# A PSEUDO DUCTILE ANGLE-PLY SUB-LAMINATE APPROACH FOR MULTIDIRECTIONAL THIN PLY CFRP LAMINATES

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**Abstract**
Analytical modelling of thin ply angle-ply $[\pm\theta/\underline{0}]_s$ carbon-epoxy layups consisting of intermediate modulus MR60 and ultra high modulus YSH70A prepreg materials has been conducted to establish a candidate configuration for use as a pseudo-ductile sub-laminate in a multidirectional laminate. These layups have demonstrated considerable pseudo-ductility via gradual failure of the 0° ply. Stress-strain predictions of $[\pm 25/\underline{0}]_s$, in particular, have shown that this layup possesses a high initial modulus of 135 GPa and produce a pseudo-ductile strain of 1.43%, for a strength of 761 MPa. Selected as a sub-laminate configuration, this layup has been applied to two stacking sequences: $[30/0/-30]_s$ and $[45/0/-45]_s$, where the global orientations correspond to the direction of the 0° ply in each sub-laminate. Classical laminate analysis indicates that these multidirectional laminates can exploit the pseudo-ductility of the sub-laminates to achieve a gradual failure at a higher scale.

## 1. Introduction

High performance composites, such as carbon fibre reinforced polymers (CFRP), are well known to possess excellent specific strength and stiffness, but often limit the efficiency of a design due to their inherent lack of ductility. Work carried out on thin ply CFRP laminates, as part of the High Performance Ductile Composite Technology (HiPerDuCT) programme grant, has previously shown that highly non-linear tensile stress-strain behaviour can be achieved [1–6].

In particular, metal-like stress-strain curves have been demonstrated with $[\pm 26_4/0]_s$ and $[\pm 26_5/0]_s$ laminates [6]. Using thin ply standard modulus CFRP (ply thickness, $t_p$ = 0.03 mm), these layups were shown experimentally to produce pseudo-ductile strains in excess of 2% via a combination of gradual failure of the central 0° due to fragmentation and fibre reorientation in the ±26° plies. In this case, pseudo-ductile strain, $\epsilon_d$, is defined by the laminate failure strain minus the strain at the same stress on a straight line of the initial modulus.

Analytical modelling of these $[\pm\theta_m/0_n]_s$ laminates allowed not only accurate predictions of the stress-strain behaviour, but also a detailed knowledge of the key parameters affecting the overall response [6]. Through variation of the ratio of $\pm\theta$ to 0° plies and the absolute number of 0° plies in the layup it was possible to control the initial modulus, 'yield' stress, pseudo-ductile strain and laminate strength. This work established that a optimum range of $\pm\theta$ values exists for pseudo-ductility, which increases as fibre angle is increased from 20°—30°. In terms of overall laminate performance, however, it has been determined that 'yield' stress can be maximised when the $\pm\theta$:0° thickness ratio is minimised.

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Work presented in [7] further developed the analytical modelling, showing that it is possible to have a pseudo-ductile stress-strain response using the thinnest possible configuration of $\pm\theta$ and 0° plies: $[\pm\theta/\underline{0}]_s$. Achieving this pseudo-ductility required the use of thin ply CFRP with ultra high modulus carbon fibres, such as Toray M55J, Nippon Graphite YSH-70A or XN-80, for the central 0° plies. The same standard modulus CFRP used in [1, 5, 6] was maintained as the $\pm\theta$ plies. These laminates indicated that it is possible to finely tune the stress-strain response, in terms of pseudo-ductile strain, 'yield' and failure stress, by altering the high modulus fibre type of the 0° and the fibre angle of the $\pm\theta$ plies.

A key feature of these laminates is their low overall thickness. Each five ply configuration measures between $t = 0.150$ mm and $t = 0.165$ mm, approximately the same as a standard thickness prepreg material. This suggests that a $[\pm\theta/\underline{0}]_s$ laminate could be used as a pseudo-ductile 'prepreg' in place of a brittle standard thickness ply in a multidirectional layup. Supplying these layup as a pseudo-ductile 'prepreg' would also avoid the need to lay up many more plies than when using a standard thickness material, which is a major obstacle for large-scale applications of thin plies in general.

