Appendix A
Matrices

Definition

A *matrix* is an array of numbers subject to certain operations. For example,

$$\begin{bmatrix} 3 & 2 & 9 & 7 \\ 0 & -63 & 49 & 5 \\ 1 & 5 & 4 & 8 \end{bmatrix} \quad 3 \text{ rows, } 4 \text{ columns}$$

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad m \text{ rows, } n \text{ columns}$$

The a_{ij} are called the *elements* of the matrix.

Notation

$$A = [A] = (a_{ij}) = [a_{ij}]_{m,n}$$

Null Matrix

In a *null matrix*, all the elements are zero, that is,

$$[N] = [0]$$

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Any matrix multiplied by a null matrix results in a null matrix. Thus,

$$[A][N] = [N]$$

Square Matrix

The number of rows, called the *order* of the matrix, is equal to the number of columns. For example,

$$[A] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

is a square matrix of order 2.

Determinant

Associated with every square matrix [*A*], there is a numerical value called its *determinant*, $|A|$.

$$[A] = a_{ij}(\text{cof } a_{ij})$$

where cof $a_{ij} = (-1)^{i+j}|M_{ij}|$. cof a_{ij} is the *cofactor* of a_{ij} and M_{ij} is the *minor* of a_{ij}, obtained by eliminating the row and the column of a_{ij}.

Consider the matrix

$$[A] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

$$\text{Determinant } [A] = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}$$

$$\text{cof } a_{11} = (-1)^2|M_{11}| = M_{11} = a_{22}$$

$$\text{cof } a_{12} = (-1)^3|M_{12}| = -M_{12} = -a_{21}$$

$$\text{cof } a_{21} = (-1)^3[M_{21}] = -M_{21} = -a_{12}$$

$$\text{cof } a_{22} = (-1)^4|M_{22}| = M_{22} = a_{11}$$

$$|A| = \sum_{i=1}^{n} a_{ij}(\text{cof } a_{ij}) = a_{11}a_{22} + a_{12}(-a_{21})$$
$$= a_{11}a_{22} - a_{12}a_{21}$$

Another example is

$$[A] = \begin{bmatrix} 1 & 2 & -1 \\ 3 & 4 & 0 \\ 0 & 3 & 2 \end{bmatrix}$$

$$\text{cof}\, a_{11} = M_{11} = \begin{vmatrix} 4 & 0 \\ 3 & 2 \end{vmatrix} = 8 - 0 = 8$$

$$\text{cof}\, a_{12} = -M_{12} = \begin{vmatrix} 3 & 0 \\ 0 & 2 \end{vmatrix} = -6 + 0 = -6$$

$$\text{cof}\, a_{13} = M_{13} = \begin{vmatrix} 3 & 4 \\ 0 & 3 \end{vmatrix} = 9 - 0 = 9$$

$$|A| = 1 \times 8 + 2 \times (-6) - 1 \times 9 = 8 - 12 - 9 = -13$$

Diagonal Matrix

A square matrix whose nondiagonal elements are zero is called a *diagonal matrix*.

$$a_{ij} = 0 \quad \text{for} \quad i \neq j$$

For example,

$$\begin{bmatrix} 3 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Identity Matrix

A diagonal matrix whose elements are unity is called an *identity matrix*.

$$[I] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[I][A] = [A]$$

Column or Row Matrix

All the elements in a column or row matrix are arranged in the form of a column or row. For example,

$$\text{column matrix} \quad \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}$$

$$\text{row matrix} \quad [\, b_1 \quad b_2 \quad \cdots \quad b_n \,]$$

Transpose Matrix

The substitution of columns by rows of the original matrix produces a *transpose matrix*. The transpose of a row matrix is a column matrix and vice versa. For example,

$$[A] = \begin{bmatrix} 0 & -5 & 1 \\ 8 & 4 & 2 \end{bmatrix} \quad [A]^{\mathrm{T}} = \begin{bmatrix} 0 & 8 \\ -5 & 4 \\ 1 & 2 \end{bmatrix}$$

$$[a] = [\, 2 \quad 3 \quad -7 \,] \quad [a]^{\mathrm{T}} = \begin{bmatrix} 2 \\ 3 \\ -7 \end{bmatrix}$$

$$[AB]^{\mathrm{T}} = [B]^{\mathrm{T}}[A]^{\mathrm{T}}$$

Symmetric Matrix

A square matrix is *symmetric* if it is equal to its transpose, that is,

$$A^{\mathrm{T}} = A$$

$$a_{ij} = a_{ij} \quad \text{for all } i \text{ and } j$$

Antisymmetric or Skew-Symmetric Matrix

$$A^{\mathrm{T}} = -A$$
$$a_{ij} = -a_{ji} \quad \text{for all } i \text{ and } j$$

