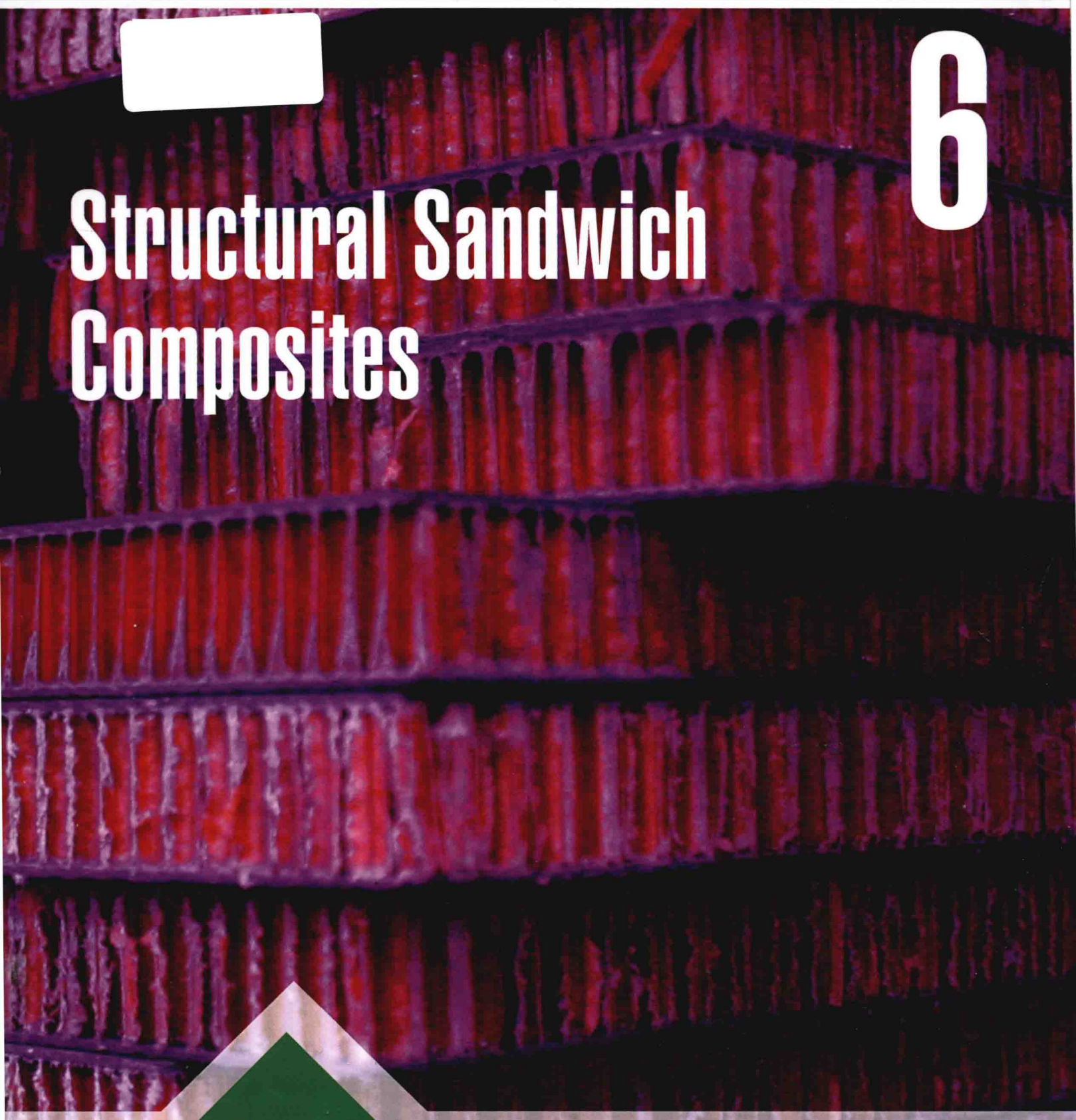
COMPOSITE MATERIALS HANDBOOK

Volume

6

Structural Sandwich Composites



CMH-17
COMPOSITE MATERIALS HANDBOOK

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National Institute for Aviation Research

