# INFLUENCE OF POINT AND HELIX ANGLE ON THRUST FORCE AND DELAMINATION FOR ONE-SHOT DRILLING OF CARBON FIBER REINFORCED PLASTIC (CFRP)

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**ABSTRACT:** Drilling operation for CFRP parts in the aircraft industry assembly line is unavoidable. Delamination frequently occurs during drilling holes in CFRP and reduces the ability of CFRP parts to carry loads and affects its service life spend. Drill reamer is enhancing the drill bits option for one-shot drilling to save time and cost. This article aims to investigate the influence on the variation of point and helix angle of drill reamer to thrust force and delamination damage. Different drills with the variation of point and helix angle were used to drill unidirectional CFRP laminates panel separately. From the thrust force curve graph, drilling using drill reamer can be divided into three main stages. Point angle geometrical feature influence in stage I while, helix angle in stage III, whereas stage II act as an opener for the drilled hole. Its found that point angle in drill reamer act as pilot drill and helix angle significantly affect to drilled holes quality. Variation of point angle features affected the thrust force measurement for stage I of drilling. The minor right-hand side helix angle reduces the delamination compared to straight flute but negatively affected when major helix angle applied. The suitable combination of drill reamers' geometry features will enhance overall drilling qualities.

**KEYWORDS**: *CFRP; One-Shot Drilling; Delamination; Thrust Force*

## 1.0 INTRODUCTION

Carbon fibre reinforced plastic (CFRP) is a new option in the manufacturing of product those required extra rugged and lightweight properties. Nowadays, CFRP also an option to produce automotive and renewable energy parts depicts widely used in aerospace manufacturing [1]. CFRP classified as hard to machined materials due to its high specific strength and stiffness to mechanical properties. Despite that, secondary machining such as drilling is the most applied process in CFRP to assemble CFRP structural parts using rivets and bolts, especially in aircraft development. Lately, in commercial aircraft production generally required more than 50,000 drilled holes in single aircraft production [2]. Therefore, the drilling process is the most critical in the assembly process and directly affects aircraft service life spend. Failure to cope with drilled hole's quality and specifications leads to catastrophic effects and significant loss to the manufacturer and consumer [3].

Famous with nature of low transverse tensile strength and low interlaminar shear strength, damages during drilling are widespread to occurred are fibre pull-out, cracks, uncut fibre, and delamination may lead to parts rejection in assembly line. In related previous conducted research, the thrust force is found as a significant contributor for delamination damage occurrence. Delamination obtained as a dangerous defect in a drilling process that can lead to reducing CFRP mechanical abilities.

In the last decades, some researchers had been conducted a research on the influence of drill geometrical features on the quality of drilled holes. They have reported that increasing point angle will increase the drilling thrust force. Numerous research found that the smaller point angle is preferred to reduce thrust force to lowered possibilities of delamination. While some researchers also found that the point angle subjected to delamination is based on drill types. Shyha et al. [4] found drilling the step-drill with 140° of point angle; delamination was reduced. Delamination damages have attracted the attention of researchers to research the influence of drill bit geometry type to delamination damage. Comparison of thrust force and delamination between standard twist drill and particular types of drill such as step drill, saw drill, and candlestick drill had been conducted by Tsao and Hocheng [5] found that special drills type contributes lower drilled holes damages compared with twist drill. However, it is still a lack of study to address influence on the combination of point angle and helix angle for thrust force and delamination generated during the drilling process. Bai et al. [6] and Su et al. [7] conducted an experiments to compare the quality of drilled holes based on helical direction. Chip removal direction and cutting angle are related to helical direction, whereas the effect on drilled holes quality. Therefore, the influence on the difference of helical angle is essential to study to achieve minimal delamination at the entry and exit side of drilled holes.

