DYNAMIC STRAIN MONITORING OF COMPOSITE LAMINATES DURING DRILLING USING FIBER BRAGG GRATING AND STRAIN GAUGE SENSORS

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Abstract

To explore the mechanism of delamination induced by drilling, the local strain responses of a composite plate are monitored with surface mounted fibre Bragg gratings and gauges during drilling. The stress concentrated response zones relative to cutting force on both surfaces of laminated composites plate are obtained under drilling loads. The characterization of the strains of the sensors at different positions with WT has been analyzed using wavelet transfer (WT). The frequency of the strain relates to the cutting speed, the number of cutting lip and its intensity subjected to the geometry and feed rate of drill tool. It is possible to identify the location and occurrence moments of the main defects by employing these strain energy distribution of frequency variations subjected to the time (drilling depth), the position of cutting lip arrival and are used for defects evaluation when drilling.

1. 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. One part made out of FRP composites is needed to be integrated with the 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. However, the defects especially delamination induced by drilling become a barrier to improve the productivity by increasing feed rate and spindle speed [1-4]. The thrust force is usually thought the main reason induced the delamination [5]. Nevertheless, the relationship between thrust force and delamination is not stable straight forward when different types of drill bits were used [6,7]. Besides the thrust force, the periphery force may bring shear effection along all directions around the drilled hole. An effective step towards addressing the pertinent problems is the real time local strain response of the plate due to drilling loads.

The strain are extensively used in structure health monitoring (SHM)[8,9]. While the strain response of the sensor has been well understood under quasi-static loads even impact loads including strain contour map [10-12], its use in drilling last loads has not been investigated. However, the cutting force stress effects are significant in the case of laminated composite plates due to the relatively low

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transverse shear modulus [13]. Thus, the effects of transverse shear deformation and longtitual accumulation to the bottom should be taken into accunt.

In the present work, The FBG and gauge sensors are utilised to monitor the transient response during drilling a glass FRP plate. The local strain responses at different locations are compared to the stress wave concentrated zones obtained from theroetical deduction. It is shown that the stress wave with long wavelength is suited for the acquisition of defects to better understand occupational defects in drilling laminated composites.

2. The stress wave generated by drilling hole

2.1. Drilling model

The drill machining is to cut materials toward the hole center and to shear at the hole edge. Khashaba [14] reported that some parts near the chisel edge of the twist drill point extrude the material, instead of cutting through it. When the feed becomes too high, the whole drill point acts as a punch that pierces the laminate [15]. As the tool moves forward in the FRP, the uncut plies under the drill are drawn downwards by the drilling force and obtain stress. An orthogonal cutting model with the cutting force components $dF_1(t)$ apply on a point P, with diameter $d(t)$ at the moment t, along an cutting edge is shown in Fig.1[16]. F_z is the thrust force from the plate and undergos elastic strain by contacting deformation. The resulting thrust force F_z can break up into two components F_{z1} on the cutting lips and F_{z2} on the chisel edge (with length b) of the drill bit, and $F_z = 2F_{z1} + F_{z2}$. In fact, F_1 is the resultant force of the thrust force F_{z1} and the periphery force F_p. F_{z1} is the projection of F_1, which is perpendicular to the cutting lip and proportional the cutting chip thickness h_D. When the drill rotates one revolution, the cutting lips contacts the FRP once, hence the basic frequency of the stress generated is obtained,

$$f = nz/60. \tag{1}$$

Where n is the rotational speed, rpm; and z is the number of cutting lip. For a fixed contacting location in the FRP, the interval of the stress pulse event occurrence is the reciprocal of its frequency. It is noted that the above deduced stress pulse series occurred during stable drilling, i.e., after the drill point fully enters into the FRP and before penetrates through the last plies of the laminates. At the beginning of the drilling, the chisel edge touches the first ply of the FRP, the stress sharply reaches the maximum with a possible platform due to the difficulty of quick piercing, and then it goes down gradually with the increase in contact length due to the principal cutting lips joining. The stress is the sum of $dF_1(t)$ loaded on working cutting lip by the integration over the cutting area. The opposite situation happens at exit due to the decrease of involved drill point.

