $[0_9/\mathrm{insert}/0_9]$
  - 试件表面喷漆处理



试件表面随机散点

- **测试方法**
  - Mode I: 双悬臂梁实验 (DCB)
  - Mode II: 端部加载劈裂实验 (ELS)
  - 位移控制循环载荷

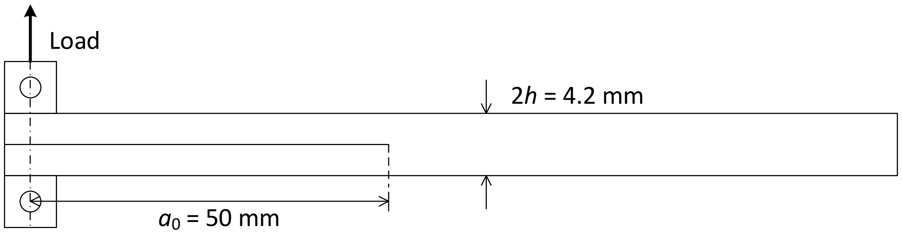
- **DIC观测相关设备**
  - 两台照相机与疲劳实验机同步，确保在最大位移处拍摄照片
  - 商业DIC软件Vic-3D处理相关实验数据



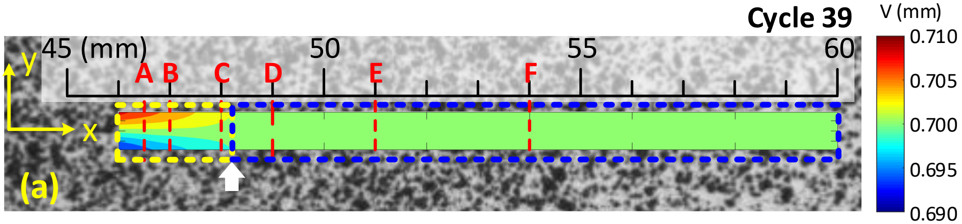