This paper is about to conduct the experiment using three types of drill reamer with different point angle and helix angle to drill actual final CFRP laminates plate and ready to assemble with 0° and 5° drilling penetration angle separately. From the experimental results, selective adaptive point angle and helix angle based on thrust force and delamination is derived. The effects of point angle (drilling stage) and helix angle (reaming stage) for drill reamer are also identified in the yield of thrust force and delamination.

## 2.0 EXPERIMENTAL SETUP

### 2.1 Materials Preparation

This experiment was using the CFRP panel as a workpiece manufactured by the local aerospace composite manufacturing company. CFRP panel specimen laminate consists of 26 UD-plies of 0.125 mm thickness each and two plies of epoxy woven fabrics of 0.08 mm thickness each at the top and bottom CFRP laminates specimen. Total workpiece thickness is 3.587 mm after base paint application. Areal density for CFRP and woven fabrics is 203 g/m$^3$ and 107 g/m$^3$, respectively. After the curing process, the laminates compacted to achieve a nominal volume fraction of 60%.

### 2.2 Cutting Tool

The drills applied in the experiment are made of tungsten carbide (WC 93% & Co 7%) with three different point angle and helix angle of drill reamer as presented in Table 1. The other tool geometry features are the same except for the point angle and helix angle. The cutting edge angles are measured in the normal plane of cutting edge.

Table 1: Drilling tool geometrical features characteristic

| Name of the tool | T1 | T2 | T3 |
|---|---|---|---|
| Point angle (°) | 110 | 100 | 90 |
| Helix angle (°) | 0 | 11 | 5.5 |
| Drill material | Tungsten carbide (WC 93% & Co 7%) | | |

The point angles for T1, T2, and T3 are 110°, 100°, and 90°, respectively. All drills also have different helix angles, 0°, 5.5°, and 11° for T1, T2, and T3 jointly with different point angle. Drill's diameter is 6.35 mm. The measurement of point angle and helix angle is based on tool grinder programming and confirmed by AutoCAD software. Flute length for all drills are 40 mm, and drilling depth is 30 mm for all trial.

## 2.3 Drilling Setup

The drilling trial was performed on 15kW DMU60 monoBLOCK® machine CNC machining centre. The CNC machine capability for five axes operations, including dynamic NC-swivel head for B-axes and spindle speed options, a maximum of 12,000 rpm. The thrust/cutting force was measured using a dynamometer by Kistler company. In this experiment, unique fixtures were designed as a backing plate and clamping plate to support the CFRP panel and firmly held the workpiece in CNC machine vice on the dynamometer to prevent any vibration. The undesirable vibration during the drilling process can affect the thrust force measurement by dynamometer [8]. The predrilled for pilot holes were made in this experiment for thrust force measurement accuracy. No coolant fluid was used to avoid contamination. Figure 1 shows the experimental setup for further experiment analysis and observation.

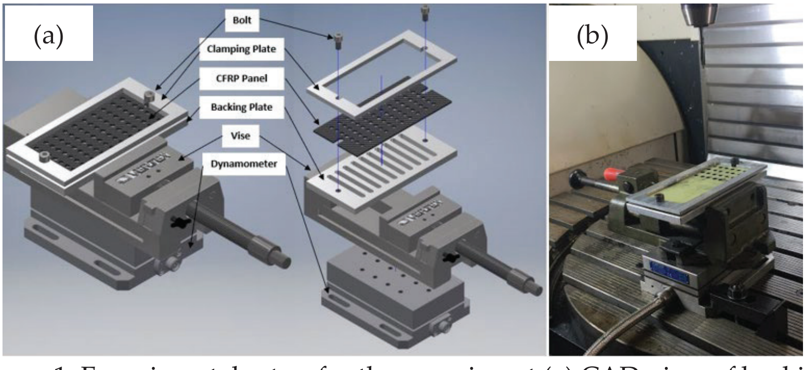


Figure 1: Experimental setup for the experiment (a) CAD view of backing plate setup and (b) actual experiment procedure