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Volume 6 of 6
July 2013

COMPOSITE MATERIALS HANDBOOK

VOLUME 6. STRUCTURAL SANDWICH COMPOSITES

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FOREWORD

The Composite Materials Handbook, CMH-17, provides information and guidance necessary to design and fabricate structural components from composite materials. Its primary purposes are a) the standardization of engineering data development methodologies related to testing, data reduction, and data reporting of property data for current and emerging composite materials, b) guidance on material and process specifications and procedures for utilization of the material data presented in the handbook, and c) methodologies for the design, analysis, certification, manufacture, and field support of composite structures. In support of these objectives, the handbook includes composite materials properties that meet specific data requirements. The Handbook therefore constitutes an overview of the field of composites technology and engineering, an area that is advancing and changing rapidly. As a result, the document will be continually revised as sections are added or modified to reflect advances in the state-of-the-art.

CMH-17 Mission

The Composite Materials Handbook organization creates, publishes and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

Goals and Objectives to Support CMH-17 Mission

- To periodically meet with experts from the field to discuss critical technical issues for composite structural applications, with an emphasis on increasing overall product efficiency, quality and safety.
- To provide comprehensive, practical engineering guidance that has proven reliable for the design, fabrication, characterization, test and maintenance of composite materials and structures.
- To provide reliable data, linked to control of processes and raw materials, thereby being a comprehensive source of material property basis values and design information that can be shared within the industry.
- To provide a resource for composite material and structure education with examples, applications and references to supporting engineering work.
- To establish guidelines for use of information in the Handbook, identifying the limitations of the data and methods.
- To provide guidance on references to proven standards and engineering practices.
- To provide for periodic updates to maintain the all-inclusive nature of the information.
- To provide information in formats best-suited for user needs.
- To serve the needs of the international composites community through meetings and dialogue between member industries, which use teamwork and the diverse member engineering skills to provide information for the handbook.

Notes

1. Every effort has been made to reflect the latest information on polymer (organic), metal, and ceramic composites. The handbook is continually reviewed and revised to ensure it is complete and current.

2. CMH-17 provides guidelines and material properties for polymer (organic), metal, and ceramic matrix composite materials. The first three volumes of this handbook currently focus on, but are not limited to, polymeric composites intended for aircraft and aerospace vehicles. Metal matrix composites (MMC), ceramic matrix composites (CMC) including carbon-carbon composites (C-C), and sandwich composites are covered in Volumes 4, 5, and 6, respectively.

3. The information contained in this handbook was obtained from materials producers, industry companies and experts, reports on Government sponsored research, the open literature, and by contract with research laboratories and those who participate in the CMH-17 coordination activity. The information in this handbook has undergone vigorous technical review and was subject to membership vote.

4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: CMH-17 Secretariat, Materials Sciences Corporation, 135 Rock Road, Horsham, PA 19044, by letter or email, handbook@materials-sciences.com.

ACKNOWLEDGEMENT

Volunteer committee members from government, industry, and academia develop, coordinate and review all the information provided in this handbook. The time and effort of the volunteers and the support of their respective departments, companies, and universities make it possible to insure the handbook reflects completeness, accuracy, and state-of-the-art composite technology.

Support necessary for the development and maintenance of the Composite Materials Handbook (CMH-17) are provided by the handbook Secretariat, Materials Sciences Corporation. The primary source of funding for the current Secretariat contract is the Federal Aviation Administration.

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CHAPTER 1 GENERAL INFORMATION

1.1 INTRODUCTION TO THE HANDBOOK

Standardized, statistically-based material property data are essential to the development of composite structures; such data are needed by material suppliers, design engineering personnel, manufacturing organizations, and structure end-users alike. In addition, reliable, proven design and analysis methods are essential to the efficient development and application of composite structures. This handbook is intended to provide these through standardization of:

1. Methods used to develop, analyze, and publish property data for composite materials.
2. Statistically-based, material property datasets for composite materials.
3. General procedures for designing, analyzing, testing, and supporting composite structures that utilize the property data published in this handbook.

In many cases, this standardization is intended to address the requirements of regulatory agencies, while providing efficient engineering practices for developing structures that meet the needs of customer organizations.

Composites is an evolving and growing technical field, and the Handbook Coordinating Committee is continuously working to incorporate new information and new material properties data as it becomes available and is proven acceptable. While the source and context for much of this information has come from experience with aerospace applications, all industries utilizing composite materials and structures, whether commercial or military, will find the handbook useful. This latest revision includes information related to broader applications from non-aerospace industries, and incorporation of non-aerospace data will increase as development of the handbook continues.