For $i = j$, $a_{ii} = -a_{ii}$, that is, the diagonal elements of a skew-symmetric matrix are zero.

Singular Matrix

A square matrix whose determinant is zero is called a *singular matrix*.

Inverse Matrix

$[A]^{-1}$ is the inverse matrix of $[A]$ such that

$$[A][A]^{-1} = [I] = [A]^{-1}[A]$$
$$[A]^{-1} = \frac{1}{[A]}[\mathrm{cof}\, A]^{T}$$

We now give some examples of inverse matrix determination.

Example 1

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$
$$[A]^{-1} = \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix} \frac{1}{a_{11}a_{22} - a_{12}a_{21}}$$

Example 2

$$A = \begin{bmatrix} a_{11} & 0 & \cdots & 0 \\ 0 & a_{22} & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \ldots & a_{nn} \end{bmatrix}$$
$$A^{-1} = \begin{bmatrix} 1/a_{11} & 0 & \cdots & 0 \\ 0 & 1/a_{22} & \cdots & 0 \\ \vdots & \vdots & \cdots & \\ 0 & 0 & \ldots & 1/a_{nn} \end{bmatrix}$$

Example 3

$$A = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$
$$|A| = \cos^2\theta + \sin^2\theta = 1$$
$$A^{-1} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

Example 4

$$T = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2 - n^2 \end{bmatrix} \begin{matrix} m = \cos\theta \\ n = \sin\theta \end{matrix}$$

There is a very important matrix called the *transformation matrix*:

$$|A| = 1$$
$$T^{-1} = \begin{bmatrix} m^2 & n^2 & -2mn \\ n^2 & m^2 & 2mn \\ mn & -mn & m^2 - n^2 \end{bmatrix}$$

Note that T^{-1} is obtained by replacing θ by $-\theta$ in T.

Some Basic Matrix Operations

The equality $[A] = [B]$ is valid if and only if $a_{ij} = b_{ij}$.

Addition and Subtraction

To perform the operations of addition or subtraction, the matrices must be *compatible*, that is, they must have the same dimension:

$$[A] + [B] + [C] = [D]$$
$$a_{ij} + b_{ij} + c_{ij} = d_{ij}$$

Similarly,

$$[E] = [A] - [B]$$
$$e_{ij} = a_{ij} - b_{ij}$$

Multiplication

To perform the operation of multiplication, the number of columns of one matrix must be equal to the number of rows of the other matrix:

$$[A]_{m\times n}[B]_{n\times r} = [C]_{m\times r}$$

$$c_{ij} = \sum_{k=1}^{n} a_{ik}b_{kj}$$

$$\begin{bmatrix} 3 & 5 \\ 9 & 8 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 4 & 3 \end{bmatrix} = \begin{bmatrix} 3\times 1+5\times 4 & 3\times 0+5\times 3 \\ 9\times 1+8\times 4 & 9\times 0+8\times 3 \end{bmatrix} = \begin{bmatrix} 23 & 15 \\ 41 & 24 \end{bmatrix}$$

Matrix multiplication is associative and distributive but not commutative. Thus,

$$[AB][C] = [A][BC]$$

$$[A][B + C] = [A][B] + [A][C]$$

$$[A][B] \neq [B][A]$$

The order of the matrix is very important in matrix multiplication.

Appendix B
Fiber Packing in Unidirectional Composites

Geometrical Considerations

Consider a composite containing uniaxially aligned fibers. Assume for the sake of simplicity that the fibers have the same cross-sectional form and area. Then for any uniaxial arrangement of fibers, we can relate the fiber volume fraction V_f, the fiber radius r, and the center-to-center spacing of fibers R as

$$V_f = \alpha\left(\frac{r}{R}\right)^2$$

where α is a constant that depends on the geometry of the arrangement of fibers.