实验装置

Mode I层间裂纹尖端识别

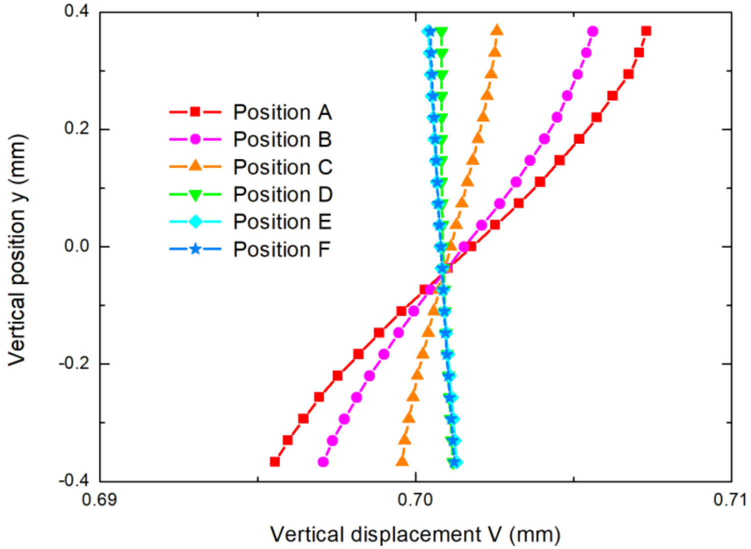
DCB实验



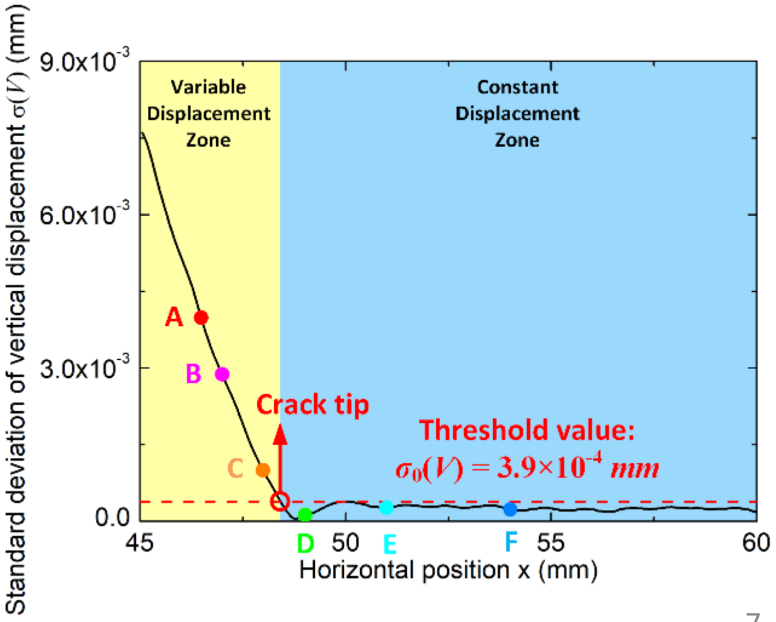
DIC结果：竖直方向位移场V



不同位置的竖直方向位移场分布

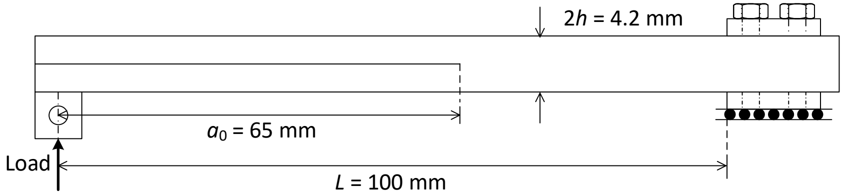


通过竖直方向位移场标准差确定裂尖位置

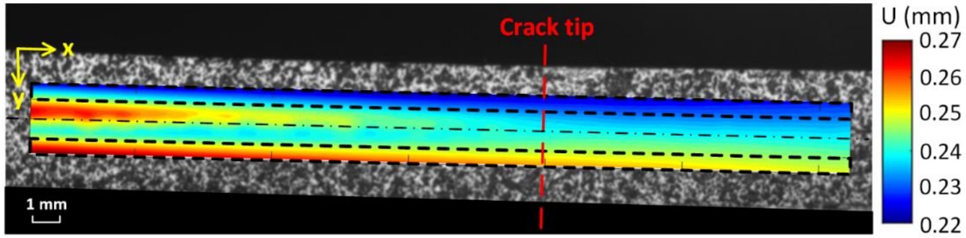


Mode II层间裂纹尖端识别

