14th IMEKO TC10 Workshop Technical Diagnostics
New Perspectives in Measurements, Tools and Techniques
for system's reliability, maintainability and safety
Milan, Italy, June 27-28, 2016

Delamination monitoring using low frequency stress wave for laminated composites

Pingyu Zhu[1,2], Zhichao Yang[1], Wei Shi[1] , Yongjing Li[1]

[1] *Guangzhou University, Guangzhou, pyzhu@gzhu.edu.cn*
[2] *EPFL Swiss Federal Institute of Technology, Lausanne, pingyu.zhu@epfl.ch*

Abstract **– Owing to the anisotropy of composite laminates, local responses happens at periphery of the drilled hole even under the same loads. The strain measurement is probably the most sensitive and better option to detect and quantify delamination inside composite materials. In the paper, dynamic strain of the composite laminates was online monitored using fiber Bragg grating (FBG) and strain gauges. Two experiments with different sensors configurations on the specimen made of glass fiber reinforced polymers (GFRP) were conducted: mounted on the entrance and the exit side of the drilled hole. The low frequency stress wave signals contained more drilling details have been extracted from those sensors at different locations. The wavelet transforms shows the time-frequency spectrum corresponds to the delamination behaviour, especially when the drill tip contacted the first ply and pierced the last plies of the GFRP laminates.**

***Keywords*: Drilling delamination; Composite laminates; Strain; Fiber Bragg grating (FBG)**

I. INTRODUCTION

Fiber reinforced polymers (FRP) are increasingly found in modern vehicles light weight structure and sports products totally beyond the initial applications only in aircraft and military. Usually, a part made out of fiber reinforced composites is needed to be integrated with other metal or FRP structure in a mechanical assembly. Hole-making is unavoidable and drilling is the most often selection machining method in the production plan of such parts. Increasing feed rate and spindle speed will surely improve productivity, but another more critical factor is hole quality. The FRP drilling is not homogeneous but brittle, therefore several aspects affect its machinability. Delamination is a main hole quality problem, which not only means time consuming to repair the material, also being dangerous for a composite structure. That is to say, although delamination sometimes is small in area, such damage can have a significant weaken effect upon the mechanical properties of the laminate [1, 2]. Besides drilling machining, low velocity impact also causes delamination, which may occur during manufacture maintenance and by careless handling. This damage tends to be created on the back face or within the laminate and hence is difficult to be visually detected. Therefore, the delamination has also been recognized as one major problem for the structure made of composite materials in use.

Cutting force, especially the thrust and sometimes torque are usually taken to explore the mechanism of drilling-induced delamination including damage prediction [3-7], drill geometry influence [8-12] and delamination-free drilling of composite [13-15]. Many experiments were conducted to obtain the total thrust and torque generated during drilling including separately the forces caused by the chisel edge, cutting lips and drill points induced by drilling FRP with or without pilot hole [16-18]. Some studies pay more attention to the details about the axial variation distribution of the force loads during drill bit entry the FRP sample. Different from above conditions, damage detection for FRP adopts strain to inverse the force, the location of the impact. Because fiber hardness is extremely high, resins are weak, local responses to the same loads will happen around the drilled hole in the composite laminate, leading to the failure in the internal structure. In fact, strain measurement is probably the most sensitive and direct constitutive relation method to detect and quantify delamination inside composite materials [19]. The best application of the method is real time situ monitoring, where strain changes induced by matrix cracking and fiber breakage can be detected directly rather than thrust force or torque. The sensibility is in the zone of damage for normal drilling, but may be lower or higher depending on where the sensor points locate and cutting conditions. Fibre Bragg grating (FBG), which is sensitive to the strain and the temperature, appears to the best candidate for fibre-optic smart materials and structures. They play an important role as they can be surface-attached to or embedded into materials to facilitate quasi-distributed strain and temperature measurement for defects detection and usage monitoring of the response [20, 21]. Examples of applications include aircraft made in composite materials are to detect the damage [22]. Consequently, different installation techniques of FBG have been developed according to the structure [23-25]. These include embedding FBGs into the structure during new laminated composites curing [26], just sticking on the surface of the structure especially for damage detecting. The experiments show that FBG installed along the strain distribution contour map will provide possibilities to both locate anomalous delamination borders and to estimate the level of the delamination after short time calculations depending on the algorithm. It is getting more accepted in structure health monitoring (SHM) by making smart structure with FBG after fast interrogation systems were developed [27]. However, the acceptance and a general use of the method mainly prefer identifying the damage by using impact loads. There have been few attempts to use dynamic response to quantify the damage mechanisms for drilling machining which is a continuous process with absolutely different repeated quasi-static loads. The response pattern may be different.