Composite Materials Handbook-17 (CMH-17) has been developed and is maintained as a joint effort of the Department of Defense and the Federal Aviation Administration, with considerable participation and input from industry, academia, and other government agencies. Although initial structural applications of composites tended to be military, recent development trends have seen increasing use of these materials in commercial applications. In part because of these trends, the formal administration of the handbook passed from the Department of Defense to the Federal Aviation Administration in 2006 and the handbook title was changed from Military Handbook-17 to Composite Materials Handbook-17. The organization of the Coordinating Committee and the purpose of the handbook did not change.

1.2 OVERVIEW OF HANDBOOK CONTENT

Composite Materials Handbook-17 is composed of a series of six volumes.

Volume 1: Polymer Matrix Composites - Guidelines for Characterization of Structural Materials

Volume 1 contains guidelines for determining the properties of polymer matrix composite material systems and their constituents, as well as the properties of generic structural elements, including test planning, test matrices, sampling, conditioning, test procedure selection, data reporting, data reduction, statistical analysis, and other related topics. Special attention is given to the statistical treatment and analysis of data. Volume 1 contains guidelines for general development of material characterization data as well as specific requirements for publication of material data in CMH-17.

Volume 2: Polymer Matrix Composites - Materials Properties

Volume 2 contains statistically-based data for polymer matrix composites that meets specific CMH-17 population sampling and data documentation requirements, covering material systems of general interest.

As of the publication of Revision G, data published in Volume 2 are under the jurisdiction of the Data Review Working Group and are approved by the overall CMH-17 Coordinating Committee. New material systems will be included and additional material data for existing systems will be added as data becomes available and are approved. Selected historical data from previous versions of the handbook that do not meet current data sampling, test methodology, or documentation requirements, but that still are of potential interest to industry are also included in this Volume.

Volume 3: Polymer Matrix Composites - Materials Usage, Design, and Analysis

Volume 3 provides methodologies and lessons learned for the design, analysis, manufacture, and field support of fiber-reinforced, polymeric-matrix composite structures. It also provides guidance on material and process specifications and procedures for utilization of the data presented in Volume 2. The information provided is consistent with the guidance provided in Volume 1, and is an extensive compilation of the current knowledge and experiences of the engineers and scientists who are active in composites from industry, government, and academia.

Volume 4: Metal Matrix Composites

Volume 4 publishes properties on metal matrix composite material systems for which data meeting the specific requirements of the handbook are available. In addition, it provides selected guidance on other technical topics related to this class of composites, including material selection, material specification, processing, characterization testing, data reduction, design, analysis, quality control, and repair of typical metal matrix composite materials.

Volume 5: Ceramic Matrix Composites

Volume 5 publishes properties on ceramic matrix composite material systems for which data meeting the specific requirements of the handbook are available. In addition, it provides selected guidance on other technical topics related to this class of composites, including material selection, material specification, processing, characterization testing, data reduction, design, analysis, quality control, and repair of typical ceramic matrix composite materials.

Volume 6: Structural Sandwich Composites

Volume 6 is an update to the cancelled Military Handbook 23 (Reference 1.2), which was prepared for use in the design of structural sandwich polymer composites, primarily for flight vehicles. The information presented includes test methods, material properties, design and analysis techniques, fabrication methods, quality control and inspection procedures, and repair techniques for sandwich structures in both military and commercial vehicles.

1.3 INTRODUCTION

The Sandwich Structures Volume of Composite Materials Handbook-17 (CMH-17), Volume 6, contains seven chapters. Chapter 1, General Information, provides the objective, background, introduction and notation utilized in sandwich structures. Chapter 2, Guidelines for Property Testing discusses property testing of sandwich constituent materials; core materials, core-to-face sheet bonds, and face sheets; as well as sandwich panels, inserts and fasteners, and other sandwich details such as ramps and closeouts. Chapter 3, Material Data, contains core, face sheet, adhesive, and self-adhesive face sheet properties. Chapter 4, Design and Analysis, provides structural design, sizing and analysis methods for critical failure modes of sandwich structures. Chapter 5, Fabrication, discusses sandwich materials and processes, and lessons learned. Chapter 6, Quality Control, discusses in-process and end-article inspection, material properties verification, and process controls as applicable to sandwich structures. Chapter 7, Supportability, discusses design practices to improve damage tolerance and repair aspects of sandwich structures. Discussions of basic design principles and fundamental formulas are included in all sections as appropriate.

