On Extension-Shearing Coupled Laminates

C B York*

Aerospace Sciences, School of Engineering, University of Glasgow, University Avenue, G12 8QQ, Glasgow, Scotland.

Abstract

The definitive list of *Extension-Shearing* coupled composite laminates with up to 21 plies is derived. The listings comprise of individual stacking sequences of entirely non-symmetric laminates, are characterized in terms of angle- and cross-ply sub-sequence relationships as well as the blend-ratio of unbalanced angle-plies. Dimensionless parameters, including lamination parameters, are provided, from which the extensional and bending stiffness terms are readily calculated. Because this new class of coupled non-symmetric laminate possesses in-plane coupling behaviour only it can also be manufactured flat under a standard elevated temperature curing process. Such laminates can be configured to produce bending-twisting coupling in wing-box type structures, which can be exploited to great effect in the design for passive load alleviation in wind-turbine blades, or for aero-elastic compliance in fixed wing aircraft or helicopter rotor-blades. It should be recognised that similar behaviour can also be achieved using less sophisticated designs, such as applying off-axis material alignment to otherwise balanced and symmetric laminates or by using un-balanced and symmetric

---

* Corresponding author:

Tel: +44 (0)141 3304345, E-mail address: Christopher.York@Glasgow.ac.uk

designs, but additional forms of coupling behaviour arise in these cases, leading to detrimental effects on both stiffness and strength, which are demonstrated though comparisons of the structural response of competing laminate designs.

Keywords

Bending-Twisting coupling; Buckling; Extensional (or Membrane) Anisotropy; Extension-Shearing Coupling; Non-dimensional Stiffness Parameters; Lamination Parameters; Laminate Stacking Sequences.

Nomenclature

A, A_{ij}	=	extensional stiffness matrix and its elements (i,j = 1, 2, 6)
B, B_{ij}	=	coupling stiffness matrix and its elements (i,j = 1, 2, 6)
D, D_{ij}	=	bending stiffness matrix and its elements (i,j = 1, 2, 6)
$E_{1,2}$, G_{12}	=	in-plane Young's moduli and shear modulus
H	=	laminate thickness (= number of plies, $n \times$ ply thickness, t)
$M_{x,\, y,\, xy}$	=	moment resultants
$N_{x,\, y,\, xy}$	=	force resultants
n	=	number of plies in laminate stacking sequence
Q_{ij}	=	reduced stiffness (i,j = 1, 2, 6)
Q'_{ij}	=	transformed reduced stiffness (i,j = 1, 2, 6)
t	=	ply thickness
U_i	=	laminate invariant (i = 1,2,3,4,5)
x,y,z	=	principal axes
z_k	=	layer k interface distance from laminate mid-plane
$\alpha_{1,2}$, α_{Iso}	=	principal and isotropic coefficients of thermal expansion
$\boldsymbol{\varepsilon}$	=	vector of in-plane strains (= $\{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}^T$)
$\boldsymbol{\kappa}$	=	vector of curvatures (= $\{\kappa_x, \kappa_y, \kappa_{xy}\}^T$)
ν_{ij}	=	Poisson ratio (i, j = 1, 2)
θ_k	=	ply orientation for layer k
$\xi_{1\text{-}4}$	=	lamination parameters for extensional stiffness
$\xi_{9\text{-}10}$	=	lamination parameters for bending stiffness

ζ = bending stiffness parameter for laminate (= n^3)

$\zeta_{\pm}$ = bending stiffness parameter for angle-ply sub-sequence

$\zeta_{\circ}, \zeta_{\bullet}$ = bending stiffness parameter for cross-ply sub-sequences

$+, -, \pm$ = angle plies, used in stacking sequence definition

$\circ, \bullet$ = cross-plies, used in stacking sequence definition

Matrix sub-scripts

0 = All elements zero

F = All elements Finite

S = Specially orthotropic or *Simple* form, see Eqs. (3) - (4)

1. Introduction

This article focuses on the identification of laminated composite materials possessing isolated mechanical *Extension-Shearing* coupling, i.e., with no other coupling present.

It is one of a series, providing a unified approach to the characterization of coupled composite laminates. The first article [1] in the series identified the 24 unique classes of thermo-mechanically coupled laminate, incorporating all possible interactions between *Extension*, *Shearing*, *Bending* and *Twisting*. Novel nomenclature and associated behavioural descriptors were developed for each laminate class; the relevant aspects of which are summarised below. Benchmark configurations were also derived with behaviour similar to conventional materials, such as metals, and against which all unique forms of laminate behaviour, arising from isolated or combined mechanical coupling effects, are now being systematically characterised.

Laminated composite materials can be characterized in terms of their response to mechanical (and/or thermal) loading, which is associated with a description of the coupling behaviour, unique to this type of material, i.e. coupling between in-plane (i.e. extension or membrane) and out-of-plane (i.e. bending or flexure) responses when $B_{ij} \neq 0$ in Eq. (1), coupling between in-plane shearing and extension when $A_{16} = A_{26} \neq 0$, and coupling between out-of-plane bending and twisting when $D_{16} = D_{26} \neq 0$.

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ & A_{22} & A_{26} \\ \text{Sym.} & & A_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \tau_{xy} \end{Bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ & B_{22} & B_{26} \\ \text{Sym.} & & B_{66} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ & B_{22} & B_{26} \\ \text{Sym.} & & B_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \tau_{xy} \end{Bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ & D_{22} & D_{26} \\ \text{Sym.} & & D_{66} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \tag{1}$$

Whilst Eq. (1) describes the well-known **ABD** relation from classical laminate plate theory, it is more often expressed using compact notation:

$$\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \end{Bmatrix} \tag{2}$$

The coupling behaviour, which is dependent on the form of the elements in each of the extensional [**A**], coupling [**B**] and bending [**D**] stiffness matrices is now described by an extended subscript notation, defined previously by the Engineering Sciences Data Unit, or ESDU [2] and subsequently augmented for the purposes of this article. Hence, balanced and symmetric stacking sequences, which generally give rise to coupling between bending and twisting and are referred to by the designation $\mathbf{A}_S\mathbf{B}_0\mathbf{D}_F$, signifying that the elements of the extensional stiffness matrix [**A**] are simple or specially orthotropic in nature, i.e. uncoupled, since:

$$A_{16} = A_{26} = 0, \tag{3}$$

the bending-extension coupling matrix [**B**] is null, whilst all elements of the bending stiffness matrix [**D**] are finite, i.e. $D_{ij} \neq 0$.

Laminates possessing coupling between in-plane shearing and extension only and, by the same rationale, are referred to by the designation $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$, signifying that all elements of the extensional stiffness matrix [**A**] are finite, i.e. $A_{ij} \neq 0$, the bending-extension coupling matrix (**B**) is null, and the elements of the bending stiffness matrix [**D**] are specially orthotropic in nature, i.e. uncoupled, since:

$$D_{16} = D_{26} = 0 \tag{4}$$

This designation is however not listed as part of the ten laminate classifications described in the ESDU data item [2]. Extensional anisotropy, or more appropriately, *Extension-Shearing* coupling, is discussed at length in much of the preamble of articles on anisotropic composite laminate materials, but no specific details of stacking sequences for such laminates are given, particularly in the context of laminates with standard ply orientations for use in air vehicle construction. Indeed recently published work [3], describing in detail an application for laminates with shear-extension coupling reveals, only through additional calculation of the laminate stiffness terms, that significant *Bending-Twisting* coupling also exists in the stacking sequences adopted. These observations suggest that there is no other currently published or accessible data on composite laminate materials with *Extension-Shearing* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$) properties. Indeed, this class of coupled non-symmetric laminate can be manufactured flat under a standard elevated temperature curing process given the absence of bending-extension coupling; elastic coupling in non-symmetric laminates is generally understood to produce warping, with respect to the intended shape.

This article presents therefore the definitive list of angle-ply stacking sequences for *Extension-Shearing* (***E-S***) coupling, with the designation $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$, together with the dimensionless stiffness parameters from which the elements of the extensional (**A**) and bending stiffness (**D**) matrices are readily calculated. These new stacking sequences complement the definitive list of Fully Orthotropic (or *Simple*) laminates, with the designation $\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$, for up to 21 plies [4].

2. Derivation of stacking sequences

Bartholomew [5] performed the original work in establishing a definitive list of specially orthotropic laminate stacking sequences ($\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$), from which the

Engineering Sciences Data Unit (ESDU) has since published [6] the so called definitive list with up to 21 plies, including information on extending this list by the addition of orthotropic plies on the top and bottom surface of the laminate. The list contains 75 symmetric sequences and 653 anti-symmetric sequences, together with 49 additional non-symmetric (asymmetric) sequences. This relatively small number of possible sequences for thin laminates clearly leaves limited scope for composite tailoring, particularly where ply terminations are necessary and specially orthotropic characteristics are a design requirement, and was the key motivation leading to the re-development of the definitive list for fully uncoupled, or specially orthotropic laminates with up to 21 plies [4], including the scope for laminate taper [7]. In the derivation of this revised list for standard ply configurations, e.g. ±45, 0 and 90°, the general rule of symmetry is relaxed. Cross plies, as well as angle plies, are therefore no longer constrained to be symmetric about the laminate mid-plane. Consequently, the mixing of 0 and 90° plies requires special attention to avoid violation of the rules for special orthotropy. The resulting sequences are characterized by sub-sequence symmetries using a double prefix notation, the first character of which relates to the form of the angle-ply sub-sequence and the second character to the cross-ply sub-sequence. The double prefix contains any combination of the following characters: *A* to indicate Anti-symmetric (angle plies only); *C* for cross-symmetric (cross plies only); *N* for Non-symmetric; and *S* for Symmetric. To avoid the trivial solution of a stacking sequence with cross plies only, all laminates have an angle-ply (+) on one surface of the laminate. As a result, the other surface ply may have equal (+) or opposite (−) orientation or it may indeed be a cross ply (○) of 0 or 90° orientation. A subscript notation, using these three symbols, is employed to differentiate between similar forms of sequence. The form (and number of sequences) in the definitive list [4] can be summarized as: *AA* (210), *AN* (14,532), *AS* (21,609), *SC* (12), *SN* (192), *SS* (1,029), $_{+}NS_{+}$ (220), $_{+}NS_{-}$ (296), $_{+}NN_{+}$ (5,498), $_{+}NN_{-}$ (15,188) and $_{+}NN_{\circ}$ (10,041). This is in contrast to the published [6] listings, containing *S* (75), *A* (653) and undefined (49) non-symmetric stacking sequences for laminates with up to 21 plies.

Extensional stiffness terms $A_{16} = A_{26} = 0$ are the key characteristics for specially orthotropic form. However, for computational expedience, this check was not formally included in the algorithm used to determine the definite list of Fully Orthotropic Laminates [4], because a simple check confirming that angle plies are balanced, i.e. that $n_+ = n_-$, is sufficient. This check led to the identification of a rather surprising and highly significant by-product with $A_{16} = A_{26} \neq 0$, resulting from $n_+ \neq n_-$, but with $B_{ij} = D_{16} = D_{26} = 0$, i.e. laminates with extensional anisotropy or *Extension-Shearing* coupling, and referred to by the designation $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$. Table 1 provides a summary of the number of *Extension-Shearing* coupled stacking sequences for each ply-number grouping up to a maximum of 21 plies and provides cross-referencing to the tables of laminate stacking sequences that follow in the appendix of supplementary data.

2.1 Arrangement and form of stacking sequence data

For compatibility with the previously published data, similar symbols have been adopted for defining all of the stacking sequences that follow. Additional symbols and parameters are necessarily included to differentiate between cross plies (0° and 90°), given that symmetry about the laminate mid-plane is no longer assumed. Also in common is the assumption of constant ply thickness throughout the laminate.

As adopted in the published ESDU listings [6], the new sequences are ordered in terms of ascending numbers of plies, n, or bending stiffness parameter ζ (= n^3), which are in turn ordered by ascending value of the bending stiffness parameter for the angle plies ($\zeta_\pm$) and finally by one of the two cross ply sub-sequences ($\zeta_\circ$) within the laminate. This ordering provides each sequence with a unique designation. The sequences are then listed in Tables A5 – A8 according to sub-sequence symmetry, with form (and number of sequences) $_+NN_+$ (296), $_+NN_-$ (28) and $_+NN_\circ$ (14).

The stiffness parameters are hereby extended to include both cross plies ($\zeta_\circ$ and $\zeta_\bullet$), including percentage values to indicate the relative proportion ($n_\pm/n$, $n_\circ/n$ and $n_\bullet/n$) and relative contribution to bending stiffness ($\zeta_\pm/\zeta$, $\zeta_\circ/\zeta$ and $\zeta_\bullet/\zeta$) of each ply sub-sequence within the laminate, i.e. a sub-sequence containing either ±, ○ or ● plies.

Comparison of the relative proportion and the contribution to bending stiffness provides a measure of efficiency of the sub-laminate for each ply orientation, in the same sense that the radius of gyration, relating cross-sectional area and second moment of area, provides as assessment of the geometric efficiency of a beam to resist bending.

Whilst the elements of the bending stiffness matrix [**D**] are readily obtained from $\zeta_\pm$, $\zeta_\circ$ and $\zeta_\bullet$, as for *Simple* or fully uncoupled laminates ($\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$), the elements of the extensional stiffness matrix [**A**] now require a modification with respect to the blend ratio of angle plies. Blend ratio is defined elsewhere [3] as the percentage proportion of negative (n_-) to positive (n_+) plies. It is redefined here however, to simplify the calculation of the elements of the extensional stiffness matrix, as the ratio of the number of positive (n_+) plies to the total number of angle plies ($n_\pm$), expressed as a percentage. The laminate sequences of Table A5 possess a blend ratio of 20%, whereas Tables A6, A7 and A8 have blend ratios of 28.6%, 71.4% and 28.6%, respectively. All stacking sequences presented in Tables A5 - A8 have even-ply numbers with non-symmetric angle-ply and cross-ply sub-sequences.

2.2 Calculation of extensional, coupling and bending stiffness terms

The calculation procedure for the elements of the extensional [**A**] and bending [**D**] stiffness matrices, using the dimensionless parameters provided in Tables 2 – 5, are as follows:

$$A_{ij} = \{n_{\pm}(n_{+}/n_{\pm})Q'_{ij+} + n_{\pm}(1 - n_{+}/n_{\pm})Q'_{ij-} + n_{\circ}Q'_{ij\circ} + n_{\bullet}Q'_{ij\bullet}\} \times t \tag{5}$$

$$D_{ij} = \{\zeta_{\pm}/2 \times Q'_{ij+} + \zeta_{\pm}/2 \times Q'_{ij-} + \zeta_{\circ}Q'_{ij\circ} + \zeta_{\bullet}Q'_{ij\bullet}\} \times t^3/12 \tag{6}$$

The form of Eq. (6) was chosen because it is then readily modified to account for laminates with bending anisotropy by replacing $\zeta_{\pm}/2 \times Q'_{ij+}$ with $\zeta_{\pm}(\zeta_{+}/\zeta_{\pm}) \times Q'_{ij+}$ or $\zeta_{+} \times Q'_{ij+}$, and $\zeta_{\pm}/2 \times Q'_{ij-}$ with $\zeta_{\pm}(1 - \zeta_{+}/\zeta_{\pm}) \times Q'_{ij-}$, or $\zeta_{-} \times Q'_{ij-}$. The use of this modified equation requires the calculation of an additional stiffness parameter, ζ_{+}, relating to the bending stiffness contribution of positive (θ) angle plies.