In this paper, the strain response during the drilling process has been presented to help understand delamination mechanism by using FBGs and strain gauges. Experimental results showed more detailed information how the drill tip worked. Some agree with the explanation made by other studies, some are the first time to be observed. They are useful for selecting appropriate drill tools and cutting parameters for drilling composite laminates, drill geometry and process planning optimization.

II. EXPERIMENT SET UP

The specimen was a piece of 18-ply thick stacked with cross-ply glass-fiber/epoxy reinforced polymers (GFRP) laminates, supplied by a company manufacturing the blade for wind turbine. The thickness of laminated plate was 8mm. The in-plane dimensions were 48mm by 167mm not exactly rectangle. The transducers were mounted on the surfaces of the specimens made of GFRP. Sensing points were approximately dotted within the zone of strain response according to finite element method (FEM) simulation. There were four strain gauges and a FBG located at the top side of the No.1 (named borehole I). The experiment was conducted on a manual drilling machine (Z5740A). Four strain gauges and four FBG sensors were at the bottom side of the No.2 hole (named borehole II). The experiment was conducted on a CNC milling machine (XK7150). A FBG interrogrator MOI SM130 was employed to demodulate the strain signal of the FBG sensors. In order to avoid errors from being induced in FBG due to the temperature, Flir InfReC R500 was employed to record the temperature of the surface when drilling borehole I for calibrating. The experimental setup for the drilling test is schematically shown in Fig.1.

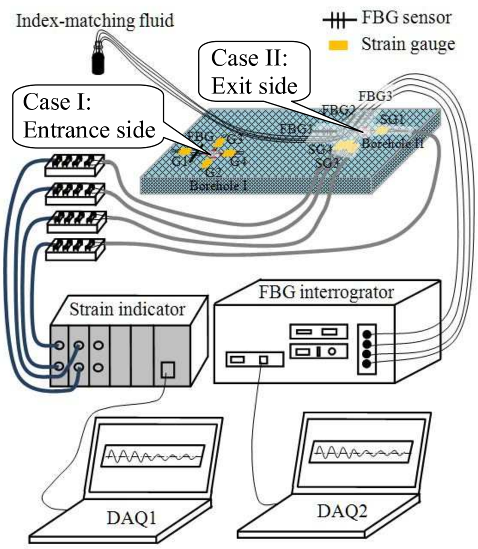

Fig. 1. Schematic of experimental setup for drilling on a GFRP sample.

III. EXPERIMENTAL ANALYSIS

3.1. Case I: Sensors were attached on the entrance side

The Bragg grating sensor wavelength was 1550 nm and sensing length was 10 mm. The legend G1, G2, G3, G4 and FBG denote the strain gauges and FBG-based results from the experiment, respectively. After the drill bit completely engaged into the sample, steady increase of strain value occurred to all the transducers till the end. The measured time was well coincided in theoretical value. And then the curves went back to their previous trends till approaching at the last moment, where a sharp drop happened. It is deduced that the drill point approached exit and was piercing the last plies of the specimen.

It is noticed that the strain of FBG was stronger than the G1 since the drill bit nearly started to make a dart cross the lower plies, although these two sensing points located very close. An assumption that the temperature contributed to increase the magnitude of FBG intensity could explain this result. It was verified from the calibration using temperature sensing characteristic of the fiber Bragg applied and the temperature recorded by an infrared thermograph. Some screen shots from drilling video are shown in Fig.2. The distributions of the temperature from the infrared thermography in different moments are shown in Fig.3. It revealed the accumulated chips of GFRP, which were pulled up by the drill bit while drilling, had major contribution to temperature of only few of upper plies of the sample quickly, especially around neighboring region of the hole where the transducers were located. The drill tip just made a pit on the specimen; few fresh chips with high temperature were produced, shown in Fig.3a. In Fig.3b, previous outer chips rapidly cooled down. A big block of chip jumped out and stayed beside the entrance of drilling hole. In Fig.2c, the drill bit finished drilling the hole, more and more chips were piled up and extended above the periphery of drilled hole. It is interesting to find that apparent elliptic belts of the temperature were forming and spreading with the accumulation of the chip of GFRP. This shape agrees with the results of the simulation of the displacement distribution pattern of local laminates under the thermal load described in previous literatures. Fig.2d was taken by the infrared thermograph directly, which explicitly shows the maximum, the minimum and the distribution of the temperature around the entrance with the temperature scale. It is therefore recommended for the temperature calibration for FBG sensor in-depth mechanism study of the delamination.