1.4 NOMENCLATURE AND DEFINITIONS

The following notation is used throughout this volume. Additionally, portions of the volume devoted to a particular component define the symbols used for the first time in that portion. An occasional symbol not in general use will appear in specific areas and not be included in this notation. Figure 1.4 shows notation for sandwich construction.

Units of dimensions, forces, stresses, constants, and other quantities are not specified unless they are employed in formulas wherein numerical coefficients are not non-dimensional. In applying formulas for which units are not specified, correct results will not be obtained unless units are consistent – for example: If thicknesses are given in inches and forces in pounds, then the length and width of a panel must be in inches (not feet) to give stresses in pounds per square inch.

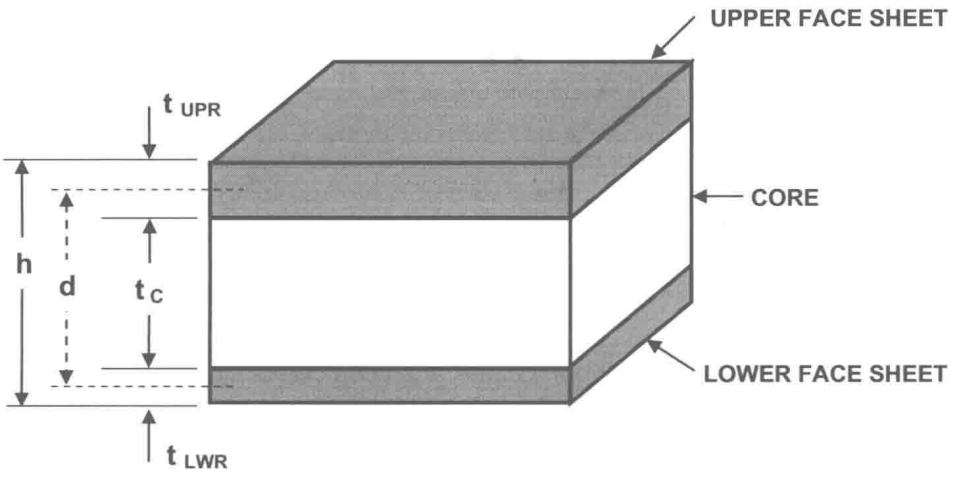

FIGURE 1.4 *Sandwich construction notation.*

1.4.1 Loads, geometry, and material properties

The following variables are used throughout this volume to represent the loads applied to a flat sandwich panel. Figure 1.4.1 gives a pictorial representation of the general load state for a sandwich panel.

N_x, N_y, N_{xy} - Distributed in-plane panel forces
M_x, M_y, M_{xy} - Applied edge moments
Q_x, Q_y - Out-of-plane edge reactions
q - Uniform pressure