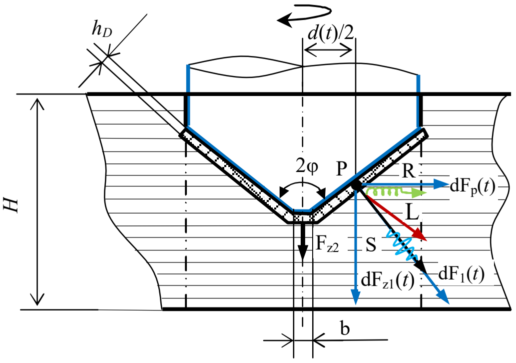

Figure 1. Drilling force applied by drill bit.

2.2. The stress wave concentrated response zones on plate surfaces

When drilling the FRP, the global behaviour of the laminates is considered as elastic deformation and the stress wave is a kind of elastic shear wave[17], which may also produce longitudinal wave (named L) and Rayleigh wave (named R) propagating in different directions. The point angle of the drill bit affects the generation of R wave and Rayleigh wave. The low frequency stress wave with long wavelength and much more energy easily penetrates the FRP whatever the resin is rich or not, and the major stress wave travels in the direction that is perpendicular to the cutting lip of the drill bit and reflects back into the FRP when arriving at free surface of the plate. With the increasing the depth of drilled hole, the stress waves travel as incidence to the exit side and reflection to the entry side many times continuously. In the meantime, the signals attenuate and decay.

The onset drilling before the drill point fully entered into the first plies and the wave lines are projected to “Entry incident I” with some width on the bottom surface. Consequently, this group of stress wave lines then reflects to “Entry reflection II” on the entrance surface and “Entry reflection III” on the bottom surface of the plate. After the drill bit penetrated several upper layers, it starts a stable stage, in which all the wave lines goes out of the diameter of drilled hole wall. And the stress wave lines move close to the edge of the drill hole diameter. This stage ends when the drill point touches the last ply. The last stage is the process to extrude the last plies using drill point. The stress wave lines project to the zone “Exit incident IV”. Consequently, this group of stress wave lines will reflects to the zones of “Exit reflection V” and “Exit reflection VII” on the entrance surface, and “Exit reflection VI” on the bottom surface of the plate. However, the stress wave lines are not strictly limited in these zones, which are some concentrated response annuluses. There are still less stress wave lines scattering to the belts between these intensive zones. The distribution of response zones on both surfaces are shown in Fig.2.

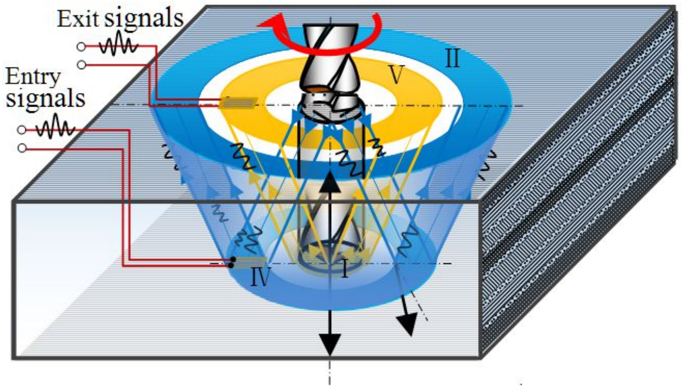

Figure 2. Drilling force applied by drill bit.

3. Experimental verification

3.1. Experimental procedure

In order to validate the response from the sensors at different concentrated stress response zones, some experiments have been carried out. The specimen was a plate 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 the calculation based on above stress wave traveling path model.

Three holes have been drilled in the same plate at different locations with different sensors layout (Fig.3). The first hole has four strain gauges and a FBG located at the entry side of the plate (cf.