The transformed reduced stiffness terms in Eqs. (5) and (6) are given by:

$$\begin{aligned}
Q'_{11} &= Q_{11}\cos^4\theta + 2(Q_{12} + 2Q_{66})\cos^2\theta\sin^2\theta + Q_{22}\sin^4\theta \\
Q'_{12} &= Q'_{21} = (Q_{11} + Q_{22} - 4Q_{66})\cos^2\theta\sin^2\theta + Q_{12}(\cos^4\theta + \sin^4\theta) \\
Q'_{16} &= Q'_{61} = \{(Q_{11} - Q_{12} - 2Q_{66})\cos^2\theta + (Q_{12} - Q_{22} + 2Q_{66})\sin^2\theta\}\cos\theta\sin\theta \\
Q'_{22} &= Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{66})\cos^2\theta\sin^2\theta + Q_{22}\cos^4\theta
\end{aligned} \tag{7}$$

$$Q'_{26} = Q'_{62} = \{(Q_{11} - Q_{12} - 2Q_{66})\sin^2\theta + (Q_{12} - Q_{22} + 2Q_{66})\cos^2\theta\}\cos\theta\sin\theta$$

$$Q'_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\cos^2\theta\sin^2\theta + Q_{66}(\cos^4\theta + \sin^4\theta)$$

and the reduced stiffness terms by:

$$\begin{aligned} Q_{11} &= E_1/(1 - \nu_{12}\nu_{21}) \\ Q_{12} &= \nu_{12}E_2/(1 - \nu_{12}\nu_{21}) = \nu_{21}E_1/(1 - \nu_{12}\nu_{21}) \\ Q_{22} &= E_2/(1 - \nu_{12}\nu_{21}) \\ Q_{66} &= G_{12} \end{aligned} \tag{8}$$

For optimum design of angle ply laminates, lamination parameters are often preferred, since these allow the stiffness terms to be expressed as linear variables. The optimized lamination parameters may then be matched against a corresponding set of laminate stacking sequences. In the context of the parameters presented in the current article, the necessary six lamination parameters are related through the following expressions:

$$\begin{aligned} \xi_1 &= \{n_\pm(n_+/n_\pm)\cos(2\theta_+) + n_\pm(1 - n_+/n_\pm)\cos(2\theta_-) + n_\circ\cos(2\theta_\circ) + n_\bullet\cos(2\theta_\bullet)\}/n \\ \xi_2 &= \{n_\pm(n_+/n_\pm)\cos(4\theta_+) + n_\pm(1 - n_+/n_\pm)\cos(4\theta_-) + n_\circ\cos(4\theta_\circ) + n_\bullet\cos(4\theta_\bullet)\}/n \\ \xi_3 &= \{n_\pm(n_+/n_\pm)\sin(2\theta_+) + n_\pm(1 - n_+/n_\pm)\sin(2\theta_-) + n_\circ\sin(2\theta_\circ) + n_\bullet\sin(2\theta_\bullet)\}/n \\ \xi_4 &= \{n_\pm(n_+/n_\pm)\sin(4\theta_+) + n_\pm(1 - n_+/n_\pm)\sin(4\theta_-) + n_\circ\sin(4\theta_\circ) + n_\bullet\sin(4\theta_\bullet)\}/n \end{aligned} \tag{9}$$

relating to extensional stiffness, and

$$\begin{aligned} \xi_9 &= \{\zeta_\pm(\zeta_+/\zeta_\pm)\cos(2\theta_+) + \zeta_\pm(1 - \zeta_+/\zeta_\pm)\cos(2\theta_-) + \zeta_\circ\cos(2\theta_\circ) + \zeta_\bullet\cos(2\theta_\bullet)\}/\zeta \\ \xi_{10} &= \{\zeta_\pm(\zeta_+/\zeta_\pm)\cos(4\theta_+) + \zeta_\pm(1 - \zeta_+/\zeta_\pm)\cos(4\theta_-) + \zeta_\circ\cos(4\theta_\circ) + \zeta_\bullet\cos(4\theta_\bullet)\}/\zeta \end{aligned} \tag{10}$$

where the bending stiffness parameter $\zeta_+ = \zeta_- = \zeta_\pm/2$ for ($A_FB_0D_S$) laminates contained in this article, hence Eqs. (10) reduce to:

$$\xi_9 = \{\zeta_\pm\cos(2\theta_\pm) + \zeta_\circ\cos(2\theta_\circ) + \zeta_\bullet\cos(2\theta_\bullet)\}/\zeta$$
$$\xi_{10} = \{\zeta_\pm\cos(4\theta_\pm) + \zeta_\circ\cos(4\theta_\circ) + \zeta_\bullet\cos(4\theta_\bullet)\}/\zeta \qquad (11)$$

Elements of the fully populated extensional stiffness matrix [**A**] are related to the lamination parameters [8] by:

$$A_{11} = \{U_1 + \xi_1 U_2 + \xi_2 U_3\} \times H$$
$$A_{12} = A_{21} = \{-\xi_2 U_3 + U_4\} \times H$$
$$A_{16} = A_{61} = \{\xi_3 U_2/2 + \xi_4 U_3\} \times H$$
$$A_{22} = \{U_1 - \xi_1 U_2 + \xi_2 U_3\} \times H \qquad (12)$$
$$A_{26} = A_{62} = \{\xi_3 U_2/2 - \xi_4 U_3\} \times H$$
$$A_{66} = \{-\xi_2 U_3 + U_5\} \times H$$

and the *Simple* or uncoupled bending stiffness matrix [**D**] by:

$$D_{11} = \{U_1 + \xi_9 U_2 + \xi_{10} U_3\} \times H^3/12$$
$$D_{12} = \{U_4 - \xi_{10} U_3\} \times H^3/12$$
$$D_{22} = \{U_1 - \xi_9 U_2 + \xi_{10} U_3\} \times H^3/12 \qquad (13)$$
$$D_{66} = \{-\xi_{10} U_3 + U_5\} \times H^3/12$$

where the laminate invariants are given in terms of the reduced stiffnesses of Eqs. (8) by:

$U_1 = \{3Q_{11} + 3Q_{22} + 2Q_{12} + 4Q_{66}\}/8$

$U_2 = \{Q_{11} - Q_{22}\}/2$

$U_3 = \{Q_{11} + Q_{22} - 2Q_{12} - 4Q_{66}\}/8$ (14)

$U_4 = \{Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66}\}/8$

$U_5 = \{Q_{11} + Q_{22} - 2Q_{12} + 4Q_{66}\}/8$

2.3 Example calculations

For IM7/8552 carbon-fiber/epoxy material with Young's moduli E_1 = 161.0GPa and E_2 = 11.38GPa, shear modulus G_{12} = 5.17GPa and Poisson ratio $\nu_{12} = 0.38$, lamina thickness *t* = 0.1397mm and stacking sequence *NN 58*: $[+/\bigcirc/-/+/-_5/\bigcirc/-/\bigcirc/-/\bigcirc/-/+_2/-]_T$, the non-dimensional parameters are verified by the calculations presented in Table 2, where the first two columns provide the ply number and orientation, respectively. Subsequent columns illustrate the summations, for each ply orientation, of $(z_k - z_{k\text{-}1})$, $(z_k^2 - z_{k\text{-}1}^2)$ and $(z_k^3 - z_{k\text{-}1}^3)$, relating to the **A**, **B** and **D** matrices, respectively. The distance from the laminate mid-plane, *z*, is expressed in term of ply thickness *t*, which is assumed to be of unit value.

The non-dimensional parameters arising from the summations of Table 2 are: n_+ (= ${}_A\Sigma_+$) = 4, n_- = 10 and $n_\bigcirc$ = 4, where $n_\pm$ = 14, and; ζ_+ (= 4 × ${}_D\Sigma_+$) = 2416, ζ_- = 2416 and $\zeta_\bigcirc$ = 1000, where $n^3 = 18^3 = \zeta = \zeta_+ + \zeta_- + \zeta_\bigcirc$ = 5832 and $\zeta_\pm$ = 4832. The **B** matrix summations confirm that $B_{ij} = 0$ for this laminate.

For fiber angles $\theta = \pm 45°$ and $0°$ in place of symbols $\pm$ and $\circ$ respectively, the transformed reduced stiffnesses are given in Table 4, which are readily calculated using Eqs. (7).

Through Eqs. (5) and (6), the final stiffness matrices are derived for the laminate:

$$\begin{bmatrix} A_{11} & A_{12} & A_{16} \\ & A_{22} & A_{26} \\ \text{Sym.} & & A_{66} \end{bmatrix} = \begin{bmatrix} 190{,}433 & 81{,}757 & -31{,}676 \\ & 105{,}963 & -31{,}676 \\ \text{Sym.} & & 83{,}771 \end{bmatrix} \text{N/mm}$$

$$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ & D_{22} & D_{26} \\ \text{Sym.} & & D_{66} \end{bmatrix} = \begin{bmatrix} 92{,}829 & 45{,}514 & 0 \\ & 58{,}485 & 0 \\ \text{Sym.} & & 46{,}575 \end{bmatrix} \text{N.mm}$$

given that:

$A_{16} = \{n_{\pm}(n_{+}/n_{\pm})Q'_{16+} + n_{\pm}(1 - n_{+}/n_{\pm})Q'_{16-} + n_{\circ}Q'_{16\circ}\} \times t$

$A_{16} = \{14 \times (4/14) \times 37{,}791 + 14(1 - 4/14) \times -37{,}791 + 4 \times 0\} \times 0.1397 = -31{,}676$ N/mm

and

$D_{16} = \{\zeta_{\pm}/2 \times Q'_{16+} + \zeta_{\pm}/2 \times Q'_{16-} + \zeta_{\circ}Q'_{16\circ}\} \times t^3/12$

$D_{16} = \{2416 \times 37{,}791 + 2416 \times -37{,}791 + 1000 \times 0\} \times 0.1397^3/12 = 0$ N.mm

Noting that $\xi_4 = 0$ for $\theta_+ = 45°$, the extensional lamination parameters (ξ_1, ξ_2 and ξ_3) are calculated from Eqs. (9):

$\xi_1 = \{n_{\pm}(n_{+}/n_{\pm})\cos(2\theta_{+}) + n_{\pm}(1 - n_{+}/n_{\pm})\cos(2\theta_{-}) + n_{\circ}\cos(2\theta_{\circ})\}/n$

$\xi_1 = \{14 \times (4/14) \times \cos(90°) + 14 \times (1 - 4/14) \times \cos(-90°) + 4 \times \cos(0°)\}/18 = 0.22$

$\xi_2 = \{n_{\pm}(n_{+}/n_{\pm})\cos(4\theta_{+}) + n_{\pm}(1 - n_{+}/n_{\pm})\cos(4\theta_{-}) + n_{\circ}\cos(4\theta_{\circ})\}/n$

ξ_2 = {14 × (4/14) × cos(180°) + 14 × (1 - 4/14) × cos(-180°) + 4 × cos(0°)}/18 = -0.56

$\xi_3 = \{n_\pm(n_+/n_\pm)\sin(2\theta_+) + n_\pm(1 - n_+/n_\pm)\sin(2\theta_-) + n_\bigcirc\sin(2\theta_\bigcirc)\}/n$

ξ_3 = {14 × (4/14) × sin(90°) + 14 × (1 - 4/14) × sin(-90°) + 4 × sin(0°)}/18 = -0.33

and the bending lamination parameters from Eqs. (11):

$\xi_9 = \{\zeta_\pm\cos(2\theta_\pm) + \zeta_\bigcirc\cos(2\theta_\bigcirc)\}/\zeta$

ξ_9 = {4832 × cos(90°) + 1000 × cos(0°)}/5832 = 0.17

$\xi_{10} = \{\zeta_\pm\cos(4\theta_\pm) + \zeta_\bigcirc\cos(4\theta_\bigcirc)\}/\zeta$

ξ_{10} = {4832 × cos(180°) + 1000 × cos(0°)}/5832 = -0.66

Lamination parameter design spaces, including all stacking sequences with up to 21 plies listed in the appendix, are illustrated in Figs (1) and (2). For standard ply orientations (±45°, 0° and 90°), these simplify to 3-dimensional extensional stiffness and 2-dimensional bending stiffness design spaces, respectively, with the bounds shown. The bounds on the extensional stiffness design space are also illustrated by way of an isometric plot for clarity.

A second stacking sequence $[-_2/+_2/\bigcirc/-/\bigcirc/-/\bigcirc/-_5/+_2/\bigcirc/-]_T$ is now presented, demonstrating the use of the modified stiffness equations described below Eq. (6), to account for laminates with *Bending-Twisting* coupling, i.e. $\mathbf{A_F B_0 D_F}$. Calculations for the non-dimensional parameters are presented in Table 3, using the same format as Table 2.

In this laminate the non-dimensional parameters arising from the summations are: n_+ (= ${}_A\Sigma_+$) = 4, n_- = 10 and $n_\bigcirc$ = 4, as before, but now ζ_+ (= 4 × ${}_D\Sigma_+$) = 1744, ζ_- = 3088 and

$\zeta_{\bigcirc}$ = 1000, where $n^3 = 18^3 = \zeta = \zeta_+ + \zeta_- + \zeta_{\bigcirc} = 5832$ and $\zeta_\pm = 4832$. The **B** matrix summations again confirm that $B_{ij} = 0$ for this laminate.

For the same material properties and fibre orientations used in the first example, the only change to the stiffness matrices between the two sequences involves the elements D_{16} and D_{26}, which are zero in the first and non-zero in the second, given that:

$$D_{16} = \{\zeta_+ \times Q'_{16+} + \zeta_- \times Q'_{16-} + \zeta_{\bigcirc} Q'_{16\bigcirc}\} \times t^3/12$$

$$D_{16} = \{1744 \times 37{,}791 + 3088 \times -37{,}791 + 1000 \times 0\} \times 0.1397^3/12 = -11{,}540 \text{ N.mm}$$

Writing the second stacking sequence in reverse order, i.e. $[-/\bigcirc/+_2/-_5/\bigcirc/-/\bigcirc/-/\bigcirc/+_2/-_2]_T$, does not change the laminate stiffness properties, but reveals that changes from the first sequence, i.e. $[+/\bigcirc/-/+/-_5/\bigcirc/-/\bigcirc/-/\bigcirc/-/+_2/-]_T$, involve only a switch in the signs of ply numbers 1, 3, 15 and 17.

3. Structural Response

This section presents a selection of results illustrating the effect of *Extension-Shearing* coupling behaviour. Such coupled laminates can be configured to produce *Bending-Twisting* coupling in wing-box type structures to achieve aero-elastic compliance in fixed wing aircraft or helicopter rotor-blades. This laminate tailoring concept can also be seen to extend to new geodesic fuselage designs, involving angled or helical stiffener arrangements [9], in order to counteract the tendency for *Bending-Twisting* coupling behaviour due to angled stiffeners at +ϕ on the inner surface of the fuselage skin and -ϕ on the outer surface.

Extension-Shearing behaviour can also be achieved by using less sophisticated designs, such as applying off-axis material alignment to otherwise balanced and symmetric laminates [10] or by using un-balanced and symmetric designs [3], but *Bending-Twisting* coupling behaviour arises in these cases, leading to detrimental effects on both stiffness and buckling strength, which is demonstrated by the structural response comparisons that follow for competing laminate designs with matching stiffness properties.

Comparisons are made against a fully uncoupled isotropic ($\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$) laminate datum configuration, and the *Extension-Shearing* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$) and *Extension-Shearing Bending-Twisting* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$) laminates derived in the previous section, where all elements of the **ABD** matrix are identical except for D_{16} and D_{26}, which are zero in the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ laminate. This latter comparison is particularly important given that $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminates may be readily derived using un-balanced and symmetric configurations, as has been demonstrated elsewhere [3]. The comparison also serves to isolate the effects of *Bending-Twisting* coupling, i.e. D_{16} and D_{26}.

3.1 Plate instability

In the first set of results, the linear (Eigenvalue) buckling response and non-linear load-deflection response of a compression (N_x) loaded, simply supported, square plate are considered, see Fig. 3.

Results were generated with the ABAQUS finite element code [11] using a thin plate element (S8R5), using the NAFEMS benchmark 3DNLG-6, for buckling of a flat plate with an initial imperfection when subjected to in-plane shear [12], but modified here for compression loading, as illustrated in Fig. 3. Plate dimensions of 250mm × 250mm, together with an 18-ply laminate, of total thickness $H = (n \times t = 18 \times 0.1397\text{mm} =)$ 2.51mm, ensure that the results are representative of the thin plate solution.

Eigenvalue results reveal that the *Extension-Shearing* and *Bending-Twisting* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$) laminate has a compression buckling strength 13.6% higher than the fully isotropic datum ($\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$) laminate, and that this increases to 15.9% when *Bending-Twisting* coupling is eliminated, i.e. for the *Extension-Shearing* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$) laminate.

Note that the $\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$ laminate datum configuration was chosen specifically to allow the Eigenvalue buckling load to be verified against the closed form buckling solution. Hence for compatibility, the boundary conditions for all cases were chosen such that at the plate centre, indicated by point (c) on Fig. 3(a), in-plane displacements, δ_x and δ_y, are prevented together with in-plane rotation, i.e. rotation about the z-axis. Out-of-plane displacement constraints, δ_z, are also applied to the plate perimeter. The NAFEMS benchmark 3DNLG-6 was found to converge to within approximately 2% of the closed form solution.

The $\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$ laminate stacking sequence is defined as *NN 1071*: $[\pm/-/\bigcirc_3/+_2/\bigcirc/\mp/\pm/-_2/\bigcirc_2/+]_T$, where the angle plies ± represent ±60°. By contrast to the stiffnesses presented in the previous section for the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ and $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminates, the stiffnesses for the $\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$ laminate are: $A_{11} = A_{22} = 173{,}473$, $A_{12} = 56{,}482$ and $A_{66} = 58{,}496$ N/mm, and $D_{Iso} = D_{11} = D_{22} = 91{,}409$, $D_{12} = 29{,}762$ and $D_{66} = 30{,}823$ N.mm. Note that the principal material axis, i.e. the 0 degree ply direction, corresponds to the x-axis of Fig. 3(a).

A fully uncoupled $\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$ laminate: $[\pm/\mp/\bigcirc_5]_A$ is also chosen for comparison since it has identical bending stiffness properties to the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ laminate: $[+/\bigcirc/-/+/-_5/\bigcirc/-/\bigcirc/-/\bigcirc/-/+_2/-]_T$.

The post-buckling results include a 1% (of the laminate thickness, *H*,) initial imperfection in the form of a single half-wave across both the length and width of the plate. A Riks analysis was performed to generate the results, with a maximum load of approaching twice the initial buckling load. The usual load-deflection curves for the out-of-plane response (δ_z) at the centre of the plate are presented in Fig. 3(c) for all three laminates, normalized against their respective Eigenvalue results, $N_{x,crit}$. Here the bifurcation point is difficult to determine. By contrast, the in-plane load-displacement behaviour offers greater fidelity. Figures 3(b) and (c) illustrate the in-plane displacements for the $\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$ and $\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$ laminates, respectively. The δ_x displacements at the two corner nodes, indicated by points (a) and (b) on the configuration sketch in Fig. 3, are identical, as expected, and represent end shortening. In-plane displacements δ_y are of equal and opposite magnitude and arise from Poisson ratio effects, which dissipate after buckling, hence the change in sign in the post-buckled state.

