ASME NM.2-2020
(Revision of ASME NM.2-2018)

Glass-Fiber-Reinforced Thermosetting-Resin Piping Systems

ASME Standards for Nonmetallic Pressure Piping Systems

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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The American Society of Mechanical Engineers
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Date of Issuance: December 31, 2020

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FOREWORD

In 2011, The American Society of Mechanical Engineers (ASME) established the Committee on Nonmetallic Pressure Piping Systems (NPPS) to develop standards for the construction of nonmetallic pressure piping systems. This Committee's goal was to specify construction[1] requirements for nonmetallic piping and piping products; such requirements were not adequately defined in existing standards.

Prior to the development of the ASME Standards for Nonmetallic Pressure Piping Systems, nonmetallic pressure piping requirements were contained within several existing standards. The nonmetallic piping requirements of the ASME B31 Code for Pressure Piping varied across Sections, with some Sections having no requirements for nonmetallic components at all. Other standards and codes, such as ASME RTP-1 and the ASME Boiler and Pressure Vessel Code (BPVC), Section X, included requirements for reinforced thermoset plastic (RTP) corrosion-resistant equipment but not for piping and piping components. ASME BPVC, Section III did have a few Code Cases that addressed requirements for some nonmetallic piping and piping components, including those made from glass-fiber-reinforced thermosetting resin (FRP) and a few thermoplastics, e.g., high-density polyethylene (HDPE) and poly(vinyl chloride) (PVC). However, the scope of these Code Cases was very limited, and in some cases the methodology was nearly 30 years old. The ASME NPPS Standards now serve as a centralized location for NPPS requirements and are developed by committees whose members are experts in this field. The NPPS Committee's functions are to establish requirements related to pressure integrity for the construction of nonmetallic pressure piping systems, and to interpret these requirements when questions arise regarding their intent.

ASME NM.2 provides requirements for construction of FRP piping and piping components. This Standard addresses pipe and piping components that are produced as standard products, and custom products that are designed for a specific application. ASME NM.2-2018 (first edition) was approved by the American National Standards Institute (ANSI) on August 13, 2018.

The 2020 edition includes revisions to Mandatory Appendix II that add example calculations, cautionary notes, and methods to compute classical lamination theory (CTE) of lamina and laminates. Additionally, Nonmandatory Appendix A has been reorganized and revised, and section A-5 has been added. Section A-5 includes a simplified stress analysis of a sample pipeline and illustrates the application of the design approach, equations, and physical properties of NM-2 piping systems. Further, the 2020 edition revises and clarifies figures, definitions, and nomenclature for NM-2 piping systems.

Following approval by the ASME NPPS Standards Committee, ASME NM.2-2020 was approved by the American National Standards Institute (ANSI) on December 9, 2020.

[1] *Construction*, as used in this Foreword, is an all-inclusive term comprising materials, design, fabrication, erection, examination, inspection, testing, and overpressure protection.

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Nonmetallic Pressure Piping Systems

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Secretary, NPPS Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
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http://go.asme.org/Inquiry

Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued to provide alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the NPPS Standards Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the NPPS Standards Committee.

Requests for interpretation should preferably be submitted through the online Interpretation Submittal Form. The form is accessible at http://go.asme.org/InterpretationRequest. Upon submittal of the form, the Inquirer will receive an automatic e-mail confirming receipt.

If the Inquirer is unable to use the online form, he/she may mail the request to the Secretary of the NPPS Standards Committee at the above address. The request for an interpretation should be clear and unambiguous. It is further recommended that the Inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. Please provide a condensed and precise question, composed in such a way that a "yes" or "no" reply is acceptable.
Proposed Reply(ies):	Provide a proposed reply(ies) in the form of "Yes" or "No," with explanation as needed. If entering replies to more than one question, please number the questions and replies.
Background Information:	Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in the format described above may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Standard requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The NPPS Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the NPPS Standards Committee.

INTRODUCTION

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The ASME Standards for Nonmetallic Pressure Piping Systems (NPPS) are as follows:

NM.1 Thermoplastic Piping Systems: This Standard contains requirements for piping and piping components that are produced using thermoplastic resins or compounds. Thermoplastics are a specific group of nonmetallic materials that, for processing purposes, are capable of being repeatedly softened by increase of temperature and hardened by decrease of temperature.

NM.2 Glass-Fiber-Reinforced Thermosetting-Resin Piping Systems: This Standard contains requirements for piping and piping components that are produced using glass-fiber reinforcement embedded in or surrounded by cured thermosetting resin.

NM.3 Nonmetallic Materials: This Standard includes specifications for nonmetallic materials (except wood, nonfibrous glass, and concrete) and, in conformance with the requirements of the individual construction standards, methodologies, design values, limits, and cautions on the use of materials. This Standard is divided into three Parts:

– NM.3.1, Nonmetallic Materials, Part 1 — Thermoplastic Material Specifications: This Part contains thermoplastic material specifications identical to or similar to those published by the American Society for Testing and Materials (ASTM International) and other recognized national or international organizations.

– NM.3.2, Nonmetallic Materials, Part 2 — Reinforced Thermoset Plastic Material Specifications: This Part contains reinforced thermoset plastic material specifications identical to or similar to those published by ASTM and other recognized national or international organizations.

– NM.3.3, Nonmetallic Materials, Part 3 — Properties: This Part provides tables and data sheets for allowable stresses, mechanical properties (e.g., tensile and yield strength), and physical properties (e.g., coefficient of thermal expansion and modulus of elasticity) for nonmetallic materials.

It is the owner's responsibility to select the piping standard that best applies to the proposed piping installation. Factors to be considered by the owner include limitations of the standard, jurisdictional requirements, and the applicability of other standards. All applicable requirements of the selected standard shall be met. For some installations, more than one standard may apply to different parts of the installation. The owner is also responsible for imposing requirements supplementary to those of the standard if such requirements are necessary to ensure safe piping for the proposed installation.

Certain piping within a facility may be subject to other codes and standards, including but not limited to the following:

ASME B31.1, Power Piping: This code contains requirements for piping typically found in electric power generating stations, industrial and institutional plants, geothermal heating systems, and central and district heating and cooling systems.

ASME B31.3, Process Piping: This code contains requirements for piping typically found in petroleum refineries; onshore and offshore petroleum and natural gas production facilities; chemical, pharmaceutical, textile, paper, ore-processing, semiconductor, and cryogenic plants; food- and beverage-processing facilities; and related processing plants and terminals.

ASME B31.4, Pipeline Transportation Systems for Liquids and Slurries: This code contains requirements for piping transporting products that are predominately liquid between plants and terminals, and within terminals and pumping, regulating, and metering stations.

ASME B31.5, Refrigeration Piping and Heat Transfer Components: This code contains requirements for piping for refrigerants and secondary coolants.

ASME B31.8, Gas Transmission and Distribution Piping Systems: This code contains requirements for piping transporting products that are predominately gas between sources and terminals, including compressor, regulating, and metering stations; and gas gathering pipelines.

ASME B31.9, Building Services Piping: This code contains requirements for piping typically found in industrial, institutional, commercial, and public buildings, and in multi-unit residences, which does not require the range of sizes, pressures, and temperatures covered in ASME B31.1.

ASME B31.12, Hydrogen Piping and Pipelines: This code contains requirements for piping in gaseous and liquid hydrogen service, and pipelines in gaseous hydrogen service.

National Fuel Gas Code: This code contains requirements for piping for fuel gas from the point of delivery to the connection of each fuel utilization device.

NFPA 99, Health Care Facilities: This standard contains requirements for medical and laboratory gas systems.

NFPA Fire Protection Standards: These standards contain requirements for fire protection systems using water, carbon dioxide, halon, foam, dry chemicals, and wet chemicals.

The ASME NPPS Standards specify engineering requirements deemed necessary for safe design and construction of nonmetallic pressure piping. These Standards contain mandatory requirements, specific prohibitions, and nonmandatory guidance for construction activities. These Standards do not address all aspects of these activities, and those aspects that are not specifically addressed should not be considered prohibited. While safety is the overriding consideration, this factor alone will not necessarily govern the final specifications for any piping installation. With few exceptions, the requirements do not, of practical necessity, reflect the likelihood and consequences of deterioration in service related to specific service fluids or external operating environments. These Standards are not design handbooks. Many decisions that must be made to produce a safe piping installation are not specified in detail within these Standards. These Standards do not serve as substitutes for sound engineering judgment by the owner and the designer. The phrase *engineering judgment* refers to technical judgments made by knowledgeable designers experienced in the application of these Standards. Engineering judgments must be consistent with the philosophy of these Standards, and such judgments must never be used to overrule mandatory requirements or specific prohibitions of these Standards.

To the greatest possible extent, Standard requirements for design are stated in terms of basic design principles and formulas. These are supplemented as necessary with specific requirements to ensure uniform application of principles and to guide selection and application of piping elements. These Standards prohibit designs and practices known to be unsafe and contain warnings where caution, but not prohibition, is warranted.

These Standards generally specify a simplified approach for many of their requirements. A designer may choose to use a more rigorous analysis to develop design and construction requirements. When the designer decides to take this approach, he or she shall provide to the owner details and calculations demonstrating that design, fabrication, examination, inspection, testing, and overpressure protection are consistent with the criteria of these Standards. These details shall be adequate for the owner to verify the validity of the approach and shall be approved by the owner. The details shall be documented in the engineering design.

The designer is responsible for complying with requirements of these Standards and demonstrating compliance with the equations of these Standards when such equations are mandatory. These Standards neither require nor prohibit the use of computers for the design or analysis of components constructed to the requirements of these Standards. However, designers and engineers using computer programs for design or analysis are cautioned that they are responsible for all technical assumptions inherent in the programs they use and for the application of these programs to their design.

These Standards do not fully address tolerances. When dimensions, sizes, or other parameters are not specified with tolerances, the values of these parameters are considered nominal, and allowable tolerances or local variances may be considered acceptable when based on engineering judgment and standard practices as determined by the designer.

Suggested requirements of good practice are provided for the care and inspection of in-service nonmetallic pressure piping systems only as an aid to owners and their inspectors.

The requirements of these Standards are not to be interpreted as approving, recommending, or endorsing any proprietary or specific design or as limiting in any way the manufacturer's freedom to choose any method of design or any form of construction that conforms to the requirements of these Standards.

It is intended that editions of the ASME NPPS Standards not be retroactive. Unless agreement is specifically made between contracting parties to use another edition, or the regulatory body having jurisdiction imposes the use of another edition, the latest edition issued at least 6 months prior to the original contract date for the first phase of activity covering a piping installation shall be the governing document for all design, materials, fabrication, erection, examination, inspection, testing, and overpressure protection for the piping until the completion of the work and initial operation. Revisions to material specifications included in ASME NM.3.1 and ASME NM.3.2 are originated by ASTM and other recognized national or international organizations, and are usually adopted by ASME. However, those revisions do not necessarily indicate that materials produced to earlier editions of specifications are no longer suitable for ASME construction. Both ASME NM.3.1 and ASME NM.3.2 include a Mandatory Appendix, "Guideline on Acceptable ASTM Editions," that lists the latest edition of material specifications adopted by ASME as well as other editions considered by ASME to be identical for ASME construction.

Users of these Standards are cautioned against making use of revisions to these Standards without assurance that they are acceptable to the proper authorities in the jurisdiction where the piping is to be installed.

ASME NM.2-2020
SUMMARY OF CHANGES

Following approval by the ASME NM Committee and ASME, and after public review, ASME NM.2-2020 was approved by the American National Standards Institute on December 9, 2020.

ASME NM.2-2020 includes the following changes identified by a margin note, **(20)**.

Page	*Location*	*Change*
xi	Introduction	Updated
1	1-2	(1) Definitions of *assembly*, *erection*, *lower deviated value (LDV)*, *may*, *manufacturing*, *pipe-supporting elements*, *shall*, *short-term hydrostatic strength (STHS)*, *should*, and *supporting structures* added (2) Definitions of *corrosion barrier* and *fabrication* revised (3) Definition of *liner* deleted
4	1-3	(1) Abbreviations of *LDV (lower deviated value)* and *STHS (short-term hydrostatic strength)* added (2) Abbreviation of *LTHS (long-term hydrostatic stress)* revised
5	2-1.1	Revised
7	2-2.2.1	Subparagraph (a) revised
8	2-2.3.1	Subparagraph (a)(4) revised
8	2-2.3.2	Revised
11	2-2.3.6	Subparagraphs (b) and (e)(3) revised
12	2-.3.2.1	Revised
12	2-3.2.2	Revised
13	2-3.2.3	Revised
13	2-3.3.1	Revised
21	2-3.8.2	Subparagraph (b) revised
23	2-4.4.1	Subparagraph (c) revised
23	2-4.4.2	Revised
24	2-4.4.4	Revised
25	2-4.5	Revised
26	2-5.1	Revised
28	2-5.9.1	Subparagraph (a) revised
33	4-3.3	Revised
43	5-3.1.2.4	Added
45	Figure 5-3.1.2.4-1	Added
54	Figure I-2.3-1	Revised
53	I-3.1	Revised
55	I-3.3	Revised
57	Figure I-3.3-1	Revised

Page	*Location*	*Change*
63	Mandatory Appendix II	Revised in its entirety
73	Figure II-4-3	Revised
107	Nonmandatory Appendix A	Revised and section A-5 added

Chapter 1
Scope and Definitions

1-1 SCOPE

(a) This Standard provides requirements for the design, materials, manufacture, fabrication, installation, examination, and testing of glass-fiber-reinforced thermosetting-resin (FRP) piping systems.

(b) FRP piping, as used in this Standard, includes pipe, flanges, bolting, gaskets, valves, fittings, special connecting components, and the pressure-containing or pressure-retaining portions of other piping components, whether manufactured in accordance with references cited in this Standard or specially designed. It also includes hangers and supports and other items necessary to prevent overstressing the pressure-containing components.

1-1.1 Content and Coverage

(a) This Standard addresses pipe and piping components that are produced as standard products, as well as custom products that are designed for a specific application. It covers FRP pipe and piping components manufactured by contact molding, centrifugal casting, filament winding, and other methods. Its intent is to provide a uniform set of requirements for FRP pipe and piping components that can be adopted by reference in the various piping codes, including sections of the ASME B31 Code for Pressure Piping. This Standard is published as a separate document to reduce duplication between piping codes.

(b) Requirements of this Standard apply to FRP piping systems typically used within the scope of the various sections of the ASME B31 Code for Pressure Piping (ASME B31.1, ASME B31.3, ASME B31.4, ASME B31.5, ASME B31.8, and ASME B31.9) and selected piping systems designed to the ASME Boiler and Pressure Vessel Code (BPVC), Section III, Division 1, Subsection ND.

1-1.2 Exclusions

This Standard does not provide requirements for the following:

(a) metallic pipe

(b) thermoplastics, ceramics, and other nonmetallic materials used to fabricate pipe and piping components

(c) dual laminate construction that combines thermoplastic linings with FRP pipe and fittings

(d) reinforced polymer mortar pipe

(e) products with fiber-reinforcement materials that are not made from glass

(f) nonmetallic pressure vessels, valves, and specialty components covered by other ASME codes and standards, such as ASME BPVC, Section X and ASME RTP-1

(g) piping for which the maximum internal pressure exceeds 1 700 kPa (250 psi)

(h) piping for which the algebraic product of internal pressure [in kilopascals gauge (pounds per square inch gauge)] and internal diameter [in meters (inches)] exceeds 1 262 kPag·m (7,200 psig·in.)

(i) piping used as ductwork conveying air or other gases at pressures within 6.89 kPag (1 psig) of the pressure of the surrounding atmosphere

1-2 TERMS AND DEFINITIONS (20)

Commonly used terms relating to FRP piping are defined below. Some terms are defined with specific reference to piping. The definitions generally agree with those in ASME BPVC, Section X; ASME RTP-1; ASTM D883; and ASTM F412. Definitions taken unchanged from other standards are indicated by a footnote.

adhesive: a material designed to join together two other component materials by surface attachment (bonding).

adhesive joint: a bonded joint made using an adhesive on the surfaces to be joined.

assembly: synonymous with fabrication.

binder[1]*:* in a reinforced plastic, the continuous phase that holds together the reinforcement.

bloom[1]*:* a visible exudation or efflorescence on the surface of a material.

bonder[2]*:* one who performs a manual or semiautomatic bonding operation.

bonding procedure[2]*:* the detailed methods and practices involved in the production of a bonded joint.

Bonding Procedure Specification (BPS): a document providing in detail the required variables and procedures for the bonding process to ensure repeatability in the bonding procedure.

[1] This definition is from ASTM D883.
[2] This definition is from ASME B31.3.

butt-and-wrapped joint: a bonded joint made by applying plies of reinforcement saturated with resin to the surfaces to be joined.

chalking[1]*:* (plastics) a powdery residue on the surface of a material resulting from degradation or migration of an ingredient, or both.

chopped roving: a collection of noncontinuous glass strands gathered without mechanical twist. Each strand is made up of glass filaments bonded together with a finish or size for application by chopper gun.

chopped-strand mat[3]*:* reinforcement made from randomly oriented glass strands that are held together in mat form using a binder. Each strand has a sizing.

composite[1]*:* a solid product consisting of two or more distinct phases, including a binding material (matrix) and a particulate or fibrous reinforcement material.

continuous roving: a collection of continuous glass strands wound into a cylindrical package without mechanical twist.

corrosion barrier: a thermosetting, resin-rich internal or external layer that inhibits penetration of corrosive chemicals to the structural layers of the laminate, inhibits erosion, and prevents leakage under strain. This layer is typically reinforced with a glass or synthetic veil and one or more layers of chopped-strand mat.

creep: the time-dependent part of strain resulting from stress.

cure: to change the properties of a polymeric system into a more stable, usable condition by the use of heat, radiation, or reaction with chemical additives.

cure time: the period of time that a reacting thermosetting material is exposed to specific conditions to reach a specified property level.

curing agent: a reactive material that when combined with a resin material initiates polymerization or reacts with a resin to polymerize the resin; also referred to as a hardener.

cyclic long-term hydrostatic pressure: the estimated internal pressure of the piping product that, when applied cyclically in accordance with ASTM D2992, Procedure A, will cause failure of the product after a specified number of cycles. The cyclic rate, specified number of cycles, and extrapolation of failure results out to the specified number of cycles are the same as for the cyclic long-term hydrostatic strength.

cyclic long-term hydrostatic strength: the hoop stress that, when applied cyclically at 25 cycles/min, is calculated to cause the failure of the pipe in a selected number of cycles.

diluent[4]*:* a reactive or nonreactive modifying material, usually liquid, that reduces the concentration of a resin material to facilitate handling characteristics and improve wetting.

erection: the installation of piping components and piping subassemblies into an entire piping system in its final installed location, including supports and other accessories as designated by the engineering design.

extrados: the outside bend radius of an elbow.

fabrication: the process of preparing and joining two or more manufactured components into piping subassemblies by processes such as bonding and bolting.

fiberglass pipe: a tubular product containing glass-fiber reinforcement embedded in or surrounded by cured thermosetting resin; the composite structure may contain thixotropic agents, pigments, or dyes; thermosetting liners or coatings may be included.

fire-retardant resin[4]*:* a specially compounded material combined with a resin material designed to reduce the tendency to burn.

flexibilizer: a modifying liquid material added to a resinous mixture designed to make the finished component flexible, bendable, or less rigid.

hydrostatic design basis (HDB): a hoop stress developed for fiberglass pipe in accordance with ASTM D2992 practice and multiplied by a service (design) factor to obtain a hydrostatic design stress. The HDB is the long-term hydrostatic strength determined in accordance with ASTM D2992 that allows the long-term hydrostatic strength to be obtained on a cyclic stress (Procedure A) or constant stress (Procedure B) basis.

hydrostatic design pressure (HDP)[5]*:* the estimated maximum internal hydrostatic pressure that can be applied cyclically (Procedure A) or continuously (Procedure B) to a piping component with a high degree of certainty that failure of the component will not occur.

hydrostatic design stress (HDS): the estimated maximum tensile stress in the wall of the pipe in the hoop direction due to internal hydrostatic pressure, as calculated per ASTM D2992, that can be applied cyclically (Procedure A) or continuously (Procedure B) with a high degree of certainty that failure of the pipe will not occur. This stress is usually established by applying an appropriate service (design) factor to the hydrostatic design basis.

intrados: the inside bend radius of an elbow.

knuckle area: in reinforced plastics, the area of transition between sections of different geometry.

laminate[1]*:* a product made by bonding together two or more layers of material or materials. There are three types, as follows:

[3] This definition is from ASME RTP-1.