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Fig.3a). The experiment was conducted on a manual drilling machine (Z5740A) using 3mm high speed steel (HSS) twist drills with 118° point angle with rotational speed 730 rev/min and feed 10mm/min. The second hole were surrounded by four strain gauges and four FBG sensors were at the exit side of the plate (cf. Fig.3b). The experiment was conducted on a CNC milling machine (XK7150) with rotational speed 532 rev/min and the same other cutting conditions in the first hole. A FBG interrogrator MOI SM130 was employed to demodulate the strain signal of the FBG sensors. The third hole has sensors on both entry and exit surfaces (cf.Fig3c). A FBG sensor with 5mm sensing length was exactly under the drill hole bottom for morning the stress wave acumulative effect within diameter range of the hole. Five gauges were placed on the both sides of the plate. Three of them were on the bottom of drill hole and two were on the entry side (Fig.3c). Two strain guages DG4 and DG3 were rigidly attached to the plate around drilled hole on opposite sides of the entry and exit respectively, as well as the guage DG2 and the gauge DG1. To follow angle effect of defect in the third hole making, the guage DG5 was placed at "Entry Reflection III" annulus along -45^0, where possible defect happens in drilling.

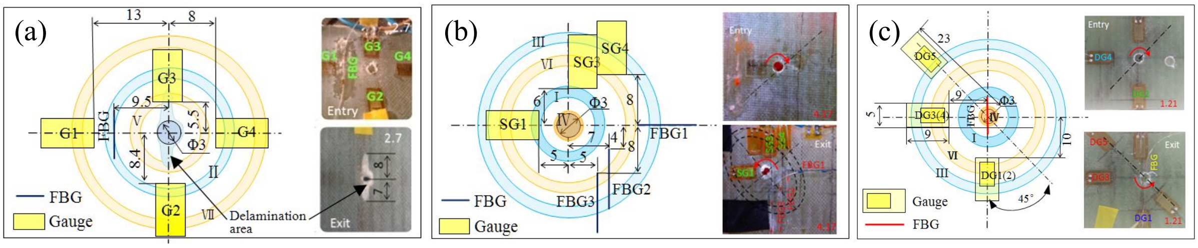

Figure 3. (a) Sensors on entry side (the first hole), (b) and sensors on exit side (the second hole) , (c) and sensors on both sides (the third hole) during drilling and photos of drilled holes.

3.2. Results

The frequencies of stress wave generated by cutting force have been obtained from the strain responses with Wavelet Transform(WT). The acquired frequencies under two sets of cutting conditions correspond well to the calculated values by Eq.(1). It can be noted that the frequencies are some light difference between FBGs and strain gauges in Fig.(4), Fig.(5) and Fig.(6). In the first hole drilling, two basic theroretical frequencies are 12.1 Hz with one cutting lip and 24.3 Hz with two cutting lip. And values are 12 Hz from strain gauges and 11.72 Hz from FBG with deviation of 0.6% and 3.1% under one cutting lip respectively. The measured strain time responses in the first hole drilling is shown in Fig.4a. After the drill bit completely engaged into the plate, steady increase of strain value occurred to all the sensors till 47.6s in time coordinate. Very short spikes were observed in all the curves when the drilling ran 34.2s, which was counted from the very beginning moment. The measured time coincided exactly with theoretical value 34.2s according to the feed and the plate thickness. This is the moment that the drill point pierced the last ply of the FRP. The drilling process did not end at the moment 47.6s until next sharp drop, where the drill bit fully extruded the plate. The legend G1, G2, G3, G4 and FBG denote the four strain gauges and FBG, respectively. The amptitudes of the sensors are different while they were at different concentrated response zones. G3 with the biggest value in time domain was the nearest loacation close to drilled hole center. Figure 4(c) shows the energy change of the strain signal with 12Hz main frequency. It is obviously found that severe delamination happened near the gauge G3. The sensors G1 and FBG have nealy the same stains since they are neighbours at the plate but further than G3. Their WT results are similar without intensive energy segments with time.