Figures 3(d) and (e) demonstrate that the responses of the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ and $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminates are identical up to initial buckling. However, the δ_x displacements are no longer identical and δ_y displacements are no longer of equal and opposite magnitude due to *Extension-Shearing* coupling. The responses of the two laminates differ in the post-buckled state due to the *Bending-Twisting* coupling of the latter, for which a mode change is apparent.

The effect of *Bending-Twisting* coupling also has a marked effect on shear buckling. This is seen from the buckling interaction curves of Figs (4) and (5). Figure (4) represents the results for a series of simply supported square plates joined end-to-end to form a long plate, supported at regular transverse intervals by ribs to form square bays. This is representative of classical 2-spar wing box construction, as illustrated in Fig. 6. The results for the fully isotropic laminate give rise to a compression buckling load factor k_x = 4.00, which is identical to the isolated square plate. However, mode interaction between adjacent bays when shear load is present leads to a higher buckling load factor than for the isolated plate. Figure (5) represents the results for an infinitely long plate, with ribs removed, also representing classical wing box construction, and for which the compression buckling load factor k_x = 4.00 for the fully isotropic laminate. Figures (4) and (5) together demonstrate that the relative increase in buckling interaction strength for each of the laminate comparators depends on geometry, boundary conditions and coupling stiffness magnitude. The *Simple* ($\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$) and *Extension-Shearing* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$) laminates share the same buckling envelope due to matching bending stiffness properties; unbalanced angle plies have no influence given that in-plane and out-of-plane actions are uncoupled, i.e. $\mathbf{B}$ = 0, and the bending stiffness is orthotropic. The buckling envelope is also symmetric, as expected, but buckling strength comparisons with the fully isotropic ($\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$) laminate, depend on boundary conditions. The effect of D_{16} and D_{26} is clearly visible from the buckling envelope of the *Extension-Shearing* and *Bending-Twisting* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$) laminate, which has matching orthotropic bending stiffness properties to the *Simple* ($\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$) and *Extension-Shearing* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$) laminates. Whilst compression buckling strength is always reduced, shear buckling strength is more favourable when the resulting principal compressive stress direction and the biased angle ply orientation (or principal bending stiffness direction) are in the same sense.

3.2 Static wing box behaviour

A second set of results is now considered for the wing-box configuration illustrated in Fig. 6, previously considered by Baker [3]. This symmetric structural configuration gives rise to bend-twist coupling deformation when unbalanced laminate skins are employed with their relative orientations aligned as shown. A similar configuration is used here, and again the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ and $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminates derived in the previous section are used for comparison, since all elements of the **ABD** matrix are identical except for D_{16} and D_{26}, which are zero in the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ laminate. The wing box structure is simplified as an open section rectangular box with a length of 5m, a width of 400mm and depth of 100mm. One end of the wing box is fully built in and a tip load of 1,000N is applied at the free end with the resultant coincident with the shear centre. This was applied though a reference node attached to nodes on the free edges of the wing box by rigid elements, from which the load-displacement behaviour could be then be interrogated. Modelling details are provided in Fig. 7.

The $\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$ laminate was first applied to all skins of the wing-box, resulting in a tip deflection of 134.77mm from a linear static analysis. The top and bottom skins were then replaced in turn by the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ laminate and then by the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminate. The $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$ skin configuration gave rise to an average tip displacement of 309.97mm, together with a tip rotation of 0.62°. The $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminate gave exactly the same results. These results suggest that *Bending-Twisting* coupling of the laminate skin panels has negligible effect on the magnitude of *Bending-Twisting* deformation of the wing box. The 0° fibre direction corresponds to the forward direction indicated on Fig. 6. This had the effect of reducing the axial stiffness along the wing, resulting in higher tip deflections that the isotropic laminate, and increasing the twist magnitude at the wing tip. It should be noted that these two laminate comparators were chosen for their matching stiffness properties rather than as a demonstration of the maximum twist that can be achieved through laminate tailoring. A geometrically non-linear analysis revealed that the twist magnitude for the $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$ laminate was augmented by approximately 13%, due to secondary *Bending-Twisting* at the laminate level. This will be investigated further in a subsequent article detailing the definitive list of laminates with *Extension-Shearing* and *Bending-Twisting* coupling ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$).

4. Tapering of Extension-Shear coupled laminates

It is well known that ply terminations of fewer than 4 plies, specifically in balanced and symmetric laminate construction, are problematic [7], and generally result in the localised introduction of undesirable mechanical coupling behaviour and thermal warping effects. Applying a tapered laminate design algorithm, developed for related work on terminations for standard [14] and non-standard [15] ply orientations, reveals that neither 2-ply nor 4-ply terminations are possible between any of the ply number groupings presented in this article, thus restricting the applicability of this class of laminate in practical construction; were ply terminations are generally required without changing the coupling characteristics of the material.

5. Conclusions

The definitive list of laminate stacking sequences for *Extension-Shearing* coupling, or extensional anisotropy, with up to 21 plies has been developed. The listings, which contain only even-ply number groupings with non-symmetric angle-ply and cross-ply sub-sequences, are presented along with dimensionless parameters from which the laminate stiffness matrix is readily calculated.

This class of coupled non-symmetric laminate can be manufactured flat under a standard elevated temperature curing process by virtue of the decoupled nature between in-plane and out-of-plane behaviour.

Like-with-Like comparisons of the structural response of laminates with matching stiffness properties reveal that those possessing *Bending-Twisting* coupling ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$) as well as *Extension-Shearing* coupling, and which can be constructed using unbalanced and symmetric designs, have no apparent additional benefit in terms of the *Bending-Twisting* coupling response of tailored wing-box structures, yet carry the penalty of a lower compression buckling strength compared to the new laminate class, presented herein, possessing *Extension-Shearing* coupling only ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$).

Acknowledgements and additional remarks

The author gratefully acknowledges Professor P. M. Weaver, from the University of Bristol, for highlighting the existence of a 36-ply symmetric laminate $[-_3/+_3/-/+_6/-/+_3/-]_S$ with extensional anisotropy ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$), which implies that there are more sub-sequence symmetries than those identified in the definitive list with up to 21 plies, presented herein. This is aligned with similar observations on Fully uncoupled Orthotropic Laminates ($\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$) in which only anti-symmetric sequences exist for laminates with 7, 8, 9, 10 and 11 plies; the many other sub-sequence symmetries, summarized in this article, are realized only as the number of plies is increased.

References

1. York, C. B. Unified approach to the characterization of coupled composite laminates: benchmark configurations and special cases. Journal of Aerospace Engineering 2010;23:219-242.

2. Engineering Sciences Data Unit. Stiffnesses of laminated plates. ESDU Item No. 94003, IHS, 1994.

3. Baker, D. Response of Damaged and Undamaged Tailored Extension-Shear-Coupled Composite Panels. J. Aircraft 2006;43:517-527.

4. York, C. B. Characterization of non-symmetric forms of fully orthotropic laminates." J. Aircraft 2009;46:1114-1125.

5. P. Bartholomew, “Ply stacking sequences for laminated plates having in-plane and bending orthotropy,” *Fibre Science and Technology*, Vol. 10, pp. 239-253, 1977.

6. Engineering Sciences Data Unit. Laminate stacking sequences for special orthotropy (Application to fibre reinforced composites). ESDU Item No. 82013, IHS, 1982.

7. York, C. B. On tapered warp-free laminates. Proceedings of the 3rd European Aeronautical Sciences Network (EASN/3) International Workshop on Aerostructures, Milano, 9-11 October 2013.

8. Tsai, S.W., Hahn, H.T. Introduction to composite materials. Technomic Publishing Co. Inc., Lancaster, 1980.

9. Niemann S., Kolesnikov B., Lohse-Busch H., Hühne C., Querin O. M., Toropov V. V. and Liu D. The use of topology optimization in the conceptual design of the next generation lattice composite aircraft fuselage structures. Aeronautical Journal, 2013;117:1139-1154.

10. Nixon, M.W. Extension-twist coupling of composite circular tubes with application to tilt rotor blade design. Proceedings of the 28th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials, Monterey, United states, Paper No. AIAA-87-0772, 1987.

11. ABAQUS/Standard, Version 6.12. Dassault Systèmes Simulia Corp., 2012.

12. Prinja, N. K. and Clegg, R. A. Assembly benchmark tests for 3D beams and shells exhibiting geometric non-linear behaviour. NAFEMS, Publication No. R0029, 1992.

13. Williams, F. W. Kennedy, D. Butler, R. and Anderson, M. S. VICONOPT: Program for exact vibration and buckling analysis or design of prismatic plate assemblies. AIAA J. 1991;29:1927-1928.

14. York, C. B. Unified approach to the characterization of coupled composite laminates: hygro-thermally curvature-stable configurations. International Journal of Structural Integrity 2011;2:406-436.

15. York, C. B. Tapered hygo-thermally curvature-stable laminates with non-standard ply orientations. Composites Part A: Applied Science and Manufacturing 2013;44:140-148.

Figures

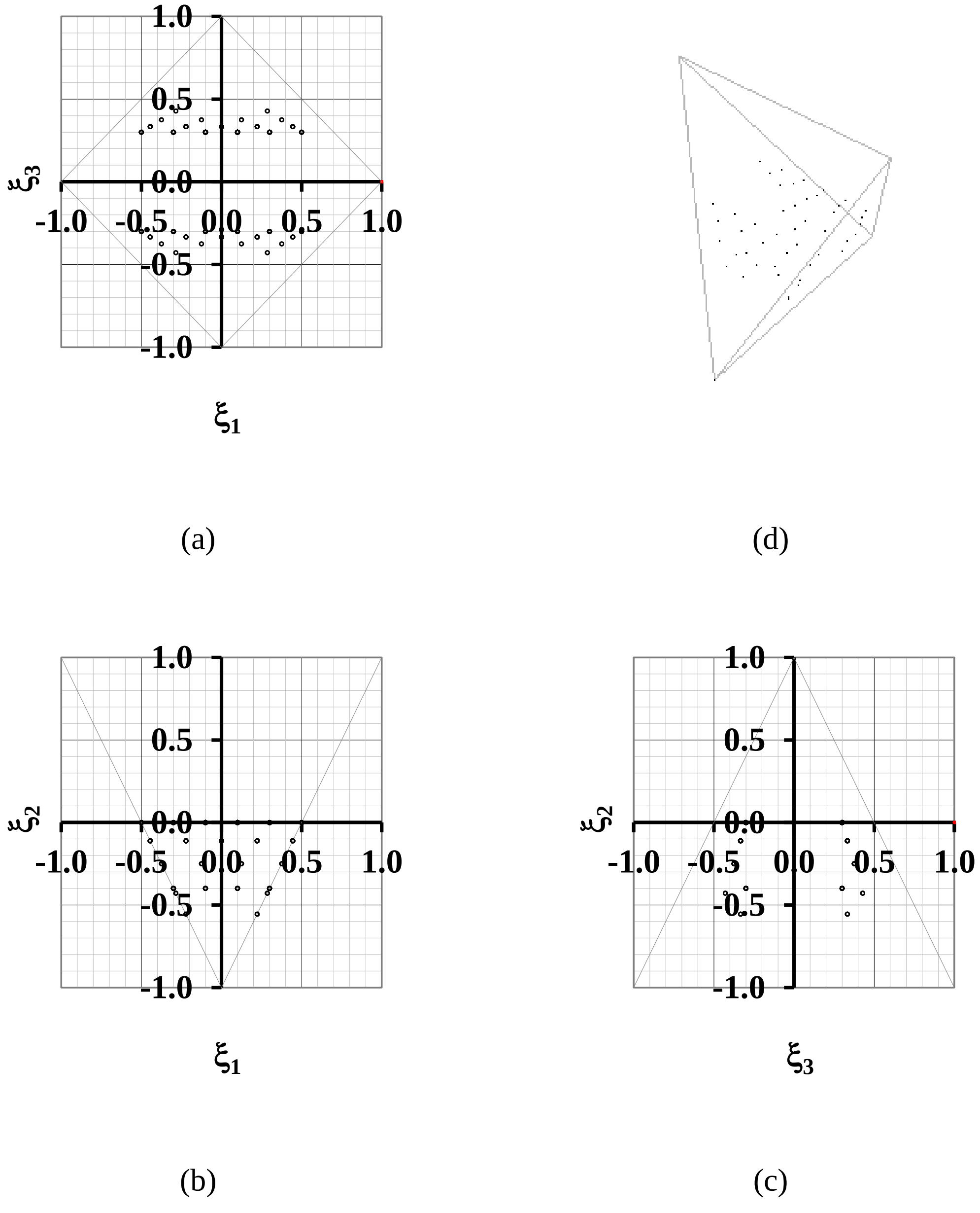


Figure 1

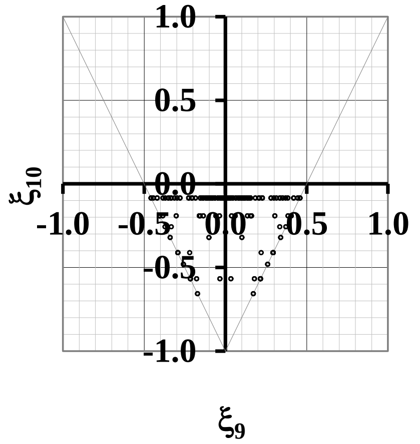
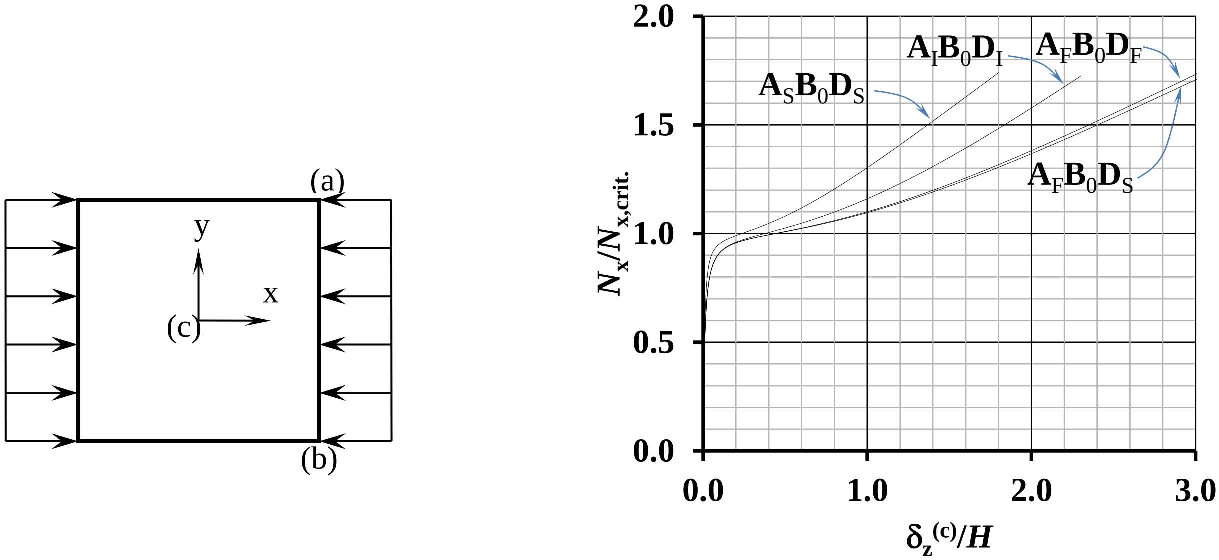
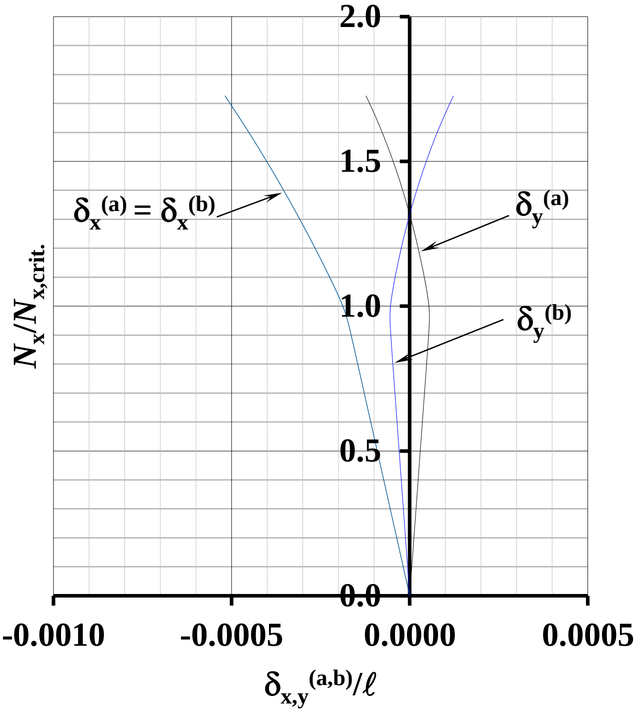