## 2.4 Experimental Design

Design of experiments widely used among engineering researchers to obtain accurate analysis and better prediction. This experiment has been done with a variety of geometrical features and fixed machining parameters, such as feed rate and spindle speed, to achieve the precise result on drilling thrust force measurement and delamination assessment. All trials had conducted with a fixed spindle speed of 2600 rpm and a feed rate of 130 mm/min. Table 2 shows the experimental factors assigned and machining parameters. For each trial, six holes are drilled at 6.35 mm in diameter, alternating with different of vertical axial penetration angle of 0° and 5° to mimic actual drilling in composites industry using pneumatic/electric powered hand drill to study effects of geometrical features in term of force and delamination during manual drilling. Various penetration angle drilling illustration, as shown in Figure 2.

Table 2: Experimental factors assigned

| Level | 1 | 2 | 3 |
|---|---|---|---|
| Drills type | T1 | T2 | T3 |
| Penetration angle ( ° ) | 0 | 5 | |
| Feed rate (mm/min) | 130 | | |
| Spindle speed (rpm) | 2600 | | |

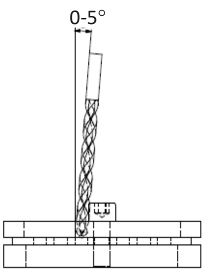


Figure 2: Different penetration angle of drilling

## 2.5 Experimental Responses

### 2.5.1 Drilling Thrust Force

Thrust force measurement data recorded using Kistler dynamometer type 5223A. The primary measurement concern in the experiment was the maximum thrust force for point angle drilling phase (Stage I), $F_{Z1max}$ and helix angle reaming phase (Stage III), $F_{Z2max}$. For interaction purposes, the ratio of $F_{Z1max}$ and $F_{Z2max}$ is determined by multiple force relationships ($N_r$) as shown in Equation (1) [7].

$$N_r = \frac{F_{Z1\max}}{F_{Z2\max}} \tag{1}$$

There were distinct differences between the measured value of the maximum thrust force in the drilling stage I and the maximum thrust force in reaming stage III. The delamination mainly occurred at reaming stage III, so the thrust force of the reaming stage is the significant factor influenced by delamination. However, the drilling stage I thrust force significantly affected by the worn tip of the cutting tool. Variance in $F_{Z1max}$ and $F_{Z2max}$ has the significance measure to define the delamination of this kind of drill, as shown in Figure 3. DynoWare processing software processes the measurement data and shown as the Z axes force graph.