Figure 5 shows the experimental results of the second hole. Fig.5(a) are strain plots with time of three independent FBG, which shows the entry details of the drill bit including the drill point proceeding. It is observed that the strain decreased or increased quickly right after the onset of contact between the

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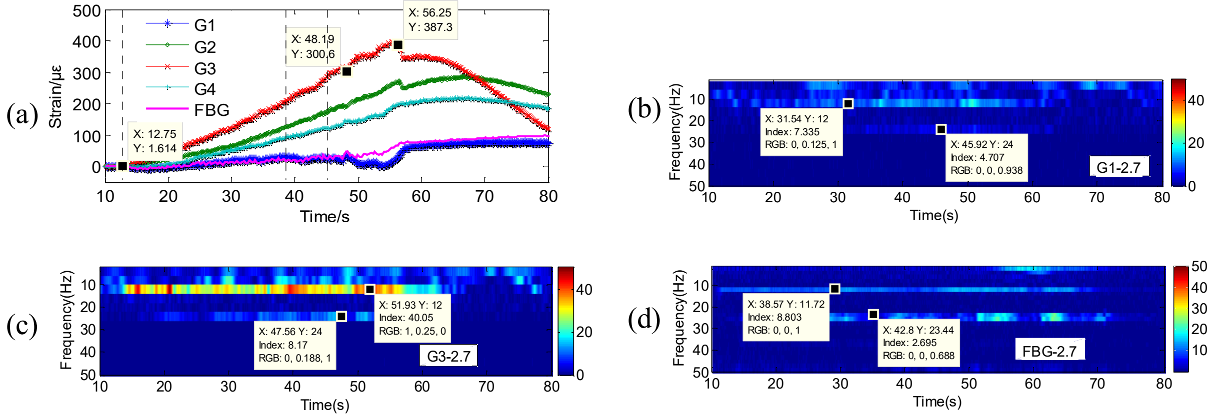

Figure 4. (a) Strain variation with time in the first hole, WT results from different sensors: (b) G1, (c) G3, (d) and FBG.

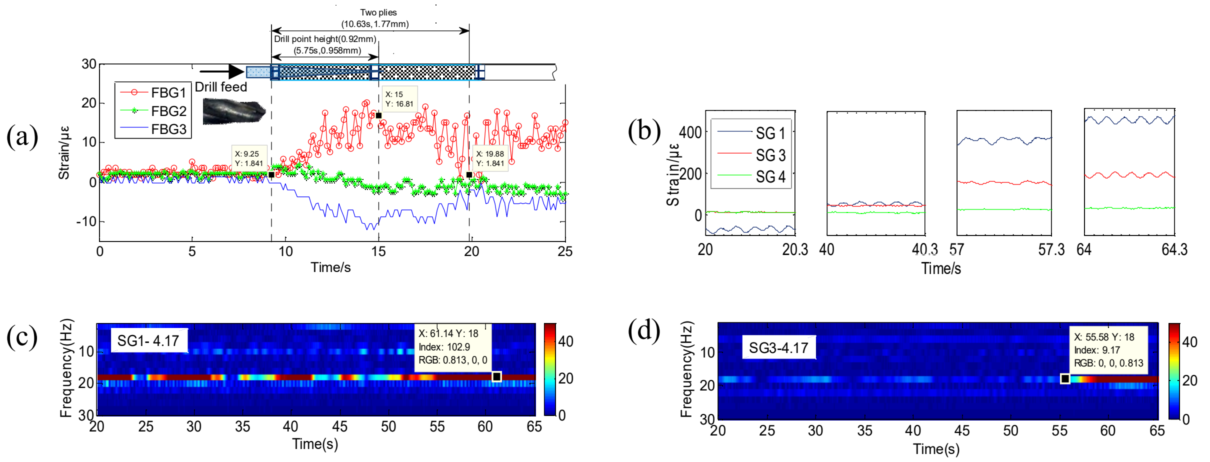

Figure 5. Strain variation with time in the second hole at the beginning (a), and some characteristic segments (b), WT results from different sensors: (c) SG1, (d) SG3.