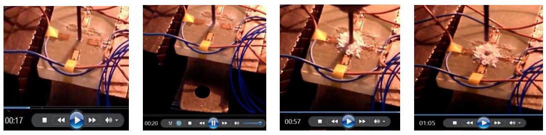

Fig.2. Screen shots during drilling GFRP

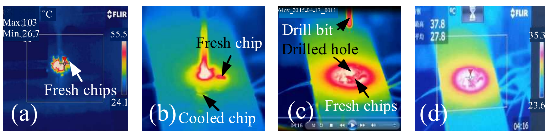

Fig.3. Distribution of the temperature from the infrared thermography at different moments: (a) *beginning*; (b) *chip produced*; (c) *finished drilling*; *and* (d) temperatures *with calibration scale.*

3.2. Case II: Sensors were stuck on the exit side

In case II, FBG sensor and the strain gauges are the same with those applied in case I. Four FBG sensors and four strain gauges were placed along two center lines of the borehole as being perpendicular to each other, as shown in Fig.1. In fact, only FBG1 and SG1 were almost in the center line of the borehole but not exactly opposite, and SG1 was the closest to the borehole. Figure 4 shows the whole drilling procedure divided into four stages: (a) entering, (b) steady drilling, (c) exiting, and (d) retracting.

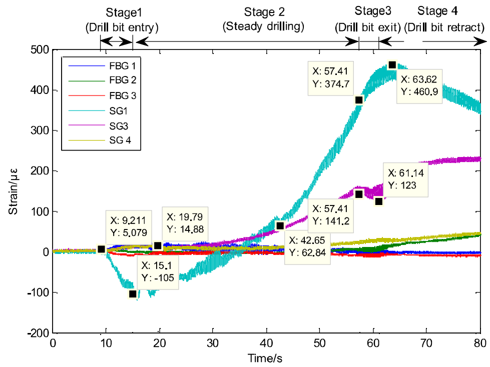

Fig.4. Strain variations in whole drilling of six transducers with time.

3.3. Results and discusses

We examine the possibilities of extracting meaningful source identification features by the use of a wavelet transform (WT). The frequency distribution with time history is well-illustrated on Fig.5. The WT provides not only the frequency content of the whole signal and allow one to easily see how the intensity of the energy in particular frequency ranges varies as a function of time. Thus, Fig.5a shows that G3 (case I) have the greatest concentration (most red color) of energy in a frequency

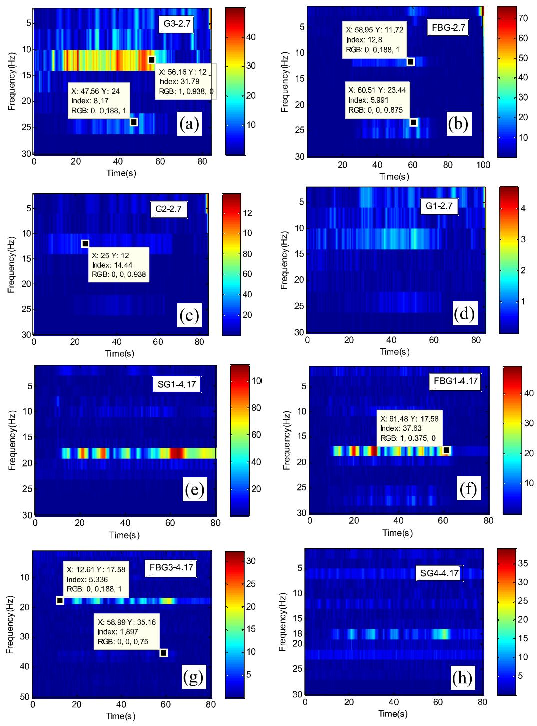

Fig.5. Typical calculated experimental signals with corresponding WT.

range of about 12 to 23.44 Hz (case I). Fig.5g shows that FBG3 is 18 to 35.16 Hz. Another large amplitude frequency of the WT is FBG1 in Fig.5f, which is centered about 17.58 Hz. These experimental results agree well with the theoretical results, which are exactly related with the spindle speeds and two cutting lips of the twist drill. The frequency spectrum in Fig.5a is more continuous than those in Fig.5e. The bigger delamination therefore happened in case I.