ELS实验

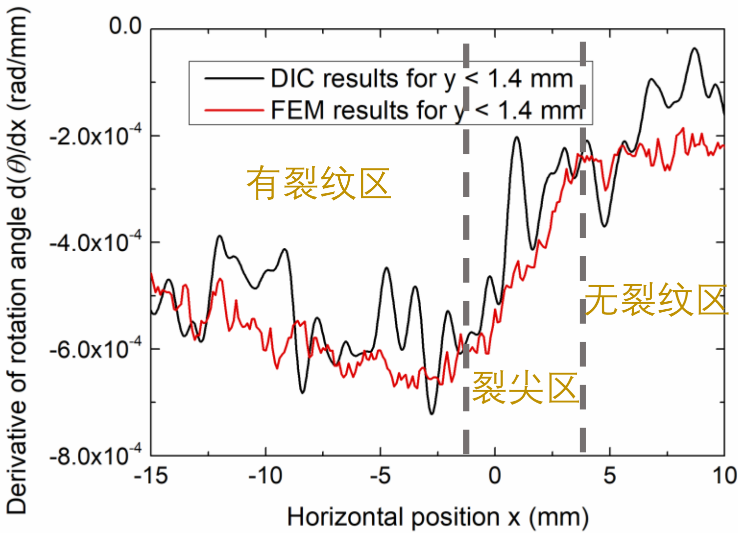


DIC结果：水平方向位移场U

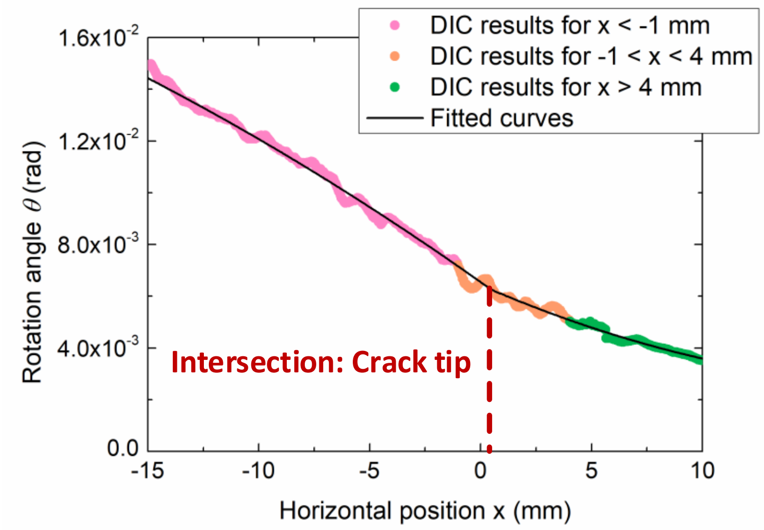


利用位移场*U*计算横截面转角 $\theta=\arcsin\left(\frac{\mathrm{d}U}{\mathrm{d}y}\right)$

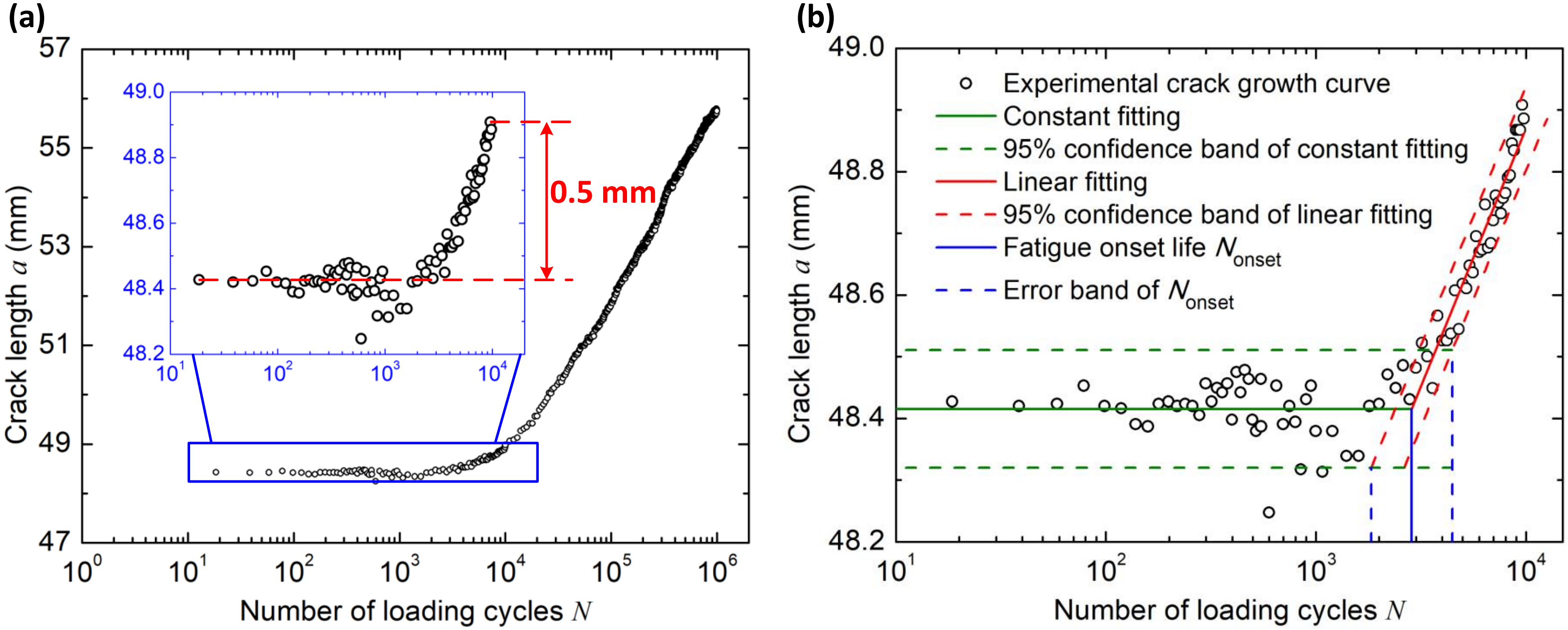
及其一阶导数 $\frac{\mathrm{d}\theta}{\mathrm{d}x}$