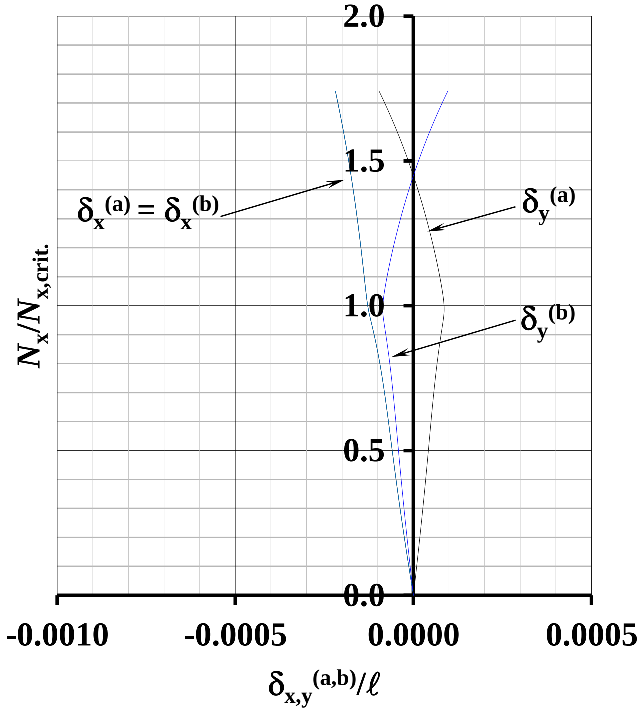
Figure 2



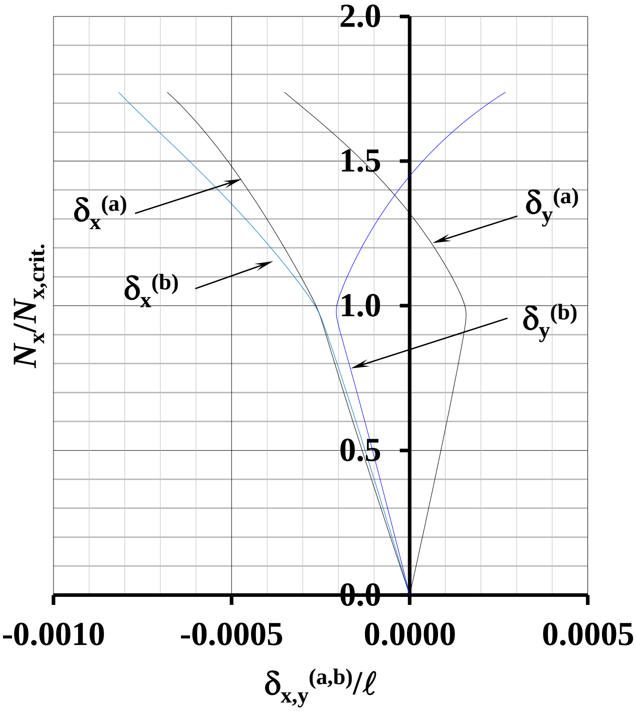
(a)



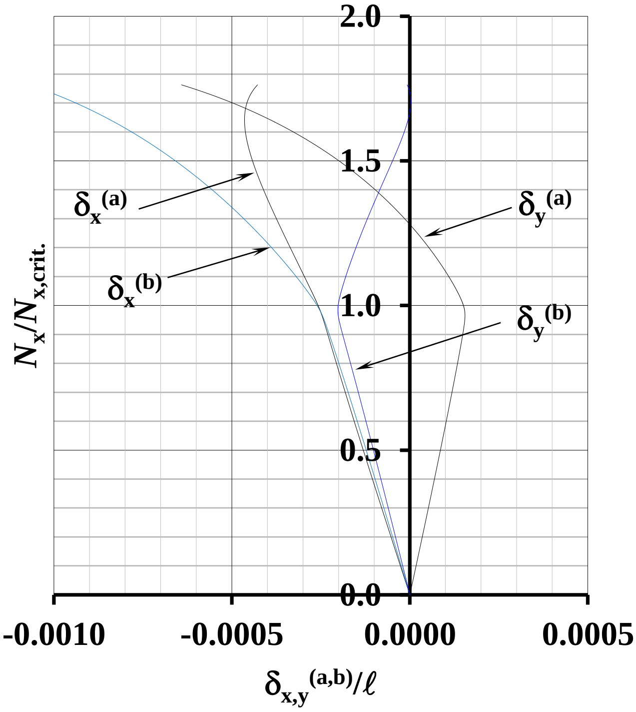
(b) – $\mathbf{A_I B_0 D_I}$



(c) – $\mathbf{A_S B_0 D_S}$



(d) – $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$



(e) – $\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$

Figure 3

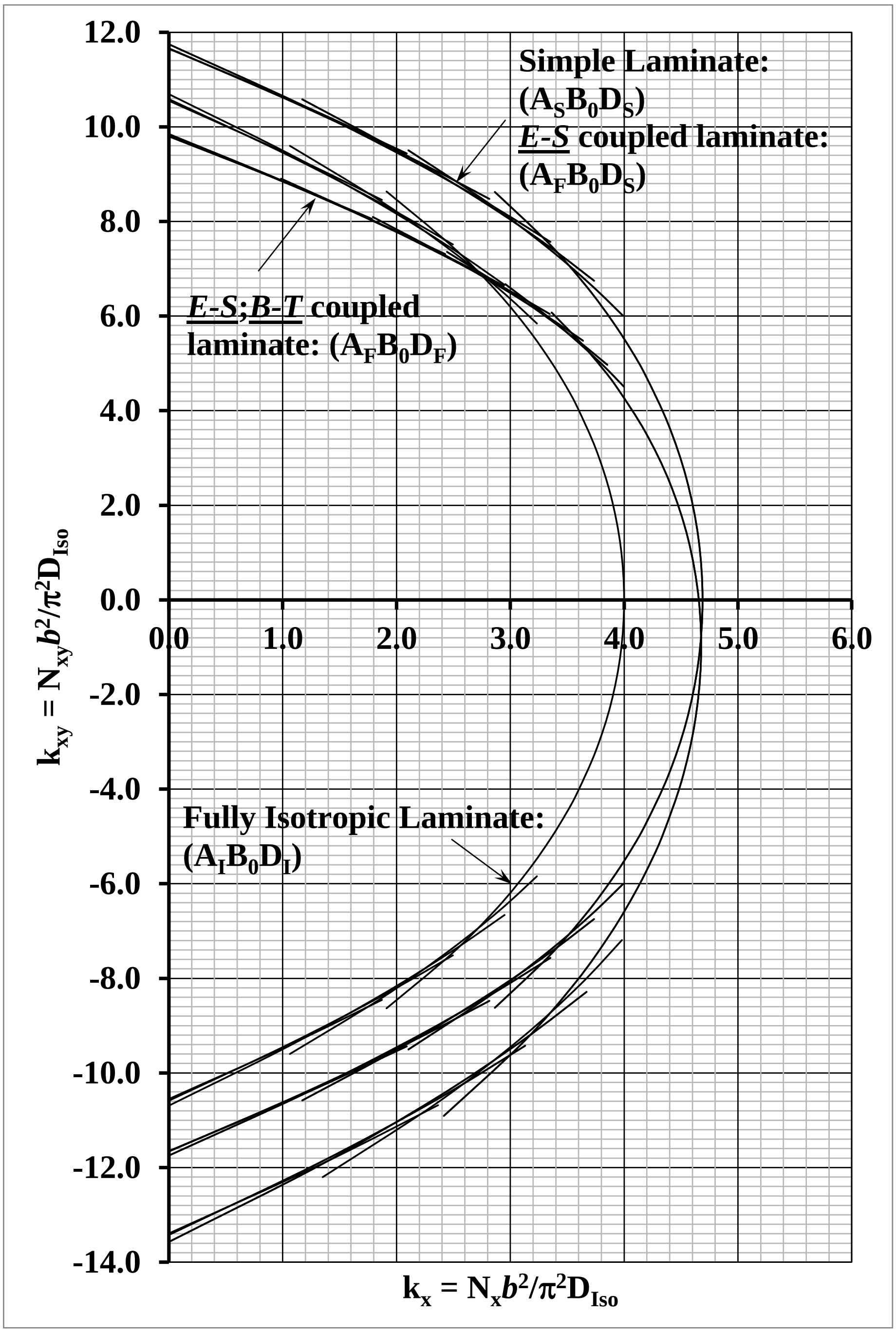
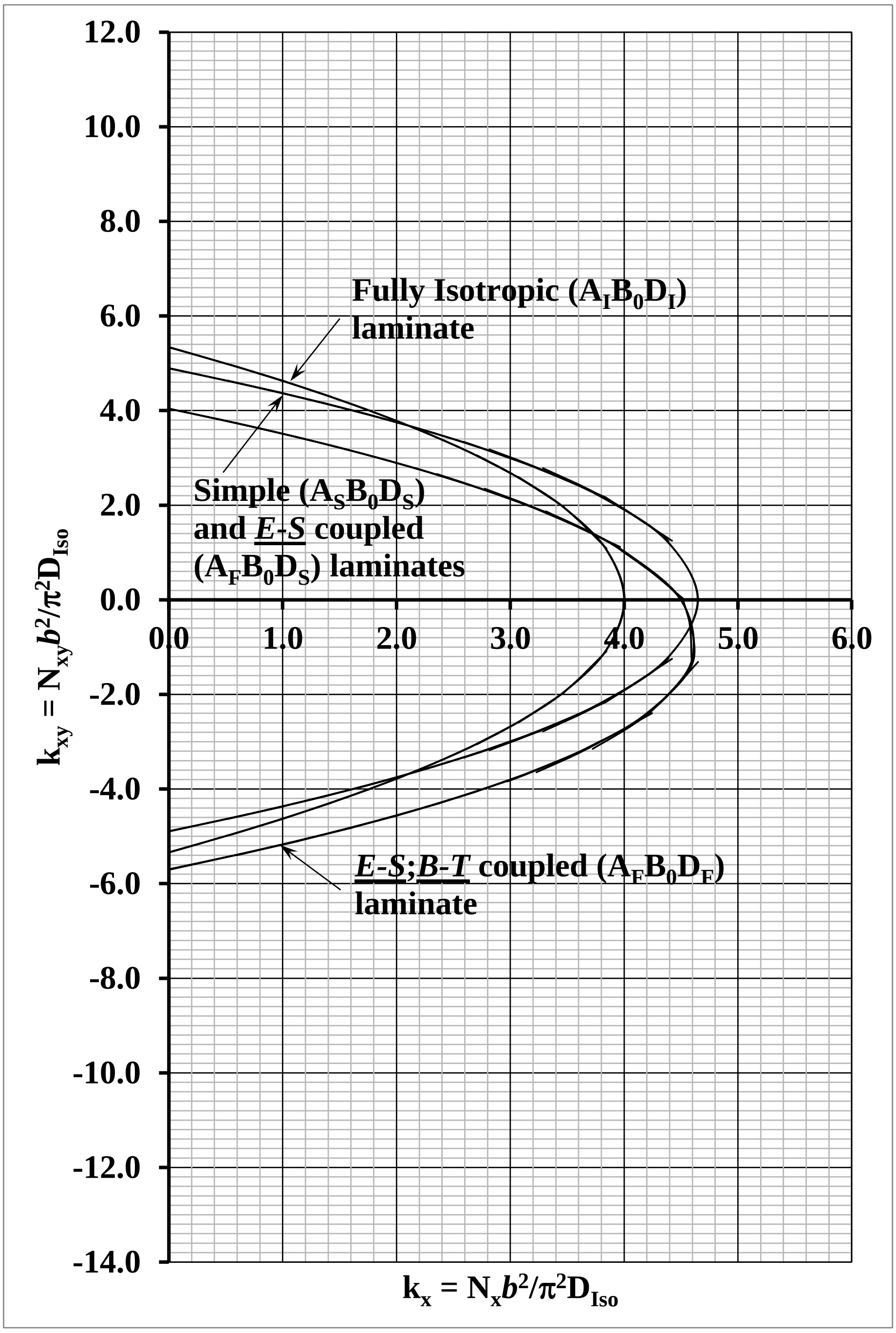
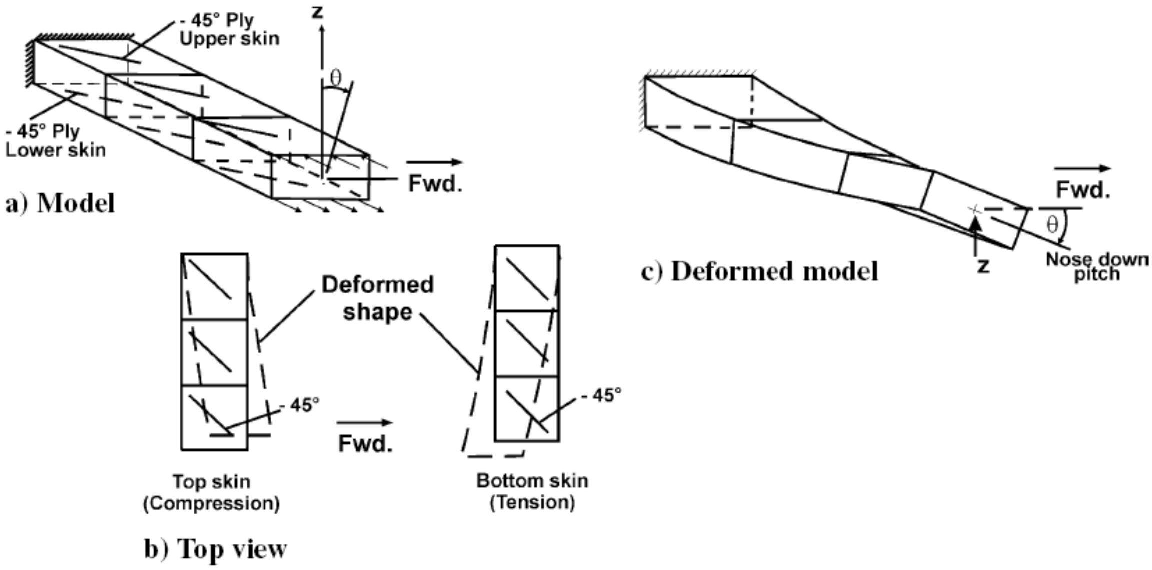

12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
$k_{xy} = N_{xy}b^2/\pi^2D_{Iso}$
$k_x = N_xb^2/\pi^2D_{Iso}$
Simple Laminate:
$(A_SB_0D_S)$
E-S coupled laminate:
$(A_FB_0D_S)$
E-S;*B-T* coupled
laminate: $(A_FB_0D_F)$
Fully Isotropic Laminate:
$(A_IB_0D_I)$

Figure 4



12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
$k_{xy} = N_{xy}b^2/\pi^2 D_{Iso}$
$k_x = N_x b^2/\pi^2 D_{Iso}$
Fully Isotropic ($A_I B_0 D_I$) laminate
Simple ($A_S B_0 D_S$) and *E-S* coupled ($A_F B_0 D_S$) laminates
E-S;*B-T* coupled ($A_F B_0 D_F$) laminate

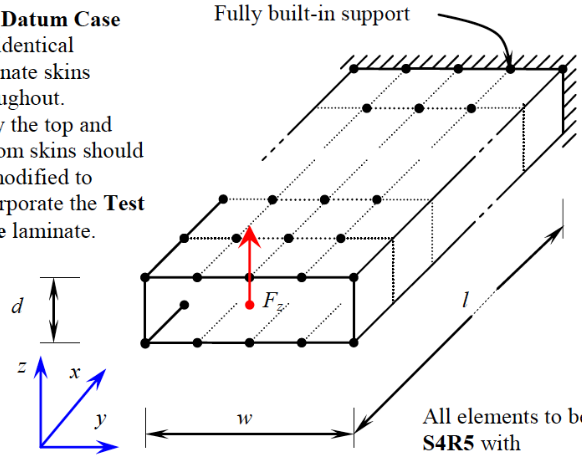
Figure 5



- 45° Ply
Upper skin
z
θ
- 45° Ply
Lower skin
Fwd.
a) Model
Fwd.
θ
z
Nose down
pitch
c) Deformed model
Deformed
shape
- 45°
Fwd.
- 45°
Top skin
(Compression)
Bottom skin
(Tension)
b) Top view

Figure 6

The **Datum Case** has identical laminate skins throughout.
Only the top and bottom skins should be modified to incorporate the **Test Case** laminate.



All elements to be **S4R5** with dimension 100 mm × 100 mm

<u>Datum Case</u>
Vertical displacements (z-axis) at shear centre:
134.77mm
Twist Rotation:
0°

<u>Test Case</u>
Vertical displacements (z-axis) at shear centre:
309.97mm
Twist Rotation:
0.62°

Material properties:
E_1 = 161,000 N/mm^2, E_2 = 11,380 N/mm^2, $G_{12} = G_{13}$ = G_{23} = 5,170 N/mm^2, ν_{12} = 0.38
Ply thickness:
t = 0.1397 mm

Wing-box dimensions:
l = 5,000 mm, w = 400 mm, d = 100 mm

Applied Load at Shear Centre: F_z = 1000 N

Laminate stacking sequences and stiffness properties

	Datum:	**Test**:
A_{11} =	**173,473**	**190,433**
A_{12} =	**56,482**	**81,757**
A_{16} =	**0**	**-31,676**
A_{22} =	**173,473**	**105,963**
A_{26} =	**0**	**-31,676**
A_{66} =	**58,496**	**83,771**
B_{11} =	**0**	**0**
B_{12} =	**0**	**0**
B_{16} =	**0**	**0**
B_{22} =	**0**	**0**
B_{26} =	**0**	**0**
B_{66} =	**0**	**0**
D_{11} =	**92,829**	**92,829**
D_{12} =	**45,514**	**45,514**
D_{16} =	**0**	**0**
D_{22} =	**92,829**	**58,485**
D_{26} =	**0**	**0**
D_{66} =	**46,575**	**46,575**

Datum: $[\pm60/-60/0_3/60_2/0/\mp60/\pm60/-60_2/0_2/60]_\mathrm{T}$
Test: $[45/0/-45/45/-45_5/0/-45/0/-45/0/-45/45_2/-45]_\mathrm{T}$

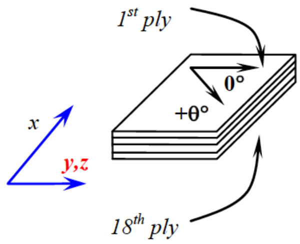


Figure 7

Figure Captions

Figure 1 – First angle projection: (a) plan; (b) front elevation and; (c) side elevation of lamination parameter design space relating to extensional stiffness for *Extension-Shearing* coupled laminates with up to 21 plies for standard ply orientations (±45°, 0° and 90°). (d) Isometric view of extensional lamination parameter design space.