Let S be the distance of closest approach between the fiber surfaces. Then

$$S = 2(R - r)$$

or

$$S = 2\left[\left(\frac{\alpha}{V_f}\right)^{1/2} r - r\right] = 2r\left[\left(\frac{\alpha}{V_f}\right)^{1/2} - 1\right]$$

Thus, the separation between two fibers is less than a fiber diameter when

$$\left[\left(\frac{\alpha}{V_f}\right)^{1/2} - 1\right] < 1$$

or

$$\left(\frac{\alpha}{V_f}\right)^{1/2} < 2$$

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Table B.1 Geometrical fiber packing parameters

Arrangement	α	$\alpha/4$	$V_{f_{max}}$
Hexagonal	$\frac{\pi}{2\sqrt{3}} = 0.912$	0.228	0.912
Square	$\frac{\pi}{4} = 0.785$	0.196	0.785

or

$$\frac{\alpha}{V_f} < 4$$

or

$$V_f > \frac{\alpha}{4}$$

The densest fiber packing $V_{f_{max}}$ corresponds to touching fibers, that is,

$$\left[\left(\frac{\alpha}{V_{f_{max}}}\right)^{1/2} - 1\right] = 0$$

or

$$V_{f_{max}} = \alpha$$

Table B.1 shows the values of α, $\alpha/4$, and $V_{f_{max}}$ for hexagonal and square arrangements of fibers.

Appendix C
Some Important Units and Conversion Factors

Stress (or Pressure)

1 dyn $= 10^5$ newton (N)
1 N $m^{-2} = 10$ dyn $cm^{-2} = 1$ pascal (Pa)
1 bar $= 10^5$ N $m^{-2} = 10^5$ Pa
1 hectobar $= 100$ bars $= 10^8$ cm^{-2}
1 kilobar $= 10^8$ N $m^{-2} = 10^9$ dyn cm^{-2}
1 mmHg $= 1$ torr $= 133.322$ Pa $= 133.322$ N m^{-2}
1 kgf $mm^{-2} = 9806.65$ kN $m^{-2} = 9806.65$ kPa $= 100$ atmospheres
1 kgf $cm^{-2} = 98.0665$ kPa $= 1$ atmosphere
1 lb $in.^{-2} = 6.89476$ kN $m^{-2} = 6.89476$ kPa
1 kgf $cm^{-2} = 14.2233$ lb $in.^{-2}$
10^6 psi $= 10^6$ lb $in^{-2} = 6.89476$ GN $m^{-2} = 6.89476$ GPa
1 GPa $= 145{,}000$ psi

Density

1 g $cm^{-3} = 62.4280$ lb $ft^{-3} = 0.0361$ lb in^{-3}
1 lb $in^{-3} = 27.68$ g cm^{-3}
1 g $cm^{-3} = 10^3$ kg m^{-3}

Viscosity

1 poise $= 0.1$ Pa s $= 0.1$ N m^{-2} s
1 GN m^{-2} s $= 10^{10}$ poise

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Energy

$1\ \text{erg cm}^{-2} = 1\ \text{mJ m}^{-2} = 10^{-3}\ \text{J m}^{-2}$
$10^{8}\ \text{erg cm}^{-2} = 47.68\ \text{ft lb in.}^{-2} = 572.16\ \text{psi in}$

Fracture Toughness

$1\ \text{psi in}^{1/2} = 1\ \text{lbf in}^{-3/2} = 1.11\ \text{kN m}^{-3/2} = 1.11\ \text{kPa m}^{-1/2}$
$1\ \text{ksi in}^{1/2} = 1.11\ \text{MPa m}^{-1/2}$
$1\ \text{MPa m}^{-1/2} = 0.90\ \text{ksi in}^{1/2}$
$1\ \text{kgf mm}^{-2}\ \text{mm}^{1/2} = 3.16 \times 10^{4}\ \text{N m}^{-2}\ \text{m}^{1/2}$

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