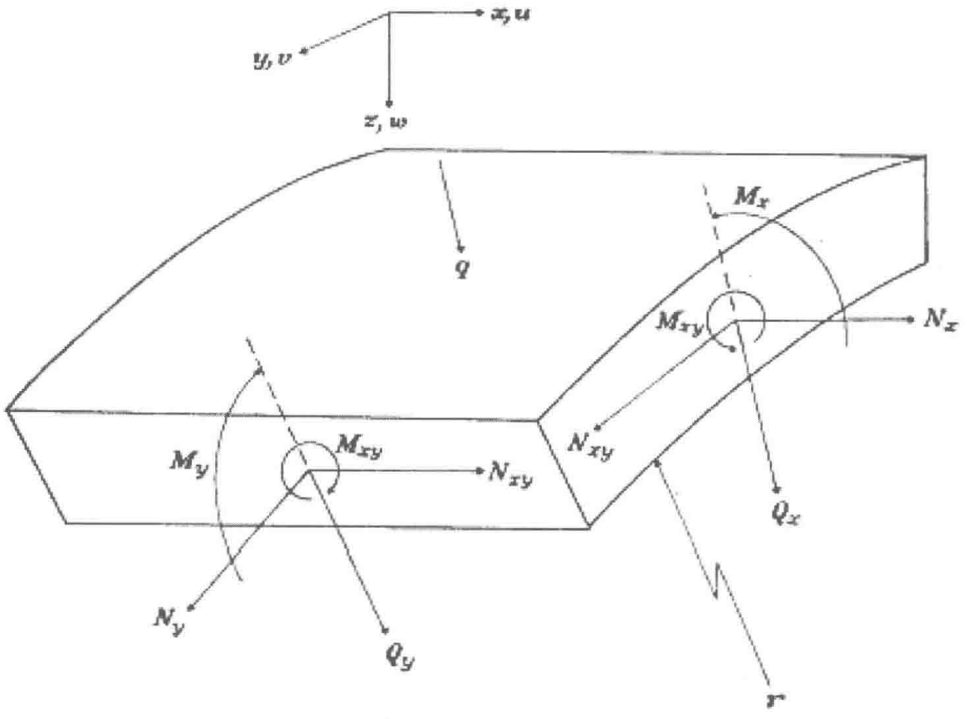

FIGURE 1.4.1 *Generalized load state for a sandwich panel.*

The following general symbols and abbreviations are considered standard for use in this volume. Where exceptions are made, they are noted in the text and tables.

A_c - core solidity, $A_c = {}^{w_c}/_{w_o}$

A_{ij} - extensional and shear stiffnesses

a - length of panel edge, parallel to the loading direction (mm, in)

B_{ij} -extensional-bending coupling stiffnesses

b - (1) length of panel edge, transverse to the loading direction (mm, in)
- (2) unsupported width of face sheet element (mm, in)
- (3) width of beam (mm, in)
- (4) width of face sheet in corrugated core (mm, in)

D - beam bending stiffness or twisting stiffness (N-m,lbf-in)

D_c - bending stiffness of the core (N-m,lbf-in)

D_f - bending stiffness of the face sheets about their individual neutral axes (N-m,lbf-in)

D_{ij} - bending and torsional stiffnesses

D_o - bending stiffness of the face sheets about the middle axis of the sandwich beam (N-m,lbf-in)

d - (1) distance between the face sheet midplanes at any point in the sandwich panel (mm, in)
- (2) mathematical operator denoting differential

E - modulus of elasticity in tension, average ratio of stress to strain for stress below proportional limit (GPa, Msi); for orthotropic face sheets: $E = [E_a E_b]^{1/2}$

E' - (1) effective modulus of elasticity; for orthotropic face sheets $E' = [E_a' E_b']^{1/2}$
- (2) core modulus in Z direction (GPa,Msi)

E_{cx} - stiffness of the core, in the direction of the beam long axis (GPa, Msi)

E_x, E_y- face sheet elastic moduli parallel to the X and Y directions, respectively (GPa, Msi)

e - distance from the midplane of the lower face sheet to the neutral axis of the beam (mm, in)

F - (1) allowable stress (MPa,ksi)
- (2) Fahrenheit

f - (1) internal (or calculated) stress (MPa,ksi)
- (2) stress applied to the gross flawed section (MPa,ksi)
- (3) creep stress (MPa,ksi)

f_{Xflat}, f_{Yflat} - flatwise tension or compression stresses at the ramp radii.

F_{12} - geometric view factor between sandwich facings

G - modulus of rigidity (shear modulus) (GPa,Msi); with subscripts G_{ab} is the modulus of rigidity associated with shear distortion of the ab plane, with subscript G_c is the modulus of the core

G' - effective modulus of rigidity

Gxy - face sheet shear modulus in the XY plane (GPa, Msi)

Gzx, Gzy - core shear moduli in the XZ and YZ planes, respectively (GPa, Msi)

GPa - gigapascal(s)

H/C - honeycomb (sandwich)

H - extensional stiffness

h - total thickness or depth of the sandwich (mm, in)

in. - inch(es)

K - (1) a coefficient
- (2) Kelvin

K_e - effective conductivity

K_o - conductivity of core ribbon material

k - conductivity (Btu in. /hr ft2 F°)

L - (1) length (mm, in)
- (2) core ribbon axis direction

lb - pound(s)