Figure 2 – Lamination parameter design space relating to bending stiffness for *Extension-Shearing* coupled laminates with up to 21 plies for standard ply orientations (±45°, 0° and 90°).

Figure 3 – Compression loaded simply supported square plate (configuration and axis system) with details of (a) out-of-plane response, δ_z, at plate centre for all laminate comparators. In-plane responses (δ_x and δ_y) at corner nodes for the: (b) fully isotropic ($\mathbf{A}_I\mathbf{B}_0\mathbf{D}_I$) laminate and; (c) fully uncoupled ($\mathbf{A}_S\mathbf{B}_0\mathbf{D}_S$); (d) *Extension-Shearing* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_S$) and; (e) *Extension-Shearing* and *Bending-Twisting* coupled ($\mathbf{A}_F\mathbf{B}_0\mathbf{D}_F$) laminates with matching stiffness properties.

Figure 4 – Buckling interaction envelopes for a square plate, continuous over supports in the longitudinal (x-axis) direction, highlighting the effect of isolated mechanical coupling properties.

Figure 5 – Buckling interaction envelopes for an infinitely long plate, highlighting the effect of isolated mechanical coupling properties.

Figure 6 – Cantilever box-beam model (*after Ref. 3*) showing (a) general configuration, uniform stresses due to bending (force resultant acting through shear centre) and relative ply orientations for top and bottom skin; (b) relative deformations (exaggerated) between top and bottom skin and; (c) bend-twist coupling deformation (exaggerated) arising from unbalanced laminate skins.

Figure 7 – Cantilever wing box model modelling details.

Tables

Table 1 – Number of extensionally anisotropic stacking sequences (AFB0DS) with cross-referencing to Tables of laminate stacking sequences for 7 through 21 ply laminates. Form corresponds to prefix designations for Non-symmetric (*N*) angle-plies and Non-symmetric (*N*) cross-plies respectively. Subscripts arranged before and after prefix designations denote angle plies (+, –) or cross plies (○) and correspond to top ply and bottom ply orientations, respectively.

Form	Number of plies, n															Table
	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
${}_{+}NN_{+}$	-	-	-	-	-	-	-	4	-	8	-	44	-	284	-	A5
${}_{+}NN_{-}$	-	-	-	-	-	-	-	-	-	-	-	4	-	24	-	A6 & A7
${}_{+}NN_{\circ}$	-	-	-	-	-	-	-	-	-	-	-	-	-	14	-	A8

Table 2 – Calculation procedure for the non-dimensional parameters for an $A_FB_0D_S$ laminate.

			A				B				D		
Ply	θ	$(z_k - z_{k\text{-}1})$	$_A\Sigma_{\bigcirc}$	$_A\Sigma_{-}$	$_A\Sigma_{+}$	$(z_k^2 - z_{k\text{-}1}^2)$	$_B\Sigma_{\bigcirc}$	$_B\Sigma_{-}$	$_B\Sigma_{+}$	$(z_k^3 - z_{k\text{-}1}^3)$	$_D\Sigma_{\bigcirc}$	$_D\Sigma_{-}$	$_D\Sigma_{+}$
			$\underline{\underline{4}}$	$\underline{\underline{10}}$	$\underline{\underline{4}}$		$\underline{\underline{0}}$	$\underline{\underline{0}}$	$\underline{\underline{0}}$		$\underline{\underline{250}}$	$\underline{\underline{604}}$	$\underline{\underline{604}}$
1	+	1			→ 1	-17			→ -17	217			→ 217
2	○	1	→ 1			-15	→ -15			169	→ 169		
3	−	1		→ 1		-13		→ -13		127		→ 127	
4	+	1			→ 1	-11			→ -11	91			→ 91
5	−	1		→ 1		-9		→ -9		61		→ 61	
6	−	1		→ 1		-7		→ -7		37		→ 37	
7	−	1		→ 1		-5		→ -5		19		→ 19	
8	−	1		→ 1		-3		→ -3		7		→ 7	
9	−	1		→ 1		-1		→ -1		1		→ 1	
10	○	1	→ 1			1	→ 1			1	→ 1		
11	−	1		→ 1		3		→ 3		7		→ 7	
12	○	1	→ 1			5	→ 5			19	→ 19		
13	−	1		→ 1		7		→ 7		37		→ 37	
14	○	1	→ 1			9	→ 9			61	→ 61		
15	−	1		→ 1		11		→ 11		91		→ 91	
16	+	1			→ 1	13			→ 13	127			→ 127
17	+	1			→ 1	15			→ 15	169			→ 169
18	−	1		→ 1		17		→ 17		217		→ 217	

Table 3 – Calculation procedure for the non-dimensional parameters for an $\mathbf{A_F B_0 D_F}$ laminate.

			A				B				D		
Ply	θ	$(z_k - z_{k\text{-}1})$	${}_{A}\Sigma_{\bigcirc}$	${}_{A}\Sigma_{-}$	${}_{A}\Sigma_{+}$	$(z_k^2 - z_{k\text{-}1}^2)$	${}_{B}\Sigma_{\bigcirc}$	${}_{B}\Sigma_{-}$	${}_{B}\Sigma_{+}$	$(z_k^3 - z_{k\text{-}1}^3)$	${}_{D}\Sigma_{\bigcirc}$	${}_{D}\Sigma_{-}$	${}_{D}\Sigma_{+}$
			4	10	4		0	0	0		250	772	436
1	–	1		1		-17		-17		217		217	
2	–	1		1		-15		-15		169		169	
3	+	1			1	-13			-13	127			127
4	+	1			1	-11			-11	91			91
5	○	1	1			-9	-9			61	61		
6	–	1		1		-7		-7		37		37	
7	○	1	1			-5	-5			19	19		
8	–	1		1		-3		-3		7		7	
9	○	1	1			-1	-1			1	1		
10	–	1		1		1		1		1		1	
11	–	1		1		3		3		7		7	
12	–	1		1		5		5		19		19	
13	–	1		1		7		7		37		37	
14	–	1		1		9		9		61		61	
15	+	1			1	11			11	91			91
16	+	1			1	13			13	127			127
17	○	1	1			15	15			169	169		
18	–	1		1		17		17		217		217	

Table 4 – Transformed reduced stiffness (N/mm^2) for IM7/8552 carbon-fiber/epoxy with θ = -45°, 45°, 0° and 90°.

θ	Q'_{11}	Q'_{12}	Q'_{16}	Q'_{22}	Q'_{26}	Q'_{66}
-45	50,894	40,554	-37,791	50,894	-37,791	41,355
45	50,894	40,554	37,791	50,894	37,791	41,355
0	162,660	4,369	0	11,497	0	5,170
90	11,497	4,369	0	162,660	0	5,170

Electronic Appendix

Supplementary data

Table A5 – Stacking sequences for 7 through 21 ply laminates of the form $_{+}NN_{+}$ with blend ratio $(n_{+}/n_{\pm}) = 20\%$.

Ref.	Sequence	n	$n_{\pm}$	$n_{\circ}$	$n_{\bullet}$	ζ	$\zeta_{\pm}$	$\zeta_{\circ}$	$\zeta_{\bullet}$	$n_{\pm}/n$ (%)	$n_{\circ}/n$ (%)	$n_{\bullet}/n$ (%)	$\zeta_{\pm}/\zeta$ (%)	$\zeta_{\circ}/\zeta$ (%)	$\zeta_{\bullet}/\zeta$ (%)
NN 1	+ ● – – – ● – – – ● – ● – +	14	10	0	4	2744	2032	0	712	71.4	0.0	28.6	74.1	0.0	25.9
NN 2	+ – ● – ● – – – ● – – – ● +	14	10	0	4	2744	2032	0	712	71.4	0.0	28.6	74.1	0.0	25.9
NN 3	+ – ○ – ○ – – – ○ – – – ○ +	14	10	4	0	2744	2032	712	0	71.4	28.6	0.0	74.1	25.9	0.0
NN 4	+ ○ – – – ○ – – – ○ – ○ – +	14	10	4	0	2744	2032	712	0	71.4	28.6	0.0	74.1	25.9	0.0
NN 5	+ ● – ● – – – ● – ● – – ● ● – +	16	10	0	6	4096	2704	0	1392	62.5	0.0	37.5	66.0	0.0	34.0
NN 6	+ – ● ● – – ● – ● – – – ● – ● +	16	10	0	6	4096	2704	0	1392	62.5	0.0	37.5	66.0	0.0	34.0
NN 7	+ ● – ○ – – – ● – ● – – ○ ● – +	16	10	2	4	4096	2704	488	904	62.5	12.5	25.0	66.0	11.9	22.1
NN 8	+ – ● ○ – – ● – ● – – – ○ – ● +	16	10	2	4	4096	2704	488	904	62.5	12.5	25.0	66.0	11.9	22.1
NN 9	+ – ○ ● – – ○ – ○ – – – ● – ○ +	16	10	4	2	4096	2704	904	488	62.5	25.0	12.5	66.0	22.1	11.9
NN 10	+ ○ – ● – – – ○ – ○ – – ● ○ – +	16	10	4	2	4096	2704	904	488	62.5	25.0	12.5	66.0	22.1	11.9
NN 11	+ – ○ ○ – – ○ – ○ – – – ○ – ○ +	16	10	6	0	4096	2704	1392	0	62.5	37.5	0.0	66.0	34.0	0.0
NN 12	+ ○ – ○ – – – ○ – ○ – – ○ ○ – +	16	10	6	0	4096	2704	1392	0	62.5	37.5	0.0	66.0	34.0	0.0
NN 13	+ ● – ● – ● – ● – – ● – – ● ● ● – +	18	10	0	8	5832	3472	0	2360	55.6	0.0	44.4	59.5	0.0	40.5
NN 14	+ ● – – ● ● – ● – ● – ● – – – ● ● +	18	10	0	8	5832	3472	0	2360	55.6	0.0	44.4	59.5	0.0	40.5
NN 15	+ – ● ● ● – – ● – – ● – ● – ● – ● +	18	10	0	8	5832	3472	0	2360	55.6	0.0	44.4	59.5	0.0	40.5
NN 16	+ ● – – ● ● ● – – – ● – ● – ● – ● +	18	10	0	8	5832	3472	0	2360	55.6	0.0	44.4	59.5	0.0	40.5
NN 17	+ ● – ● – ● – ● – – – ● ● ● – – ● +	18	10	0	8	5832	3472	0	2360	55.6	0.0	44.4	59.5	0.0	40.5
NN 18	+ ● ● – – – ● – ● – ● – ● ● – – ● +	18	10	0	8	5832	3472	0	2360	55.6	0.0	44.4	59.5	0.0	40.5
NN 19	+ ● – ● – ● – ○ – – ○ – – ● ● ● – +	18	10	2	6	5832	3472	56	2304	55.6	11.1	33.3	59.5	1.0	39.5
NN 20	+ – ● ● ● – – ○ – – ○ – ● – ● – ● +	18	10	2	6	5832	3472	56	2304	55.6	11.1	33.3	59.5	1.0	39.5
NN 21	+ ● – – ● ○ ● – – – ● – ○ – ● – ● +	18	10	2	6	5832	3472	296	2064	55.6	11.1	33.3	59.5	5.1	35.4
NN 22	+ ● – ● – ○ – ● – – – ● ○ ● – – ● +	18	10	2	6	5832	3472	296	2064	55.6	11.1	33.3	59.5	5.1	35.4
NN 23	+ ● – – ○ ● ○ – – – ○ – ● – ○ – ● +	18	10	4	4	5832	3472	712	1648	55.6	22.2	22.2	59.5	12.2	28.3
NN 24	+ ● – ○ – ● – ○ – – – ○ ● ○ – – ● +	18	10	4	4	5832	3472	712	1648	55.6	22.2	22.2	59.5	12.2	28.3
NN 25	+ ● – ○ – ● – ● – – ● – – ● ○ ● – +	18	10	2	6	5832	3472	728	1632	55.6	11.1	33.3	59.5	12.5	28.0
NN 26	+ – ● ○ ● – – ● – – ● – ● – ○ – ● +	18	10	2	6	5832	3472	728	1632	55.6	11.1	33.3	59.5	12.5	28.0
NN 27	+ ● – ○ – ● – ○ – – ○ – – ● ○ ● – +	18	10	4	4	5832	3472	784	1576	55.6	22.2	22.2	59.5	13.4	27.0
NN 28	+ – ● ○ ● – – ○ – – ○ – ● – ○ – ● +	18	10	4	4	5832	3472	784	1576	55.6	22.2	22.2	59.5	13.4	27.0
NN 29	+ ● – – ○ ○ – ○ – ○ – ○ – – – ○ ● +	18	10	6	2	5832	3472	1008	1352	55.6	33.3	11.1	59.5	17.3	23.2
NN 30	+ ● – – ○ ○ ○ – – – ○ – ○ – ○ – ● +	18	10	6	2	5832	3472	1008	1352	55.6	33.3	11.1	59.5	17.3	23.2

Continued

Continued

NN 31	+●–○–○–○–	––○○○––●+	18	10	6	2	5832	3472	1008	1352	55.6	33.3	11.1	59.5	17.3	23.2
NN 32	+●○–––○–○	–○–○○––●+	18	10	6	2	5832	3472	1008	1352	55.6	33.3	11.1	59.5	17.3	23.2
NN 33	+●––○○–●–	○–●–––●○+	18	10	4	4	5832	3472	1072	1288	55.6	22.2	22.2	59.5	18.4	22.1
NN 34	+○●–––●–○	–●–○○––●+	18	10	4	4	5832	3472	1072	1288	55.6	22.2	22.2	59.5	18.4	22.1
NN 35	+●○–––○–●	–○–●●––○+	18	10	4	4	5832	3472	1288	1072	55.6	22.2	22.2	59.5	22.1	18.4
NN 36	+○––●●–○–	●–○–––○●+	18	10	4	4	5832	3472	1288	1072	55.6	22.2	22.2	59.5	22.1	18.4
NN 37	+○––●●–●–	●–●–––●○+	18	10	2	6	5832	3472	1352	1008	55.6	11.1	33.3	59.5	23.2	17.3
NN 38	+○––●●●––	–●–●–●–○+	18	10	2	6	5832	3472	1352	1008	55.6	11.1	33.3	59.5	23.2	17.3
NN 39	+○–●–●–●–	––●●●––○+	18	10	2	6	5832	3472	1352	1008	55.6	11.1	33.3	59.5	23.2	17.3
NN 40	+○●–––●–●	–●–●●––○+	18	10	2	6	5832	3472	1352	1008	55.6	11.1	33.3	59.5	23.2	17.3
NN 41	+–○●○––●–	–●–○–●–○+	18	10	4	4	5832	3472	1576	784	55.6	22.2	22.2	59.5	27.0	13.4
NN 42	+○–●–○–●–	–●––○●○–+	18	10	4	4	5832	3472	1576	784	55.6	22.2	22.2	59.5	27.0	13.4
NN 43	+–○●○––○–	–○–○–●–○+	18	10	6	2	5832	3472	1632	728	55.6	33.3	11.1	59.5	28.0	12.5
NN 44	+○–●–○–○–	–○––○●○–+	18	10	6	2	5832	3472	1632	728	55.6	33.3	11.1	59.5	28.0	12.5
NN 45	+○––●○●––	–●–○–●–○+	18	10	4	4	5832	3472	1648	712	55.6	22.2	22.2	59.5	28.3	12.2
NN 46	+○–●–○–●–	––●○●––○+	18	10	4	4	5832	3472	1648	712	55.6	22.2	22.2	59.5	28.3	12.2
NN 47	+○––○●○––	–○–●–○–○+	18	10	6	2	5832	3472	2064	296	55.6	33.3	11.1	59.5	35.4	5.1
NN 48	+○–○–●–○–	––○●○––○+	18	10	6	2	5832	3472	2064	296	55.6	33.3	11.1	59.5	35.4	5.1
NN 49	+–○○○––●–	–●–○–○–○+	18	10	6	2	5832	3472	2304	56	55.6	33.3	11.1	59.5	39.5	1.0
NN 50	+○–○–○–●–	–●––○○○–+	18	10	6	2	5832	3472	2304	56	55.6	33.3	11.1	59.5	39.5	1.0
NN 51	+○––○○–○–	○–○–––○○+	18	10	8	0	5832	3472	2360	0	55.6	44.4	0.0	59.5	40.5	0.0
NN 52	+–○○○––○–	–○–○–○–○+	18	10	8	0	5832	3472	2360	0	55.6	44.4	0.0	59.5	40.5	0.0
NN 53	+○––○○○––	–○–○–○–○+	18	10	8	0	5832	3472	2360	0	55.6	44.4	0.0	59.5	40.5	0.0
NN 54	+○–○–○–○–	––○○○––○+	18	10	8	0	5832	3472	2360	0	55.6	44.4	0.0	59.5	40.5	0.0
NN 55	+○○–––○–○	–○–○○––○+	18	10	8	0	5832	3472	2360	0	55.6	44.4	0.0	59.5	40.5	0.0
NN 56	+○–○–○–○–	–○––○○○–+	18	10	8	0	5832	3472	2360	0	55.6	44.4	0.0	59.5	40.5	0.0
NN 61	+●–●–●●●––	–●––●●●●–+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 62	+●●––●●––●	–●–●–●●●–+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 63	+●●●–––●––	–●●●●●–●–+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 64	+–●–●●●●●–	––●–––●●●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8