[4] This definition is from ASME B31.1.
[5] This definition is from ASTM D2992.

(a) Type I. See ASME NM.3.2, SC-582.
(b) Type II. See ASME NM.3.2, SC-582.
(c) Type III. See Mandatory Appendix IV.

lay[1]*:*

(a) the length of twist produced by stranding filaments, such as fibers, wires, or roving; length of twist of a filament is usually measured as the distance parallel to the axis of the strand between successive turns of the filament.

(b) the angle that such filaments make with the axis of the strand during a stranding operation.

lay up[1]*:* in reinforced plastics, to assemble layers of resin-impregnated material for processing.

lay-up[1]*:* in reinforced plastics, an assembly of layers of resin-impregnated material ready for processing.

NOTE: Within this Standard, the noun *lay-up* is hyphenated to differentiate it from the verb *lay up*.

listed components: piping components manufactured in accordance with the specifications listed in Table 4-1.1-1.

long-term hydrostatic pressure (LTHP): the estimated internal pressure of the piping product that, when applied continuously in accordance with ASTM D2992, Procedure B, will cause failure of the product after a specified number of hours. The specified number of hours and the extrapolation of failure results out to the specified number of hours are the same as for the long–term hydrostatic strength.

long-term hydrostatic strength (LTHS): the hoop stress that when applied continuously is calculated to cause the failure of the pipe in a specified number of hours, as set by the product standard. These strengths are usually obtained by extrapolation of log–log regression equations or plots of actual failure times for a range of stresses out to the selected interval.

lower deviated value (LDV): the test mean value less two standard deviations [see para. 2-2.3.3(c)].

may: used to denote permission; neither a requirement nor a recommendation.

manufacturing: the production of piping components by combining constituent materials using processes such as contact molding, filament winding, compression molding, and centrifugal casting.

pipe-supporting elements: pipe-supporting elements consist of fixtures and structural attachments as follows:

(a) fixtures: fixtures include elements that transfer the load from the pipe or structural attachment to the supporting structure, tank, vessel, or equipment. They include hanging-type fixtures, such as hanger rods, spring hangers, sway braces, turnbuckles, struts, guides, and anchors; and bearing-type fixtures, such as saddles, bases, brackets, and sliding supports.

(b) structural attachments: structural attachments include elements that are bonded, bolted, or clamped to the pipe, such as clips, lugs, rings, clamps, clevises, straps, and stanchions.

pressure design basis (PDB): an internal pressure developed for a fiberglass piping product and multiplied by a service (design) factor to obtain a hydrostatic design pressure. The PDB is the long-term hydrostatic pressure determined in accordance with ASTM D2992; ASTM D2992 allows the long-term hydrostatic pressure to be obtained on a cyclic stress (Procedure A) or constant stress (Procedure B) basis.

pressure rating (PR): the estimated maximum pressure in a piping component that can be exerted continuously with a high degree of certainty that failure of the piping component will not occur.

Procedure Qualification Record (PQR): a record of the bonding data used to bond a test piece. The PQR is a record of variables recorded during the bonding of the test pieces. It also contains the test results of the tested specimens. Recorded variables normally fall within a small range of the actual variables that will be used in production bonding.

reinforced thermoset resin pipe: a term used synonymously with FRP pipe.

reinforcement[3]*:* glass fibers having the form of chopped roving, continuous roving, fabric, or chopped-strand mat. These fibers are added to the resin matrix to strengthen and improve the properties of the resin.

resin[3]*:* the matrix of the laminate.

restrained piping system: a piping system or portion thereof that includes no changes in direction and is restrained from axial movement.

service (design) factor: a number not greater than 1.0 that is multiplied by the long-term hydrostatic strength (or long-term hydrostatic pressure) to obtain the hydrostatic design stress (or hydrostatic design pressure). The factor may vary depending on the service conditions, hazard, length of service desired, and properties of the pipe.

shall: "shall" or "shall not" is used to indicate that a provision or prohibition is mandatory.

short-term hydrostatic strength (STHS): the lower deviated value (LDV) of the tensile strength of the pipe in the hoop direction when the pipe is tested in accordance with ASTM D1599 [see para. 2-2.3.3(c)].

should: "should" or "it is recommended" is used to indicate that a provision is not mandatory but recommended as good practice.

stiffness factor[4]*:* the measurement of a pipe's ability to resist deflection, as determined in accordance with ASTM D2412.

supporting structures (not covered by this Standard): structures that permit the transfer of piping forces through pipe-supporting elements. They consist of

(a) independent structures: free-standing structures include T-poles, frames, bents attached to grade.

(b) building or nonbuilding structures, tanks, vessels, and equipment: these structures can be made of concrete, steel, or other materials.

(c) auxiliary steel: this includes brackets, beams, or frames welded or bolted to building or nonbuilding structures, tanks, vessels, or equipment.

surfacing veil: a thin mat of fine fibers used primarily to produce a smooth surface on a reinforced plastic.

thermoset resin: a plastic that, after having been cured by heat or other means, is substantially infusible and insoluble.

thermosetting: capable of being changed into a substantially infusible or insoluble product when cured by heat or other means.

thixotropic agent: a material added to resin to impart high static shear strength (viscosity) while retaining the resin's low dynamic shear strength.

trim piping: piping that is attached to vessels or equipment, such as, but not limited to, overflows, vents, and drains.

ultraviolet absorber: a material that when combined in a resin mixture will selectively absorb ultraviolet radiation.

unlisted components: piping components not manufactured in accordance with the specifications listed in Table 4-1.1-1.

woven roving: a glass-fiber fabric-reinforcing material made by the weaving of glass-fiber roving.

1-3 ABBREVIATIONS (20)

The following abbreviations may be used in this Standard to replace lengthy phrases in the text:

Abbreviation	Term
BPS [Note (1)]	Bonding Procedure Specification
EP [Note (2)]	Epoxy, epoxide
FF [Note (2)]	Furan-formaldehyde resin
FRP	Glass-fiber-reinforced thermosetting resin
HDB [Note (3)]	Hydrostatic design basis
HDP [Note (3)]	Hydrostatic design pressure
LDV	Lower deviated value
HDS [Note (4)]	Hydrostatic design strength
LTHP [Note (3)]	Long-term hydrostatic pressure
LTHS [Note (4)]	Long-term hydrostatic strength
PDB [Note (4)]	Pressure design basis
PQR [Note (1)]	Procedure Qualification Record
RTP [Note (5)]	Reinforced thermoset plastic
RTR	Reinforced thermoset resin
STHS	Short-term hydrostatic strength

NOTES:
(1) Abbreviation is in accordance with ASME B31.3
(2) Abbreviation is in accordance with ASTM D1600.
(3) Abbreviation is in accordance with ASTM D2992.
(4) Abbreviation is in accordance with ASTM F412.
(5) Abbreviation is in accordance with ASME RTP-1.

Chapter 2
Design

2-1 DESIGN CONDITIONS

This section states the qualifications of the designer; defines the pressures, temperatures, and forces applicable to the design of piping; and states the considerations to be given to various effects and their consequent loadings. See also section 2-6.

(20) 2-1.1 Qualifications of the Designer

The designer is the person in charge of the engineering design of a piping system. The designer shall be experienced in the design of FRP piping systems and in the use of this Standard. The designer shall meet at least one of the following qualifications:

(a) completion of an engineering degree, accredited by an independent agency such as the Accreditation Board for Engineering and Technology (ABET), requiring the equivalent of at least 4 yr of study that provides exposure to fundamental subject matter relevant to the design of piping systems, plus a minimum of 5 yr of experience in the design of related pressure piping

(b) professional engineering registration, recognized by the local jurisdiction, and at least 5 yr of experience in the design of related pressure piping

(c) completion of a science-based degree, an accredited engineering technician's or associate's degree or certificate requiring the equivalent of at least 2 yr of study, plus a minimum of 10 yr of experience in the design of related pressure piping

Experience in the design of related pressure piping is satisfied by piping design experience that includes design calculations for pressure, sustained and occasional loads, and piping flexibility.

2-1.2 Design Pressure

2-1.2.1 General

(a) The design pressure of each component in a piping system shall be not less than the pressure at the most severe condition of coincident internal or external pressure and temperature (minimum or maximum) expected during service, except as provided in para. 2-2.2.3.

(b) The most severe condition shall be that which results in the greatest required component thickness and the highest component rating.

(c) When a pipe is separated into individualized pressure-containing chambers (jacketed piping, blanks, etc.), the partition wall shall be designed on the basis of the most severe coincident temperature (minimum or maximum) and differential pressure between the adjoining chambers expected during service, except as provided in para. 2-2.2.3.

2-1.2.2 Required Pressure Containment or Relief

(a) Provision shall be made to safely contain or relieve any expected pressure to which the piping may be subjected. Piping that is not protected by a pressure-relieving device or that can be isolated from a pressure-relieving device shall be designed for at least the highest pressure that can be developed.

(b) Sources of pressure to be considered include ambient influences, pressure oscillations and surges, decomposition of unstable fluids, static head, and failure of control devices.

(c) The allowances of para. 2-2.2.3(d) shall be permitted, provided that the other requirements of para. 2-2.2.3 are also met.

2-1.2.3 Maximum Operating Pressure. The maximum operating pressure for the piping system is the maximum sustained operating pressure to which the piping components can be exposed in service. The maximum operating pressure, along with the coincident temperature, shall be used in the pipe stress analysis (see section 2-4).

2-1.3 Design Temperature

2-1.3.1 General. The design temperature of each component in a piping system is the temperature at which, under the coincident pressure, the greatest thickness is required in accordance with para. 2-1.2.

NOTE: To satisfy the requirements of para. 2-2.2, different components in the same piping system may have different design temperatures.

In establishing design temperatures, the designer shall consider, at minimum, the fluid temperatures, ambient temperatures, solar radiation, heating or cooling medium temperatures, and the applicable provisions of para. 2-2.3.

2-1.3.2 Minimum Design Temperature. The minimum design temperature is the lowest component temperature expected in service. This temperature can establish special design requirements and material qualification requirements. See also para. 2-1.4(d).

2-1.3.3 Uninsulated Components. The component design temperature for uninsulated components shall be the fluid temperature, unless a higher temperature will result from solar radiation or other external heat sources, or unless calculations, tests, or service experience based on measurements support the use of another temperature.

2-1.3.4 Externally Insulated Piping. The component design temperature for externally insulated components shall be the fluid temperature unless calculations, tests, or service experience based on measurements support the use of another temperature. If piping is to be heated or cooled by tracing or jacketing, this effect shall be considered in establishing component design temperatures.

2-1.3.5 Internally Insulated Piping. The component design temperature for internally insulated components shall be based on heat transfer calculations or tests.

2-1.3.6 Maximum Operating Temperature. The maximum operating temperature for the piping system is the maximum sustained operating temperature to which the piping components can be exposed in service. The maximum operating temperature, along with the coincident pressure, shall be used in the pipe stress analysis (see section 2-4).

2-1.4 Ambient Effects

For piping systems in which fluids can be trapped (e.g., in double-seated valves) and subjected to heating and consequent expansion, pressure relief shall be provided or means shall be provided to enable the system to withstand the pressure buildup.

(a) Cooling: Effects on Pressure. The cooling of a gas or vapor in a piping system can reduce the pressure sufficiently to create an internal vacuum. In such a case, the piping shall be capable of withstanding the external pressure at the lower temperature, or provision shall be made to break the vacuum.

(b) Fluid Expansion Effects. Provision shall be made in the design to enable the system either to withstand or relieve increased pressure caused by the heating of static fluid in a piping component.

(c) Atmospheric Icing. If the design minimum temperature of a piping system is below 0°C (32°F), the possibility of moisture condensation and buildup of ice shall be considered and provisions made in the design to avoid any resultant malfunctions. This applies to surfaces of moving parts of shutoff valves; control valves; pressure relief devices, including discharge piping; and other components.

(d) Low Ambient Temperature. Low-ambient-temperature conditions shall be considered in the pipe stress analysis.

2-1.5 Dynamic Effects

Dynamic effects include the following:

(a) Impact. Impact forces caused by external or internal conditions (including changes in flow rate, hydraulic shock, liquid or solid slugging, flashing, and geysering) shall be taken into account in the design of piping.

(b) Wind. The effect of wind loading shall be taken into account in the design of exposed piping. The analysis considerations and loads may be as described in ASCE/SEI 7. Authoritative local meteorological data may also be used to define or refine the design wind loads.

(c) Earthquake. The effect of earthquake loading shall be taken into account in the design of piping. The analysis considerations and loads may be as described in ASCE/SEI 7. Authoritative local seismological data may also be used to define or refine the design earthquake loads.

(d) Vibration. Piping shall be designed, arranged, and supported so as to eliminate excessive and harmful effects of vibration, which can arise from such sources as impact, pressure pulsation, turbulent flow vortices, resonance in compressors, and wind.

(e) Discharge Reactions. Piping shall be designed, arranged, and supported so as to withstand reaction forces due to let-down or discharge of fluids.

2-1.6 Weight Effects

The following weight effects, combined with loads and forces from other causes, shall be taken into account in the design of piping:

(a) Live Loads. These loads include the weight of the medium transported or the medium used for test. Snow and ice loads due to both environmental and operating conditions shall be considered.

(b) Dead Loads. These loads consist of the weight of piping components, insulation, and other superimposed permanent loads supported by the piping.

2-1.7 Thermal Expansion and Contraction Effects

The following thermal effects, combined with loads and forces from other causes, shall be taken into account in the design of piping. Thermal expansion and contraction shall be accounted for, preferably by the use of elbows, offsets, or changes in direction of the pipeline.

(a) Thermal Loads Due to Restraints. These loads consist of thrusts and moments that arise when restraints or anchors prevent free thermal expansion and contraction of the piping.

(b) Loads Due to Temperature Gradients. These loads arise from stresses in pipe walls resulting from large, rapid temperature changes or from unequal temperature

distribution as may result from a high heat flux through a comparatively thick pipe or bowing of the line caused by stratified two-phase flow.

(c) Loads Due to Differences in Expansion Characteristics. These loads result from differences in thermal expansion that occur when materials with different thermal expansion coefficients are combined, as in double-containment or metallic–nonmetallic piping.

2-1.8 Effects of Support, Anchor, and Terminal Movements

The effects of movements of piping supports, anchors, and connected equipment shall be taken into account in the design of piping. These movements can result from the flexibility and/or thermal expansion of equipment, supports, or anchors, and from settlement, tidal movements, or wind sway.

2-1.9 Reduced Impact Resistance

The harmful effects of reduced impact resistance shall be taken into account in the design of piping. The effects can, for example, result from low operating temperatures, including the chilling effect of sudden loss of pressure on highly volatile fluids. Low ambient temperatures expected during operation shall be considered.

2-1.10 Cyclic Effects

The effects of pressure cycling, thermal cycling, and other cyclic loadings shall be considered in the design of piping.

2-2 DESIGN CRITERIA

Section 2-2 states pressure–temperature design criteria, stress criteria, design allowances, and minimum design values, together with permissible variations of these factors as applied to the design of piping.

2-2.1 General

The designer shall be satisfied as to the adequacy of the material and its manufacture, considering at least the following:

(a) long- or short-term tensile, compressive, flexural, and shear strengths, and modulus of elasticity, at design temperature
(b) creep rate at design conditions
(c) design stress and its basis
(d) ductility and plasticity
(e) impact and thermal shock properties
(f) temperature limits
(g) transition temperature: melting and vaporization
(h) porosity and permeability
(i) testing methods
(j) methods of making joints and their efficiency
(k) possibility of deterioration in service

2-2.2 Pressure–Temperature Design Criteria

2-2.2.1 Listed Components Having Established Ratings. (20) FRP piping components manufactured in accordance with the specifications listed in Table 4-1.1-1 are acceptable for use in accordance with this Standard, provided they comply with one of the following:

(a) The hydrostatic design stress (HDS) or hydrostatic design pressure (HDP) is determined in accordance with para. 2-2.3.3, Design Method B, and the components are designed in accordance with the requirements of section 2-3.

(b) The maximum design pressure is established in accordance with para. 2-2.3.6.

2-2.2.2 Unlisted Components. FRP piping components not manufactured in accordance with the specifications listed in Table 4-1.1-1 but for which allowable stresses have been established in accordance with para. 2-2.3.3 or para. 2-2.3.4 shall be tested in accordance with para. 2-2.3.6 to establish maximum design pressures. These components are referred to as "unlisted components" throughout this Standard.

2-2.2.3 Allowances for Pressure and Temperature Variations. Occasional variations of pressure and/or temperature may occur in a piping system. Such variations shall be considered in the selection of design pressure (see para. 2-1.2) and design temperature (see para. 2-1.3). The most severe coincident pressure and temperature shall determine the design conditions unless all of the following criteria are met:

(a) In no case shall the increased pressure exceed the test pressure specified in section 6-3 for the piping system.

(b) Combined longitudinal stresses shall not exceed the limits established in section 2-4.

(c) The total number of pressure variations plus the total number of temperature variations above the design conditions shall not exceed 1,000 during the life of the piping system.

(d) Occasional variations above design conditions shall remain within the following limits for pressure design. The designer shall determine, using methods acceptable to the owner, that the effects of such variations will be safe over the service life of the piping system.

Subject to the owner's approval, it is permissible to exceed the pressure rating or the allowable stress for pressure design at the temperature of the increased condition by not more than

(1) 20% for no more than 1 h at any one time and no more than 10 h/yr, or

(2) 10% for no more than 10 h at any one time and no more than 100 h/yr

(e) The combined effects of the sustained and cyclic variations on the serviceability of all components in the system shall have been evaluated.

(f) The application of pressures exceeding pressure–temperature ratings of valves may under certain conditions cause loss of seat tightness or difficulty of operation. The differential pressure on the valve closure element should not exceed the maximum differential pressure rating established by the valve manufacturer. Such applications are the owner's responsibility.

2-2.2.4 Junction of Different Services. When two services that operate at different pressure–temperature conditions are connected, the valve segregating the two services shall be rated for the more severe service condition. For piping on either side of the valve, however, each system shall be designed for the conditions of the service to which it is connected.

2-2.3 Allowable Stresses and Other Design Limits

(20) **2-2.3.1 General**

(a) Both prescriptive and performance-based methods may be used to determine the allowable stress values for FRP piping materials; these methods include application of successful in-service experience, proof-of-design testing, and detailed stress analysis using laminate theory with a quadratic interaction failure criterion. The magnitude of the design factors used depends on the level of confidence of the material properties. Components qualified with the highest level of confidence have the lowest design factors, and components designed by prescription methods and with lower levels of confidence have the highest design factors. This Standard recognizes the following methods of design:

(1) Method A — Design by Rules. Allowable stresses are listed in ASME NM-3.3 for defined materials.