The current work develops this concept, proposing multidirectional laminates where each 'ply' consists of a $[\pm\theta/\underline{0}]_s$ sub-laminate. Analytical predictions of $[\pm\theta/\underline{0}]_s$ layups are made to establish the most promising configurations for pseudo-ductile stress-strain responses. The modelled sub-laminates are then arranged into stacking sequences that aim to achieve gradual failure of the entire laminate. The ply-level stresses are then compared for the chosen configurations.

## 2. Modelling procedure

The analytical modelling conducted in the current work makes use of the approach discussed at length in [4, 6], so shall only the key facets shall be presented here. The model, coded in Matlab®, is iterative and non-linear, taking account of the fibre rotations and matrix plasticity that occur in the $\pm\theta$ plies. The stress-strain behaviour of the 0° layers is assumed to be linear-elastic in the fibre direction. The first failure in the 0° plies occurs when the fibre failure strain is reached, satisfying the inequality: $\sigma_{11}/E_{11} \geq \epsilon^*_{11}$. Where $\sigma_{11}$, $E_{11}$ and $\epsilon^*_{11}$ are the fibre direction stress, modulus and strain to failure of the material respectively. Whether further strain develops at this point depends on the relative strengths and thickness of the $\pm\theta$ and 0° plies, as well as the absolute thickness of the 0°. Crucially, if the strength of the $\pm\theta$ plies is high enough to resist the stress redistribution caused by the failure of the 0°, then non-linear behaviour will occur. If, however, the strength is not sufficient, the laminate will fail before any non-linearity can develop. This is determined by comparing the known strength of the $\pm\theta$ layers to the stress at the fracture, $\sigma_{\text{crack}}$, given by Equation 1:

$$\sigma_{\text{crack}} = K_t \sigma_x \left(\frac{t}{t_{\text{AP}}}\right). \quad (1)$$

The stress concentration factor, $K_t = 1.08$, as used in [4, 6], accounts for the local redistribution of stress at the crack tip and $\sigma_x$, $t$ and $t_{\text{AP}}$ refer to the global applied stress, laminate thickness and angle-ply thickness respectively.

If the laminate does not fail at this point, multiple fractures (termed fragmentations) of the 0° plies will occur in regions of uniform stress. Assuming a constant fibre strength, this leads to a stress plateau during the development of fragmentations to their saturation. For a given layup, these fragmentations will have a critical spacing, $l_c$ which is determined via a force balance between the fractured 0° ply and the shear stress at the $-\theta/0$ interface:

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$$l_c = \frac{2\sigma^*_{11} t_{UD}}{\tau_Y}. \tag{2}$$

The interface is assumed elastic-plastic with a constant shear stress at the interface. Taken in this case as the 'yield' point of the matrix in shear, $\tau_Y = 55$ MPa [1]. Fragmentations continue to occur until the stress in the 0° is no longer uniform at any point and the material has broken into pieces between $l_c/2$ and $l_c$ in length, known as fragmentation saturation.

Additional to the fragmentations, Mode II delaminations may also take place at the $-\theta/0$ interfaces. Equation 3 defines whether these delaminations will occur over the course of the stress plateau following the initial fracture of the 0°.

$$\sigma_{del} = \frac{1}{t_{AP} + t_{UD}} \sqrt{\frac{2G_{IIc} E_x^{AP} t_{AP} (E_x^{AP} t_{AP} + E_{11} t_{UD})}{E_{11} t_{UD}}} \tag{3}$$

The critical strain energy release rate for Mode II delaminations is given by $G_{IIc} = 0.75$ N/mm (determined from experimental testing of laminates discussed in [7]). The accumulation of fragmentation and dispersed delaminations, as well as the non-linear stress-strain behaviour of the $\pm\theta$ plies, lead to a reduction in $\sigma_{del}$ as the strain on the laminate increases. It can be seen that the relative thickness of the $\pm\theta$ and 0° plies, $t_{AP}$ and $t_{UD}$ respectively, also have an influence on the delamination stress level. For example, an increase in $t_{UD}$ for a given $t_{AP}$ will cause $\sigma_{del}$ to reduce.