通过拟合转角随位置变化函数确定裂尖位置



疲劳起始寿命确定

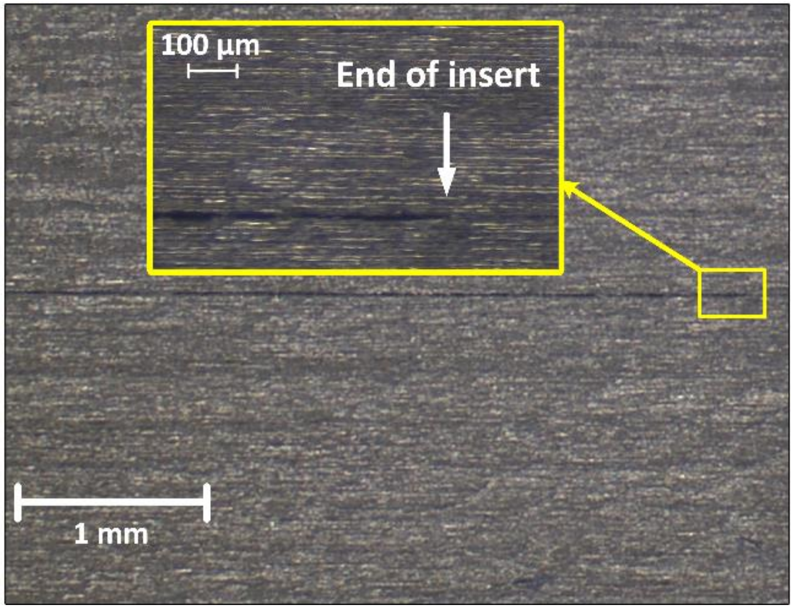


$$x = f(N) = \begin{cases} \boxed{a_0}, & 1 < N \le \boxed{N_{\text{onset}}} \\ \boxed{\alpha}\left(N - N_{\text{onset}}\right) + a_0, & N > N_{onset} \end{cases}$$

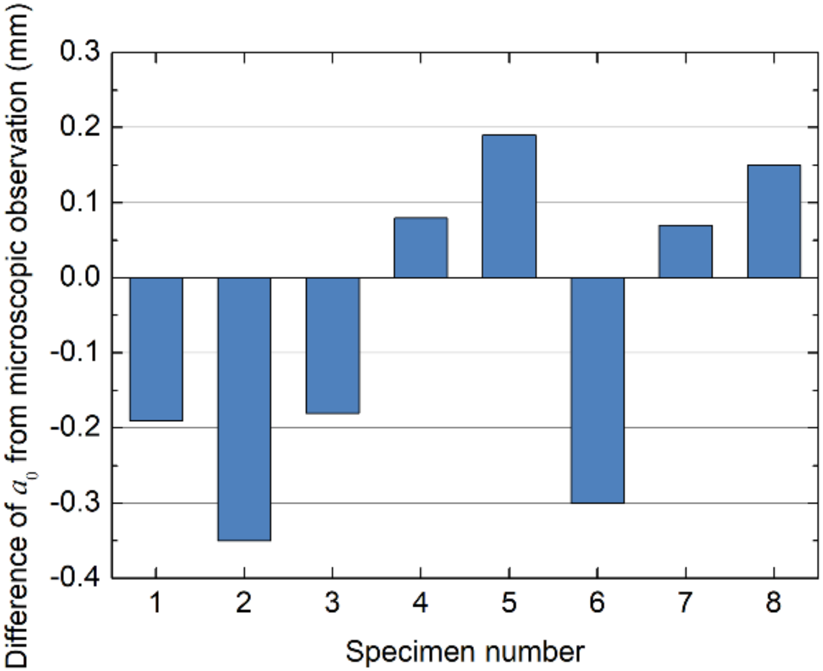
$$S = \sum \left[f(N_i) - x_i \right]^2 \rightarrow \min$$