M - applied bending moment or couple (N-m,in-lbf)

m - (1) half width of corrugation
- (2) number of half waves
- (3) cos(θ) when used in coordinate transformations

MPa - megapascal(s)

MS - military standard

M.S. - margin of safety

N - (1) design load per unit length of panel edge
- (2) Newton(s)
- (3) exponent in core shear interaction criterion

n - (1) number of half waves
- (2) sin(θ) when used in coordinate transformations

NA - neutral axis

P - applied load (N,lbf)

pcf - pounds per cubic foot

psi - pounds per square inch

Q - face sheet dissimilarity index $Q = 1/[1+(E_{LWR}'t_{LWR}/E_{UPR}'t_{UPR})]$

q - (1) normal pressure (Pa, psi)
- (2) intensity of distributed load

R - (1) ramp radius (mm, in)
- (2) the ratio of the applied stress or load under combined loading to the buckling stress or load under separate loading
- (3) radius of curvature (mm, in)
- (4) ratio of lower to upper face sheet stiffness and thickness, $E_{LWR}\ t_{LWR}\ /\ E_{UPR}\ t_{UPR}$

r - radius (mm,in)

S - (1) shear bending stiffness
- (2) shear load normal to surface of panel

s - core cell size (diameter of inscribed circle) (mm, in)

T - (1) temperature (°C,°F)
- (2) applied torsional moment (N-m,in-lbf)
- (3) core axis direction (through the thickness of the sandwich panel)

T_m - mean temperature
t - thickness (mm,in)
t_{UPR}, t_{LWR} - thickness of the upper and lower face sheets, respectively (mm, in)
tc - core depth (mm, in)
te - edgeband thickness (mm, in)
U - transverse sandwich shear stiffness
u - deflection in direction of x axis (mm, in)
V - (1) volume (mm^3,in^3)
- (2) shear force (N,lbf)
- (3) parameter relating shear and bending stiffness
V_2 - special parameter relating shear and bending stiffness for sandwich with corrugated core
V_t - parameter relating shear and bending stiffness for sandwich strip with triangular or trapezoidal section
v - deflection in direction of y axis (mm, in)
W - (1) sandwich weight per unit area (N,lbf)
- (2) core axis direction perpendicular to the ribbon axis L
- (3) special parameter relating shear and bending stiffness for sandwich
W_t - parameter relating shear and bending stiffness for sandwich strip with triangular or trapezoidal section and corrugated core
w - (1) transverse deflection (mm, in)
- (2) density
x - distance along a coordinate axis
y - (1) deflection (due to bending) of elastic curve of a beam (mm,in)
- (2) distance from neutral axis to given point
- (3) distance along a coordinate axis, perpendicular to x-axis
Z - parameter for trapezoidal sandwich strips: $Z= (b/h) \tan \alpha$
z - distance along a coordinate axis, perpendicular to x-y plane
α - (1) $[E_b'/E_a']^{1/2}$
- (2) angle giving the rise of a trapezoidal or triangular sandwich strip
α_1, α_2 - scale factors relating curvilinear and Cartesian coordinates
β - $\alpha\nu_{ab}+2\gamma$
δ - elongation or deflection (mm,in)
ε - (1) compression or extension strain
- (2) emissivity
- (3) mid-plane strains
κ - curvatures
λ - (1) load factor
- (2) one minus the product of two Poisson's ratios ($\lambda = 1 - \nu_{ab}\nu_{ba}$)
η_X, η_Y - (1) Percent rotational fixity for panel edges normal to the X and Y directions, respectively
= 1.0 for fully fixed
= 0.0 for simply supported
- (2) Plasticity coefficient
- (3) convective heat transfer coefficient
ρ - radius of gyration
ν - Poisson's ratio
ν_{XY}, ν_{YX} - face sheet Poisson's ratios. The term, ν_{XY}, is defined as the absolute ratio of strain in the Y direction to strain in the X direction when load is applied uniaxially in the X direction ($E_X \nu_{YX} = E_Y \nu_{XY}$)
ν_{ab}, ν_{ba} - face sheet Poisson's ratios, in directions aligned with panel sides
γ - shear strain; elastic property parameter $\gamma = \lambda Gba'/[Ea'Eb']1/2$
Σ - total, summation
σ - Stefan-Boltzmann constant