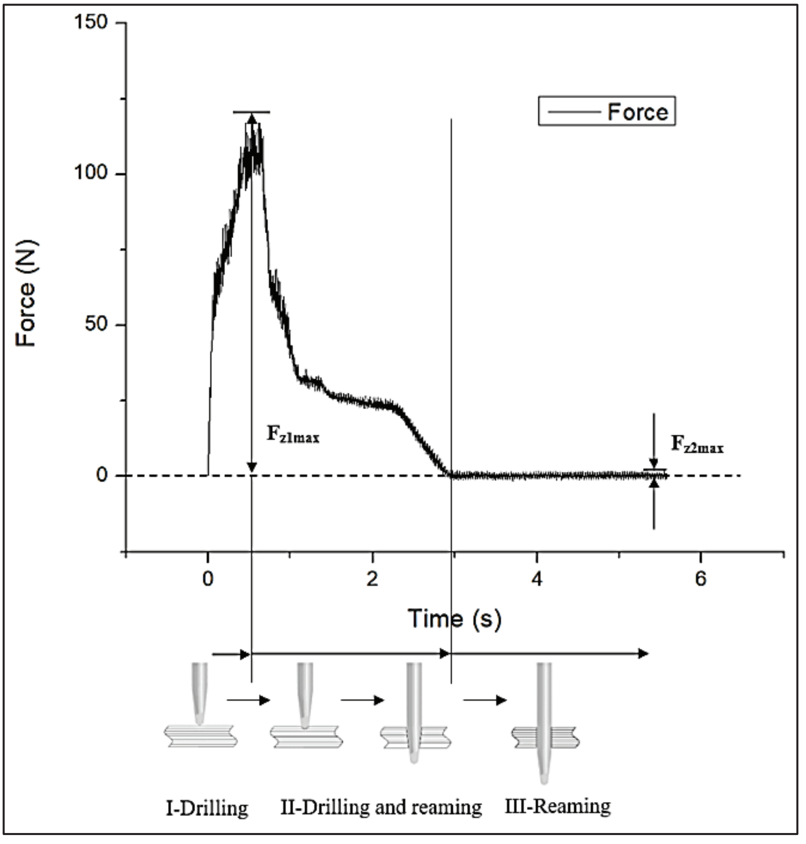


Figure 3: Region of thrust force measurement of stage I (drilling), II (drilling and reaming) and III (reaming)

### 2.5.2 Entry and Exit Delamination

All drilled holes observed using optical microscope EMZ-Meiji equipped with a digital camera and processed by image processing software (ImageJ by JAVA) with selective brightness, noise, contrast, and the threshold for better delamination observation and delamination area measurement. Figure 4 shows the illustration of the delamination area measured both sides for the entry and exit of the drilled hole. Observed delamination at drilled holes measured to obtain the area delamination factor, $F_A$ as in Equation (2):

$$F_A = \frac{A_d}{A_0} \tag{2}$$

where $A_d$ is the delamination area, and $A_0$ is the nominal area of the hole.

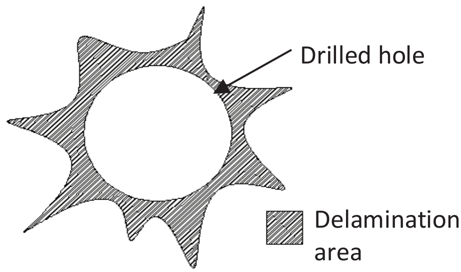


Figure 4: Schematic diagram of the delamination area

In this experiment analysis, the delamination factor as Equation (2) was used [9]. This delamination factor uses the total delaminated area to nominal drilled area to obtain the ratio of the delaminated area for each side of the hole. Commonly in other research work, researchers using the delamination factor of the maximum diameter of delamination to nominal hole diameter but not represent actual delamination observation. As shown in Figure 4, delamination damage does not spread at an entire area of measured diameter [10].

## 3.0 RESULTS AND DISCUSSION

### 3.1 Drilling Thrust Force Analysis

Based on drill reamer design geometry, five stages of drilling can be simplified into three stages for analysis convenience. Figure 5 shows the three drilling stages for experimental analysis. Stage I representing start drilling when drill tip at drill point angle touches the workpiece until the first primary region fully penetrate, Stage II is drilling and reaming process until second primary region complete entering and stage III is reaming process until drill backing out from the workpiece. These stages were shown clearly in the thrust force versus time graph, as depicted in Figure 3.

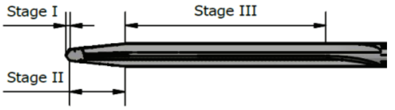


Figure 5: Drilling process stages for drill reamer

Drill reamer point angle distinctly influences the thrust force measurement. Figure 6 shows the variation of measurement thrust force data recorded for different point angle. $F_{Z1max}$ represents thrust force for stage I drilling, whereas influenced by point angle of the drill. T1 with 110° of point angle recorded highest thrust force followed by T2 and T3 with 100° and 90° of point angle, respectively.