(2) Method B — Design by Long-Term Testing. Allowable stresses are determined based on the results of long-term pressure testing.

(3) Method C — Design by Short-Term Testing. Allowable stresses are determined based on the results of short-term testing.

(4) Method D — Design by Stress Analysis. Allowable stresses are determined based on the results of laminate, layer, or macrolayer testing or from using strain limits.

(b) FRP is, in general, a nonisotropic, nonhomogeneous material. The strength of the material in one direction, e.g., the longitudinal direction, depends on the stress in the orthogonal direction, e.g., the hoop direction. To account for this behavior, an allowable stress envelope as shown in Figure 2-2.3.1-1 is used to define the allowable stresses. The allowable stress envelope defines the allowable longitudinal stress as a function of the coincident hoop stress.

Regardless of the design method used, a minimum of two points must be determined to develop the allowable stress envelope. The two points are

(1) $S_{A(0:1)}$, the allowable longitudinal tensile stress with no coincident hoop stress

(2) $S_{A(2:1)}$, the allowable longitudinal tensile stress with coincident hoop stress equal in magnitude to twice that of the allowable longitudinal stress

Additional points may be used to develop a more complex allowable stress envelope.

It is permissible to use $-S_{A(0:1)}$ for $S_{A(0:-1)}$.

It is permissible to use more than one design method to determine the points of the allowable stress envelope. For example, Design Method B (see para. 2-2.3.3) could be used to determine $S_{A(2:1)}$, and Design Method C (see para. 2-2.3.4) could be used to determine $S_{A(0:1)}$.

(c) Particular types of FRP laminates have greater strength in the hoop direction than in the longitudinal direction. An example of such a laminate is filament-wound pipe with a winding angle of 55 deg to the pipe axis. Designing the thickness of these types of laminates solely to resist pressure loads could result in a pipe with insufficient capacity to withstand longitudinal loads other than pressure. Consideration shall be given therefore to providing additional longitudinal load-carrying capacity.

Regardless of the design method used to determine the pipe thickness required for pressure design, the pipe thickness shall be increased beyond that required for pressure by the following factor:

$$K_1 = 0.67 \times S_{H(2:1)}/S_{A(0:1)} + 0.33$$

where K_1 < 1.67 and

$S_{A(0:1)}$ = allowable longitudinal stress with no coincident hoop stress

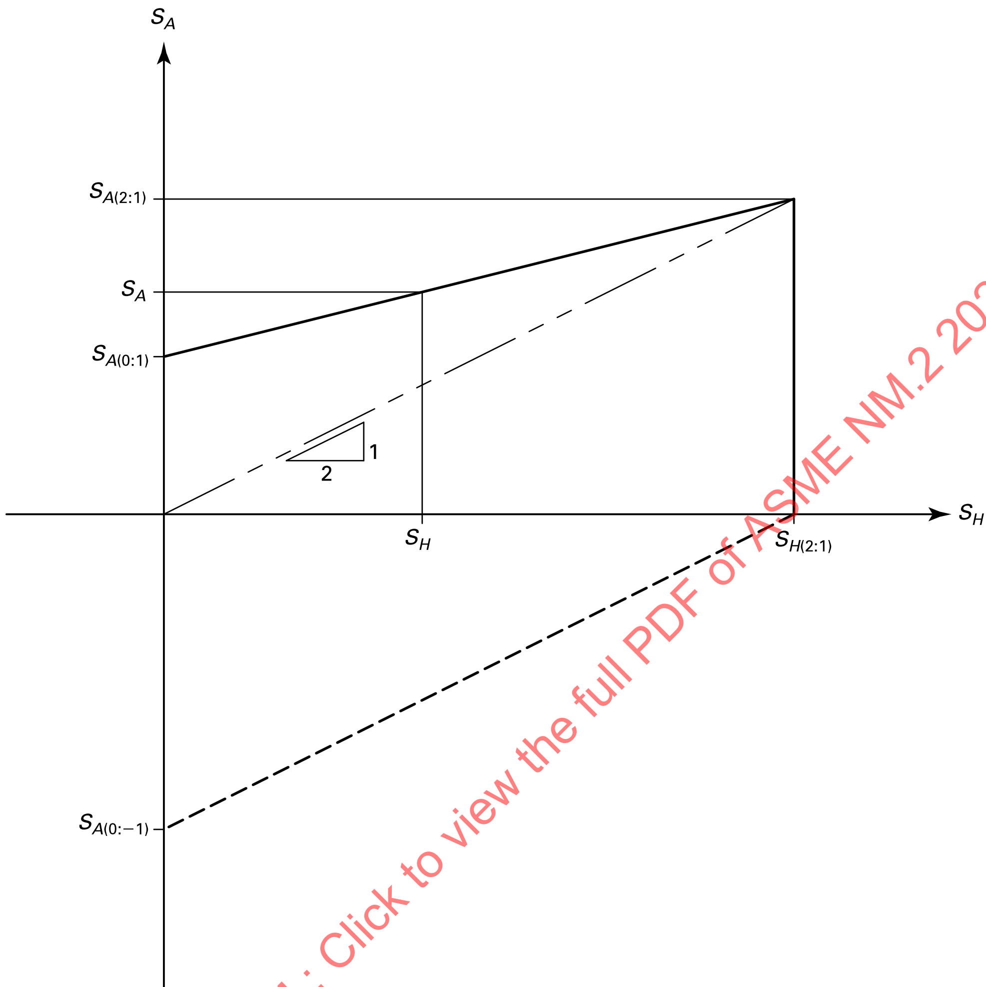
$S_{H(2:1)}$ = allowable hoop stress with coincident longitudinal stress equal in magnitude to one-half that of the hoop stress

2-2.3.2 Design Method A — Design by Rules. Allowable stresses have been established for standard materials as listed in ASME NM.3.3. The allowable stresses listed in ASME NM.3.3 are based on not greater than one-eighth of the laminate strength. Pressure design of piping components shall be in accordance with section 2-3. (20)

2-2.3.3 Design Method B — Design by Long-Term Testing. Allowable stresses for pressure design per Design Method B are to be determined in accordance with the procedures described in ASTM D2992. The allowable stresses so determined are defined as the hydrostatic design stresses (HDS), and shall be in accordance with the following requirements and limits:

(a) For the purposes of this Standard, the long-term hydrostatic strength (LTHS) is defined as the lower 95% prediction limit of the estimated tensile stress in the wall of the pipe in the hoop direction due to internal hydrostatic pressure that will cause failure of the pipe after the design life of the piping. If the cyclic LTHS is used as per ASTM D2992, Procedure A, the design number of cycles shall not be less than 262 800 000

Figure 2-2.3.1-1 Allowable Stress Envelope



cycles. If the static LTHS is used as per ASTM D2992, Procedure B, the design number of hours shall not be less than 175 200 h.

(b) The HDS is determined by multiplying the LTHS by a suitable service (design) factor.

(1) If the cyclic LTHS is used, the service (design) factor shall not exceed 1.0.

(2) If the static LTHS is used, the service (design) factor shall not exceed 0.5.

The designer should select the service (design) factor after evaluating fully the service conditions and the engineering properties of the specific material under consideration. See also section 2-6.

(c) The HDS shall not be taken as greater than one-quarter of the short-term hydrostatic strength (STHS) of the pipe. The STHS is defined as the LDV of the tensile strength of the pipe in the hoop direction when the pipe is tested in accordance with ASTM D1599. The LDV is defined as the test mean value less two standard deviations.

(d) The HDS is valid in the temperature range listed in Table 3-3.1-1. For design temperatures in excess of those listed in Table 3-3.1-1, the testing shall be conducted at no less than the design temperature.

(e) $S_{H(2:1)}$ shall be taken as not greater than the HDS. $S_{A(2:1)}$ shall be taken as not greater than HDS/2.

(f) Strain in lieu of stress may be used when data is analyzed in accordance with ASTM D2992. The LTHS and HDS in this case would be strain values rather than stress values.

(g) Pressure in lieu of stress may be used when data is analyzed in accordance with ASTM D2992. The long-term hydrostatic pressure (LTHP) is defined as the lower 95% prediction limit of the estimated pressure that will cause failure of the pipe after the design life of the piping. When the cyclic LTHP is used as per ASTM D2992, Procedure A, the design number of cycles shall not be less than 262 800 000 cycles. When the static LTHP is used as per ASTM D2992, Procedure B, the design number of hours shall not be less than 175 200 h.

The hydrostatic design pressure (HDP) is determined by multiplying the LTHP by a suitable service (design) factor.

(1) When the cyclic LTHP is used, the service (design) factor shall not exceed 1.0.

(2) When the static LTHP is used, the service (design) factor shall not exceed 0.5.

The designer should select the service (design) factor after evaluating fully the service conditions and the engineering properties of the specific material under consideration. See also section 2-6.

(h) The HDS (or HDP) is valid only for the materials and laminate constructions used in the test specimens. Changes to materials or laminate constructions require retesting to establish alternative allowable stresses (strains).

(i) Components that have been designed using the HDS (or HDP) shall be constructed of the same materials and laminate constructions as those used in the long-term test specimens.

(j) Components for which the allowable stresses have been determined in accordance with Design Method B and that have been designed in accordance with the rules in section 2-3 do not need to be tested in accordance with para. 2-2.3.6. All other components shall be tested in accordance with para. 2-2.3.6.

Currently, there are no long-term test methods available for determining other points on the allowable stress envelope. Therefore, short-term test methods shall be used to supplement the long-term pressure testing in order to construct the full allowable stress envelope.

2-2.3.4 Design Method C — Design by Short-Term Testing. Allowable stresses per Design Method C shall be determined using the results from short-term tests as described below. In all cases, the allowable stresses shall be not greater than one-sixth of the LDV of the material strength. The LDV is defined as the test mean value less two standard deviations.

(a) The hoop tensile strength under biaxial pressure, $S_{H(2:1)}$, shall be determined in accordance with ASTM D1599, Procedure A or Procedure B, as the hoop stress (or strain) at maximum pressure. Free end closures shall be used for this testing. For either Procedure A or Procedure B, it is permissible to exceed the 70-s time to reach the burst pressure.

NOTE: For quasi-isotropic materials such as Type I or Type II laminates, $S_{H(1:0)}$ [see (b)] may be used for $S_{H(2:1)}$.

(b) The hoop tensile strength under uniaxial loading, $S_{H(1:0)}$, shall be determined in accordance with ASTM D638; ASTM D2290, Procedure A; ASTM D3039; or ASTM D5083.

NOTE: $S_{H(2:1)}$ may be used for $S_{H(1:0)}$.

(c) The axial tensile strength under biaxial pressure, $S_{A(2:1)}$, shall be determined in accordance with ASTM D1599, Procedure A or Procedure B, as the axial stress (or strain) at maximum pressure. Free end closures shall be used for this testing. For either Procedure A or Procedure B, the 70-s time to reach the burst pressure may be exceeded.

NOTE: $S_{A(0:1)}$ [see (d)] may be used for $S_{A(2:1)}$.

(d) The axial tensile strength under uniaxial loading, $S_{A(0:1)}$, shall be determined in accordance with ASTM D638, ASTM D2105, ASTM D3039, or ASTM D5083.

NOTE: The axial bending strength of filament-wound pipe can be greater than the axial tensile strength. That additional bending strength may be used for pipe bending loads.

(e) Except as provided in para. 3-2.4, the allowable stresses (or strains) are valid only for the materials and laminate constructions used in the test specimens. Except as provided in para. 3-2.4, changes to materials or laminate constructions shall require retesting to establish alternative allowable stresses (strains).

(f) Components that have been designed using these allowable stresses (or strains) shall be constructed of the same materials and shall have the same laminate constructions as those used in the short-term test specimens.

(g) The allowable stresses are valid in the temperature range as listed in Table 3-3.1-1. For design temperatures in excess of those listed in Table 3-3.1-1, the testing shall be conducted at no less than the design temperature.

(h) Components for which the allowable stresses have been determined in accordance with Design Method C and that have been designed in accordance with the requirements in section 2-3 do not need to be tested in accordance with para. 2-2.3.6. All other components shall be tested in accordance with para. 2-2.3.6.

2-2.3.5 Design Method D — Design by Stress Analysis. Design Method D consists of two steps: first, a biaxial stress analysis of the component to determine the stress state at points of concern in the component as determined by the designer, and second, the application of the quadratic interaction criterion to demonstrate that the stress state is within permissible limits.

(a) *Biaxial Stress Analysis*

(1) Various methods of stress analysis may be used to determine the biaxial stress state in the component. These include

(-a) finite element analysis

(-b) application of closed-form solutions that yield the complete biaxial stress state

(-c) back calculation of the biaxial state of stress using strain gauge data

(2) The elastic constants to be used in the stress analysis shall be determined from one of the following:

(-a) the elastic properties listed in ASME NM.3.3

(-b) testing of the laminate

(-c) testing of the individual layers (lamina) or macrolayers and using laminate analysis as defined in Mandatory Appendix II

(-d) micromechanics and laminate analysis as defined in Mandatory Appendix II

(b) Quadratic Interaction Criterion

(1) The quadratic interaction criterion requires calculation of the strength ratio of each individual lamina [see (2) below] for each loading combination using stress limits determined from one of the following (or a combination thereof):

(-a) testing of individual layers (lamina) or macrolayers (as defined in Mandatory Appendix II). Test results shall be based on the LDV of the layer strength. The LDV is defined as the test mean value less two standard deviations.

(-b) the strain limits listed in Mandatory Appendix II, with stress limits calculated from the strain limits using the appropriate modulus of elasticity values.

(2) For quasi-isotropic materials such as Type I and Type II laminates, the quadratic interaction criterion may be applied to the entire laminate rather than to the individual layers. The stress limits in this case shall be determined by testing of the laminate.

(3) For any layer or macrolayer for which the stress limit has been calculated from the strain limits, the strength ratio shall not be less than 8. For any laminate, layer, or macrolayer for which the stress limit has been determined by testing, the strength ratio shall not be less than 6.

(4) The stress limits are applicable to the temperature range as listed in Table 3-3.1-1. For design temperatures in excess of those listed in Table 3-3.1-1, the stress limits shall be determined by testing at no less than the design temperature.

(20) **2-2.3.6 Proof-of-Design Testing of Piping Components.** Except as noted in (e) below, proof-of-design testing is required to establish or verify the maximum design pressure of piping components for which the allowable stresses have been determined in accordance with Design Method B or Design Method C. Proof-of-design testing may also be used to qualify individual components designed by means other than Design Method B or Design Method C. The requirements for proof-of-design testing are as follows:

(a) Fittings and joints shall be pressure tested in accordance with the proof-of-design requirements in ASME SD-6041, or in accordance with the pressure test requirements of ASME SD-5685. Flanges shall be tested in accordance with the performance requirements of ASME SD-4024 or ASME SD-5421, as applicable.

(b) The minimum proof test pressure depends on the number of components of a given type and size that are proof tested. The proof test pressures listed in ASME SD-6041, ASME SD-5685, ASME SD-4024 or ASME SD-5421, as applicable, shall be increased by the following factors:

Number of Components Tested	Proof Test Factor
1	1.5
2	1.375
>=3	1.25

(c) The ranges of component sizes that may be qualified by proof testing are shown in Table 2-2.3.6-1.

(d) The proof-of-design testing shall be conducted at a temperature in the range of 15°C to 25°C (60°F to 77°F). The maximum design pressures established by the testing are suitable for the design temperature ranges listed in Table 3-3.1-1. For design temperatures in excess of those listed in Table 3-3.1-1, the testing shall be conducted at no less than the design temperature.

(e) Proof-of-design testing shall not be required for piping components complying with any of the following:

(1) Piping components have been designed in accordance with Design Method A.

(2) Allowable stresses have been determined in accordance with Design Method B or Design Method C, and the piping components have been designed in accordance with the requirements in section 2-3.

(3) Piping components have been designed in accordance with Design Method D.

Table 2-2.3.6-1 Component Sizes Qualified by Proof-of-Design Testing

Size of Test Component, DN (NPS)	Qualified Component Sizes, DN (NPS)
50 (2)	20–150 (0.75–6)
80 (3)	25–200 (1–8)
100 (4)	40–300 (1.5–12)
150 (6)	50–450 (2–18)
200 (8)	65–600 (2.5–24)
250 (10)	125–600 (5–24)
300 (12)	150–600 (6–24)
350 (14)	200–700 (8–28)
400 (16)	200–800 (8–32)
450 (18)	250–900 (10–36)
500 (20)	250–1 000 (10–40)
600 (24)	300–1 200 (12–48)
750 (30)	400–1 500 (16–60)
900 (36)	450–1 800 (18–72)

GENERAL NOTE: For test components of sizes other than those listed above, size range of qualified components would be $\frac{1}{2}$ to 2 times the size of the tested component.

2-2.3.7 Limits of Calculated Stresses Due to Sustained and Operating Loads

(a) Internal Pressure Stresses. Limits of stress due to internal pressure are as stated in paras. 2-2.3.2 through 2-2.3.5. The following also apply:

(1) Sustained Loads. Limits of stress due to internal pressure and other sustained loads such as weight are as stated in section 2-4.

(2) Operating Loads. Limits of stress due to sustained loads plus operating loads such as those due to restraint of thermal expansion/contraction are as stated in section 2-4.

(b) External Pressure Stresses. The stress due to external pressure shall be considered adequate if it is not greater than one-quarter of the collapse pressure determined by test or calculation.

2-2.3.8 Limits of Calculated Stresses Due to Occasional Loads

(a) Operation. The total stress in any component due to the following loads shall not exceed the limits stated in section 2-4:

(1) sustained loads such as pressure and weight

(2) sustained plus operating loads such as those due to the restraint of thermal expansion and/or contraction

(3) occasional loads such as wind or earthquake

NOTE: Wind and earthquake forces need not be considered as acting concurrently.

(b) Test. Stresses due to test conditions are subject to the limitations in (a). It is not necessary to consider other occasional loads, such as wind and earthquake, as occurring concurrently with test loads.

2-2.3.9 Allowances. The minimum required thickness of a piping component shall include allowances for corrosion, erosion, and thread or groove depth. See also section 2-5.

2-3 PRESSURE DESIGN OF PIPING COMPONENTS

2-3.1 General

Components manufactured in accordance with specifications listed in Table 4-1.1-1 shall be considered suitable for use at their respective maximum design pressures in accordance with para. 2-2.2.1. The requirements in paras. 2-3.2 through 2-3.9 are intended for uniform static pressure design of components not covered by the specifications in Table 4-1.1-1, but may be used for a special or more rigorous design of such components, or to satisfy requirements of para. 2-2.2.2. Designs shall be checked for adequacy of mechanical strength under applicable loadings as described in section 2-1.

2-3.2 Straight Pipe

2-3.2.1 General (20)

(a) The required thickness of straight sections of pipe shall be determined by eq. (2-3-1):

$$t_m = t + c \tag{2-3-1}$$

where

c = sum of mechanical allowances (thread or groove depth) plus corrosion-barrier and erosion allowances, mm (in.). For threaded components, the nominal thread depth (dimension h of ASME B1.20.1) shall apply. If the tolerance of machined surfaces or grooves is not specified, it shall be assumed to be 0.5 mm (0.02 in.) plus the specified depth of the cut. Unless otherwise specified by the owner, the corrosion-barrier thickness shall be considered as sacrificial and shall not be included for structural contributions.

t = pressure design structural thickness, mm (in.), as calculated in accordance with para. 2-3.2.2 for pipe under internal pressure or para. 2-3.2.3 for pipe under external pressure. For piping with both internal and external pressure design requirements, minimum structural thickness shall be taken as the maximum value required. Minimum structural thickness shall not be less than 2.0 mm (0.080 in.).

t_m = minimum required thickness, mm (in.), including the corrosion-barrier and mechanical and erosion allowances

The measured total pipe wall thickness, T, for the manufactured pipe shall not be less than t_m. In addition, the measured thickness of the structural wall shall not be less than t.