If $\sigma_{del}$ is decreased to the point at which it is equal to $\sigma_x$ at the initial fracture of the 0°, then a large, unstable delamination will occur at the $\theta/0$ interface. A large load drop follows and greatly reduces the integrity of the laminate. An improved situation is if $\sigma_{del} > \sigma_x$ when the 0° fractures, but then reduces to the level of the stress plateau. This means that fragmentations will occur prior to delaminations, which will be local to each fragmentation and only propagate a short distance from the fracture. These dispersed delaminations represent a stable accumulation of damage and do not lead to a drop in stress after the initial 0° fracture.

Following saturation of fragmentations and delaminations, the $\pm\theta$ plies carry the majority of the stress on the laminate. As such, the models assumes that the failure of the laminate is dependent on the angle-ply strength and occurs when the following relation is satisfied:

$$\sigma^*_{AP} \leq \sigma_{AP} = \sigma_x \frac{t}{t_{AP}} \tag{4}$$

At this point the model halts without additional increments and stores all relevant data.

## 3. Analytical predictions for $[\pm\theta/\underline{0}]_s$ laminates

The analytical model has been used to give stress-strain predictions of $[\pm\theta/\underline{0}]_s$ configurations that will give the optimal pseudo-ductile performance as sub-laminates in a multidirectional laminate. Consistent with [7], North Thin Ply Technology (NTPT) CFRP containing the following ultra high modulus carbon fibre has been selected for the 0° ply: Nippon Graphite YSH-70A ($E_f = 720$ GPa [8]). This material shall be paired with an intermediate modulus SK Chemicals Skyflex UIN020 (MR60 carbon fibre, $E_f$

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Table 1: Material properties of CFRP containing MR60 and YSH70A.

| Material Type | $E_{11}$ [GPa] | $E_{22}$ [GPa] | $G_{12}$ [GPa] | $\nu_{12}$ | $\sigma^*_{11}$ [MPa] | $\epsilon^*_{11}$ [%] | $t_p$ [mm] |
|---|---|---|---|---|---|---|---|
| UIN020 | 146 | 6.6 | 2.9 | 0.29 | 2800 | 1.9 | 0.025 |
| NTPT YSH70A | 362 | 6.0 | 4.0 | 0.3 | 1810 | 0.5 | 0.030 |

= 290 GPa [9]) that will make up the $\pm\theta$ plies. This material combination will be referred to hence as: UIN-YSH70. The material properties for these materials are presented in Table 1.

Predictions commence with $\theta = 20°$, as it has been shown previously that $[\pm\theta_5]_s$ laminates with fibre angles below this value do not result in any significant non-linear behaviour under tensile loading [1]. The fibre angle has been incremented by 1° over the range $20° \geq \theta \leq 25°$ and the results collated on a single stress-strain plot.

### 3.1. UIN-YSH layups

The predictions for the UIN-YSH combinations presented in Figure 1 show pseudo-ductility across the entire range of $\pm\theta$ angles. All configurations display three distinct regions on the stress-strain plot: an initial linear response; stress plateau, and further loading up to laminate failure. All pseudo-ductility is due to fragmentation only, no dispersed delaminations are predicted to occur for these layups. Up to the initial YSH-70A fibre failure at $\epsilon_x = 0.5\%$, these layups each display a high initial modulus — $E_{x\text{i}}$ increases from 135 GPa to 150 GPa as $\pm\theta$ goes from 25° to 20°. These values are very promising, as they are in line with standard modulus CFRP, such as AS4-8552.