Continued

Continued

NN 65	+●–●–●–●●–	●●–––●–●●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 66	+–●●●–●–●–	●––●●––●●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 67	+●–●–●–●●●	–––●●––●●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 68	+●●–––●●●–	●–●–●––●●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 69	+●●––●–●–●	–●●●–––●●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 70	+–●●●●––●–	––●●●–●–●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 71	+●●––●●–––	●●●–●–●–●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 72	+●●–●–––●●	–●●–●–●–●+	20	10	0	10	8000	4336	0	3664	50.0	0.0	50.0	54.2	0.0	45.8
NN 73	+●–●–●–●○–	●○–––●–●●+	20	10	2	8	8000	4336	56	3608	50.0	10.0	40.0	54.2	0.7	45.1
NN 74	+●●–●–––○●	–○●–●–●–●+	20	10	2	8	8000	4336	56	3608	50.0	10.0	40.0	54.2	0.7	45.1
NN 75	+●●●–––○––	–●○●●●–●–+	20	10	2	8	8000	4336	152	3512	50.0	10.0	40.0	54.2	1.9	43.9
NN 76	+–●–●●●○●–	––○–––●●●+	20	10	2	8	8000	4336	152	3512	50.0	10.0	40.0	54.2	1.9	43.9
NN 77	+●●–––●○●–	●–○–●––●●+	20	10	2	8	8000	4336	152	3512	50.0	10.0	40.0	54.2	1.9	43.9
NN 78	+●●––●–○–●	–●○●–––●●+	20	10	2	8	8000	4336	152	3512	50.0	10.0	40.0	54.2	1.9	43.9
NN 79	+●●––●○––●	–●–○–●●●–+	20	10	2	8	8000	4336	296	3368	50.0	10.0	40.0	54.2	3.7	42.1
NN 80	+–●●●–○–●–	●––○●––●●+	20	10	2	8	8000	4336	296	3368	50.0	10.0	40.0	54.2	3.7	42.1
NN 81	+●–●–●–○○○	–––●○––●●+	20	10	4	6	8000	4336	352	3312	50.0	20.0	30.0	54.2	4.4	41.4
NN 82	+●●––○●–––	○○○–●–●–●+	20	10	4	6	8000	4336	352	3312	50.0	20.0	30.0	54.2	4.4	41.4
NN 83	+●●––○●––○	–○–○–●●●–+	20	10	4	6	8000	4336	424	3240	50.0	20.0	30.0	54.2	5.3	40.5
NN 84	+–●●●–○–○–	○––●○––●●+	20	10	4	6	8000	4336	424	3240	50.0	20.0	30.0	54.2	5.3	40.5
NN 85	+●●–––○●○–	○–●–○––●●+	20	10	4	6	8000	4336	424	3240	50.0	20.0	30.0	54.2	5.3	40.5
NN 86	+●●––○–●–○	–○●○–––●●+	20	10	4	6	8000	4336	424	3240	50.0	20.0	30.0	54.2	5.3	40.5
NN 87	+●–●–○●●––	–●––○●●●–+	20	10	2	8	8000	4336	488	3176	50.0	10.0	40.0	54.2	6.1	39.7
NN 88	+●–●–○–●●●	–––●○––●●+	20	10	2	8	8000	4336	488	3176	50.0	10.0	40.0	54.2	6.1	39.7
NN 89	+–●●●○––●–	––●●○–●–●+	20	10	2	8	8000	4336	488	3176	50.0	10.0	40.0	54.2	6.1	39.7
NN 90	+●●––○●–––	●●●–○–●–●+	20	10	2	8	8000	4336	488	3176	50.0	10.0	40.0	54.2	6.1	39.7
NN 91	+●–●–●○○––	–○––○●●●–+	20	10	4	6	8000	4336	496	3168	50.0	20.0	30.0	54.2	6.2	39.6
NN 92	+–●●●○––○–	––○○●–●–●+	20	10	4	6	8000	4336	496	3168	50.0	20.0	30.0	54.2	6.2	39.6
NN 93	+●●–––○○○–	○–○–○––●●+	20	10	6	4	8000	4336	576	3088	50.0	30.0	20.0	54.2	7.2	38.6
NN 94	+●●––○–○–○	–○○○–––●●+	20	10	6	4	8000	4336	576	3088	50.0	30.0	20.0	54.2	7.2	38.6

Continued

Continued

NN 95	+●–●–○–●○–	○●–––○–●●+	20	10	4	6	8000	4336	640	3024	50.0	20.0	30.0	54.2	8.0	37.8
NN 96	+●●–○–––●○	–○●–○–●–●+	20	10	4	6	8000	4336	640	3024	50.0	20.0	30.0	54.2	8.0	37.8
NN 97	+●–●–○●○––	–○––●○●●–+	20	10	4	6	8000	4336	712	2952	50.0	20.0	30.0	54.2	8.9	36.9
NN 98	+●–●–○–○●–	●○–––○–●●+	20	10	4	6	8000	4336	712	2952	50.0	20.0	30.0	54.2	8.9	36.9
NN 99	+–●●○●––○–	––○●○–●–●+	20	10	4	6	8000	4336	712	2952	50.0	20.0	30.0	54.2	8.9	36.9
NN 100	+●●–○–––○●	–●○–○–●–●+	20	10	4	6	8000	4336	712	2952	50.0	20.0	30.0	54.2	8.9	36.9
NN 101	+●–●–○○●––	–○––●●○●–+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 102	+●●––○○––●	–○–●–●○●–+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 103	+●○●–––●––	–○○○●●–●–+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 104	+–●○●–●–○–	●––○○––●●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 105	+●–○–●–●○●	–––○○––●●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 106	+●○––●–●–●	–○○○–––●●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 107	+–●–●●○○○–	––●–––●○●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 108	+●●–––○○○–	●–●–●––○●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 109	+–●○●●––○–	––●○○–●–●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 110	+●●––○○–––	●○●–●–○–●+	20	10	4	6	8000	4336	928	2736	50.0	20.0	30.0	54.2	11.6	34.2
NN 111	+●○–––●●●–	○–○–○––●●+	20	10	4	6	8000	4336	1000	2664	50.0	20.0	30.0	54.2	12.5	33.3
NN 112	+●–●–○–○●○	–––●●––○●+	20	10	4	6	8000	4336	1000	2664	50.0	20.0	30.0	54.2	12.5	33.3
NN 113	+●●––○–○–○	–●●●–––○●+	20	10	4	6	8000	4336	1000	2664	50.0	20.0	30.0	54.2	12.5	33.3
NN 114	+●○––●●–––	○●○–○–●–●+	20	10	4	6	8000	4336	1000	2664	50.0	20.0	30.0	54.2	12.5	33.3
NN 115	+●–○–●●●––	–●––●●○●–+	20	10	2	8	8000	4336	1016	2648	50.0	10.0	40.0	54.2	12.7	33.1
NN 116	+–●○●●––●–	––●●●–○–●+	20	10	2	8	8000	4336	1016	2648	50.0	10.0	40.0	54.2	12.7	33.1
NN 117	+●●○–––○––	–●●○●○–●–+	20	10	4	6	8000	4336	1096	2568	50.0	20.0	30.0	54.2	13.7	32.1
NN 118	+–●–○●○●●–	––○–––○●●+	20	10	4	6	8000	4336	1096	2568	50.0	20.0	30.0	54.2	13.7	32.1
NN 119	+–●–●○●○○–	––●–––●●○+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 120	+●–●–○–○○–	●●–––●–●○+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 121	+●–●–○–○○●	–––●●––●○+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 122	+●○––●●––○	–○–●–●○●–+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 123	+○●●–––●––	–○○●○●–●–+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 124	+●–○–●–●○–	○●–––●–○●+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6

Continued

Continued

NN 125	+–●○●–●–○–	○––●●––○●+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 126	+○●––●●–––	●○○–○–●–●+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 127	+○●–●–––●●	–○○–○–●–●+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 128	+●○–●–––●○	–○●–●–○–●+	20	10	4	6	8000	4336	1216	2448	50.0	20.0	30.0	54.2	15.2	30.6
NN 129	+●–○–●○●––	–●––○○●●–+	20	10	4	6	8000	4336	1264	2400	50.0	20.0	30.0	54.2	15.8	30.0
NN 130	+–●●○○––●–	––●○●–○–●+	20	10	4	6	8000	4336	1264	2400	50.0	20.0	30.0	54.2	15.8	30.0
NN 131	+●–○–●●○––	–○––●●●○–+	20	10	4	6	8000	4336	1288	2376	50.0	20.0	30.0	54.2	16.1	29.7
NN 132	+●●○–––○––	–○●●●●–○–+	20	10	4	6	8000	4336	1288	2376	50.0	20.0	30.0	54.2	16.1	29.7
NN 133	+–○–●●●●○–	––○–––○●●+	20	10	4	6	8000	4336	1288	2376	50.0	20.0	30.0	54.2	16.1	29.7
NN 134	+●–○–●–○●–	●○–––●–○●+	20	10	4	6	8000	4336	1288	2376	50.0	20.0	30.0	54.2	16.1	29.7
NN 135	+–○●●●––○–	––○●●–○–●+	20	10	4	6	8000	4336	1288	2376	50.0	20.0	30.0	54.2	16.1	29.7
NN 136	+●○–●–––○●	–●○–●–○–●+	20	10	4	6	8000	4336	1288	2376	50.0	20.0	30.0	54.2	16.1	29.7
NN 137	+●○––●●––●	–●–●–●●○–+	20	10	2	8	8000	4336	1352	2312	50.0	10.0	40.0	54.2	16.9	28.9
NN 138	+●○●–––●––	–●●●●●–○–+	20	10	2	8	8000	4336	1352	2312	50.0	10.0	40.0	54.2	16.9	28.9
NN 139	+–○–●●●●●–	––●–––●○●+	20	10	2	8	8000	4336	1352	2312	50.0	10.0	40.0	54.2	16.9	28.9
NN 140	+–○●●–●–●–	●––●●––○●+	20	10	2	8	8000	4336	1352	2312	50.0	10.0	40.0	54.2	16.9	28.9
NN 141	+●○–––●●●–	●–●–●––○●+	20	10	2	8	8000	4336	1352	2312	50.0	10.0	40.0	54.2	16.9	28.9
NN 142	+●○––●–●–●	–●●●–––○●+	20	10	2	8	8000	4336	1352	2312	50.0	10.0	40.0	54.2	16.9	28.9
NN 143	+●○●–––○––	–●●●○○–●–+	20	10	4	6	8000	4336	1360	2304	50.0	20.0	30.0	54.2	17.0	28.8
NN 144	+–●–○○●●●–	––○–––●○●+	20	10	4	6	8000	4336	1360	2304	50.0	20.0	30.0	54.2	17.0	28.8
NN 145	+–●●○–○–●–	○––●●––●○+	20	10	4	6	8000	4336	1384	2280	50.0	20.0	30.0	54.2	17.3	28.5
NN 146	+○●––●●––○	–●–○–○●●–+	20	10	4	6	8000	4336	1384	2280	50.0	20.0	30.0	54.2	17.3	28.5
NN 147	+●–○–●–●○○	–––●●––●○+	20	10	4	6	8000	4336	1408	2256	50.0	20.0	30.0	54.2	17.6	28.2
NN 148	+○●––●●–––	○○●–●–○–●+	20	10	4	6	8000	4336	1408	2256	50.0	20.0	30.0	54.2	17.6	28.2
NN 149	+●–○–●–○○○	–––○●––○●+	20	10	6	4	8000	4336	1440	2224	50.0	30.0	20.0	54.2	18.0	27.8
NN 150	+●○––●○–––	○○○–●–○–●+	20	10	6	4	8000	4336	1440	2224	50.0	30.0	20.0	54.2	18.0	27.8
NN 151	+●–○–●–○●–	○●–––●–●○+	20	10	4	6	8000	4336	1456	2208	50.0	20.0	30.0	54.2	18.2	27.6
NN 152	+○●–●–––●○	–●○–●–○–●+	20	10	4	6	8000	4336	1456	2208	50.0	20.0	30.0	54.2	18.2	27.6
NN 153	+●–○–○●●––	–●––○●○●–+	20	10	4	6	8000	4336	1504	2160	50.0	20.0	30.0	54.2	18.8	27.0
NN 154	+●○●–––○––	–●○●●●–○–+	20	10	4	6	8000	4336	1504	2160	50.0	20.0	30.0	54.2	18.8	27.0

Continued

Continued

NN 155	+ – ○ – ● ● ● ○ ● –	– – ○ – – – ● ○ ● +	20	10	4	6	8000	4336	1504	2160	50.0	20.0	30.0	54.2	18.8	27.0
NN 156	+ ● ○ – – – ● ○ ● –	● – ○ – ● – – ○ ● +	20	10	4	6	8000	4336	1504	2160	50.0	20.0	30.0	54.2	18.8	27.0
NN 157	+ ● ○ – – ● – ○ – ●	– ● ○ ● – – – ○ ● +	20	10	4	6	8000	4336	1504	2160	50.0	20.0	30.0	54.2	18.8	27.0
NN 158	+ – ● ○ ● ○ – – ● –	– – ● ● ○ – ○ – ● +	20	10	4	6	8000	4336	1504	2160	50.0	20.0	30.0	54.2	18.8	27.0
NN 159	+ ● – ○ – ● – ○ ○ –	○ ○ – – – ● – ● ○ +	20	10	6	4	8000	4336	1512	2152	50.0	30.0	20.0	54.2	18.9	26.9
NN 160	+ ● – ○ – ● ○ ○ – –	– ○ – – ○ ● ○ ● – +	20	10	6	4	8000	4336	1512	2152	50.0	30.0	20.0	54.2	18.9	26.9
NN 161	+ ● ○ – – ● ○ – – ○	– ○ – ○ – ● ○ ● – +	20	10	6	4	8000	4336	1512	2152	50.0	30.0	20.0	54.2	18.9	26.9
NN 162	+ – ● ○ ● – ○ – ○ –	○ – – ○ ● – – ○ ● +	20	10	6	4	8000	4336	1512	2152	50.0	30.0	20.0	54.2	18.9	26.9
NN 163	+ – ● ○ ● ○ – – ○ –	– – ○ ○ ● – ○ – ● +	20	10	6	4	8000	4336	1512	2152	50.0	30.0	20.0	54.2	18.9	26.9
NN 164	+ ○ ● – ● – – – ○ ○	– ○ ○ – ● – ○ – ● +	20	10	6	4	8000	4336	1512	2152	50.0	30.0	20.0	54.2	18.9	26.9
NN 165	+ – ○ ● ● – ● – ○ –	○ – – ● ● – – ● ○ +	20	10	4	6	8000	4336	1576	2088	50.0	20.0	30.0	54.2	19.7	26.1
NN 166	+ ● ○ – – – ● ● ○ –	○ – ● – ● – – ● ○ +	20	10	4	6	8000	4336	1576	2088	50.0	20.0	30.0	54.2	19.7	26.1
NN 167	+ ○ ● – – ● ● – – ○	– ○ – ● – ● ● ○ – +	20	10	4	6	8000	4336	1576	2088	50.0	20.0	30.0	54.2	19.7	26.1
NN 168	+ ● – ○ – ○ – ● ● ●	– – – ○ ● – – ○ ● +	20	10	4	6	8000	4336	1576	2088	50.0	20.0	30.0	54.2	19.7	26.1
NN 169	+ ○ ● – – ● – ● – ○	– ○ ● ● – – – ○ ● +	20	10	4	6	8000	4336	1576	2088	50.0	20.0	30.0	54.2	19.7	26.1
NN 170	+ ● ○ – – ● ○ – – –	● ● ● – ○ – ○ – ● +	20	10	4	6	8000	4336	1576	2088	50.0	20.0	30.0	54.2	19.7	26.1
NN 171	+ ● ○ – – ● – ○ – ●	– ○ ● ● – – – ● ○ +	20	10	4	6	8000	4336	1648	2016	50.0	20.0	30.0	54.2	20.6	25.2
NN 172	+ ● ○ – – ● ○ – – ●	– ● – ○ – ● ● ○ – +	20	10	4	6	8000	4336	1648	2016	50.0	20.0	30.0	54.2	20.6	25.2
NN 173	+ – ○ ● ● – ○ – ● –	● – – ○ ● – – ○ ● +	20	10	4	6	8000	4336	1648	2016	50.0	20.0	30.0	54.2	20.6	25.2
NN 174	+ ○ ● – – – ● ● ○ –	● – ○ – ● – – ○ ● +	20	10	4	6	8000	4336	1648	2016	50.0	20.0	30.0	54.2	20.6	25.2
NN 175	+ – ● ○ ● ○ – – ● –	– – ○ ● ● – ● – ○ +	20	10	4	6	8000	4336	1696	1968	50.0	20.0	30.0	54.2	21.2	24.6
NN 176	+ ○ – ● – ● ● ○ – –	– ● – – ○ ● ○ ● – +	20	10	4	6	8000	4336	1696	1968	50.0	20.0	30.0	54.2	21.2	24.6
NN 177	+ ● ○ – – – ● ○ ○ –	○ – ○ – ● – – ● ○ +	20	10	6	4	8000	4336	1728	1936	50.0	30.0	20.0	54.2	21.6	24.2
NN 178	+ ● – ○ – ○ ● ○ – –	– ○ – – ● ○ ○ ● – +	20	10	6	4	8000	4336	1728	1936	50.0	30.0	20.0	54.2	21.6	24.2
NN 179	+ ○ ● – – ● – ○ – ○	– ○ ○ ● – – – ○ ● +	20	10	6	4	8000	4336	1728	1936	50.0	30.0	20.0	54.2	21.6	24.2
NN 180	+ – ● ○ ○ ● – – ○ –	– – ○ ● ○ – ○ – ● +	20	10	6	4	8000	4336	1728	1936	50.0	30.0	20.0	54.2	21.6	24.2
NN 181	+ ○ – ● – ● – ● ● –	● ● – – – ● – ● ○ +	20	10	2	8	8000	4336	1736	1928	50.0	10.0	40.0	54.2	21.7	24.1
NN 182	+ ○ – ● – ● – ● ● ●	– – – ● ● – – ● ○ +	20	10	2	8	8000	4336	1736	1928	50.0	10.0	40.0	54.2	21.7	24.1
NN 183	+ ○ ● – – – ● ● ● –	● – ● – ● – – ● ○ +	20	10	2	8	8000	4336	1736	1928	50.0	10.0	40.0	54.2	21.7	24.1
NN 184	+ ○ ● – – ● – ● – ●	– ● ● ● – – – ● ○ +	20	10	2	8	8000	4336	1736	1928	50.0	10.0	40.0	54.2	21.7	24.1