(b) The requirements of para. 2-3.2 are intended to address uniform static pressure design only. Additional thickness may be required for other loadings, dynamic effects, or stability as required by section 2-4.

2-3.2.2 Straight Pipe Under Internal Pressure. To ensure that straight pipe has adequate axial-direction strength for loads other than pressure, it is necessary to include provisions for additional axial strength capacity in the initial internal pressure design equations. The internal pressure design structural thickness, t, shall not be less than that calculated by eq. (2-3-2). The stress values for eq. (2-3-2) shall be taken from the appropriate table in ASME NM-3.3 or determined from qualification testing. (20)

$$t = K_1 \frac{PD}{2S} \tag{2-3-2}$$

where

D = inside diameter of pipe structural wall, mm (in.)
= $(D_i + 2c)$
c = sum of allowances defined in para. 2-3.2.1, mm (in.)
D_i = inside diameter of pipe, mm (in.)

K_1 = factor to provide additional available axial strength for loads other than pressure
= 1.0 for Type I and Type II laminates
= 1.67 for Type III laminates
= $0.67(S_{H(2:1)}/S_{A(0:1)}) + 0.33$ for all other laminates, where $(S_{H(2:1)}/S_{A(0:1)})$ shall be taken as greater than or equal to 1.0 but need not exceed 2.0
$S_{A(0:1)}$ = allowable longitudinal tensile stress with no coincident hoop stress, MPa (psi)
$S_{H(2:1)}$ = allowable hoop stress with coincident longitudinal stress equal in magnitude to one-half that of the hoop stress, MPa (psi)

P = internal design gauge pressure, MPa (psi)
S = design stress from applicable table in ASME NM.3.3 or from qualification testing, MPa (psi)

(20) **2-3.2.3 Straight Pipe Under Uniform External Pressure**

(a) Without Qualified Rib Stiffeners. The external pressure design structural thickness, t, shall be established following the procedures outlined in ASTM D2924, or shall not be less than that calculated by eq. (2-3-3). The elastic modulus and Poisson's ratio values for eq. (2-3-3) shall be taken from the appropriate table in ASME NM-3.3 or calculated by lamination analysis in accordance with Mandatory Appendix II. For laminate types other than Type I, II, or III, in the absence of appropriate Poisson's ratio values, the product of Poisson's ratios, $\nu_{ah} \times \nu_{ha}$, may be taken as zero for conservatism in the following equation. A design factor, F, of at least 4.0 for external pressure shall be used:

$$t = \sqrt[3]{\frac{F P_e D_o^3 (1 - \nu_{ah}\nu_{ha})}{2E_{hf}}} \qquad (2\text{-}3\text{-}3)$$

where

D_o = outside diameter of pipe, mm (in.)
E_{hf} = pipe hoop-direction flexural modulus, MPa (psi)
F = design factor; F is ≥ 4.0
P_e = external or vacuum design gauge pressure, MPa (psi)
ν_{ah} = Poisson's ratio in the axial direction
ν_{ha} = Poisson's ratio in the hoop direction

(b) With Qualified Rib Stiffeners. Qualified rib stiffeners are defined as circumferential stiffener rings that meet the requirements for minimum moment of inertia, I_s, as calculated by eq. (2-3-4):

$$I_s = \frac{P_e L_s D_o^3 F}{24E_2} \qquad (2\text{-}3\text{-}4)$$

where

E_2 = hoop tensile modulus of stiffener, MPa (psi)
L_s = one-half the distance from the centerline of the stiffener to the next stiffener on one side plus one-half the centerline distance to the next stiffener on the other side of the stiffener, both measured parallel to the axis of the cylinder, mm (in.)

The external pressure design structural thickness, t, shall be not less than that calculated by eq. (2-3-5) but need not exceed the value calculated by eq. (2-3-3). The elastic modulus and Poisson's ratio values for eq. (2-3-5) shall be taken from the appropriate table in ASME NM-3.3 or calculated by lamination analysis in accordance with Mandatory Appendix II. For laminate types other than Type I, II, or III, in the absence of appropriate Poisson's ratio values, the product of Poisson's ratios, $\nu_{ah} \times \nu_{ha}$, may be taken as zero for conservatism in the following equation:

$$t = \left(\frac{P_e (1 - \nu_{ah}\nu_{ha})^{3/4} L_c \left(\frac{D_o}{2}\right)^{3/2} F}{0.8531 \mathrm{KD}\, \gamma\, E_{hf}^{3/4} E_{at}^{1/4}} \right)^{2/5} \qquad (2\text{-}3\text{-}5)$$

where

E_{at} = pipe axial tensile modulus, MPa (psi)
KD = a knockdown factor to cover all data points
= 1.0 for Type I, Type II, and Type III laminates
= 0.84 for all other laminate types
L_c = greatest center-to-center distance between any two adjacent stiffener rings, mm (in.)
t = external pressure design structural thickness, mm (in.)
γ = reduction factor to better correlate theoretical predictions and test results
= $1 - 0.001Z_p$ if $Z_p \leq 100$
= 0.9 if $Z_p > 100$

$$Z_p = \frac{E_{hf}^{3/4} E_{at}^{1/2}}{E_{af}^{2}} (1 - \nu_{ah}\nu_{ha})^{1/2} \frac{L_c^2}{\left(\frac{D_o}{2} t\right)}$$

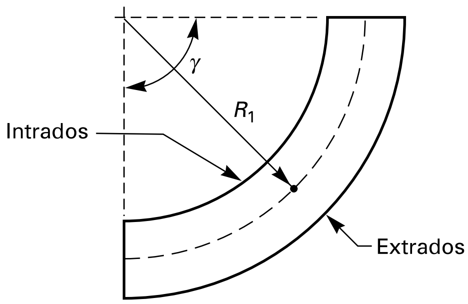
where E_{af} is the axial flexural modulus, MPa (psi)

ν_{ah} = Poisson's ratio in the axial direction
ν_{ha} = Poisson's ratio in the hoop direction

2-3.3 Curved and Mitered Segments of Pipe

2-3.3.1 Smooth Radius Elbows Under Uniform Internal Pressure. To ensure that smooth radius elbows have adequate hoop-direction strength capacity for combined stresses due to internal pressure and bending, it is necessary to include provisions for (20)

Figure 2-3.3.1-1 Nomenclature for Smooth Radius Elbows



additional strength capacity in the initial internal pressure design equations. The minimum required thickness, t_m, of a smooth radius elbow shall be determined in accordance with eq. (2-3-1), with pressure design structural thickness, t, calculated using eq. (2-3-6):

$$t = K_2 m \frac{PD}{2S} \tag{2-3-6}$$

where

D = inside diameter of pipe structural wall, mm (in.)
= $(D_i + 2c)$
  c = sum of allowances defined in para. 2-3.2.1, mm (in.)
  D_i = inside diameter of pipe, mm (in.)
K_2 = factor to provide additional available strength for loads other than pressure
= 1.2 for Type I and Type II laminates
m = pressure stress multiplier for location on elbow
P = internal design gauge pressure, MPa (psi)
S = design stress from applicable table in ASME NM.3.3 or from qualification testing, MPa (psi)

At the intrados (inside bend radius)

$$m = \frac{4(R_1/D) - 1}{4(R_1/D) - 2} \geq 1.0 \tag{2-3-7}$$

At the extrados (outside bend radius)

$$m = \frac{4(R_1/D) + 1}{4(R_1/D) + 2} \geq 1.0 \tag{2-3-8}$$

where

R_1 = bend radius of elbow, mm (in.); $R_1 \geq D$

At the sidewall on the elbow centerline radius, $m = 1.0$.

Thickness variations from the intrados to the extrados and along the length of the elbow shall be gradual. The thickness requirements apply at the midspan of the elbow, $\gamma/2$, at the intrados, extrados, and elbow centerline radius (see Figure 2-3.3.1-1). The minimum thickness at the end tangents and extrados shall not be less than the requirements of para. 2-3.2 for straight pipe ($m \geq 1.0$).

2-3.3.2 Mitered Elbows Under Uniform Internal Pressure. Acceptable methods for pressure design of multiple and single miter bends are given in (a) and (b), where the requirements in (c) and (d) apply. Refer to Figure 2-3.3.2-1 for nomenclature used in eqs. (2-3-9) through (2-3-11) for the internal pressure design of mitered elbows.

(a) Multiple-Miter Elbows. The maximum allowable internal pressure, P_m, shall be the lesser value calculated from eqs. (2-3-9) and (2-3-10). These equations are not applicable when angle θ exceeds 22.5 deg:

$$P_m = \frac{St}{r_2}\left(\frac{t}{t + 0.643 \tan \theta \sqrt{r_2 t}}\right) \tag{2-3-9}$$

$$P_m = \frac{St}{r_2}\left(\frac{R_1 - r_2}{R_1 - 0.5 r_2}\right) \tag{2-3-10}$$

where

S = design stress from applicable table in ASME NM.3.3 or from qualification testing, MPa (psi)

(b) Single-Miter Elbows

(1) The maximum allowable internal pressure, P_m, for a single miter bend with angle θ not greater than 22.5 deg shall be calculated by eq. (2-3-9).

(2) The maximum allowable internal pressure, P_m, for a single miter bend with angle θ greater than 22.5 deg shall be calculated by eq. (2-3-11):

$$P_m = \frac{St}{r_2}\left(\frac{t}{t + 1.25 \tan \theta \sqrt{r_2 t}}\right) \tag{2-3-11}$$

(c) The miter pipe wall thickness, t, used in eqs. (2-3-9) through (2-3-11) shall extend a distance not less than M from the inside crotch of the end miter welds, where M equals the larger of the following:

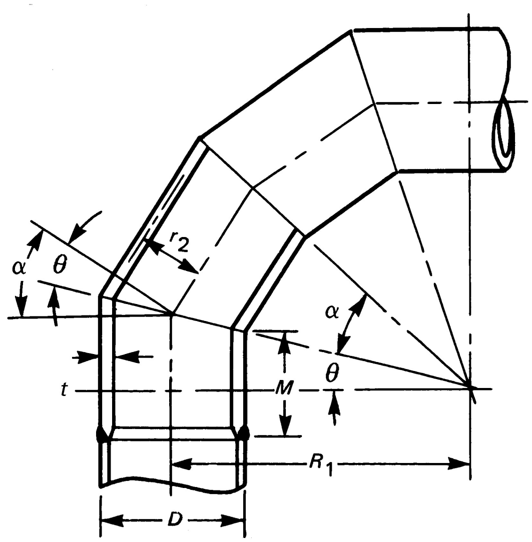
$$2.5(r_2 t)^{0.5}$$

or

$$\tan \theta (R_1 - r_2)$$

(d) For all miter elbows for which the inside joint is accessible, 30% to 50% of the required miter joint shall be applied as an inside lay-up. A corrosion barrier shall be applied over the inside joint. The requirement for an inside lay-up is mandatory for miters where $D_i \geq 600$ mm (24 in.) diameter.

Figure 2-3.3.2-1 Nomenclature for Mitered Elbows



GENERAL NOTE: Corrosion barrier not shown for clarity.

2-3.3.3 Curved and Mitered Segments of Pipe Under Uniform External Pressure. The wall thickness of curved and mitered segments of pipe subjected to external pressure may be determined as specified for straight pipe in paras. 2-3.2.1 and 2-3.2.3.

2-3.4 Branch Connections

2-3.4.1 Fabricated Branch Connections. A pipe having a branch connection is weakened by the opening that must be made in it, and unless the wall thickness of the pipe is sufficiently in excess of that required to sustain the pressure, it is necessary to provide added reinforcement. The design of branch connections shall be based on the following, except as provided in paras. 2-3.4.2 and 2-3.4.3.

(a) Nomenclature. The following nomenclature is used in the equations for pressure design of branch connections:

A_p = area of reinforcement required on each side of branch, mm^2 (in.^{2}); $A_p \geq A_T/2$
A_T = total area of reinforcement required on run pipe, mm^2 (in.^{2})
D = inside diameter of run pipe, mm (in.)
d = inside diameter of branch pipe, mm (in.)
E_{OL} = tensile modulus of the reinforcement (minimum of hoop and axial moduli), MPa (psi)
E_P = tensile modulus of the run pipe (maximum of hoop and axial moduli), MPa (psi)
F = design factor
= 10.0 minimum
L_b = length of reinforcement on branch pipe, mm (in.)
L_c = longest chord length of opening, mm (in.)
L_p = width of reinforcement pad on run pipe, mm (in.)
L_{pi} = width of reinforcement pad on inside of run pipe, mm (in.)
L_{po} = width of reinforcement pad on outside of run pipe, mm (in.)
P = design pressure, MPa (psi)
S = design stress from applicable table in ASME NM.3.3 or from qualification testing, MPa (psi)
S_{OL} = tensile strength of reinforcement (minimum of hoop and axial strengths), MPa (psi)
S_{sb} = shear strength of secondary bond on branch pipe, MPa (psi)
S_{sh} = shear strength of secondary bond on run pipe, MPa (psi)
S_{UP} = tensile strength of the run pipe (maximum of hoop and axial strengths), MPa (psi)
t_b = thickness of reinforcement on branch pipe, mm (in.)
T_h = thickness of run pipe required for pressure rating, mm (in.)
T_p = thickness of reinforcement pad on run pipe, mm (in.)
T_{pi} = thickness of reinforcement pad on inside of run pipe, mm (in.)
T_{po} = thickness of reinforcement pad on outside of run pipe, mm (in.)

(b) General Provisions and Requirements. The following general provisions and requirements apply to the procedures presented in (c) and (d) for pressure design of branch connections:

(1) These procedures apply to branch connections for which $d/D \leq 0.5$. Branch connections for which $d/D > 0.5$ shall be designed by Design Method B, C, or D (see paras. 2-2.3.3 through 2-2.3.5).

(2) These procedures apply for branch connections for which the angle between the branch and run pipe is ≥ 45 deg.

(3) For all branch connections for which the inside joint is accessible, 30% to 50% of the required reinforcement shall be applied as an inside lay-up. A corrosion barrier shall be applied over the inside joint. The requirement for an inside lay-up is mandatory for branch connections where $D \geq 600$ mm (24 in.) and $d \geq 200$ mm (8 in.).

(4) These procedures are intended to address pressure design only. Additional thicknesses may be required for external loads.

(5) When any two or more branches are so closely spaced that their reinforcements overlap, each branch connection shall be reinforced as required by (c) and (d). No portion of the reinforcement shall be considered as applying to more than one branch connection.

(c) Reinforcement of the Run Pipe

(1) The total area for reinforcement of the run pipe shall not be less than that determined by eqs. (2-3-12) and (2-3-13):

$$A_T \geq K_1 L_c T_h \frac{S_{UP}}{S_{OL}} \quad (2\text{-}3\text{-}12)$$

$$A_T \geq K_1 L_c T_h \frac{E_P}{E_{OL}} \quad (2\text{-}3\text{-}13)$$

where

K_1 = 1.5 if reinforcement is applied only to the outside of the joint. See Figure 2-3.4.1-1, illustration (a).

= 1.0 if reinforcement is applied to the inside and outside of the joint. See Figure 2-3.4.1-1, illustration (b).

If test data are not available for the tensile strength of the run pipe, S_{UP}, it is permissible to use $0.015E_P$. If test data are not available for the tensile strength of the reinforcement, S_{OL}, it is permissible to use $0.010E_{OL}$.

(2) The area of run pipe reinforcement on each side of the branch shall not be less than that determined by eq. (2-3-14):

$$A_p \geq \frac{A_T}{2} \quad (2\text{-}3\text{-}14)$$

(3) The minimum width of reinforcement pad on the run pipe shall not be less than that determined by eq. (2-3-15):

$$L_p \geq \frac{\pi L_c P}{4(S_{sh}/F)} \quad (2\text{-}3\text{-}15)$$

The minimum width of reinforcement pad shall not be less than 75 mm (3.0 in.).

The secondary bond shear strength on the run pipe, S_{sh}, shall not be taken to be greater than 7 MPa (1,000 psi).

For joints with inside reinforcement, the total length of the inside and outside reinforcement shall not be less than that determined by eq. (2-3-15). The length of the inside reinforcement shall not be less than 30% of that determined by eq. (2-3-15). The inside and outside reinforcements shall each be no less than 75 mm (3.0 in.).

For joints with reinforcement only on the outside, no less than 66% of A_p shall be applied within the first third of L_p from the branch pipe. The thickness of this portion of the reinforcement shall not be less than $2A_p/L_p$. The remainder of the reinforcement shall taper uniformly to the end of L_p at a minimum length-to-thickness taper of 4:1.

(4) The following general provisions and requirements apply to the reinforcement of the run pipe:

(-a) A maximum of 50% of the length of the tapered reinforcement may be considered as contributing to the required area of reinforcement.

(-b) The minimum structural thickness, not including the corrosion barrier, of the inside or outside reinforcement shall not be less than 6 mm (0.25 in.).

(-c) Not less than 50% of the total external reinforcement thickness shall extend up the branch pipe. These layers shall have a minimum length-to-thickness taper of 4:1 beginning above the run pipe reinforcement pad. For joints with inside reinforcement, it is permissible to include the reinforcement that extends into the branch pipe as contributing to the inside reinforcement of the run pipe. The maximum length of the reinforcement that can be considered as run pipe reinforcement is $T_h + T_p$.

(-d) Resin putty shall be used at the intersection to form a smooth lay-up surface. The finished radius of the putty shall not exceed 10 mm (3⁄8 in.).

(d) *Reinforcement of the Branch Pipe*

(1) The minimum length of reinforcement on the branch pipe shall not be less than that determined by eq. (2-3-16):

$$L_b \geq \frac{Pd}{4(S_{sb}/F)} \quad (2\text{-}3\text{-}16)$$

(-a) No more than 50% of the taper length shall be included as contributing to the minimum reinforcement length on the branch, L_b. The minimum reinforcement length of the branch pipe shall not be less than 75 mm (3.0 in.).

(-b) The secondary bond shear strength on the branch pipe, S_{sb}, shall not be taken to be greater than 14 MPa (2,000 psi).

(2) The minimum thickness of the reinforcement on the branch pipe shall not be less than that determined by eq. (2-3-17):

$$t_b \geq \frac{K_2 Pd}{2(S_{OL}/F)} \quad (2\text{-}3\text{-}17)$$

where

K_2 = 1.5 if reinforcement is applied only to the outside of the joint. See Figure 2-3.4.1-1, illustration (a).

= 1.0 if reinforcement is applied to the inside and outside of the joint. See Figure 2-3.4.1-1, illustration (b).