Though there is limited difference between the plateau stress levels for each layup, the effect of the angle-ply fibre direction on the pseudo-ductility and strength can be clearly seen in Figure 1. The $[\pm 20/\underline{0}]_s$ has the shortest fragmentation plateau with a subsequent large increase in stress up to failure at 1246 MPa. This sort of stress-strain behaviour gives a very conservative but inefficient use of the layup, because the fragmentation stress is much lower than the strength. Maximising pseudo-ductility is key, so the $[\pm 25/\underline{0}]_s$ presents the best choice for a sub-laminate. The initial modulus and fragmentation stress of 135 GPa and 653 MPa, respectively, are not reduced greatly from the $[\pm 20/\underline{0}]_s$ layup, but the pseudo-ductile strain is much improved from $\epsilon_d = 1.16\%$ to $\epsilon_d = 1.43\%$. In addition, the $[\pm 25/\underline{0}]_s$ layup has a margin of 108 MPa between the fragmentation stress and strength. This is a much more efficient layup, but the margin should be sufficient to avoid failure before fragmentation saturation.

## 4. Multidirectional laminates

Having selected a sub-laminate layup for the UIN-YSH material combination, it has been arranged into multidirectional stacking sequences. A standard quasi-isotropic (QI) [0/45/90] layup has not been chosen, as the 90° plies will constrain the angle-ply fibre rotation that is vital to the non-linear behaviour. The selected laminate stacking sequences are: $[30/0/-30]_s$ and $[45/0/-45]_s$, where these global orientations correspond to the direction of the high modulus ply in each sub-laminate. Written out in full, with the global orientations given in bold, each laminate is as follows:

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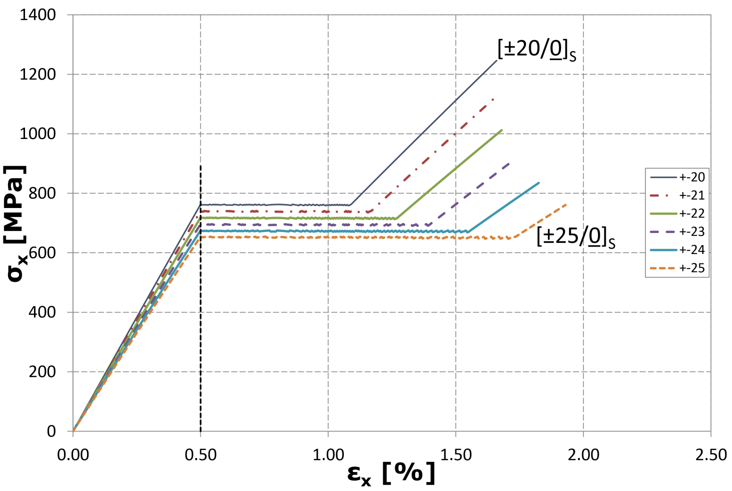


Figure 1: Analytical predictions for UIN-YSH [$\pm\theta/\underline{0}$]$_s$ configurations. For 20° ≤ $\theta$ ≥ 25°, all layups display a pseudo-ductile response. The vertical dashed line indicates the point of initial fracture of the 0° ply.

- UIN-YSH
  - [30/0/ − 30]$_s$ → [(55/5/**30**/5/55)/(25/ − 25/**0**/ − 25/25)/(−5/ − 55/**-30**/ − 55/ − 5)]$_s$
  - [45/0/ − 45]$_s$ → [(70/20/**45**/20/70)/(25/ − 25/**0**/ − 25/25)/(−20/ − 70/**-45**/ − 70/ − 20)]$_s$

The use of high stiffness [±25/$\underline{0}$]$_s$ sub-laminates means that the homogenised laminate properties are also very respectable. The [30/0/ − 30]$_s$ and [45/0/ − 45]$_s$ laminates have an laminate modulus of $E_x$ = 106 GPa and $E_x$ = 86 GPa respectively, which gives them an excellent initial load carrying capability. An additional benefit of using these sub-laminates, rather than UD plies, is that the fibre directions are well distributed through the thickness of the laminate. This in turn improves the laminate transverse and shear modulus, as shown in Table 2.