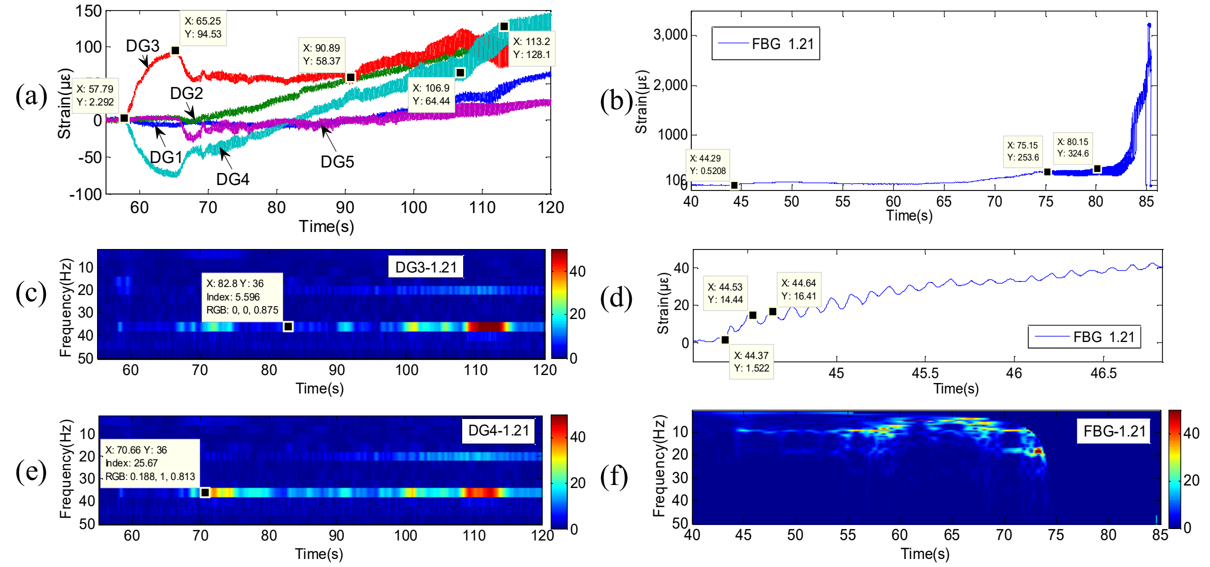

Figure 6. Strain variation with time in the third hole: (a) gauges, (b) FBG duration, (d) FBG beginning; WT results from different sensors: (c) DG3, (e) DG4, (f) and FBG.

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drill tip and the target, as expected. When the drill bit proceeding, the magnitude of the strain had a spur and undulated till 19.88 s. Machining time to study the procedure of the drill bit working revealed it to be of clearness for one ply of the laminates. The first continuous change time △t1 (increasing or decreasing) in the curves was 5.75s obtained by two moments (15 minus 9.25). According to cutting parameters (feed rate vf is 10 mm/min), the drilling depth can be obtained (0.958mm). The point height of standard twist drill applied in this experiment is 0.9~1mm. The thickness of one ply of the GFRP specimen for wind turbine blade is 0.89mm. From the comparison of three values of drilling depth, drill point height and one ply thickness, it become therefore reasonable that the drill point just penetrated the first ply of the specimen and arrived at the matrix. It is noted that the gauge SG3 mainly covered the zone “Exit incident IV”, therefore its energy was concentrated at the end of drilling time, as shown in Fig.5(d).

Figure 6 shows the experimental results of the third hole. The gauges of DG3and DG4 are quite symmetrical from opposite positions. FBG has changeable frequencies since it was mounted under the drilled hole. And the strain went up dramatically before break by drilling. As expected that each ‘impact’ action of applied cutting force can be found clearly from these peaks at the start of strain domain curve, which is corresponded to the rotating of the cutting lip in Fig.6(d).

4. Conclusions

In this study the strain response of GFRP cross ply laminates is examined under drilling. The stress wave originates from the thrust actions of the cutting edge and the chisel edge. The frequency of the location strain is strongly related to the gerometry of the drill bit, while it is also well related to the degradation of the running modulus for different cutting parameters. The strain amplitude is used to correlate with the extent of local tension or pressure. Parameters like the strain energy distribution and their frequencies are found from WT to be sensitive to the damage accumulation and failure mode, since they shift as the dominant fracture position changes around drilled hole. Therefore, they may be studied as defects indices in composite laminates when drilling load.

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