Based on the above observations, it can be addressed that low frequency stress wave governed delamination not visual damage in upper and lower plies of the composite laminates. It therefore should pay more attention to lower frequency when the drill tip firstly contacted the specimen whatever the front surface or the last plies. Especially the low frequency stress wave would assemble in the last plies and keep reflecting back to the upper layers from starting drilling since the lower frequency could propagate to the distal side in our experiments.

The quality of drilled holes is shown in Fig.6. The entrance is much better than the exit in two drilled holes. The delamination took place at both cases. Based on the above observations, it can be addressed that low frequency stress wave governed delamination not visual damage in upper and lower plies of the composite laminates. It therefore should pay more attention to lower frequency when the drill tip firstly contacted the specimen whatever the front surface or the last plies. Especially the low frequency stress wave would assemble in the last plies and keep reflecting back to the bottom from starting drilling since the lower frequency could propagate to the distal side in our experiments.

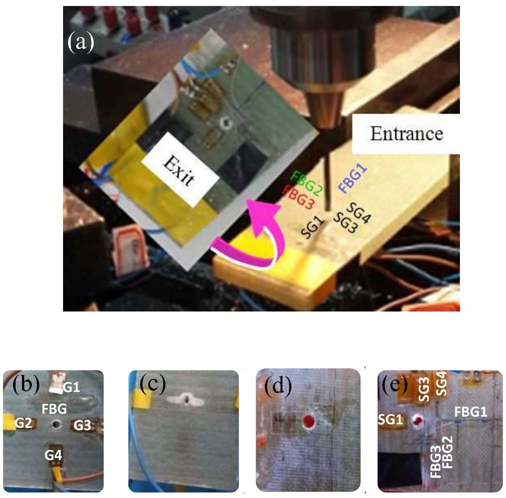

Fig.5. The drilled holes in two experiments: (a) *experiment set up*(*case II*); (b) *entrance, and* (c) *exit* (*case I*); (d) *entrance*, *and* (e) *exit* (*case II*).

IV. CONCLUSIONS

Through the current experimental analysis of dynamic strain responses, it was shown that a greater amount of information and more details could be extracted for overall drilling machining process. The ability of FBGs and strain gauges to detect dynamic response of composite laminates has been demonstrated for both front and distal back surfaces of GFRP laminates. Some conclusions could be summarized as the followings:

(1) The low frequency strains can be obtained from the locations within 4X the diameter of drilled hole. These basic low frequencies are related with the spindle speed and the number of cutting lip.

(2) The local strains around drilled hole provide more details during drill bit working. Moreover, for GFRP laminates, when the local strain within 2X the diameter of drilled hole exceeds around 320 $\mu\varepsilon$, it predicts the delamination or damage whatever the sensor is on the same drilling surface or not.

(3) The WT clearly reveal the distribution of the whole signal and easily see how the intensity of the energy in particular features frequency as a function of time.

(4) The affect of the temperature should be taken into account when the FBG is mounted on the entry of the specimen. The temperature of entry of the GFRP sample increased mainly contributed by the cutting chips from the drilling hole.

Local strain response is sensitive to drill bit working. That may be more effective for drill design and drilling parameters optimization with the help of real time monitoring drilling process. To obtain more general relationship between the delamination and the strain, more experiments and stress wave propagation analysis are future work.

V. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of National Natural Science Foundation of China, grant No. 51105140 and 2014 Program of Study Abroad for Young Scholar sponsored by CSC (China Scholarship Council), and deeply appreciate the assistance provided by Professor Luc Thévenaz's GFO from Swiss Federal Institute of Technology (EPFL).

REFERENCES

[1] E.Persson, I.Eriksson, L.Zackrisson, Effect of hole machining defects on strength and fatigue life of composite laminates, Composites Part A 28(2)(1997)141-151.

[2] E.Capello, V. Tagliaferri, Drilling damage of GFRP and residual mechanical behavior—part II:static and cyclic bearing load, Journal of Composites Technology Research 23(2)(2001)131-137.