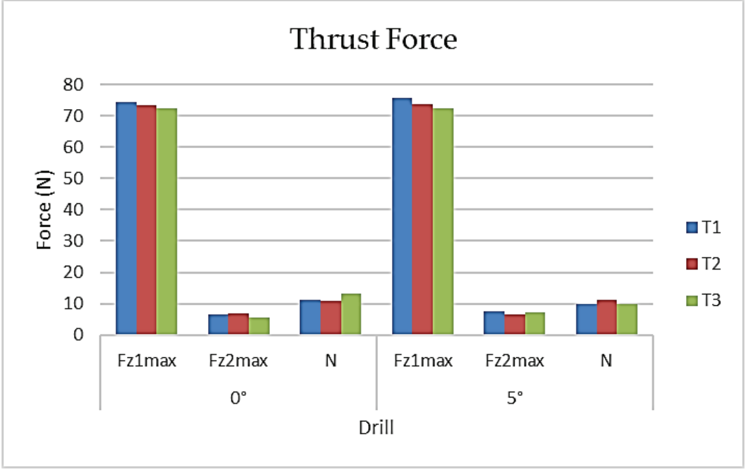


Figure 6: Thrust force measurement

The drilling thrust force measurement proved the stage I of drilling posted dominant high thrust force compared to reaming stage III of drilling. The spike of force is due to the cutting tool tip start to indent the workpiece. From the measurement data, it found that increases in the point angle increase the thrust force measurement for both drilling penetration angle. Drill bit point angle plays an important role as this geometrical feature placed the first contact with CFRP workpiece. To minimise the drilling thrust force, the point angle must in a small value to reduce the cutting area contact within the cutting tool and workpiece. Figure 7 clarifies the cutting area comparison between various point angle values in the same drilling depth.

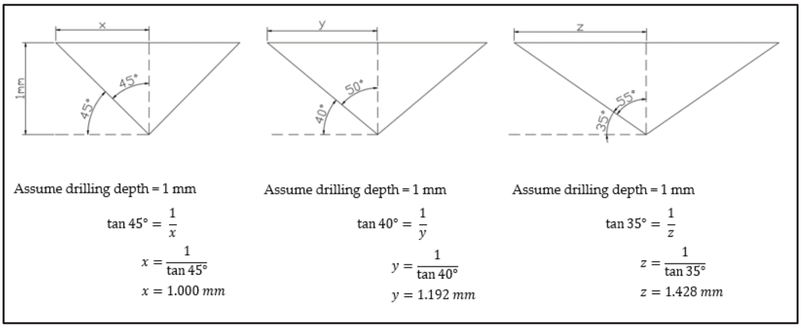


Figure 7: Concept of point angle during drilling

Increases the point angle will result in the higher value of contact area with CFRP workpiece. The larger area of the cutting tool which contact with the workpiece increases the drilling thrust force measurement. The drilling thrust force results found that the 90° of point angle obtained the lowest thrust force followed by 100° and 110° of point angle, respectively. However, there were no distinct differences in thrust force between 0° and 5° penetration angle drilling due to the variance of the cutting area in minor difference drilling penetration angle does not contribute significantly on the thrust force.

Drilling thrust force for reaming stage III plays an important role in obtaining less delamination. Stage I and II drilling act as hole opener, but the quality of the drilled hole depends on stage III reaming. From the results, helix angle 5.5° posted the lowest thrust force, followed by 0° and 11°, respectively. Unidirectional CFRP laminates are anisotropy materials properties. Hence, a lower helix angle of cutting tool produced better-drilled holes quality. Cutting force concept for helix angle have axial and radial forces components that affect the thrust force generation. Increasing the helix angle leads to a larger proportion of the axial force of the cutting tool. Figure 8 shows the influence of helix angle on cutting force and chip removal velocity. 5.5° helix angle reduces the cutting force generation and increases the chip removal velocity opposed when compared to 11° helix angle. At 0° helix angle, the axial force assumed as constant and only radial force exists. The low drilling cutting force for CFRP obtained at the low value of helix angle and increases for the higher value of helix angle.