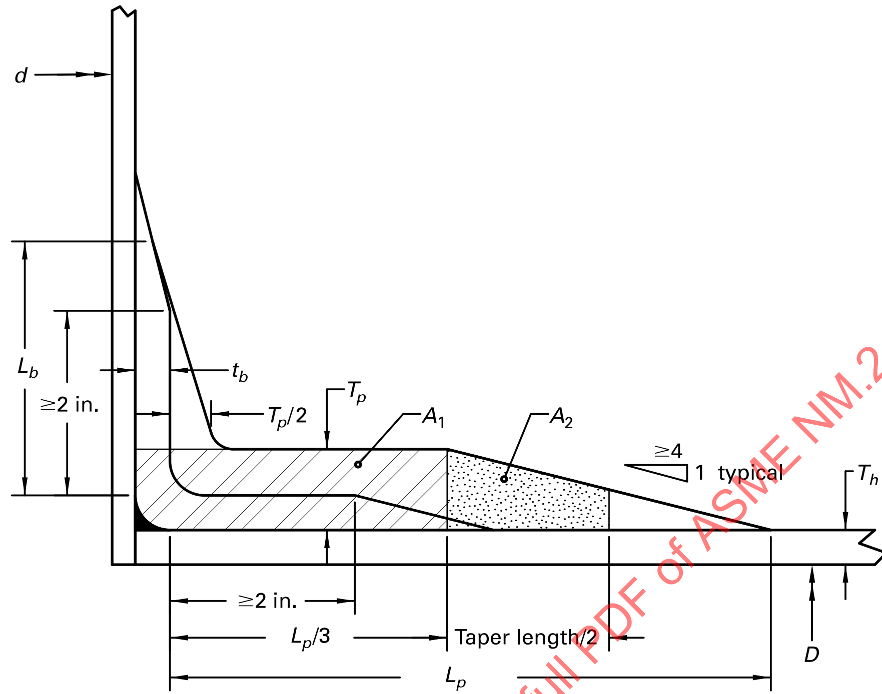
(-a) The full thickness reinforcement on the branch pipe shall extend a minimum of 50 mm (2.0 in.) onto the run pipe, beyond the resin putty, followed by a minimum length-to-thickness taper of 4:1.

(-b) If test data is not available for the tensile strength of the reinforcement, S_{OL}, it is permissible to use $0.010E_{OL}$.

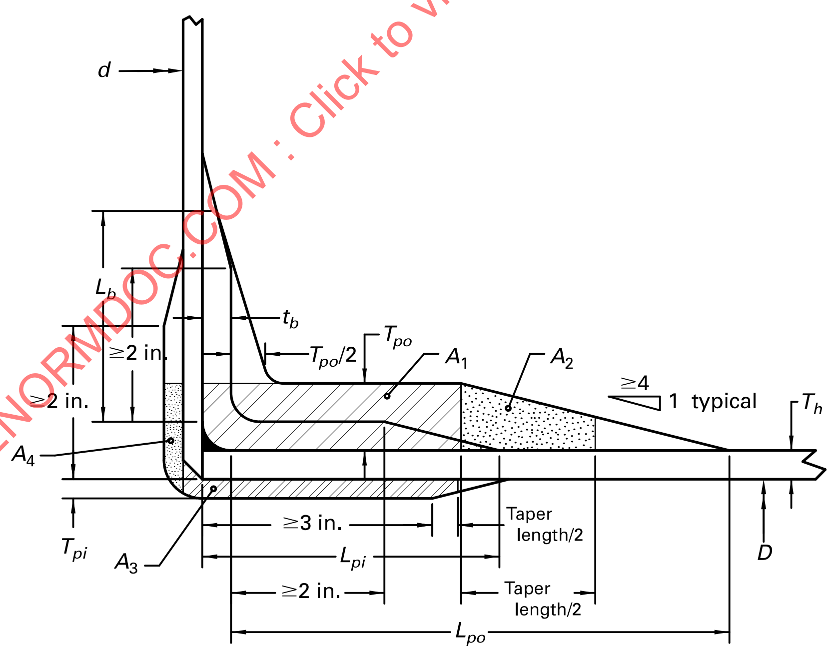
(-c) The minimum thickness of the reinforcement shall not be less than 6 mm (0.25 in.). The reinforcement on the branch pipe shall be applied before the run pipe reinforcement layers are applied or shall be uniformly interspersed with the run pipe reinforcement layers.

2-3.4.2 Branch Connections Using Listed Fittings. It may be assumed, without calculation, that a branch connection has adequate strength to sustain the internal

Figure 2-3.4.1-1 Detail for Fabricated Branch



(a) Reinforcement on Outside Only [Note (1)]



(b) Reinforcement on Inside and Outside [Note (2)]

GENERAL NOTE: Corrosion barrier not shown for clarity.

NOTES:
(1) $A_P = A_1 + A_2$.
(2) $A_P = A_1 + A_2 + A_3 + A_4$.

and external pressures that will be applied to it if it uses a listed fitting (a tee, lateral, or cross) in accordance with para. 2-3.1.

2-3.4.3 Integrally Molded Tee Fittings

(a) The minimum required pressure design structural thickness, t, of the main run and branch regions of a molded tee shall be determined in accordance with eq. (2-3-18):

$$t = m\frac{PD_R}{2S} \quad (2\text{-}3\text{-}18)$$

where

D_R = inside diameter of the main run structural wall, mm (in.)

m = pressure stress multiplier for integral tees = $1.4\lambda_z^{0.25}$

The geometry factor, λ_z, is given by the following equations:

(1) For equal tees, $D_B = D_R$

$$\lambda_z = \frac{D_R}{2t_R} \quad (2\text{-}3\text{-}19)$$

(2) For unequal or reducing tees, $D_B < D_R$

$$\lambda_z = \left(\frac{D_B}{2t_B}\right)^2\left(\frac{2t_R}{D_R}\right) \quad (2\text{-}3\text{-}20)$$

where

D_B = inside diameter of the tee branch structural wall, mm (in.)

t_B = minimum structural thickness of the tee branch, mm (in.); see Figure 2-3.4.3-1

t_R = minimum structural thickness of the main run of the tee, mm (in.); see Figure 2-3.4.3-1

(b) The following general provisions and requirements apply to the design of molded tees:

(1) The design approach is applicable only to molded tees made of Type I or Type II laminates where $D_R \leq 600$ mm (24 in.) and the run and branch regions are integrally formed with continuous laminates. Fabricated tees constructed from separate run and branch pipe joined together shall be qualified in accordance with para. 2-3.4.1 or para. 2-3.9.2, as applicable.

(2) The minimum thickness of the reinforced region at the junction of the run and branch shall not be less than $1.5t_R$. See Figure 2-3.4.3-1.

(3) The length of reinforced thickness of the branch region, L_B, shall be greater than or equal to half of the branch diameter, $0.5D_B$, but shall not be less than 100 mm (4.0 in.).

(4) For $D_B \leq 0.25D_R$, the minimum diameter of the reinforced thickness of the run region shall not be less than $3D_B$ or [D_B + 200 mm (8 in.)], whichever is greater, followed by a minimum length-to-thickness taper of 4:1. See Figure 2-3.4.3-1, illustration (a).

(5) For $D_B > 0.25D_R$, the reinforced thickness of the main run, t_R, shall encompass the entire circumference of the run pipe. The minimum length of the reinforced thickness of the main run shall not be less than ($D_B + D_R$) or [D_B + 200 mm (8 in.)], whichever is greater. See Figure 2-3.4.3-1, illustration (b).

(6) The requirements of para. 2-3.4.3 are intended to achieve sufficient thickness and length of the reinforced regions to manage pressure stresses at the junction of the run and branch. The dimensions of the fitting may need to be increased to allow for joining methods or thickness transitions. Refer to para. 2-3.4.4 for additional design considerations for tees.

2-3.4.4 Additional Design Considerations. The requirements of paras. 2-3.4.1 through 2-3.4.3 are intended to ensure satisfactory performance of a branch connection subjected only to uniform static pressure loading. The designer shall also consider the following:

(a) In addition to static pressure loadings, external forces and moments are applied to a branch connection by dynamic unbalanced pressure, thermal expansion and contraction, dead and live loads, and movement of piping terminals and supports. Branch connections shall be designed to withstand these forces and moments.

(b) Adequate flexibility shall be provided in a small line that branches from a large run, to accommodate thermal expansion and other movements of the larger line.

(c) If ribs, gussets, or clamps are used to stiffen the branch connection, their areas shall not be counted as contributing to the reinforcement areas determined in paras. 2-3.4.1 and 2-3.4.3.

2-3.5 Closures

2-3.5.1 General

(a) Closures not in accordance with para. 2-3.1 or (b) shall be qualified as required by para. 2-3.9.2.

(b) Ellipsoidal (2:1), hemispherical, and torispherical closures with internal pressure on the concave side shall be as calculated in eq. (2-3-21):

$$t_m = t + c \quad (2\text{-}3\text{-}21)$$

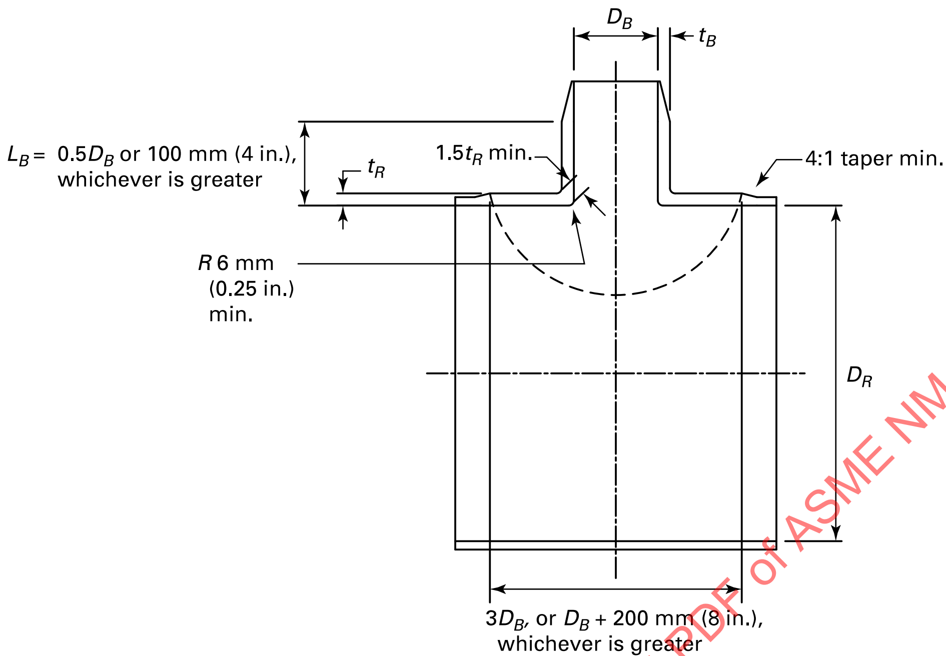
where

c = sum of allowances defined in para. 2-3.2.1, mm (in.)

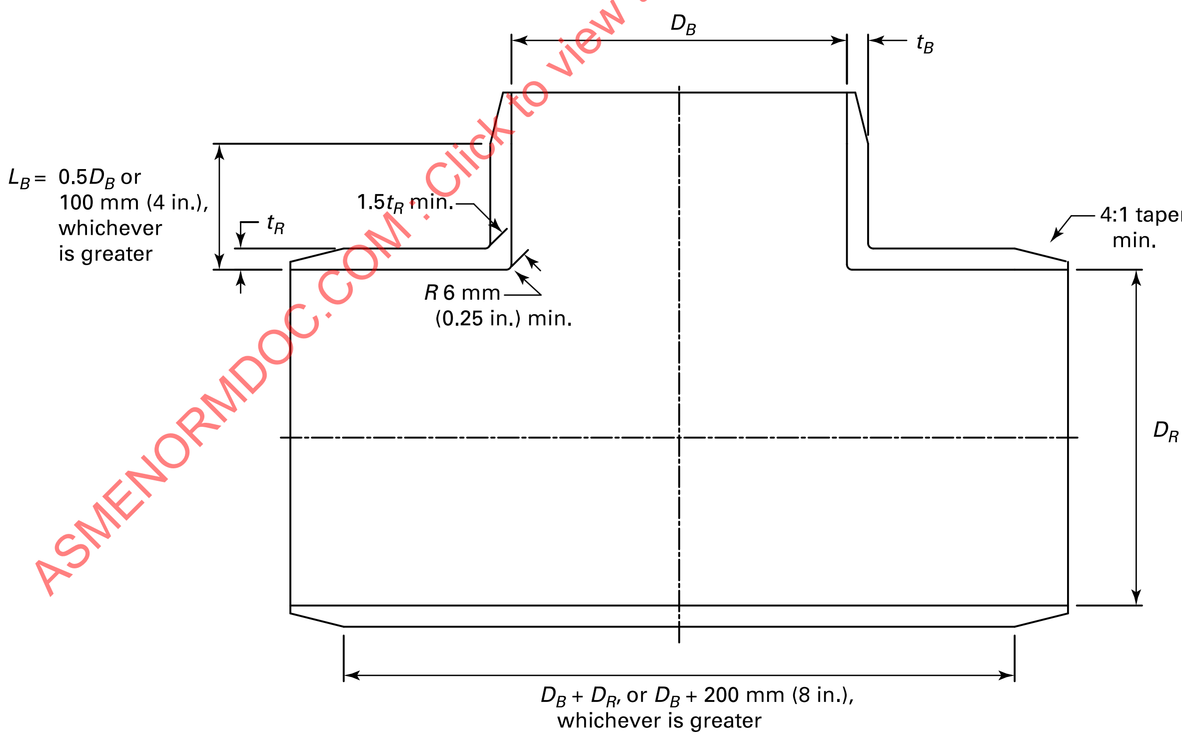
t = pressure design structural thickness, calculated for the type of closure using eq. (2-3-22), (2-3-23), or (2-3-24), mm (in.)

t_m = minimum required thickness, including the corrosion-barrier and mechanical and erosion allowances, mm (in.)

Figure 2-3.4.3-1 Detail for Integrally Molded Tees



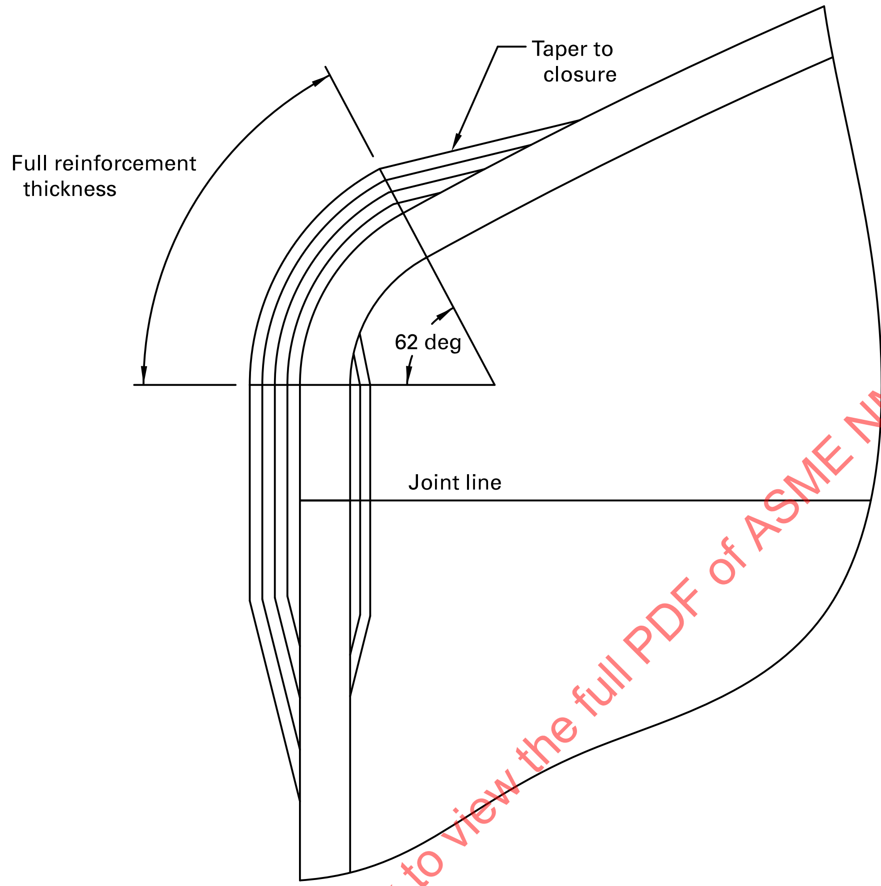
(a) $D_B \leq 0.25D_R$



(b) $D_B > 0.25D_R$

GENERAL NOTE: Corrosion barrier not shown for clarity.

Figure 2-3.5.1-1 Knuckle Reinforcement for Torispherical Closures



(1) For an ellipsoidal (2:1) closure, concave to pressure

$$t = \frac{PD}{2S} \tag{2-3-22}$$

where

D = inside diameter of pipe structural wall, mm (in.)
= $D_i + 2c$
D_i = inside diameter of pipe, mm (in.)
P = internal design gauge pressure, MPa (psi)
S = design stress from applicable table in ASME NM.3.3 or from qualification testing, MPa (psi)

(2) For a hemispherical closure, concave to pressure

$$t = \frac{PR_s}{2S} \tag{2-3-23}$$

where

R_s = inside spherical radius, mm (in.)

(3) For a torispherical closure, concave to pressure

$$t = \frac{MPR_c}{2S} \tag{2-3-24}$$

where

M = $\frac{1}{4}[3 + (R_c/r)^{0.5}]$
r = head knuckle radius, mm (in.); $r \geq 0.06R_c$
R_c = head crown radius, mm (in.); $R_c \leq D$

For torispherical closures, the knuckle radius shall be externally reinforced in accordance with Figure 2-3.5.1-1. The reinforcement thickness shall be equal to the thickness of the closure as calculated in eq. (2-3-24). The thickness of a joint overlay near the knuckle radius tangent line contributes to the knuckle reinforcement.

(c) Joint overlays for connections to closures are subject to the requirements of para. 2-3.8.2.

2-3.5.2 Openings in Closures. A closure is weakened by an opening, and unless the thickness of the closure is sufficiently in excess of that required to sustain pressure, it is necessary to provide added reinforcement.

(a) For openings not larger than one-half the inside diameter of the closure, the amount of reinforcement required shall be determined in accordance with para. 2-3.4.1.

(b) All other openings in closures shall be qualified as required by para. 2-3.9.2.

2-3.6 Flanges

2-3.6.1 General

(a) Flanges not in accordance with para. 2-3.1, para. 2-3.6.2, or (b) shall be qualified as required by para. 2-3.9.2.

(b) Flat-face flanges for use with full-face, flat-ring gaskets shall be designed in accordance with Mandatory Appendix I.

2-3.6.2 Blind Flanges. Blind flanges not in accordance with para. 2-3.1 shall be designed in accordance with eq. (2-3-25). Otherwise, they shall be qualified as required by para. 2-3.9.2.

$$t_m = D_{bc}\sqrt{0.25P/S} + c \qquad (2\text{-}3\text{-}25)$$

where

c = sum of allowances defined in para. 2-3.2.1, mm (in.)

D_{bc} = bolt circle diameter, mm (in.)

P = internal design gauge pressure, MPa (psi)

S = design stress from applicable table in ASME NM.3.3 or from qualification testing, MPa (psi)

t_m = minimum required thickness, including the corrosion-barrier and mechanical and erosion allowances, mm (in.)

2-3.7 Reducers

Reducers not in accordance with para. 2-3.1 shall satisfy the minimum thickness requirements specified for straight pipe in para. 2-3.2 based on the diameter at any corresponding point along the length of the reducer.

2-3.8 Joints

2-3.8.1 General. Joints or joining components, including adhesive joints, not in accordance with para. 2-3.1, para. 2-3.6, or para. 2-3.8.2 shall be qualified as required by para. 2-3.4.2.

(20) **2-3.8.2 Butt Joints**

(a) Joints not in accordance with para. 2-3.1 shall satisfy the minimum thickness requirements specified for straight pipe in para. 2-3.2 using the appropriate design stress, S, and other material properties for the joint laminate type from the applicable table in ASME NM.3.3 or from qualification testing.