Continued

Continued

NN 185	+○●––●●–––	●●●–●–●–○+	20	10	2	8	8000	4336	1736	1928	50.0	10.0	40.0	54.2	21.7	24.1
NN 186	+○●–●–––●●	–●●–●–●–○+	20	10	2	8	8000	4336	1736	1928	50.0	10.0	40.0	54.2	21.7	24.1
NN 187	+–○–●●○●●–	––○–––●●○+	20	10	4	6	8000	4336	1768	1896	50.0	20.0	30.0	54.2	22.1	23.7
NN 188	+●○–––○●●–	●–○–●––●○+	20	10	4	6	8000	4336	1768	1896	50.0	20.0	30.0	54.2	22.1	23.7
NN 189	+●○––●○–––	●●○–●–●–○+	20	10	4	6	8000	4336	1768	1896	50.0	20.0	30.0	54.2	22.1	23.7
NN 190	+○●●–––○––	–●●○●●–○–+	20	10	4	6	8000	4336	1768	1896	50.0	20.0	30.0	54.2	22.1	23.7
NN 191	+○–●–●–○●●	–––○●––○●+	20	10	4	6	8000	4336	1768	1896	50.0	20.0	30.0	54.2	22.1	23.7
NN 192	+○●––●–○–●	–●●○–––○●+	20	10	4	6	8000	4336	1768	1896	50.0	20.0	30.0	54.2	22.1	23.7
NN 193	+●–○–○●○––	–○––○●●○–+	20	10	6	4	8000	4336	1776	1888	50.0	30.0	20.0	54.2	22.2	23.6
NN 194	+●○––○●––○	–○–○–●●○–+	20	10	6	4	8000	4336	1776	1888	50.0	30.0	20.0	54.2	22.2	23.6
NN 195	+–○●●–○–○–	○––●○––○●+	20	10	6	4	8000	4336	1776	1888	50.0	30.0	20.0	54.2	22.2	23.6
NN 196	+●○–––○●○–	○–●–○––○●+	20	10	6	4	8000	4336	1776	1888	50.0	30.0	20.0	54.2	22.2	23.6
NN 197	+●○––○–●–○	–○●○–––○●+	20	10	6	4	8000	4336	1776	1888	50.0	30.0	20.0	54.2	22.2	23.6
NN 198	+–○●●○––○–	––○●○–○–●+	20	10	6	4	8000	4336	1776	1888	50.0	30.0	20.0	54.2	22.2	23.6
NN 199	+○–●–●–●○–	●○–––●–●○+	20	10	4	6	8000	4336	1792	1872	50.0	20.0	30.0	54.2	22.4	23.4
NN 200	+○●–●–––○●	–○●–●–●–○+	20	10	4	6	8000	4336	1792	1872	50.0	20.0	30.0	54.2	22.4	23.4
NN 201	+●○––○●––●	–●–●–○○●–+	20	10	4	6	8000	4336	1792	1872	50.0	20.0	30.0	54.2	22.4	23.4
NN 202	+–●○○–●–●–	●––●○––○●+	20	10	4	6	8000	4336	1792	1872	50.0	20.0	30.0	54.2	22.4	23.4
NN 203	+–○●●–○–○–	○––○●––●○+	20	10	6	4	8000	4336	1872	1792	50.0	30.0	20.0	54.2	23.4	22.4
NN 204	+○●––●○––○	–○–○–●●○–+	20	10	6	4	8000	4336	1872	1792	50.0	30.0	20.0	54.2	23.4	22.4
NN 205	+●–○–○–○●–	○●–––○–○●+	20	10	6	4	8000	4336	1872	1792	50.0	30.0	20.0	54.2	23.4	22.4
NN 206	+●○–○–––●○	–●○–○–○–●+	20	10	6	4	8000	4336	1872	1792	50.0	30.0	20.0	54.2	23.4	22.4
NN 207	+–●○○–●–●–	●––○●––●○+	20	10	4	6	8000	4336	1888	1776	50.0	20.0	30.0	54.2	23.6	22.2
NN 208	+○●–––●○●–	●–○–●––●○+	20	10	4	6	8000	4336	1888	1776	50.0	20.0	30.0	54.2	23.6	22.2
NN 209	+○●––●–○–●	–●○●–––●○+	20	10	4	6	8000	4336	1888	1776	50.0	20.0	30.0	54.2	23.6	22.2
NN 210	+–●○○●––●–	––●○●–●–○+	20	10	4	6	8000	4336	1888	1776	50.0	20.0	30.0	54.2	23.6	22.2
NN 211	+○–●–●○●––	–●––●○○●–+	20	10	4	6	8000	4336	1888	1776	50.0	20.0	30.0	54.2	23.6	22.2
NN 212	+○●––●○––●	–●–●–○○●–+	20	10	4	6	8000	4336	1888	1776	50.0	20.0	30.0	54.2	23.6	22.2
NN 213	+●–○–○–●○○	–––●○––●○+	20	10	6	4	8000	4336	1896	1768	50.0	30.0	20.0	54.2	23.7	22.1
NN 214	+●○––○–●–○	–○○●–––●○+	20	10	6	4	8000	4336	1896	1768	50.0	30.0	20.0	54.2	23.7	22.1

Continued

Continued

NN 215	+●○○–––●––	–○○●○○–●–+	20	10	6	4	8000	4336	1896	1768	50.0	30.0	20.0	54.2	23.7	22.1
NN 216	+–●–○○●○○–	––●–––○○●+	20	10	6	4	8000	4336	1896	1768	50.0	30.0	20.0	54.2	23.7	22.1
NN 217	+○●–––●○○–	○–●–○––○●+	20	10	6	4	8000	4336	1896	1768	50.0	30.0	20.0	54.2	23.7	22.1
NN 218	+○●––○●–––	○○●–○–○–●+	20	10	6	4	8000	4336	1896	1768	50.0	30.0	20.0	54.2	23.7	22.1
NN 219	+●–○–○–○○–	○○–––○–○●+	20	10	8	2	8000	4336	1928	1736	50.0	40.0	10.0	54.2	24.1	21.7
NN 220	+●–○–○–○○○	–––○○––○●+	20	10	8	2	8000	4336	1928	1736	50.0	40.0	10.0	54.2	24.1	21.7
NN 221	+●○–––○○○–	○–○–○––○●+	20	10	8	2	8000	4336	1928	1736	50.0	40.0	10.0	54.2	24.1	21.7
NN 222	+●○––○–○–○	–○○○–––○●+	20	10	8	2	8000	4336	1928	1736	50.0	40.0	10.0	54.2	24.1	21.7
NN 223	+●○––○○–––	○○○–○–○–●+	20	10	8	2	8000	4336	1928	1736	50.0	40.0	10.0	54.2	24.1	21.7
NN 224	+●○–○–––○○	–○○–○–○–●+	20	10	8	2	8000	4336	1928	1736	50.0	40.0	10.0	54.2	24.1	21.7
NN 225	+●○––○–●–●	–●●○–––●○+	20	10	4	6	8000	4336	1936	1728	50.0	20.0	30.0	54.2	24.2	21.6
NN 226	+–○●●○––●–	––●○●–●–○+	20	10	4	6	8000	4336	1936	1728	50.0	20.0	30.0	54.2	24.2	21.6
NN 227	+○–●–●○●––	–●––○●●○–+	20	10	4	6	8000	4336	1936	1728	50.0	20.0	30.0	54.2	24.2	21.6
NN 228	+○●–––○●●–	●–●–○––○●+	20	10	4	6	8000	4336	1936	1728	50.0	20.0	30.0	54.2	24.2	21.6
NN 229	+●–○–○○●––	–○––●○●○–+	20	10	6	4	8000	4336	1968	1696	50.0	30.0	20.0	54.2	24.6	21.2
NN 230	+–○●○●––○–	––●○○–○–●+	20	10	6	4	8000	4336	1968	1696	50.0	30.0	20.0	54.2	24.6	21.2
NN 231	+–●○○–●–○–	○––●○––●○+	20	10	6	4	8000	4336	2016	1648	50.0	30.0	20.0	54.2	25.2	20.6
NN 232	+●○–––○○●–	○–●–○––●○+	20	10	6	4	8000	4336	2016	1648	50.0	30.0	20.0	54.2	25.2	20.6
NN 233	+○●––○●––○	–○–●–○○●–+	20	10	6	4	8000	4336	2016	1648	50.0	30.0	20.0	54.2	25.2	20.6
NN 234	+○●––○–●–○	–●○○–––○●+	20	10	6	4	8000	4336	2016	1648	50.0	30.0	20.0	54.2	25.2	20.6
NN 235	+○–●–●–○○○	–––●○––●○+	20	10	6	4	8000	4336	2088	1576	50.0	30.0	20.0	54.2	26.1	19.7
NN 236	+●○––○–○–●	–●○○–––●○+	20	10	6	4	8000	4336	2088	1576	50.0	30.0	20.0	54.2	26.1	19.7
NN 237	+○●––○●–––	○○○–●–●–○+	20	10	6	4	8000	4336	2088	1576	50.0	30.0	20.0	54.2	26.1	19.7
NN 238	+●○––○○––●	–●–○–○○●–+	20	10	6	4	8000	4336	2088	1576	50.0	30.0	20.0	54.2	26.1	19.7
NN 239	+–●○○–○–●–	●––○○––○●+	20	10	6	4	8000	4336	2088	1576	50.0	30.0	20.0	54.2	26.1	19.7
NN 240	+○●–––○○●–	●–○–○––○●+	20	10	6	4	8000	4336	2088	1576	50.0	30.0	20.0	54.2	26.1	19.7
NN 241	+–○●○–●–●–	●––●○––●○+	20	10	4	6	8000	4336	2152	1512	50.0	20.0	30.0	54.2	26.9	18.9
NN 242	+–○●○●––●–	––●●○–●–○+	20	10	4	6	8000	4336	2152	1512	50.0	20.0	30.0	54.2	26.9	18.9
NN 243	+●○–○–––●●	–●●–○–●–○+	20	10	4	6	8000	4336	2152	1512	50.0	20.0	30.0	54.2	26.9	18.9
NN 244	+○–●–○●●––	–●––●○●○–+	20	10	4	6	8000	4336	2152	1512	50.0	20.0	30.0	54.2	26.9	18.9

Continued

Continued

NN 245	+○●––○●––●	–●–●–○●○–+	20	10	4	6	8000	4336	2152	1512	50.0	20.0	30.0	54.2	26.9	18.9
NN 246	+○–●–○–●●–	●●–––○–○●+	20	10	4	6	8000	4336	2152	1512	50.0	20.0	30.0	54.2	26.9	18.9
NN 247	+–●–○○○●○–	––●–––○●○+	20	10	6	4	8000	4336	2160	1504	50.0	30.0	20.0	54.2	27.0	18.8
NN 248	+○●–––○●○–	○–●–○––●○+	20	10	6	4	8000	4336	2160	1504	50.0	30.0	20.0	54.2	27.0	18.8
NN 249	+○●––○–●–○	–○●○–––●○+	20	10	6	4	8000	4336	2160	1504	50.0	30.0	20.0	54.2	27.0	18.8
NN 250	+–○●○●––○–	––○○●–●–○+	20	10	6	4	8000	4336	2160	1504	50.0	30.0	20.0	54.2	27.0	18.8
NN 251	+○●○–––●––	–○●○○○–●–+	20	10	6	4	8000	4336	2160	1504	50.0	30.0	20.0	54.2	27.0	18.8
NN 252	+○–●–●○○––	–○––●○●○–+	20	10	6	4	8000	4336	2160	1504	50.0	30.0	20.0	54.2	27.0	18.8
NN 253	+●○–○–––○●	–○●–○–●–○+	20	10	6	4	8000	4336	2208	1456	50.0	30.0	20.0	54.2	27.6	18.2
NN 254	+○–●–○–●○–	●○–––○–○●+	20	10	6	4	8000	4336	2208	1456	50.0	30.0	20.0	54.2	27.6	18.2
NN 255	+○–●–○–●●●	–––●○––●○+	20	10	4	6	8000	4336	2224	1440	50.0	20.0	30.0	54.2	27.8	18.0
NN 256	+○●––○●–––	●●●–○–●–○+	20	10	4	6	8000	4336	2224	1440	50.0	20.0	30.0	54.2	27.8	18.0
NN 257	+●○––○○–––	●●○–○–●–○+	20	10	6	4	8000	4336	2256	1408	50.0	30.0	20.0	54.2	28.2	17.6
NN 258	+○–●–○–○●●	–––○○––○●+	20	10	6	4	8000	4336	2256	1408	50.0	30.0	20.0	54.2	28.2	17.6
NN 259	+●○––○○––●	–○–●–●○○–+	20	10	6	4	8000	4336	2280	1384	50.0	30.0	20.0	54.2	28.5	17.3
NN 260	+–○○●–●–○–	●––○○––○●+	20	10	6	4	8000	4336	2280	1384	50.0	30.0	20.0	54.2	28.5	17.3
NN 261	+–○–●●○○○–	––●–––○●○+	20	10	6	4	8000	4336	2304	1360	50.0	30.0	20.0	54.2	28.8	17.0
NN 262	+○●○–––●––	–○○○●●–○–+	20	10	6	4	8000	4336	2304	1360	50.0	30.0	20.0	54.2	28.8	17.0
NN 263	+–●–○○○○○–	––○–––○●○+	20	10	8	2	8000	4336	2312	1352	50.0	40.0	10.0	54.2	28.9	16.9
NN 264	+–●○○–○–○–	○––○○––●○+	20	10	8	2	8000	4336	2312	1352	50.0	40.0	10.0	54.2	28.9	16.9
NN 265	+○●–––○○○–	○–○–○––●○+	20	10	8	2	8000	4336	2312	1352	50.0	40.0	10.0	54.2	28.9	16.9
NN 266	+○●––○–○–○	–○○○–––●○+	20	10	8	2	8000	4336	2312	1352	50.0	40.0	10.0	54.2	28.9	16.9
NN 267	+○●––○○––○	–○–○–○○●–+	20	10	8	2	8000	4336	2312	1352	50.0	40.0	10.0	54.2	28.9	16.9
NN 268	+○●○–––○––	–○○○○○–●–+	20	10	8	2	8000	4336	2312	1352	50.0	40.0	10.0	54.2	28.9	16.9
NN 269	+○–●–○–●○–	○●–––○–●○+	20	10	6	4	8000	4336	2376	1288	50.0	30.0	20.0	54.2	29.7	16.1
NN 270	+–●–○○○○●–	––●–––●○○+	20	10	6	4	8000	4336	2376	1288	50.0	30.0	20.0	54.2	29.7	16.1
NN 271	+–●○○○––●–	––●○○–●–○+	20	10	6	4	8000	4336	2376	1288	50.0	30.0	20.0	54.2	29.7	16.1
NN 272	+○●–○–––●○	–○●–○–●–○+	20	10	6	4	8000	4336	2376	1288	50.0	30.0	20.0	54.2	29.7	16.1
NN 273	+○–●–○○●––	–●––○○○●–+	20	10	6	4	8000	4336	2376	1288	50.0	30.0	20.0	54.2	29.7	16.1
NN 274	+○○●–––●––	–●○○○○–●–+	20	10	6	4	8000	4336	2376	1288	50.0	30.0	20.0	54.2	29.7	16.1