### 4.1. Stress distribution at fragmentation initiation

Classical laminate analysis (CLA) has been employed to check the stress state in the laminates at the point of fragmentation initiation, immediately prior to non-linearity. The ultra high moduli of the YSH-70A fibres means that the plies oriented in the $x$-direction will take the majority of the loading up their failure point. It is important to check that the stresses in the adjacent UIN plies are sufficiently low that failure does not occur with the first fibre fracture. Figures 2a and 2b detail the fibre direction ply stresses,

Table 2: Multidirectional laminate properties of UIN-YSH [30/0/ − 30]$_s$ and [45/0/ − 45]$_s$.

| Material Type | $E_x$ [GPa] | $E_y$ [GPa] | $G_{xy}$ [GPa] | $\nu_{xy}$ | $t_p$ [mm] |
|---|---|---|---|---|---|
| [30/0/ − 30]$_s$ | 106 | 23 | 26 | 0.91 | 0.78 |
| [45/0/ − 45]$_s$ | 86 | 43 | 29 | 0.55 | 0.78 |

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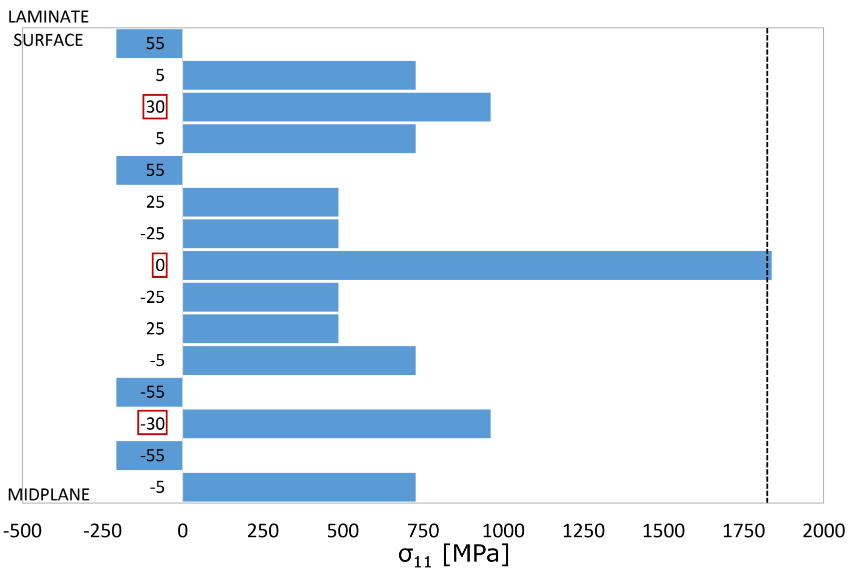
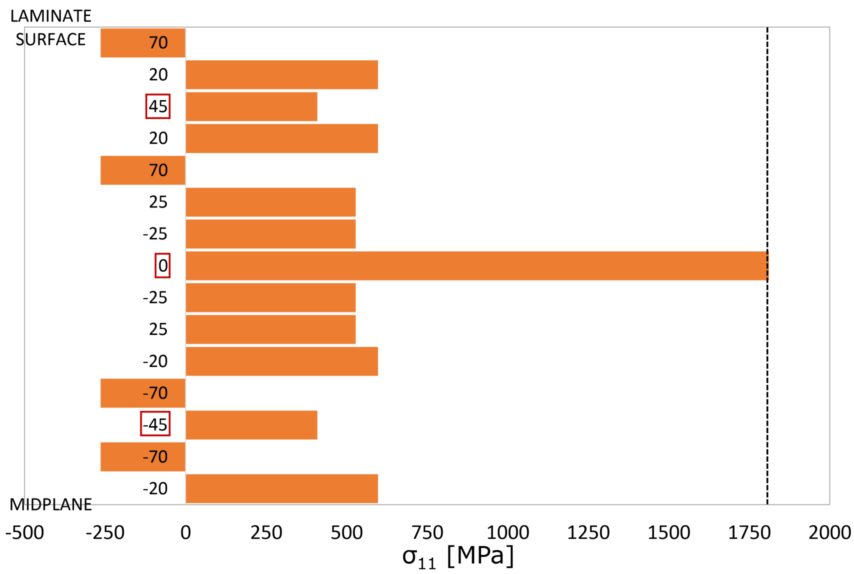
$\sigma_{11}$, in the $[30/0/-30]_s$ and $[45/0/-45]_s$ laminates respectively. Due to symmetry, only one half of the laminate is shown in these plots.