(b) In addition to meeting the requirements of (a) for hoop-direction pressure loading, the butt-joint structural thickness shall provide axial-direction strength and stiffness that is no less than that of the components being joined. The minimum structural thickness of the butt-joint laminate, t_j, shall also not be less than that determined by eqs. (2-3-26) and (2-3-27):

$$t_j \geq t_p \frac{E_p}{E_j} \qquad (2\text{-}3\text{-}26)$$

$$t_j \geq t_p \frac{S_p}{S_j} \qquad (2\text{-}3\text{-}27)$$

where

E_j = minimum axial modulus of butt-joint structural wall, MPa (psi)

E_p = maximum axial modulus of pipe structural wall, MPa (psi)

S_j = minimum axial strength of butt-joint structural wall, MPa (psi)

S_p = maximum axial strength of pipe structural wall, MPa (psi). If test data are not available for S_p, it is permissible to use $0.015E_p$. If the pipe and joint are constructed of the same structural laminate type and sequence, S_p may be taken as equal to S_j.

t_j = minimum required structural thickness of the butt-joint laminate, mm (in.)

t_p = minimum required structural thickness of the pipe, mm (in.)

The minimum full thickness joint length per side shall not be less than 50 mm (2.0 in.).

Beyond the full thickness length, the butt-joint laminate shall taper at a minimum length-to-thickness ratio of 6:1 on each side.

The length of the butt-joint overlay shall be sufficient to provide average secondary bond shear strength at least equal to the axial tensile strength of the weaker part. The minimum secondary bond length of the butt-joint laminate on each side of the joint centerline, L_j, shall not be less than that determined by eq. (2-3-28):

$$L_j = t_p \frac{S_p}{S_{ss}} \qquad (2\text{-}3\text{-}28)$$

where

L_j = minimum required joint bond length, per side, mm (in.)

S_{ss} = minimum secondary bond shear strength, MPa (psi). S_{ss} shall not be taken to be greater than 10 MPa (1,500 psi).

No more than 50% of the taper length may be included in the calculations for minimum secondary bond length, L_j.

(c) The following general provisions and requirements apply to the design of butt joints:

(1) For all butt joints for which an inside joint is not accessible, a corrosion-barrier laminate shall be applied before the structural joint.

(2) For all butt joints for which an inside joint is accessible, 30% to 50% of the required joint structural thickness shall be applied as an inside lay-up. A corrosion barrier shall be applied internally, over the inside structural joint. The requirement for an inside corrosion-barrier lay-up is mandatory for butt joints where the pipe diameter is ≥ 600 mm (24 in.).

(3) The requirements of para. 2-3.8.2 are intended to provide adequate performance of butt joints connecting two sections of straight pipe. For butt joints connecting pipe to fittings, or connecting fittings, additional structural thickness or length may be necessary to account for other loadings or to satisfy the system analysis requirements as defined in section 2-4.

2-3.9 Other Components

2-3.9.1 Listed Components. Pressure-containing components manufactured in accordance with specifications in Table 4-1.1-1 but not covered elsewhere in section 2-3 may be used in accordance with para. 2-2.2.1.

2-3.9.2 Unlisted Components. Pressure design of unlisted components and joints to which the requirements elsewhere in section 2-3 do not apply shall be verified by proof testing in accordance with para. 2-2.2.2.

2-4 PIPE STRESS ANALYSIS

2-4.1 Design Considerations

(a) Piping systems shall be designed to function and perform as intended. The piping system design shall prevent expansion or contraction, pressure expansion, or movement of piping supports and terminals, or any other loads from causing

(1) failure of piping or supports from overstrain, point loads, or fatigue

(2) leakage at joints

(3) detrimental stresses or distortion in piping or in connected equipment (e.g., pumps) resulting from excessive thrusts and moments in the piping

(b) Section 2-4 provides guidance, concepts, and data to assist the designer in ensuring adequate flexibility in piping systems. As the behavior of FRP differs considerably from that of metals, care shall be taken to define the specific laminate to be used and the material properties required.

(c) Piping systems should be designed and laid out so that stresses resulting from displacement due to expansion, contraction, and other movement are minimized. This concept requires special attention to supports, terminals, and other restraints, and to the techniques for developing sufficient flexibility outlined in para. 2-4.7. See also para. 2-4.2.2(b).

2-4.2 Concepts and Definition of Pipe Stress Analysis

Concepts of pipe stress analysis are covered in paras. 2-4.2.1 through 2-4.2.3. Special consideration is given to displacements (strains) in the piping system, and to resultant bending and torsional stresses.

2-4.2.1 Displacement Strains. The concepts of strain imposed by restraint of expansion or contraction and by external movement apply in principle to FRP piping. Stresses throughout the piping system may be predicted from these strains as fully elastic behavior is valid within the defined working range of the material.

The piping system should include suitable anchors and guides; the low moduli of the piping materials may enable the system to absorb the displacement strains.

2-4.2.2 Displacement Stresses

(a) Elastic Behavior. Displacement strains will produce a sufficiently wide range of proportional stresses to justify an elastic stress analysis for FRP piping. Fabrication methods and laminate types of pipe and fittings can vary between manufacturers. The designer should understand the construction of components when applying elastic properties for a piping system.

(b) Overstrained Behavior. Strain and displacements shall be controlled by system layout, proper support, special joints, and/or expansion devices (see para. 2-4.7).

2-4.2.3 Cold Spring. Cold spring is the intentional deformation of piping during assembly to produce a desired initial displacement and stress. Cold spring is beneficial in that it serves to balance the magnitude of stress under initial and extreme displacement conditions.

Cold spring is an acceptable means of controlling thermal loads and displacements in FRP systems. However, special consideration should be given to the design and system layout when cold spring is present, including loads on connections. Consideration should be given to the effects of construction methods and environmental conditions on the accuracy of cold-spring design. Cold spring shall not be used for alignment of the piping system during construction.

2-4.3 Properties for Pipe Stress Analysis

Paragraphs 2-4.3.1 through 2-4.3.5 deal with properties of FRP piping materials and their application in piping stress analysis.

2-4.3.1 Thermal Expansion Data. ASME NM.3.3 lists coefficients of thermal expansion for FRP materials. More precise values in some instances may be obtained from manufacturers of components. If these values are to be used in stress analysis, the thermal displacements shall be determined as stated in para. 2-4.4.

2-4.3.2 Modulus of Elasticity. ASME NM.3.3 lists representative data on the tensile and flexural modulus of elasticity, *E*, in the hoop and axial directions for the defined FRP laminate types as obtained under typical laboratory rate of strain (loading) conditions. More precise values of the short-term and working estimates of effective moduli of elasticity for given conditions of loading and temperature may be obtained from the manufacturer. The modulus can also vary with the fiber content and orientation and type of resin. Additionally, the modulus can vary with the orientation of the specimen during testing, especially for laminates with filament-wound reinforcement.

2-4.3.3 Poisson's Ratio. The Poisson's ratio for FRP pipe and fittings can vary depending on a number of factors, including type of resin, fiber content, orientation of the fiber reinforcement material, and temperature. For that reason, simplified formulas used in stress analysis for metals are not generally valid for FRP. More precise values in some instances may be obtained from component manufacturers. Values for standard materials are listed in ASME NM.3.3.

2-4.3.4 Allowable Stresses. FRP is an orthotropic material with properties that are not necessarily the same in the axial and hoop directions. However, Type I and Type II FRP laminates are considered quasi-isotropic materials, since they typically have the same properties in the hoop and axial directions. Proper analysis of FRP piping shall account for differences in material properties.

(a) The analysis approach herein uses allowable stress envelopes, which relate the allowable axial stress to the applied hoop stress.

(b) See ASME NM.3.3 for allowable stresses of listed laminate types for use with Design Method A (see para. 2-2.3.2).

2-4.3.5 Dimensions. Nominal thicknesses and outside diameters of pipe and fittings shall be used in pipe stress analysis calculations. Corrosion barrier shall be included for weight and thermal considerations although it is not considered a structural component.

2-4.4 Analysis

(20) **2-4.4.1 Analysis Not Required.** No formal analysis is required for a piping system that meets any of the following conditions:

(a) The piping system duplicates or replaces, without change to materials, method of construction, system arrangement, and operating conditions, a system operating with a successful service record.

(b) The piping system is nearly identical in system arrangement, piping materials, and operating conditions to an existing system that can readily be judged adequate by comparison with previously analyzed systems.

(c) The piping system is laid out with an inherent flexibility that can be judged adequate for the given design conditions, or uses joining methods or expansion joint devices, or a combination of these methods, that are intended to absorb the majority of thermal displacement throughout the piping system and are selected and installed in accordance with manufacturer's instructions. As FRP piping has a lower stiffness than metallic piping, expansion joints with lower spring rates for ease of activation shall be selected.

2-4.4.2 Methods of Analysis. For a piping system that does not meet the criteria of para. 2-4.4.1, the designer shall demonstrate that the piping system is adequate for the service by simplified, approximate, or comprehensive piping system analysis, using a method that can be shown to be valid for the specific case. Any analysis shall consider the effects of all sustained loads (weight, pressure, etc.) with and without thermal effects, and occasional loads (wind, seismic, etc.). (20)

(a) Simplified. The simplified analysis should include consideration of the piping system's flexibility and thermal displacement. The analysis may be based on table or chart data, such as for spans between supports or cantilevered transitions. The analysis should determine the minimum number of anchor points needed to ensure system stability. A free-floating, anchor-free system shall not be used. The simplified analysis should also determine a regular occurrence of guide restraint to ensure reasonable lateral support and stability. A piping system suitable for a simplified analysis is characterized by the following features:

(1) The piping system displays reasonable flexibility with areas of isolated restraint, which would lead to a pure compressive stress condition between rigid restraints, anchors, or terminal points.

(2) There is limited opportunity for thermal displacement, i.e., the differential temperature is less than 40°C (75°F) between the installation temperature and the minimum or maximum exposure temperature.

(b) Approximate. A piping system that is suitable for an approximate evaluation is characterized by the following features:

(1) There is a significant differential temperature between the installation temperature and the minimum or maximum exposure temperature.

(2) The piping system complies with either of the following:

(-a) The piping system is substantially restrained by periodic rigid anchors that maintain the straight lengths of piping in a pure tensile or compressive stress condition between anchor points, isolating terminal points and changes in direction from excessive strain.

(-b) The piping system includes flexible joints or other displacement-absorbing devices that are located in a manner to ensure a minimized stress state in the piping system. Where flexible joints and displacement-absorbing devices are implemented, sufficient anchor and guide supports shall be incorporated to ensure that the piping movement is directed into the flexible joint.

(c) Comprehensive. A comprehensive piping system analysis shall be performed using a formal pipe stress analysis program. The comprehensive piping system analysis shall include the following elements:

(1) an accurate model of the piping system routing and all components, including weights and dimensions.

(2) actual orthotropic material properties that concisely represent the specified piping materials and construction, including resin type, wind angle, and glass content. Material properties may be based on historical test data or calculated properties.

(3) stress intensification factors and flexibility factors based on tested data or calculated values.

(4) estimated stiffness of pipe supports and supporting structures.

(5) estimated stiffness of terminal points and connecting equipment. Results shall be carefully evaluated to verify that they are realistic for the FRP system.

(6) an evaluation of all design conditions, including occasional loading and transient events, if known.

Allowable stresses values shall be based on the methods defined in para. 2-2.3.

2-4.4.3 Basic Assumptions and Requirements. The designer shall treat the piping system as a whole. The designer shall recognize the significance of all parts of the line and of all restraints introduced to reduce moments and forces on equipment or small branch lines, and the restraint introduced by support friction.

(20) **2-4.4.4 Pipe Stress Analysis Requirements**

(a) Hoop Stress. For each load case, the applied hoop stress, S_H, shall be calculated using eq. (2-4-1):

$$S_H = \sqrt{\left[\frac{mPD_m}{2T_s} + \frac{\sqrt{(i_{ih}M_i)^2 + (i_{oh}M_o)^2}}{Z_s}\right]^2 + \left(\frac{i_tM_t}{Z_s}\right)^2} \tag{2-4-1}$$

where

D_m = mean diameter of component, mm (in.)
= $D_o - T_S$

D_o = outside diameter of component, mm (in.)

i_{ih} = stress intensification factor, hoop stress due to in-plane moment (see Mandatory Appendix III)

i_{oh} = stress intensification factor, hoop stress due to out-of-plane moment (see Mandatory Appendix III)

i_t = torsional stress intensification factor (see Mandatory Appendix III)

m = pressure stress multiplier (see Mandatory Appendix III)

M_i = in-plane moment, N·mm (in.-lb)

M_o = out-of-plane moment, N·mm (in.-lb)

M_t = torsional moment, N·mm (in.-lb)

P = pressure, MPa (psi)

T_L = corrosion barrier thickness, mm (in.)

T_N = nominal thickness of component, mm (in.)
= $T_S + T_L$

T_S = structural wall thickness of component, mm (in.)
= $T_N - T_L$

Z_S = section modulus, mm^3 (in.^{3})
= $\pi[(D_o^4 - (D_o - 2T_S)^4]/32D_o$

(b) Longitudinal Stress (Axial Tensile Stress). For each load case, the applied longitudinal stress (axial stress), S_A, shall be calculated using eq. (2-4-2a), eq. (2-4-2b), eq. (2-4-3a), or eq. (2-4-3b), as applicable.

(1) For All Piping Systems Other Than Restrained Piping Systems

(-a) For $\dfrac{PD_{is}^2}{D_o^2 - D_{is}^2} + \dfrac{F_{ax}}{A_s} \geq 0$

$$S_A = \sqrt{\left[\frac{PD_{is}^2}{D_o^2 - D_{is}^2} + \frac{F_{ax}}{A_s} + \frac{\sqrt{(i_iM_i)^2+(i_oM_o)^2}}{Z_s}\right]^2 + \left(\frac{i_tM_t}{Z_s}\right)^2} \tag{2-4-2a}$$

(-b) For $\dfrac{PD_{is}^2}{D_o^2 - D_{is}^2} + \dfrac{F_{ax}}{A_s} < 0$

$$S_A = -\sqrt{\left[\frac{PD_{is}^2}{D_o^2 - D_{is}^2} + \frac{F_{ax}}{A_s} - \frac{\sqrt{(i_iM_i)^2+(i_oM_o)^2}}{Z_s}\right]^2 + \left(\frac{i_tM_t}{Z_s}\right)^2} \tag{2-4-2b}$$

where

A_s = area, mm^2 (in.^{2})
= $\pi[D_o^2 - D_{is}^2]/4$

D_{is} = inside diameter of structural wall, mm (in.)
= $D_o - 2T_S$

F_{ax} = axial force (excluding pressure), N (lb)

i_i = stress intensification factor, axial stress due to in-plane moment (see Mandatory Appendix III)

i_o = stress intensification factor, axial stress due to out-of-plane moment (see Mandatory Appendix III)

(2) For Restrained Piping Systems

(-a) For $\nu_{hl}\frac{E_a}{E_h} \times \frac{PD_m}{2T_s} + \frac{F_{ax}}{A_s} \geq 0$

$$S_A = \sqrt{\left[\nu_{hl}\frac{E_a}{E_h}\times\frac{PD_m}{2T_s} + \frac{F_{ax}}{A_s} + \frac{\sqrt{(i_iM_i)^2 + (i_oM_o)^2}}{Z_s}\right]^2 + \left(\frac{i_tM_t}{Z_s}\right)^2} \quad (2\text{-}4\text{-}3a)$$

(-b) For $\nu_{hl}\frac{E_a}{E_h} \times \frac{PD_m}{2T_s} + \frac{F_{ax}}{A_s} < 0$

$$S_A = -\sqrt{\left[\nu_{hl}\frac{E_a}{E_h}\times\frac{PD_m}{2T_s} + \frac{F_{ax}}{A_s} - \frac{\sqrt{(i_iM_i)^2 + (i_oM_o)^2}}{Z_s}\right]^2 + \left(\frac{i_tM_t}{Z_s}\right)^2} \quad (2\text{-}4\text{-}3b)$$

where

E_a = axial modulus of elasticity, MPa (psi)

E_h = hoop modulus of elasticity, MPa (psi)

ν_{hl} = Poisson's ratio for hoop stress causing longitudinal strain

Internal pressure produces tensile stress in a restrained piping system and therefore reduces the compressive axial stress when there are positive changes in temperature. The possibility of low pressure during such load cases shall be considered.

Restrained piping systems shall also be checked for column-type buckling in accordance with Nonmandatory Appendix A.

(c) Stresses Due to Sustained Loads. The stresses due to sustained loads such as pressure and weight shall meet the following criteria:

$$S_H \leq k_1 S_{H\max}$$
$$S_A \leq k_1 S_{A\text{allow}}$$

where

k_1 = 1.0 for sustained loads excluding the effects of displacement loads such as those induced by thermal displacement

= 1.1 for sustained loads including the effects of displacement loads such as those induced by thermal displacement and settlement

$S_{A\text{allow}}$ = allowable longitudinal stress, MPa (psi). The allowable longitudinal stress depends on the magnitude of the applied hoop stress, S_H (see para. 2-2.3).

$S_{H\max}$ = maximum allowable hoop stress (see para. 2-2.3), MPa (psi)

(d) Stresses Due to Occasional Loads. The total stress due to sustained loads and occasional loads such as wind or seismic shall meet the following criteria:

$$S_H \leq k_2 S_{H\max}$$
$$S_A \leq k_2 S_{A\text{allow}}$$

where

k_2 = 1.20 for occasional loads acting for no more than 8 h at any one time and no more than 800 h/yr

= 1.33 for occasional loads acting for no more than 1 h at any one time and no more than 80 h/yr

= 1.33 for pressure testing and leak testing loads

It is not necessary to consider wind loads, seismic loads, or testing loads as acting concurrently.

(e) Displacement Stresses. Stresses due to displacement strains such as those induced by thermal displacement shall be calculated using the modulus of elasticity at ambient temperature or the modulus of elasticity at design temperature, whichever is higher.

(f) Thermal Displacement. Thermal expansion shall be calculated using the maximum exposure temperature and the minimum expected installation temperature. Thermal contraction shall be calculated using the minimum exposure temperature and the maximum expected installation temperature.

(g) Elongation Due to Pressure. Elongation of the piping due to pressure shall be considered in the analysis. The strain due to pressure elongation shall be calculated using eq. (2-4-4):

$$\varepsilon_l = \frac{S_{Ap}}{E_l} - \nu_{hl}\frac{PD_m}{2T_S E_h} \quad (2\text{-}4\text{-}4)$$

where

E_h = hoop modulus of elasticity, MPa (psi)

E_l = longitudinal (axial) modulus of elasticity, MPa (psi)

S_{Ap} = longitudinal (axial) stress due to pressure, MPa (psi)

ε_l = longitudinal (axial) strain due to pressure

ν_{hl} = Poisson's ratio for hoop stress causing longitudinal strain

2-4.5 Reactions (20)

Reaction forces and moments are used in design of restraints and supports for a piping system, and in evaluation of the effects of piping displacements on connected equipment. See para. 2-4.4.2 for analysis methods to determine reactions.

Where dynamic loads are identified, the piping shall be evaluated for those defined loads. Dynamic reactions due to pumps or valve actions should be evaluated. Proper restraints shall be added if required by stress analysis.

2-4.6 Movements

Special attention shall be given to movement (displacement or rotation) of piping with respect to supports and points of close clearance. Movements of the run pipe at the junction of a small branch connection shall be considered in determining the need for flexibility in the branch pipe. Large axial movements into a joined fitting can cause the pipe to peel when it is exposed to large displacements. Torsional movements should be evaluated.

2-4.7 Means of Increasing Flexibility

Piping layout often provides adequate inherent flexibility through changes in direction, wherein displacements produce chiefly bending and torsional strains of low magnitude. The amount of tension or compression strain (which can produce larger reactions) usually is small. However, due to FRP piping's large coefficient of expansion, large displacements are possible.