Continued

Continued

NN 275	+ – ○○●● – – ○ –	– – ○●○ – ● – ○ +	20	10	6	4	8000	4336	2400	1264	50.0	30.0	20.0	54.2	30.0	15.8
NN 276	+ ○ – ● – ○●○ – –	– ○ – – ●●○○ – +	20	10	6	4	8000	4336	2400	1264	50.0	30.0	20.0	54.2	30.0	15.8
NN 277	+ ○ – ● – ○ – ○● –	●○ – – – ○ – ●○ +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 278	+ – ○●○ – ○ – ● –	● – – ○○ – – ●○ +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 279	+ ○● – ○ – – – ○●	– ●○ – ○ – ● – ○ +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 280	+ ●○ – – ○○ – – –	○●● – ● – ○ – ○ +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 281	+ ●○ – ○ – – – ○○	– ●● – ● – ○ – ○ +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 282	+ ○● – – ○○ – – ●	– ● – ○ – ○●○ – +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 283	+ ●○○ – – – ○ – –	– ●●○●○ – ○ – +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 284	+ – ○ – ○●○●● –	– – ○ – – – ○○● +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 285	+ ○ – ○ – ● – ●● –	○○ – – – ○ – ○● +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 286	+ ○ – ○ – ● – ●●○	– – – ○○ – – ○● +	20	10	6	4	8000	4336	2448	1216	50.0	30.0	20.0	54.2	30.6	15.2
NN 287	+ – ○ – ●○●○○ –	– – ● – – – ●○○ +	20	10	6	4	8000	4336	2568	1096	50.0	30.0	20.0	54.2	32.1	13.7
NN 288	+ ○○● – – – ● – –	– ○○●○● – ○ – +	20	10	6	4	8000	4336	2568	1096	50.0	30.0	20.0	54.2	32.1	13.7
NN 289	+ – ○●○○ – – ○ –	– – ○○○ – ● – ○ +	20	10	8	2	8000	4336	2648	1016	50.0	40.0	10.0	54.2	33.1	12.7
NN 290	+ ○ – ● – ○○○ – –	– ○ – – ○○●○ – +	20	10	8	2	8000	4336	2648	1016	50.0	40.0	10.0	54.2	33.1	12.7
NN 291	+ ○ – ○ – ● – ●○●	– – – ○○ – – ●○ +	20	10	6	4	8000	4336	2664	1000	50.0	30.0	20.0	54.2	33.3	12.5
NN 292	+ ○○ – – ● – ● – ●	– ○○○ – – – ●○ +	20	10	6	4	8000	4336	2664	1000	50.0	30.0	20.0	54.2	33.3	12.5
NN 293	+ ○● – – – ○○○ –	● – ● – ● – – ○○ +	20	10	6	4	8000	4336	2664	1000	50.0	30.0	20.0	54.2	33.3	12.5
NN 294	+ ○● – – ○○ – – –	●○● – ● – ○ – ○ +	20	10	6	4	8000	4336	2664	1000	50.0	30.0	20.0	54.2	33.3	12.5
NN 295	+ – ○ – ○○●●● –	– – ○ – – – ○●○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 296	+ ○○ – – – ●●● –	○ – ○ – ○ – – ●○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 297	+ – ○●○ – ○ – ● –	○ – – ●● – – ○○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 298	+ ○ – ● – ○ – ○●○	– – – ●● – – ○○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 299	+ ○● – – ○ – ○ – ○	– ●●● – – – ○○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 300	+ ○○ – – ●● – – –	○●○ – ○ – ● – ○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 301	+ – ○●○○ – – ● –	– – ○●● – ○ – ○ +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 302	+ ○ – ○ – ●●○ – –	– ● – – ○○●○ – +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 303	+ ○○ – – ●● – – ○	– ● – ○ – ○●○ – +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6
NN 304	+ ○●○ – – – ○ – –	– ●●●○○ – ○ – +	20	10	6	4	8000	4336	2736	928	50.0	30.0	20.0	54.2	34.2	11.6

Continued

Continued

NN 305	+○–○–●–●○–	○●–––●–○○+	20	10	6	4	8000	4336	2952	712	50.0	30.0	20.0	54.2	36.9	8.9
NN 306	+–○○●○––●–	––●○●–○–○+	20	10	6	4	8000	4336	2952	712	50.0	30.0	20.0	54.2	36.9	8.9
NN 307	+○○–●–––●○	–○●–●–○–○+	20	10	6	4	8000	4336	2952	712	50.0	30.0	20.0	54.2	36.9	8.9
NN 308	+○–○–●○●––	–●––○●○○–+	20	10	6	4	8000	4336	2952	712	50.0	30.0	20.0	54.2	36.9	8.9
NN 309	+○–○–●–○●–	●○–––●–○○+	20	10	6	4	8000	4336	3024	640	50.0	30.0	20.0	54.2	37.8	8.0
NN 310	+○○–●–––○●	–●○–●–○–○+	20	10	6	4	8000	4336	3024	640	50.0	30.0	20.0	54.2	37.8	8.0
NN 311	+○○–––●●●–	●–●–●––○○+	20	10	4	6	8000	4336	3088	576	50.0	20.0	30.0	54.2	38.6	7.2
NN 312	+○○––●–●–●	–●●●–––○○+	20	10	4	6	8000	4336	3088	576	50.0	20.0	30.0	54.2	38.6	7.2
NN 313	+–○○○●––●–	––●●○–○–○+	20	10	6	4	8000	4336	3168	496	50.0	30.0	20.0	54.2	39.6	6.2
NN 314	+○–○–○●●––	–●––●○○○–+	20	10	6	4	8000	4336	3168	496	50.0	30.0	20.0	54.2	39.6	6.2
NN 315	+○–○–●–○○○	–––○●––○○+	20	10	8	2	8000	4336	3176	488	50.0	40.0	10.0	54.2	39.7	6.1
NN 316	+–○○○●––○–	––○○●–○–○+	20	10	8	2	8000	4336	3176	488	50.0	40.0	10.0	54.2	39.7	6.1
NN 317	+○○––●○–––	○○○–●–○–○+	20	10	8	2	8000	4336	3176	488	50.0	40.0	10.0	54.2	39.7	6.1
NN 318	+○–○–●○○––	–○––●○○○–+	20	10	8	2	8000	4336	3176	488	50.0	40.0	10.0	54.2	39.7	6.1
NN 319	+–○○○–●–●–	●––○●––○○+	20	10	6	4	8000	4336	3240	424	50.0	30.0	20.0	54.2	40.5	5.3
NN 320	+○○–––●○●–	●–○–●––○○+	20	10	6	4	8000	4336	3240	424	50.0	30.0	20.0	54.2	40.5	5.3
NN 321	+○○––●–○–●	–●○●–––○○+	20	10	6	4	8000	4336	3240	424	50.0	30.0	20.0	54.2	40.5	5.3
NN 322	+○○––●○––●	–●–●–○○○–+	20	10	6	4	8000	4336	3240	424	50.0	30.0	20.0	54.2	40.5	5.3
NN 323	+○–○–○–●●●	–––○●––○○+	20	10	6	4	8000	4336	3312	352	50.0	30.0	20.0	54.2	41.4	4.4
NN 324	+○○––●○–––	●●●–○–○–○+	20	10	6	4	8000	4336	3312	352	50.0	30.0	20.0	54.2	41.4	4.4
NN 325	+–○○○–●–○–	○––●○––○○+	20	10	8	2	8000	4336	3368	296	50.0	40.0	10.0	54.2	42.1	3.7
NN 326	+○○––○●––○	–○–●–○○○–+	20	10	8	2	8000	4336	3368	296	50.0	40.0	10.0	54.2	42.1	3.7
NN 327	+–○–○○○●○–	––●–––○○○+	20	10	8	2	8000	4336	3512	152	50.0	40.0	10.0	54.2	43.9	1.9
NN 328	+○○–––○●○–	○–●–○––○○+	20	10	8	2	8000	4336	3512	152	50.0	40.0	10.0	54.2	43.9	1.9
NN 329	+○○––○–●–○	–○●○–––○○+	20	10	8	2	8000	4336	3512	152	50.0	40.0	10.0	54.2	43.9	1.9
NN 330	+○○○–––●––	–○●○○○–○–+	20	10	8	2	8000	4336	3512	152	50.0	40.0	10.0	54.2	43.9	1.9
NN 331	+○–○–○–○●–	○●–––○–○○+	20	10	8	2	8000	4336	3608	56	50.0	40.0	10.0	54.2	45.1	0.7
NN 332	+○○–○–––●○	–●○–○–○–○+	20	10	8	2	8000	4336	3608	56	50.0	40.0	10.0	54.2	45.1	0.7
NN 333	+–○–○○○○○–	––○–––○○○+	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 334	+○–○–○–○○–	○○–––○–○○+	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0

Continued

Continued

NN 335	+ – ○○○ – ○ – ○ –	○ – – ○○ – – ○○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 336	+ ○ – ○ – ○ – ○○○	– – – ○○ – – ○○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 337	+ ○○ – – – ○○○ –	○ – ○ – ○ – – ○○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 338	+ ○○ – – ○ – ○ – ○	– ○○○ – – – ○○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 339	+ – ○○○○ – – ○ –	– – ○○○ – ○ – ○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 340	+ ○○ – – ○○ – – –	○○○ – ○ – ○ – ○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 341	+ ○○ – ○ – – – ○○	– ○○ – ○ – ○ – ○ +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 342	+ ○ – ○ – ○○○ – –	– ○ – – ○○○○ – +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 343	+ ○○ – – ○○ – – ○	– ○ – ○ – ○○○ – +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0
NN 344	+ ○○○ – – – ○ – –	– ○○○○○ – ○ – +	20	10	10	0	8000	4336	3664	0	50.0	50.0	0.0	54.2	45.8	0.0

Concluded.

Table A6 – Stacking sequences for 7 through 21 ply laminates of the form $_{+}NN_{-}$ with blend ratio ($n_{+}/n_{\pm}$) = 28.6%.

Ref.	Sequence	n	$n_{\pm}$	$n_{\circ}$	$n_{\bullet}$	ζ	$\zeta_{\pm}$	$\zeta_{\circ}$	$\zeta_{\bullet}$	$n_{\pm}/n$ (%)	$n_{\circ}/n$ (%)	$n_{\bullet}/n$ (%)	$\zeta_{\pm}/\zeta$ (%)	$\zeta_{\circ}/\zeta$ (%)	$\zeta_{\bullet}/\zeta$ (%)
NN 57	+ ● − + − − − − − ● − ● − ● − + + −	18	14	0	4	5832	4832	0	1000	77.8	0.0	22.2	82.9	0.0	17.1
NN 58	+ ○ − + − − − − − ○ − ○ − ○ − + + −	18	14	4	0	5832	4832	1000	0	77.8	22.2	0.0	82.9	17.1	0.0
NN 359	+ − ● + − − ● − ● − ● − − − − ● ● + + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 360	+ − ● + − − ● ● − − − − ● − ● − ● + + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 361	+ − ● + ● − − − − − ● − ● − ● ● − + + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 362	+ ● − + − ● − − − − − ● ● ● − ● − + + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 367	+ − ● + − − ● ○ − − − − ○ − ● − ● + + −	20	14	2	4	8000	6272	152	1576	70.0	10.0	20.0	78.4	1.9	19.7
NN 369	+ − ● + ○ − − − − − ● − ● − ● ○ − + + −	20	14	2	4	8000	6272	728	1000	70.0	10.0	20.0	78.4	9.1	12.5
NN 371	+ − ○ + ● − − − − − ○ − ○ − ○ ● − + + −	20	14	4	2	8000	6272	1000	728	70.0	20.0	10.0	78.4	12.5	9.1
NN 373	+ − ○ + − − ○ ● − − − − ● − ○ − ○ + + −	20	14	4	2	8000	6272	1576	152	70.0	20.0	10.0	78.4	19.7	1.9
NN 375	+ − ○ + − − ○ − ○ − ○ − − − − ○ ○ + + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0
NN 376	+ − ○ + − − ○ ○ − − − − ○ − ○ − ○ + + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0
NN 377	+ − ○ + ○ − − − − − ○ − ○ − ○ ○ − + + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0
NN 378	+ ○ − + − ○ − − − − − ○ ○ ○ − ○ − + + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0

Table A7 – Stacking sequences for 7 through 21 ply laminates of the form $_{+}NN_{-}$ with blend ratio $(n_{+}/n_{\pm})$ = 71.4%.

Ref.	Sequence	n	$n_{\pm}$	$n_{○}$	$n_{●}$	ζ	$\zeta_{\pm}$	$\zeta_{○}$	$\zeta_{●}$	$n_{\pm}/n$ (%)	$n_{○}/n$ (%)	$n_{●}/n$ (%)	$\zeta_{\pm}/\zeta$ (%)	$\zeta_{○}/\zeta$ (%)	$\zeta_{●}/\zeta$ (%)
NN 59	+ − − + ● + ● + ● + + + + + − + ● −	18	14	0	4	5832	4832	0	1000	77.8	0.0	22.2	82.9	0.0	17.1
NN 60	+ − − + ○ + ○ + ○ + + + + + − + ○ −	18	14	4	0	5832	4832	1000	0	77.8	22.2	0.0	82.9	17.1	0.0
NN 363	+ − − + ● + ● ● ● + + + + + ● + − + ● −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 364	+ − − + ● ● + ● + ● + + + + + ● − ● + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 365	+ − − ● + ● + ● + + + + ● ● + + − ● + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 366	+ − − ● ● + + + + ● + ● + ● + + − ● + −	20	14	0	6	8000	6272	0	1728	70.0	0.0	30.0	78.4	0.0	21.6
NN 368	+ − − ● + ● + ○ + + + + ○ ● + + − ● + −	20	14	2	4	8000	6272	152	1576	70.0	10.0	20.0	78.4	1.9	19.7
NN 370	+ − − + ○ ● + ● + ● + + + + + ○ − ● + −	20	14	2	4	8000	6272	728	1000	70.0	10.0	20.0	78.4	9.1	12.5
NN 372	+ − − + ● ○ + ○ + ○ + + + + + ● − ○ + −	20	14	4	2	8000	6272	1000	728	70.0	20.0	10.0	78.4	12.5	9.1
NN 374	+ − − ○ + ○ + ● + + + + ● ○ + + − ○ + −	20	14	4	2	8000	6272	1576	152	70.0	20.0	10.0	78.4	19.7	1.9
NN 379	+ − − ○ ○ + + + + ○ + ○ + ○ + + − ○ + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0
NN 380	+ − − ○ + ○ + ○ + + + + ○ ○ + + − ○ + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0
NN 381	+ − − + ○ ○ + ○ + ○ + + + + + ○ − ○ + −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0
NN 382	+ − − + ○ + ○ ○ ○ + + + + + ○ + − + ○ −	20	14	6	0	8000	6272	1728	0	70.0	30.0	0.0	78.4	21.6	0.0

Table A8 - Stacking sequences for 7 through 21 ply laminates of the form $_{+}NN_{\bigcirc}$ with blend ratio ($n_{+}/n_{\pm}$) = 28.6%.

Ref.	Sequence	n	$n_{\pm}$	$n_{\bigcirc}$	$n_{\bullet}$	ζ	$\zeta_{\pm}$	$\zeta_{\bigcirc}$	$\zeta_{\bullet}$	$n_{\pm}/n$ (%)	$n_{\bigcirc}/n$ (%)	$n_{\bullet}/n$ (%)	$\zeta_{\pm}/\zeta$ (%)	$\zeta_{\bigcirc}/\zeta$ (%)	$\zeta_{\bullet}/\zeta$ (%)
NN 345	+ ● – ● – + – ● – – – – ● – – ● + + – ●	20	14	0	6	8000	5024	0	2976	70.0	0.0	30.0	62.8	0.0	37.2
NN 346	+ ● – ● – + – ○ – – – – ○ – – ● + + – ●	20	14	2	4	8000	5024	152	2824	70.0	10.0	20.0	62.8	1.9	35.3
NN 347	+ ○ – ○ – + – ● – – – – ● – – ○ + + – ○	20	14	4	2	8000	5024	2824	152	70.0	20.0	10.0	62.8	35.3	1.9
NN 348	+ ○ – ○ – + – ○ – – – – ○ – – ○ + + – ○	20	14	6	0	8000	5024	2976	0	70.0	30.0	0.0	62.8	37.2	0.0
NN 349	+ – – ● + ● ● – – ● – – – – – ● + – + ●	20	14	0	6	8000	5648	0	2352	70.0	0.0	30.0	70.6	0.0	29.4
NN 350	+ ● – – + – ● ● – – – ● – ● – – + – + ●	20	14	0	6	8000	5648	0	2352	70.0	0.0	30.0	70.6	0.0	29.4
NN 351	+ ● – – + ● – – – ● ● – – ● – – + – + ●	20	14	0	6	8000	5648	0	2352	70.0	0.0	30.0	70.6	0.0	29.4
NN 352	+ ● – – + ● – – – ○ ○ – – ● – – + – + ●	20	14	2	4	8000	5648	8	2344	70.0	10.0	20.0	70.6	0.1	29.3
NN 353	+ ● – – + – ○ ● – – – ● – ○ – – + – + ●	20	14	2	4	8000	5648	296	2056	70.0	10.0	20.0	70.6	3.7	25.7
NN 354	+ ○ – – + – ● ○ – – – ○ – ● – – + – + ○	20	14	4	2	8000	5648	2056	296	70.0	20.0	10.0	70.6	25.7	3.7
NN 355	+ ○ – – + ○ – – – ● ● – – ○ – – + – + ○	20	14	4	2	8000	5648	2344	8	70.0	20.0	10.0	70.6	29.3	0.1
NN 356	+ – – ○ + ○ ○ – – ○ – – – – – ○ + – + ○	20	14	6	0	8000	5648	2352	0	70.0	30.0	0.0	70.6	29.4	0.0
NN 357	+ ○ – – + – ○ ○ – – – ○ – ○ – – + – + ○	20	14	6	0	8000	5648	2352	0	70.0	30.0	0.0	70.6	29.4	0.0
NN 358	+ ○ – – + ○ – – – ○ ○ – – ○ – – + – + ○	20	14	6	0	8000	5648	2352	0	70.0	30.0	0.0	70.6	29.4	0.0