[3] C.C. Tsao, W.C. Chen, Prediction of the location of delamination in the drilling of composite laminates, Journal of Materials Processing Technology 70(1)

(1997) 185-189.
[4] L.B. Zhang, L.J. Wang, X.Y. Liu, A mechanical model for predicting critical thrust forces in drilling composite laminates, proc. Inst. Mech. Eng. Part B 215 (2)(2001) 135-146.
[5] E.J.A. Armarego, J.D. Wright, Predictive models for drilling thrust and torque-a comparison of three flank configurations, Ann. CIRP 33 (1984) 5-10.
[6] Campos Rubio J. Abrao AM, Faria PE, Esteves Correia A, Davim JP, Effects of high speed in the drilling of GFRP: Evaluation of the delamination factor. International Journal of Machine Tools & Manufacture 48 (2008)715-720.
[7] V. Chandrasekharan, S.G. Kapoor, R.E. DeVor, A mechanistic approach to predicting the cutting forces in drilling: with application to fiber-reinforced composite materials, Transaction of the ASME, Journal of Engineering for Industry 117(1995)559-570.
[8] Hocheng H, Tsao C.C., Comprehensive analysis of delamination in drilling of composite materials with various drill bits. Journal of Materials Processing Technology, 140(1-3) (2003)335-339.
[9] Velayudham A, Krishnamurthy R. Effect of point geometry and their influence on thrust and delamination in drilling of polymetric composites. Journal of materials Processing Technology, 185 (2007)209-209.
[10] Piquet R, Ferret B, Lachaud F, Swider P. Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. Composites A, 31(2000)1107-1115.
[11] M.B. Lazar, P. Xirouchakis. Experimental analysis of drilling fiber reinforced composites. International Journal of Machine Tools & Manufacture 51(2011)937-946.
[12] I.S. Shyha, D.K. Aspinwall, S.L. Soo, S. Bradley. Drill geometry and operating effects when cutting small diameter holes in CFRP. International Journal of Machine Tools & Manufacture, 49(2009):1008-1014.
[13] S. Jain, D. C. H. Yang. Delamination-Free drilling of composite laminates. Journal of Engineering for Industry, 116(1994)475-481.
[14] H.Hocheng, C.C. Tsao. The path towards delamination-free drilling of composite materials. Journal of materials Processing Technology 167(2005)251-264.
[15] V. Krishnaraj, A. Prabukarthi, A. Ramanathan, N. Elanghovan et.al. Optimization of machining parameters at high speed drilling of carbonfiber reinforced plastic(CFRP) laminates. Composites:Part B 43(2012) 1791-1799.
[16] Liu D F，Tang Y J，Cong W L．A review of mechanical drilling for composite laminates. Composite Structures, 94(4)(2012)1265-1279.
[17] Desh Bandhu. A Review of drilling of carbon fiber reinforced plastic composite materials. International Journal of Current Engineering and Technology, 2014, 4(3) :1749-1752.
[18] Norberto F., José D., Antonio D., José L. C. and María H. Experimental analysis of the influence of drill point angle and wear on the drilling of woven CFRPs. Materials, 7(2014) 4258-4271.
[19] Yin Yao, Shaohua Chen, Peijian Chen. The effect of a graded inter phase on the mechanism of stress transfer in a fiber-reinforced composite. Mechanics of Materials, 58 (2013):335-54.
[20] Klute S. M., Sang A. K., Gifford D. K., et al. Defect detection during manufacture of composite wind turbine blade with embedded fiber optic distributed strain sensor. 2011 SAMPE Fall Technical Conference, Ft. Worth, Texas, Oct. 17-20(2011).
[21] Geert Luyckx, Eli Voet, Nicolas Lammens and Joris Degrieck. Strain measurements of composite laminates with embedded fibre Bragg gratings: criticism and opportunities for research. Sensors, 11(2011) 384-408.
[22] Gayan C. Kahandawa, Jayantha Epaarachchi, Hao Wang et al. Use of FBG sensors for SHM in aerospace structures. Photonic Sensors,2(3) (2012) 203-214.
[23] D. Karalekas, J. Cugnoni & J. Botsis. Monitoring of process induced strain in a single fibre composite using FBG sensor: a methodological study. Composites Part A, 39 (2008)1118-1127.
[24] S. Takeda, S. Minakuchi, Y. Okabe, N. Takeda. Delamination monitoring of laminated composites subjected to low-velocity impact using small-diameter FBG sensors. Composites: Part A, 36 (2005) 903-908.
[25] A.R. Chambers, M.C. Mowlem, L. Dokos. Evaluating impact damage in CFRP using fiber optic sensors. Composites Science and Technology 67(2007)1235-1242.
[26] Nanya Li, Yingguang Li, Jing Zhou, et al. Drilling delamination and thermal damage of carbon nanotube/carbon fiber reinforced epoxy composites processed by microwave curing [J]. International Journal of Machine Tools & Manufacture, 97 (2015)11-17.
[27] H. Tsuda. Ultrasound and damage detection in CFRP using fiber Bragg grating sensors. Composites Science and Technology 66(2006)676-683.