Where piping lacks inherent flexibility or is unbalanced, additional flexibility may be provided by one or more of the following means: elbows, loops, or offsets; flexible joints; bellows expansion joints; or other devices permitting angular, rotational, or axial movement. Suitable anchors, ties, or other devices shall be provided as necessary to resist end forces produced by fluid pressure, frictional resistance to movement, and other causes.

2-5 PIPING SUPPORT

(20) 2-5.1 General

The design of supporting structures (not covered by this Standard) and of pipe-supporting elements shall be based on all concurrently acting loads transmitted into such supports. These loads, defined in section 2-1, include weight effects and loads introduced by service pressures and temperatures, vibration, wind, earthquake, shock, and displacement strain (see para. 2-4.2.1).

The weight of liquid may be excluded from the weight calculations for piping containing gas or vapor if the designer has taken specific precautions to prevent liquid from entering the piping, and if the piping is not to be subjected to hydrostatic testing at initial construction or subsequent inspections.

2-5.1.1 Layout Considerations

(a) The layout and design of piping and its supporting elements shall be directed toward preventing the following:

(1) piping stresses in excess of those permitted in this Standard

(2) leakage at joints

(3) excessive thrusts and moments on connected equipment (such as pumps and turbines)

(4) excessive stresses in the supporting (or restraining) elements

(5) resonance with imposed or fluid-induced vibrations

(6) excessive interference with thermal expansion and contraction in piping that is otherwise adequately flexible

(7) unintentional disengagement of piping from its supports

(8) excessive distortion or sag of piping

(9) excessive deflection of pipe-supporting elements

(b) Piping shall be supported, guided, and anchored in such a manner as to prevent damage to the piping. Point loads and narrow areas of contact between piping and supports shall be avoided. Suitable padding shall be placed between piping and supports where damage to piping may occur.

(c) Valves and equipment that may transmit excessive loads to the piping shall be independently supported to prevent such loads. The effects from the weight of automated actuators at valves and other in-line components and from the cantilever moments created by the actuators shall be evaluated in the piping and support system design. The actuators shall be independently supported as needed.

(d) Piping manufacturer's recommendations for support should be considered.

(e) Pipe-supporting elements shall be designed to accommodate the expected pipe movement at supporting structures.

(f) Where there are long runs, the low modulus of the material may be sufficient to accommodate axial expansion, thus eliminating the need for expansion joints.

(g) FRP pipe shall not be used to support other piping unless agreed to by the owner.

(h) FRP piping should be adequately supported to ensure that the attachment of hoses at locations such as utility or loading stations does not result in the pipe being pulled in a manner that could overstress the material.

(i) Where grounding of the pipeline is required, additional design may be needed to provide a proper path to earth.

2-5.1.2 Analysis of Pipe Support Elements. In general, the location and design of pipe-supporting elements may be based on simple calculations and engineering judgment. However, when a more refined analysis is required and a piping analysis, which may include support stiffness, is performed, the stresses, moments, and reactions determined thereby shall be used in the design of supporting elements.

2-5.2 Allowable Stress Values for Metallic Pipe Support Elements

(a) Allowable stress values tabulated in MSS SP-58 may be used for the base metallic materials of all parts of pipe-supporting elements.

(b) If allowable stress values for a metallic material specification are not listed in MSS SP-58, allowable stress values from ASME BPVC, Section II, Part D, Tables 1A and 1B may be used, provided allowable stress values in shear shall not exceed 80% of the values listed and shall not exceed 160% of the values listed in bearing. If there are no stress values given in BPVC Section II, Part D, Tables 1A and 1B, an allowable stress value of 25% of the minimum tensile strength given in the material specification may be used.

(c) For a steel material of unknown specification, or of a specification not listed in MSS SP-58, an allowable stress value of 30% of yield strength (0.2% offset) at room temperature may be used. The yield strength shall be determined through a tensile test of a specimen of the material and shall be the value corresponding to 0.2% permanent strain (offset) of the specimen. The allowable stress values for such materials shall not exceed 65.5 MPa (9,500 psi).

2-5.3 Materials

(a) Permanent supports and restraints shall be of material suitable for the service conditions. If steel is cold-formed to a centerline radius less than twice its thickness, it shall be annealed or normalized after forming.

(b) Ductile and malleable iron may be used for pipe and beam clamps, hanger flanges, clips, brackets, and swivel rings.

(c) Wood or other materials may be used for pipe-supporting elements, provided the supporting element is properly designed, with consideration given to its strength, durability, and suitability for the intended environment.

(d) Attachments bonded to the piping shall be of a material compatible with the piping and service. For other requirements, see para. 2-5.6.2.

2-5.4 Threads

Screw threads shall conform to ASME B1.1 unless other threads are required for adjustment under heavy loads. Turnbuckles and adjusting nuts shall have the full length of internal threads engaged. Any threaded adjustment shall be provided with a locknut, unless locked by other means.

2-5.5 Fixtures

2-5.5.1 Anchors and Guides

(a) A supporting element used as an anchor shall be designed to maintain an essentially fixed position.

(b) To protect terminal equipment or other (weaker) portions of the system, restraints (such as anchors and guides) shall be provided where necessary to control movement or to direct expansion into those portions of the system that are designed to absorb them. The design, arrangement, and location of restraints shall ensure that expansion joint movements occur in the directions for which the joint is designed. In addition to the other thermal forces and moments, the effects of friction in other supports of the system shall be considered in the design of such anchors and guides.

(c) If expansion joints exist in the piping system, the designer shall consider the effects of pressure thrusts on anchors and guides.

2-5.5.2 Inextensible Supports Other Than Anchors and Guides

(a) Supporting elements shall be designed to permit the free movement of piping caused by expansion and contraction.

(b) Hangers include pipe and beam clamps, clips, brackets, rods, straps, chains, and other devices. They shall be proportioned for all required loads. Safe loads for threaded parts shall be based on the root area of the threads.

(c) Sliding supports (or shoes) and brackets shall be designed to resist the forces caused by friction in addition to the loads imposed by bearing. The dimensions of the support shall provide for the expected movement of the supported piping.

2-5.5.3 Springs

(a) Spring supports shall be designed to exert a supporting force, at the point of attachment to the pipe, equal to the load as determined by weight balance calculations. They shall be provided with means to prevent misalignment, buckling, or eccentric loading of the springs, and to prevent unintentional disengagement of the load.

(b) The designer shall consider the variation of load from empty to full fluid conditions. Means shall be provided to prevent overstressing by the spring supports due to excessive deflections. It is recommended that all spring supports be provided with limit stops to prevent overstressing the pipe in its empty condition.

2-5.5.4 Hydraulic Supports. A hydraulic cylinder may be used to give a constant supporting force. Safety devices and stops shall be provided to support the load in case of hydraulic failure.

2-5.6 Structural Attachments

External and internal attachments to piping shall be designed so that they will not cause undue flattening of the pipe, excessive localized bending stresses, or harmful thermal gradients in the pipe wall. It is important that attachments be designed to minimize stress concentration, particularly in cyclic services.

2-5.6.1 Nonintegral Attachments. Nonintegral attachments, in which the reaction between the piping and the attachment is by contact, include clamps, slings, cradles, U-bolts, saddles, straps, and clevises. All metal attachments to the pipe shall be cushioned with an elastomeric liner. If the weight of a vertical pipe is supported by a clamp, the clamp shall be located below a flange, a fitting, or shear collars bonded to the pipe.

2-5.6.2 Integral Attachments. Integral attachments, such as anchors, lugs, shoes, shear collars, and stanchions, are components that are bonded to the piping. Integral attachments shall be of a compatible material [see para. 2-5.3(d) for material requirements]. Consideration shall be given to the localized stresses induced in the piping component by bonding the integral attachment, and to the differential thermal displacement strains between the attachment and the component to which it is attached.

Intermediate pads, integral reinforcement, complete encirclement reinforcement, or other means of reinforcement bonded or built up on the piping may be used to distribute stresses.

2-5.7 Structural Connections

The load from piping and pipe-supporting elements (including restraints and braces) shall be suitably transmitted to a pressure vessel, building, platform, support structure, or foundation, or to other piping capable of bearing the load without deleterious effects.

2-5.8 Support Spacing

Supports shall be spaced to avoid excessive sag or deformation at the design temperature and within the design life of the piping system. Reduction in the modulus of elasticity with increasing temperature and creep of material with time shall be considered, when applicable. The coefficient of thermal expansion shall be considered in the design and location of supports. See Nonmandatory Appendix A.

2-5.9 Pipe-Support Contact Surface

(20) **2-5.9.1 General**

(a) Supports in all cases should have sufficient axial length to support the piping without causing significant localized stress and should be lined with an elastomer or other suitable soft material. The minimum saddle axial length should be the greater of one nominal pipe diameter or 75 mm (3 in.) unless another axial length is justified by analysis. Large loads shall be addressed on a case-by-case basis for design of saddle length along the axis of the pipe.

(b) Clamping forces, where applied, shall not cause significant localized stress. Manufacturing tolerances for the outer diameter should be provided by the pipe manufacturer. All clamps shall have an elastomeric liner to protect the pipe.

(c) Supports should be located on straight pipe sections rather than at fittings or joints.

2-5.9.2 Supports Permitting Pipe Movement. Any support that allows movement inside the support shall have wear protection for the pipe in the form of saddles, wear-resistant materials, or sheet metal.

2-5.9.3 Anchors and Axial Stops. The anchor and axial stops shall be capable of transferring the required axial loads to the pipe without causing overstress of the FRP pipe material. Shear collars shall be placed on one or both sides of 360-deg anchor clamps as required; the shear collar shall be equal in thickness to the outer diameter of the clamp and long enough to develop shear strength to resist the anchor load.

2-6 SPECIAL CRITERIA

Section 2-6 provides requirements, guidance, and recommendations for specific service conditions.

2-6.1 Chemical Environment and Erosive Services

2-6.1.1 Chemical Environment. The following considerations shall be given to the effect of the chemical environment on the piping material:

(a) The FRP pipe materials shall be suitable for and compatible with the specific application.

(b) The FRP pipe material suppliers should be consulted about the selection of materials.

(c) A wide body of knowledge in the form of both test results and actual case histories is available for the performance of specific materials in many chemical environments.

(d) If the chemical environment is known to degrade the integrity of the piping materials over the life of the piping system, additional consideration shall be given to enhancing the construction of the liner and increasing the design factors of the piping.

2-6.1.2 Erosive Services. For services in which erosive fluids come in contact with internal or external surfaces of the pipe, consideration shall be given to enhancing the erosion resistance of the corrosion/erosion barrier by

(a) using alternative surfacing veils

(b) adding erosion-resistant fillers, such as silicon carbide, to the resin

(c) increasing the thickness of the liner

(d) reducing fluid velocities by increasing diameter and/or utilizing longer radius fittings for directional changes and angled fittings for intersections

2-6.2 Compressed Gas Services

2-6.2.1 Limitations of Use

(a) FRP piping should not be used in compressed gas services with a design pressure greater than 100 kPa (15 psig).

(b) For applications with a design pressure greater than 100 kPa (15 psig), special consideration shall be given to the risks associated with the release of process fluid and stored energy, including the potential for injury from fragments, shock waves, or other consequences due to pressurized system failure.

2-6.2.2 Pneumatic Testing

(a) Pneumatic testing shall be performed only when one of the following conditions exists:

(1) Piping systems are to be used in services in which traces of the testing medium cannot be tolerated.

(2) Liquids from a hydrostatic test could damage linings within the pipe.

(3) Piping systems or supporting structures are so designed that the pipe cannot be filled with water.

(b) The test pressure and holding time shall be the same as the minimum requirements for hydrostatic testing defined in section 6-3.

(c) A risk assessment and appropriate pneumatic test procedure shall be developed based on criteria outlined in ASME PCC-2, Article 501.

2-6.3 Buried Piping

Design and installation of buried FRP pipe is well documented in AWWA M45 and in piping manufacturer literature. It is not the intent of this section to provide details or step-by-step design and installation procedures but rather to provide a high-level overview of what is required, identify some potential pitfalls, and provide acceptable references for the design and installation of underground FRP piping.

2-6.3.1 Design

(a) The designer should consult AWWA M45, Chapter 5, for the design of buried FRP pipe. The design of buried pipe shall account for

(1) external earth loads

(2) vehicular traffic loads designated by the American Association of State Highway and Transportation Officials (AASHTO)[6] as axle loads HS-20 or HS-25, or similar vehicular loads designated by other applicable standards

(3) buoyant loads from high water table or local flooding

(4) surge pressures from operation

(5) internal pressure

(6) frost line

(7) thermal expansion

(8) vacuum condition

(9) differential settlement

(b) Required information for proper design involves knowledge of the native earth in which the pipe will be installed. ASTM D2487 may be used to classify the soil types for design purposes.

(c) The design approach in AWWA M45 uses the HDB of the pipe.

(1) For FRP pipe for which an HDB has not been established, buried pipe design shall take into account a maximum strain or stress for the design conditions being considered.

(2) The AWWA M45 equations shall be modified to meet the criteria for the strain- or stress-limiting design.

(d) Strain or stress limits, along with deflection limits, shall be agreed upon between the supplier and the end user.

(1) For corrosive applications, the strain of the liner can be the limiting factor for overall design.

(2) Each load case shall be clearly identified as occasional load or sustained load.

(e) When butt and strap jointing is used for assembly of underground FRP piping, thrust blocks may not be required.

(1) Thrust blocks or anchors may be used at connections to sumps, valves, or other control devices.

(2) Underground piping connections to valves should incorporate provisions to allow for maintenance and gasket replacement.

(f) A stress analysis of the buried piping system shall be performed to demonstrate that the design strain or stress levels are not exceeded.

(1) The stress analysis should be used to determine which areas of the piping require additional reinforcement to address high stresses, such as those near branch connections, tees, and elbows.

(2) If the stress analysis determines that additional flexibility is required at branch connections, the pipe may be wrapped with compressible material.

(3) Flanged connections should not be used except in valve pits where they can be inspected and serviced as needed. Flanged connections may require a more robust design due to the bending and axial loads that are applied to the flanges. Analysis of these loads on the flanges may be undertaken using the equivalent pressure analysis method or an alternative analysis methodology.

2-6.3.2 Installation. The designer should refer to AWWA M45, Chapter 6, for information on buried FRP pipe. The following installation requirements shall be considered to ensure successful performance of the piping system:

(a) The bedding, embedment, compaction, and backfill used in installation shall comply with that used for the design and analysis.

(b) A detailed outline of the requirements for foundation, haunches, embedment, and final backfill shall be provided and followed.

[6] American Association of State and Highway Transportation Officials (AASHTO), 444 North Capitol Street N.W., Suite 249, Washington, DC 20001 (www.transportation.org)

(c) During installation, personnel shall inspect the site to confirm trench condition, haunch condition, compaction, and installed-pipe deflection. The parties responsible for the installation shall maintain a written record of the inspections and the findings.

(d) Underground joints not pressure tested prior to installation shall remain visible until after they have been hydrotested, and shall be examined during the test.

(1) Long sections of pipe without joints may need to be buried to secure the pipeline and prevent it from moving during hydrotesting.

(2) The hydrotest procedure shall address the provisions described in (1).

(e) Caution shall be exercised when installing underground pipe and when open trenches are present during rainstorms.

NOTE: During rainstorms, the trenches can fill up and the empty pipe can lift out of the trenches, potentially damaging the pipe and surrounding equipment.

(f) All trenching activities shall follow safe excavation procedures to prevent collapse and maintain worker safety.

(1) Environmental conditions shall be considered when laying and joining pipe.

(2) Procedures outlined in AWWA M45 shall be followed to prevent damage to pipe during installation.

(g) A tracer wire on the top of the FRP pipe should be installed prior to final burial.

NOTE: The tracer wire will aid in locating the pipes at a later date and can help prevent damage to the pipe by external probes that might otherwise be required to locate the pipe.

(h) Where FRP pipe penetrates concrete valve boxes or sumps, the pipe should be anchored using a water stop or other suitable method.

(i) Consideration should be given to fitting structural sleeves around buried pipes installed under roadways, railways, and areas that are difficult access.

Chapter 3
Constituent Materials

3-1 GENERAL

Chapter 3 states limitations and required qualifications for constituent materials based on their inherent properties. Their use in piping shall be subject to requirements and limitations in other parts of this Standard.

3-2 MATERIALS AND SPECIFICATIONS

3-2.1 Listed Constituent Materials

Listed constituent materials are shown in Table 3-2.1-1. Quality assurance procedures related to these constituent raw materials may be found in Mandatory Appendices V and VI.

3-2.2 Unlisted Constituent Materials

Constituent materials not listed in Table 3-2.1-1 may be used provided they conform to a published specification covering chemistry, physical and mechanical properties, and quality control, and otherwise meet the requirements of this Standard.

3-2.3 Unknown Constituent Materials

Materials of unknown specification shall not be used for pressure-piping components.

3-2.4 Constituent Material Changes

(a) General

(1) Changes to constituent materials, procedures, and processing-aid materials used in the manufacturing of component products shall not require complete requalification as long as they are "replacement in kind."

(2) To qualify a material or procedure as a replacement in kind, the manufacturer shall show that the replacement is identical to the original in form, fit, and function and that it satisfies the design requirements.

(b) Substitution of Constituent Materials

(1) Substitution of constituent materials shall require verification by the manufacturer, to the satisfaction of the designer and the owner, that the alternative constituent material is a replacement in kind and functionally equivalent to the constituent materials on which the original design was based.

(2) A functionally equivalent determination shall require the following:

(-a) Fitness for Use. The constituent material shall be deemed suitable for use via testing or experience, or judged acceptable by a qualified individual.

(-b) Constituent Material Supplier Data. Constituent (cured) physical property data shall be at least 90% of the original constituent material data.

(-c) Verification. A functionally equivalent determination shall be verified by a short-term test (e.g., ASTM D1599) using a construction identical to the construction originally built to verify component properties. The resulting values shall be at least 90% of those originally determined.

(-d) Record Keeping. The manufacturer shall maintain records substantiating the substitution of constituent materials.

Table 3-2.1-1 Listed Constituent Materials

Constituent Material	Quality Assurance Appendix Reference
E or E–CR glass	See Mandatory Appendix V
Unsaturated polyester resins	See Mandatory Appendix VI
Vinyl ester resins	See Mandatory Appendix VI

3-3 TEMPERATURE LIMITATIONS

The designer shall verify that materials meeting all other requirements of this Standard are suitable for service throughout the design temperature range, the operating temperature range, and any anticipated temperature excursions.

3-3.1 General

(a) Listed Materials

(1) Upper and lower temperature limits for listed materials are provided in Table 3-3.1-1 and detailed in para. 3-3.2.

(2) Listed materials whose temperature limits lie outside those in Table 3-3.1-1 may be used, provided all of the following conditions are satisfied:

(-a) Test results shall be provided showing that the physical and mechanical properties meet or exceed the design requirements.

Table 3-3.1-1 Temperature Limits for Acceptable Polymeric Materials

Polymeric Material [Note (1)]	Temperature Limits	
	Lower	Upper [Note (2)]
Unsaturated polyester resin (polymer) system	−40°C (−40°F)	$G'T_g$ − 17°C (30°F) or HDT − 17°C (30°F)
Vinyl ester resin (polymer) system	−40°C (−40°F)	$G'T_g$ − 17°C (30°F) or HDT − 17°C (30°F)
Epoxy resin (polymer) system (amine or anhydride)	−40°C (−40°F)	$G'T_g$ − 22°C (40°F) or HDT − 22°C (40°F)

GENERAL NOTE: The requirements in this Table are in addition to the requirements of the applicable material specification.