裂纹尖端识别精度分析

光学显微镜观测初始裂纹长度

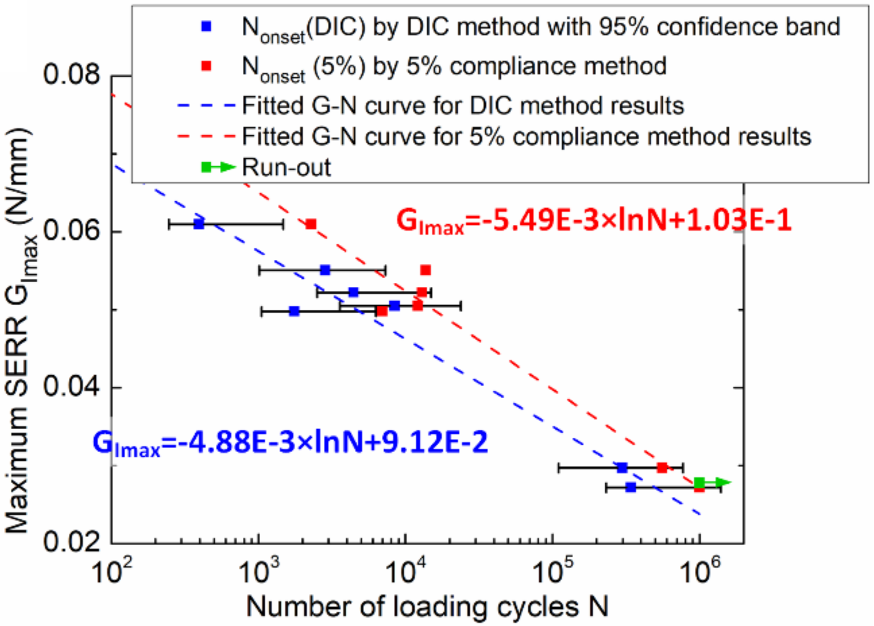


初始裂纹长度误差<0.35 mm

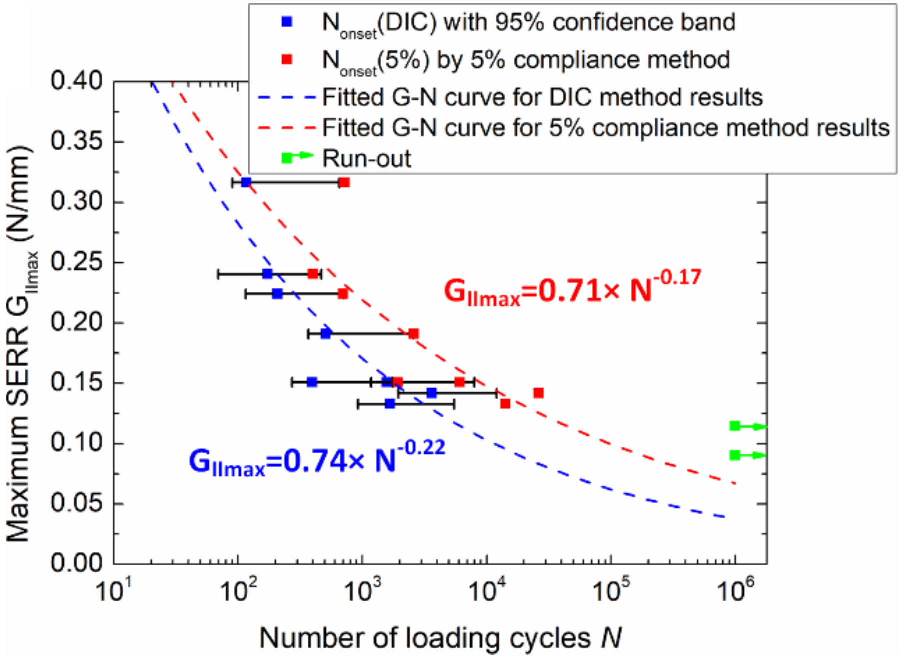


疲劳分层起始：G-N曲线

Mode I



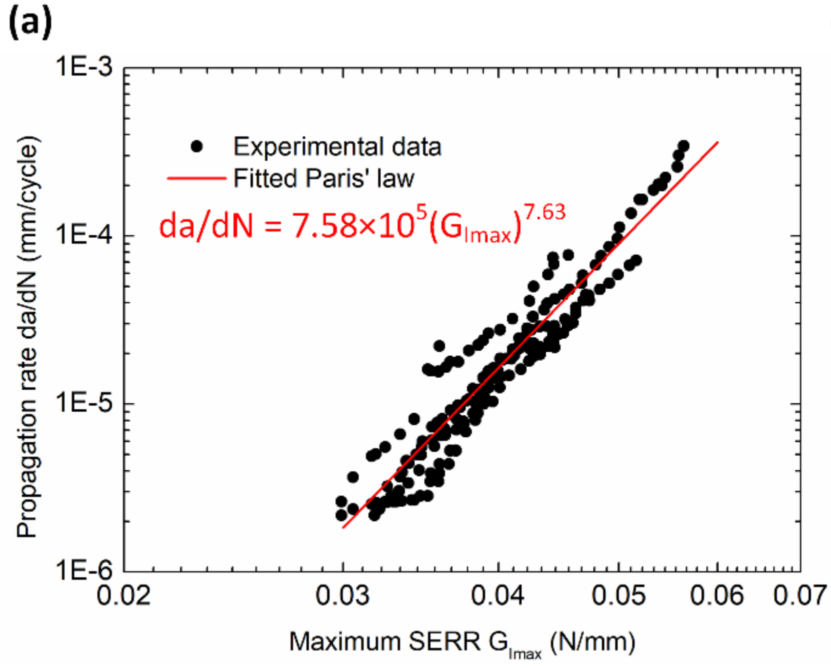
Mode II



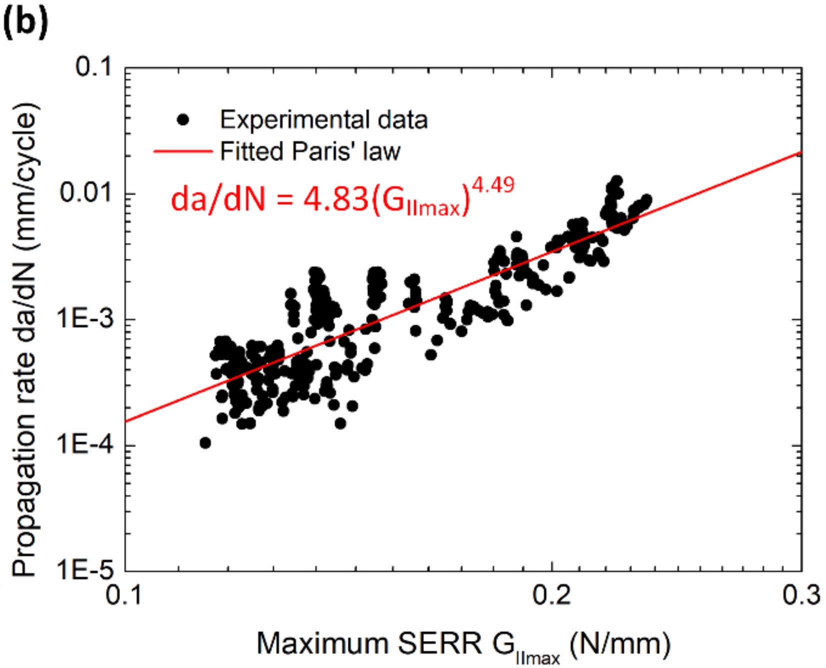
对比柔度方法，基于DIC的实验表征方法获得的疲劳分层起始寿命更加保守。

疲劳分层扩展：Paris’ law

Mode I



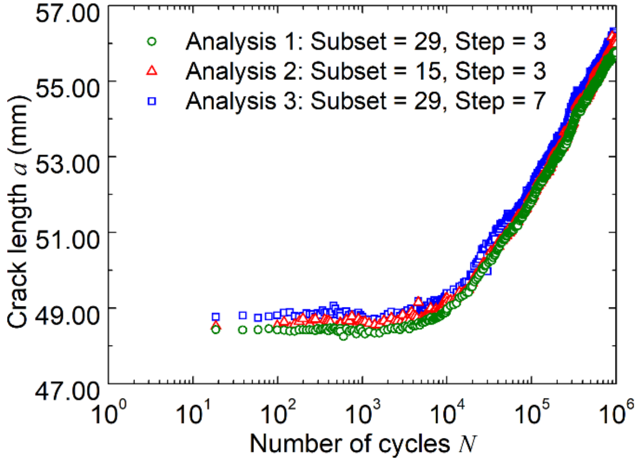
Mode II