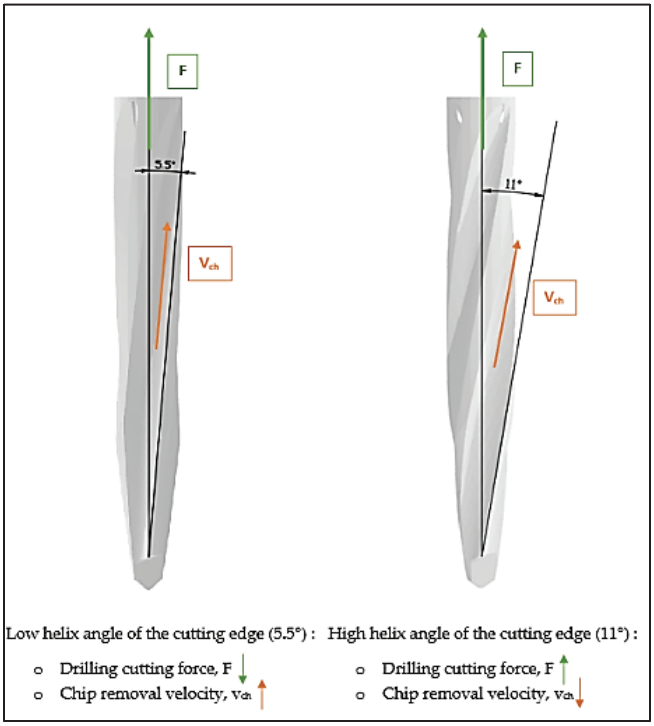


Figure 8: Influence of helix angle on cutting force and chip removal velocity

The 11° helix angle obtained the lowest drilling thrust force for 5° penetration angle drilling, followed by 5.5° and 0°, respectively. The drilling thrust force for 5° of drilling penetration reduced with increasing the helix angle. This condition was due to the slanting penetration of drilling conditions increase the efficiency of chip removal however, only the marginal effects of thrust force identified between the minor difference of drilling penetration angle. There was a critical need to combine the lowest thrust force generation by point angle and helix angle to present the lowest thrust force in the overall drilling process as in Equation (2) for $N_r$ (drilling thrust force ratio).

## 3.2 Delamination Analysis

Entry and exit delamination had been processed for further analysed for variation of drill geometrical features in the different drilling penetration angle. The helix angle was a significant factor that contributes to delamination damages. From the measurement data, it proves that the 0° helix angle posted the highest delamination area at the entry and exit side for both drilling penetration angle, followed by 11° helix angle. 5.5° helix angle obtained the lowest delamination area for both drilling penetration angle. Figure 9 and Figure 10 show the delamination factor and delamination processed images for the conducted experiment.