Figures 2a and 2b show that the level of $\sigma_{11}$ is very low in the ±25° UIN plies adjacent to the YSH-70A, measuring 486 MPa and 528 MPa respectively. It is clear that these plies should not fail at the point of initial YSH-70A fracture, allowing the stress to be redistributed successfully. In both laminates, it is the ±30° and ±45° YSH plies that should take an increased stress following the failure of the 0° YSH ply and govern the subsequent stress-strain behaviour. The presence of ±70° plies in the $[45/0/-45]_s$ laminate may lead to a high stress transverse to the fibres, $\sigma_{22}$, and could influence the response. It is believed, however, that, as previously shown in [1], the very thin ply thickness of these layers, will




(a) $[30/0/-30]_s$




(b) $[45/0/-45]_s$

Figure 2: The ply-by-ply distributions of $\sigma_{11}$ in the $[30/0/-30]_s$ and $[45/0/-45]_s$ laminates at the point of initial YSH-70A fracture ($\epsilon_x = 0.5\%$) are shown. Due to laminate symmetry, only half the plies are displayed in each case. The dashed line indicates the YSH-70A fibre direction failure stress, $\sigma_{11}^* = 1810$ MPa.

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suppress damage, such as matrix cracking, and allow the development of pseudo-ductile strain in the laminate. Further analysis of these laminates, using a progressive damage approach is necessary to better understand how the failure of each ply will occur following the initial YSH fracture.

## 5. Conclusions

The pseudo-ductile tensile stress-strain responses of thin ply CFRP $[\pm\theta/\underline{0}]_s$ layups have been predicted using an established analytical modelling procedure and then combined as sub-laminates in multidirectional stacking sequences.

Using SK Chemicals Skyflex UIN020 containing intermediate modulus MR60 carbon fibres and North TPT with ultra high modulus YSH70A, as the $\pm\theta$ and 0° plies, respectively, the modelling has shown that gradual failure of the $[\pm\theta/\underline{0}]_s$ should be possible over the range of $20° \geq \theta \leq 25°$. Pseudo-ductile strain is seen to increase with $\pm\theta$ fibre angle, but the presence of YSH70A fibres limits the reduction of the initial modulus — $E_{xi}$ varies from 150 GPa for 20° to 135 GPa at 25°. In selecting a sub-laminate layup, pseudo-ductility was maximised by using the $[\pm25/\underline{0}]_s$. Though a lower strength and modulus, the pseudo-ductile strain was predicted to be 1.43%, compared to 1.16% for the highest strength configuration of $[\pm20/\underline{0}]_s$.

This chosen sub-laminate has been used to analyse multidirectional laminates with global stacking sequences of $[30/0/-30]_s$ and $[45/0/-45]_s$, where the orientations correspond to the direction of the high modulus 0° ply of each sub-laminate. CLA has indicated that these laminates possess respectable values of modulus at 106 GPa and 86 GPa for the $[30/0/-30]_s$ and $[45/0/-45]_s$, respectively. Importantly, prior to the initial failure of the YSH70A fibres, CLA also shows that the YSH70A fibres take the majority of the load on the laminate and the stresses in the surrounding UIN020 plies are very much lower. This suggests that the laminates will not fail catastrophically at the point of initial fracture, allowing stress to redistribute and the gradual failure of the $[\pm25/\underline{0}]_s$ sub-laminates to occur. Further work is required to confirm this via progressive damage analysis and experimental testing.

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