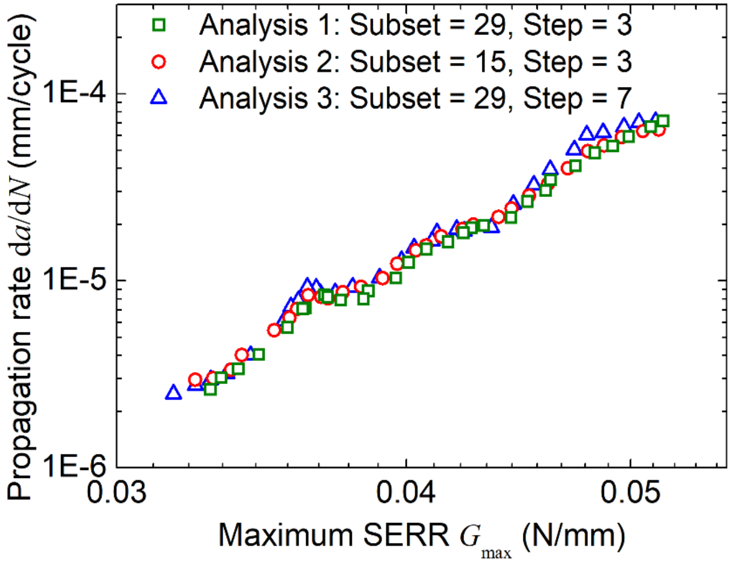
利用基于DIC技术的裂纹尖端识别算法，能够自动、快速地获得分层裂纹扩展速率，建立描述疲劳分层扩展行为地Paris’ law。

DIC处理参数的影响

Analysis No.	**1**	**2**	**3**
Subset size (pixel)	29	15	29
Step size (pixel)	3	3	7



No.	a_0(DIC) (mm)	Error (mm)	N_{onset} (cycle)
1	48.42 (48.32 ~ 48.51)	-0.30	2858 (1839 ~ 4462)
2	48.62 (48.46 ~ 48.77)	-0.10	1908 (283 ~ 10130)
3	48.82 (48.64 ~ 49.00)	+0.10	2795 (1115 ~ 7157)



- 对初始裂纹长度及疲劳起始寿命有一定影响
- 对裂纹扩展Paris’ law几乎没有影响
- 较大的subset和较小的step size导致更小的误差范围

结论

- 利用DIC技术建立了I型及II型疲劳分层实验中裂纹尖端识别算法，该算法得到的初始裂纹长度与显微镜观测结果能够很好的吻合；
- 基于裂纹尖端识别算法建立针对复合材料层合板I型及II型疲劳分层起始寿命的确定方法，并对疲劳分层起始及扩展行为进行了实验表征；
- 相较于实验标准ASTM D6115中推荐的柔度方法，基于DIC的实验方法专注裂纹尖端的行为，获得的疲劳分层起始寿命更加保守；
- 该方法实现了对复合材料中疲劳裂纹扩展的自动追踪，极大地减少疲劳实验中的人工消耗。

谢谢观看！