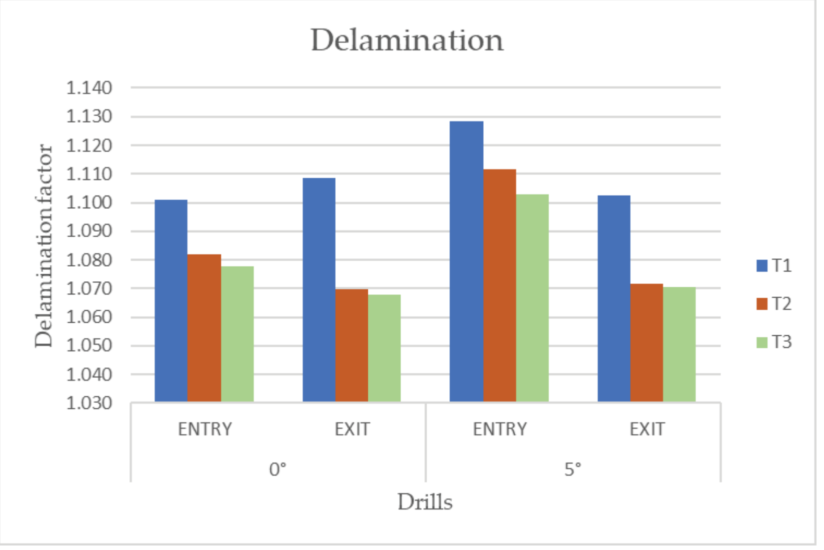


Figure 9: Delamination factor

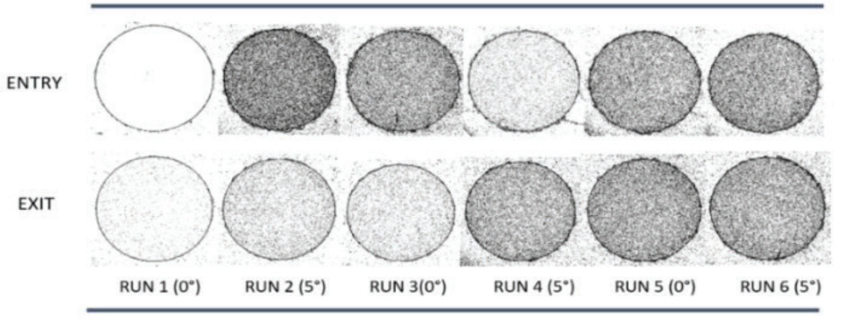


Figure 10: Example of processed delamination observation using ImageJ

From the experiment, it proved that slanting drilling would cause high delamination. Straight flute drill reamer contributing higher delamination compared with drills that have a helix angle. This finding has the same agreement with Su et al. [7] that found the right-hand side helix angle at Stage III leads to lower delamination and better-drilled holes quality. From the experiment, the right-hand side 5.5° helix angle (T3) induced better delamination factor compared to 11° of helix angle (T2). The T2 and T3 drills contribute low delamination damage for both the entry and exit of drilled holes. Increasing the drilling penetration angle will escalate entry delamination, but at the exit, there is no significant effect occurred. On the other hand, for the other types of drills, it shows a significant effect of delamination at the exit side of drilled holes [6-7]. Figure 11 shows the loading force concept for the helix angle. The 0° helix angle produced radial force and escalating to the right-hand side which it helps to increase the axial force upwards and reduces the radial force, hence reduce the delamination damages and produce more high quality of drilled holes. However, for CFRP drilling, too wide helix angle will negatively affect the drilled hole quality, thus should be avoided.

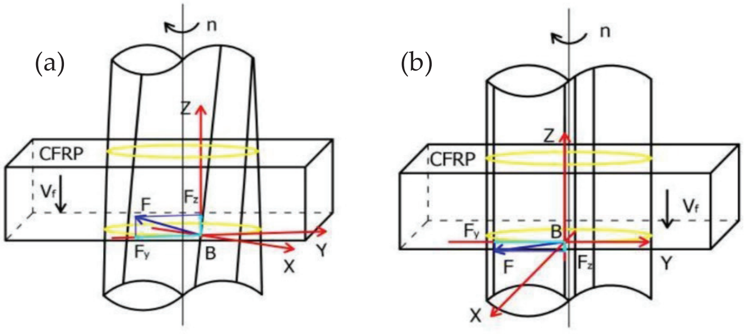


Figure 11: Concept for helix angle loading force in drilling
(a) right-hand and (b) straight flute [6]

## 4.0 CONCLUSION

From the conducted experiment, several conclusions have been made:

i. Increasing point angle and helix angle leads to increase thrust force in stage I and decreasing the thrust force in stage III of drill reamer.
ii. The suitable combination of point angle and helix angle is needed to reduce the trust force ratio ($N_r$) and generates low overall drilling thrust force.
iii. Helix angle at stage III significantly contributes to delamination. Delamination at 5° of drilling penetration angle is higher compared 0°.
iv. Delamination for straight flute drill reamer is higher compared with helical drill reamer but generally worsen when higher helix angle applied.
v. In order to minimise the delamination, only a minor increase in the helix angle for stage III of drilling is needed.

## ACKNOWLEDGMENTS

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