NOTES:
(1) See para. 3-3.2 for limitations on resin systems.
(2) See para. 3-3.2 for definitions of $G'T_g$ and HDT, and para. 3-3.3 for determination of $G'T_g$ and HDT.

(-b) The use of such materials is not prohibited elsewhere in this Standard.

(-c) The user's acceptance of the material shall be documented prior to its use.

(b) Unlisted Materials. Materials other than those meeting the requirements of (a)(1) and (a)(2) shall be considered unlisted materials and may be used provided they satisfy all of the following requirements:

(1) Unlisted materials shall be certified by the material manufacturer as satisfying the requirements of a specification listed in the applicable section of ASME NM.2 or the applicable section of the ASME B31 Code for Pressure Piping.

(2) The allowable stresses of the unlisted materials shall be determined in accordance with the requirements of para. 2-2.3.

(3) Unlisted materials shall be qualified for service within a stated range of minimum and maximum temperatures based on data associated with successful experience, tests, or analysis, or a combination thereof.

(4) The designer shall document the user's acceptance of the unlisted material for use.

(5) All other requirements of this Standard are satisfied.

3-3.2 Temperature Limits of Listed and Unlisted Polymeric Materials

Table 3-3.1-1 shall be used for polymeric materials for which the elastic or storage modulus glass transition temperature ($G'T_g$) or heat deflection temperature (HDT) has been supplied by the resin (polymer) provider.

3-3.2.1 Temperature Limits for Polyesters and Vinyl Esters. If more than 3% (by weight) of any combination of non-styrene materials is added to the resin system that was not provided by the resin vendor, the $G'T_g$ or HDT of the resin system shall be determined, and Table 3-3.1-1 may be used to determine the upper temperature limit. Styrene additions up to 3% (by weight) may be made without $G'T_g$ or HDT testing.

3-3.2.2 Temperature Limits for Epoxy Resin Systems. If more than 2% of any combination of materials is added to the resin system, or the stoichiometric ratios vary by more than 2% from those recommended by the resin (polymer) vendor, the $G'T_g$ or HDT of the resin (polymer) system shall be determined and Table 3-3.1-1 shall be used to determine the upper temperature limit.

3-3.3 Determination of Temperature Limits

$G'T_g$ or HDT is the onset of loss of modulus with a rise in temperature. The $G'T_g$ or HDT for polymeric materials may be determined as follows:

(a) $G'T_g$ shall be determined in accordance with ASTM D4065.

(b) HDT shall be determined in accordance with ASTM D648. When ASTM D648 is used, specimen thickness shall be a nominal 3.2 mm ($^1/_8$ in.) with a loading of 1.82 MPa (264 psi).

If the both $G'T_g$ and HDT for the polymeric system are available from the resin (polymer) provider, then either of the two values may be used for determining temperature limits per Table 3-3.1-1.

Chapter 4
Standards for Piping Components

4-1 DIMENSIONS AND RATINGS OF COMPONENTS

4-1.1 Listed Piping Components

(a) Specifications for piping components are listed in Table 4-1.1-1, and related test methods are listed in Table 4-1.1-2. (Procurement information is provided in Table 4-1.1-3.)

(b) The pressure–temperature ratings of listed components shall meet the requirements of para. 2-2.2.1.

(c) When conflicts exist between the specific requirements of this Standard and those of referenced standards or specifications, the requirements of this Standard shall take precedence.

4-1.2 Unlisted Piping Components

Piping components not manufactured in compliance with the specifications listed in Table 4-1.1-1 shall

(a) conform to the applicable provisions of para. 2-2.2.2

(b) meet the pressure design requirements described in para. 2-2.3.3 or para. 2-2.3.4

(c) meet the mechanical strength requirements described in para. 2-2.3.6

4-1.3 Threads

(a) The dimensions of piping connection threads not otherwise covered by a governing component standard or specification shall conform to the requirements of the applicable specification listed in Table 4-1.1-1.

(b) When conflicts exist between the specific requirements of this Standard and those of referenced standards and specifications, the requirements of this Standard shall take precedence.

4-2 REFERENCES

The specifications listed in Table 4-1.1-1 contain references to codes, standards, and specifications not listed in Table 4-1.1-1. Such unlisted codes, standards, and specifications shall be used only in the context of the listed specifications in which they appear.

4-3 QUALITY ASSURANCE AND CONFORMANCE

4-3.1 Manufacturing Quality Assurance

The degree of cure and the reinforcement content shall be verified using the appropriate ASTM standard (see Table 4-1.1-2).

4-3.2 Final Component Inspection

(a) Visual and dimensional inspection for each component shall be performed per the requirements of the appropriate ASME specification (see Table 4-1.1-1).

(b) Absent an inspection criteria in the component specification or other agreement with the owner, the inner surface, interior layer, and structural layer of each component shall comply with the Level 2 standard defined in Table 4-3.2-1.

4-3.3 Labeling (20)

Components shall be labelled at least once in such a manner that the information remains legible under normal handling and installation practices. Components shall be labelled with ASME NM.2-X, nominal pipe size, design pressure, and manufacturer's name or trademark, where *X* represents the design method for the component, i.e. *A*, *B*, *C*, or *D* as defined in para. 2-2.3. Components may also be marked according to the requirements associated with the applicable component specifications listed in Table 4-1.1-1.

4-3.4 Conformance

(a) If requested, the manufacturer shall certify that the material conforms to the applicable specification. The certification shall consist of a copy of the manufacturer's test report or a statement (accompanied by a copy of the test results) that the material has been sampled, tested, and inspected in accordance with the provisions of the specification.

(b) Each certification furnished as described in (a) shall be signed by an authorized agent of the manufacturer.

(c) When original identity of the material cannot be established, certification shall be based only on the sampling procedure provided by the applicable specification.

Table 4-1.1-1 Component Specifications

Designation	Title
ASME SC-582	Specification for Contact-Molded Reinforced Thermosetting Plastic (RTP) Laminates for Corrosion-Resistant Equipment
ASME SD-1763	Specification for Epoxy Resins
ASME SD-2517	Specification for Reinforced Epoxy Resin Gas Pressure Pipe and Fittings
ASME SD-2996	Specification for Filament-Wound "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
ASME SD-2997	Specification for Centrifugally Cast "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
ASME SD-3517	Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe
ASME SD-3754	Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer and Industrial Pressure Pipe
ASME SD-4024	Specification for Machine Made "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Flanges
ASME SD-4161	Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Joints Using Flexible Elastomeric Seals
ASME SD-5421	Specification for Contact Molded "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Flanges
ASME SD-5677	Specification for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Pipe Fittings, Adhesive Bonded Joint Type, for Aviation Jet Fuel Lines
ASME SD-5685	Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe Fittings
ASME SD-6041	Specification for Contact-Molded "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Corrosion Resistant Pipe and Fittings
ASME SF-477	Specification for Elastomeric Seals (Gaskets) for Joining Plastic Pipe
ASME SF-913	Specification for Thermoplastic Elastomeric Seals (Gaskets) for Joining Plastic Pipe
ASME SF-1173	Specification for Thermosetting Resin Fiberglass Pipe Systems to Be Used for Marine Applications
AWWA C950	Fiberglass Pressure Pipe
AWWA M45	Fiberglass Pipe Design

GENERAL NOTES:
(a) See ASME NM.3.2 for the ASME specifications.
(b) See Table 4-1.1-3 for procurement information.

Table 4-1.1-2 Test Methods and Other Standards

Designation	Title
ASCE/SEI 7	Minimum Design Loads and Associated Criteria for Buildings and Other Structures
ASME B1.1	Unified Inch Screw Threads (UN, UNR, and UNJ Thread Forms)
ASME B1.20.1	Pipe Threads, General Purpose (Inch)
ASME B18.21.1	Washers: Helical Spring-Lock, Tooth Lock, and Plain Washers (Inch Series)
ASME B31	ASME Code for Pressure Piping
B31.1	Power Piping
B31.3	Process Piping
B31.4	Pipeline Transportation Systems for Liquids and Slurries
B31.5	Refrigeration Piping and Heat Transfer Components
B31.8	Gas Transmission and Distribution Piping Systems
B31.9	Building Services Piping
ASME BPVC	ASME Boiler and Pressure Vessel Code
Section II	Materials, Part D — Properties
Section III	Rules for Construction of Nuclear Facility Components; Division I — Subsection ND, Class 3 Components
Section X	Fiber-Reinforced Plastic Pressure Vessels
ASME NM.3.2	Nonmetallic Materials, Part 2 — Reinforced Thermoset Plastic Material Specifications
ASME NM.3.3	Nonmetallic Materials, Part 3 — Properties
ASME PCC-2	Repair of Pressure Equipment and Piping
ASME RTP-1	Reinforced Thermoset Plastic Corrosion-Resistant Equipment
ASQ Z1.4	Sampling Procedures and Tables for Inspection by Attributes
ASTM C581	Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D648	Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D696	Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between −30°C and 30°C With a Vitreous Silica Dilatometer
ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM D883	Standard Terminology Relating to Plastics
ASTM D1598	Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure
ASTM D1599	Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings
ASTM D1600	Standard Terminology for Abbreviated Terms Relating to Plastics
ASTM D2105 [Note (1)]	Standard Test Method for Longitudinal Tensile Properties of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube
ASTM D2143	Standard Test Method for Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe
ASTM D2290	Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe
ASTM D2412	Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading
ASTM D2487	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
ASTM D2563	Standard Practice for Classifying Visual Defects in Glass-Reinforced Plastic Laminate Parts
ASTM D2583	Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
ASTM D2584	Standard Test Method for Ignition Loss of Cured Reinforced Resins
ASTM D2924	Standard Test Method for External Pressure Resistance of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe
ASTM D2925	Standard Test Method for Beam Deflection of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Pipe Under Full Bore Flow
ASTM D2992	Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings

Table 4-1.1-2 Test Methods and Other Standards (Cont'd)

Designation	Title
ASTM D3039/D3039M	Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
ASTM D3567	Standard Practice for Determining Dimensions of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Pipe and Fittings
ASTM D3681	Standard Test Method for Chemical Resistance of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe in a Deflected Condition
ASTM D4065	Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures
ASTM D5083	Standard Test Method for Tensile Properties of Reinforced Thermosetting Plastics Using Straight-Sided Specimens
ASTM E84	Standard Test Method for Surface Burning Characteristics of Building Materials
ASTM F336	Standard Practice for Design and Construction of Nonmetallic Enveloped Gaskets for Corrosive Service
ASTM F412	Standard Terminology Relating to Plastic Piping Systems
MSS SP-58	Pipe Hangers and Supports — Materials, Design, Manufacture, Selection, Application, and Installation
NBIC	National Board Inspection Code
PFI ES-3	Fabricating Tolerances

GENERAL NOTE: See Table 4-1.1-3 for procurement information.

NOTE: (1) See Nonmandatory Appendix B for alternative requirements.

Table 4-1.1-3 Procurement Information

Organization	Contact Information	Organization	Contact Information
ASCE	American Society of Civil Engineers 1801 Alexander Bell Drive Reston, VA 20191 (www.asce.org)	AWWA	American Water Works Association 6666 West Quincy Avenue Denver, CO 80235 (www.awwa.org)
ASME	The American Society of Mechanical Engineers Two Park Avenue New York, NY 10016-5990 (www.asme.org)	MSS	Manufacturers Standardization Society of the Valve and Fittings Industry, Inc. 127 Park St. NE Vienna, VA 22180-4602 (www.msshq.org)
ASQ	American Society for Quality P.O. Box 3005 Milwaukee, WI 53201 (www.asq.org)	NBIC	National Board of Boiler and Pressure Vessel Inspectors 1055 Crupper Avenue Columbus, OH 43229 (www.nationalboard.org)
ASTM	American Society for Testing and Materials 100 Barr Harbor Drive P.O. Box C700 West Conshohocken, PA 19428-2959 (www.astm.org)	PFI	Pipe Fabrication Institute 511 Avenue of the Americas, No. 601 New York, NY, 10011 (www.pfi-institute.org)

Table 4-3.2-1 Visual Inspection Acceptance Criteria

Definition of Visual Inspection Levels (to Be Specified by User or User's Agent): Level (1) = Critically Corrosion Resistant Level (2) = Standard Corrosion Resistant		Maximum Size and Cumulative Sum of Imperfections Allowable [After Repair. See General Notes (a) and (b). Imperfections Subject to Cumulative Sum Limitation Are Highlighted With an Asterisk.]						
		Inner Surface Veil(s), Surfacing Mat		Interior Layer (~0.125 in. Thick) Mat or Chopped-Strand Spray Layers		Structural Layer Balance of Laminate (Including Outer Surface)		
Imperfection Name	Definition of Imperfection	Level (1)	Level (2)	Level (1)	Level (2)	Level (1)	Level (2)	Notes
Burned areas	Showing evidence of thermal decomposition through discoloration or heavy distortion	None	None	None	None	None	Never in more than one ply and not to exceed 16 in.^{2} in any vessel	Discoloration only, never delamination or decomposition
Chips (surface)	Small pieces broken off an edge or surface	*$^1/_8$ in. diameter max. by 30% of veil(s) thickness max.	*$^1/_8$ in. diameter max. by 50% of veil(s) thickness max.	...	...	*$^1/_4$ in. diameter or $^1/_2$ in. length max. by $^1/_{16}$ in. deep	*$^1/_2$ in. diameter or 1 in. length max. by $^1/_{16}$ in. deep	...
Cracks	Actual ruptures or debond of portions of the structure	None	None	None	None	None	None	Not to include areas to be covered by joints
Crazing (surface)	Fine cracks at the surface of a laminate	None	None	...	...	Max. 1 in. long by $^1/_{64}$ in. deep, max. density three in any square foot	Max. 2 in. long by $^1/_{64}$ in. deep, max. density five in any square foot	...
Delamination (internal)	Separation of the layers in a laminate	None	None	None	None	None	*None in three plies adjacent to interior layer, none larger than 1 in.^{2} total area	...
Dry spot (surface)	Area of surface where the reinforcement has not been wetted with resin	None	None	...	...	None	None	...
Edge exposure	Exposure of multiple layers of the reinforcing matrix to the vessel contents, usually as a result of shaping or cutting a section to be secondary bonded (interior of vessel only)	None	None	...	...	None	None	Edges exposed to contents shall be covered with same number of veils as inner surface

Table 4-3.2-1 Visual Inspection Acceptance Criteria (Cont'd)

Definition of Visual Inspection Levels (to Be Specified by User or User's Agent): Level (1) = Critically Corrosion Resistant Level (2) = Standard Corrosion Resistant		Maximum Size and Cumulative Sum of Imperfections Allowable [After Repair. See General Notes (a) and (b). Imperfections Subject to Cumulative Sum Limitation Are Highlighted With an Asterisk.]						
		Inner Surface Veil(s), Surfacing Mat		Interior Layer (~0.125 in. Thick) Mat or Chopped-Strand Spray Layers		Structural Layer Balance of Laminate (Including Outer Surface)		
Imperfection Name	Definition of Imperfection	Level (1)	Level (2)	Level (1)	Level (2)	Level (1)	Level (2)	Notes
Foreign inclusion	Particles included in a laminate that are foreign to its composition (not a minute speck of dust)	*$^{3}/_{16}$ in. long max. by dia. or thickness not more than 30% of veil(s) thickness	*$^{1}/_{4}$ in. long max. by dia. or thickness not more than 50% of veil(s) thickness	*$^{1}/_{2}$ in. long max. by dia. or thickness not more than 30% of interior layer thickness	*$^{1}/_{2}$ in. long max. by dia. or thickness not more than 50% of interior layer thickness	*Dime size, never to penetrate lamination to lamination	*Nickel size, never to penetrate lamination to lamination	Shall be fully resin wetted and encapsulated
Gaseous bubbles or blisters	Air entrapment within, on, or between plies of reinforcement, 0.015 in. diameter and larger	*Max. diameter $^{1}/_{16}$ in. by 30% of veil (s) thickness deep	*Max. diameter $^{1}/_{16}$ in. by 50% of veil(s) thickness deep	*Max. diameter $^{1}/_{8}$ in.	*Max. diameter $^{1}/_{8}$ in.	*Max. diameter $^{3}/_{16}$ in.	*Max. diameter $^{1}/_{4}$ in.	Shall not be breakable with a sharp point
		Refer to User's Specification for quantity limitations						
Pimples (surface)	Small, sharp, conical elevations on the surface of a laminate	*Max. height or diameter $^{1}/_{64}$ in.	*Max. height or diameter $^{1}/_{32}$ in.	…	…	No limit		Shall be fully resin filled and wetted; generally, captured sanding dust
Pit (surface)	Small crater in the surface of a laminate	*$^{1}/_{8}$ in. diameter max. by 30% of veil(s) thickness max.	*$^{1}/_{8}$ in. diameter max. by 50% of veil(s) thickness max.	…	…	*$^{1}/_{4}$ in. diameter max. by $^{1}/_{16}$ in. deep max.	*$^{1}/_{4}$ in. diameter max. by $^{3}/_{32}$ in. deep max.	No fibers may be exposed
Porosity (surface)	Presence of numerous visible tiny pits (pinholes), approximate dimension 0.005 in. (for example, five in any square inch)	None more than 30% of veil(s) thickness	None more than 50% of veil(s) thickness	…	…	None to fully penetrate the exterior gel coat or gel-coated exterior veil; no quantity limit		No fibers may be exposed
Scratches (surface)	Shallow marks, grooves, furrows, or channels caused by improper handling	*None	*None	…	…	*None more than 6 in. long	*None more than 12 in. long	No fibers may be exposed
Wet blisters (surface)	Rounded elevations of the surface, somewhat resembling a blister on the human skin; not reinforced	*None over $^{3}/_{16}$ in. diameter by $^{1}/_{16}$ in. in height	*None over $^{3}/_{16}$ in. diameter by $^{1}/_{16}$ in. in height	…	…	No limit		Shall be fully resin filled, not drips loosely glued to surface, which are to be removed

Table 4-3.2-1 Visual Inspection Acceptance Criteria (Cont'd)

Definition of Visual Inspection Levels (to Be Specified by User or User's Agent): Level (1) = Critically Corrosion Resistant Level (2) = Standard Corrosion Resistant		Maximum Size and Cumulative Sum of Imperfections Allowable [After Repair. See General Notes (a) and (b). Imperfections Subject to Cumulative Sum Limitation Are Highlighted With an Asterisk.]						
		Inner Surface Veil(s), Surfacing Mat		Interior Layer (~0.125 in. Thick) Mat or Chopped-Strand Spray Layers		Structural Layer Balance of Laminate (Including Outer Surface)		
Imperfection Name	Definition of Imperfection	Level (1)	Level (2)	Level (1)	Level (2)	Level (1)	Level (2)	Notes
Wet-out inadequate	Resin has failed to saturate reinforcing (particularly woven roving)	None	None	None	None	Dry mat or prominent and dry woven roving pattern not acceptable; discernible but fully saturated woven pattern acceptable		Split tests on cutouts may be used to discern degree of saturation on reinforcing layers
Wrinkles and creases	Generally linear, abrupt changes in surface plane caused by laps of reinforcing layers, irregular mold shape, or Mylar overlap	Max. deviation 20% of wall or $^{1}/_{16}$ in., whichever is less	Max. deviation 20% of wall or $^{1}/_{8}$ in., whichever is less	...	...	Max. deviation 20% of wall or $^{1}/_{8}$ in., whichever is less		Not to cause a cumulative linear defect (outside defect adding to inside defect)
Allowable cumulative sum of highlighted imperfections	Maximum allowable in any square foot	3	5	3	5	5	5	...
	Maximum allowable in any square yard	15	20	20	30	30	40	...
Maximum % repairs	The maximum allowable area of repairs made in order to pass visual inspection	3%	10%	3%	10%	3% to structural, no limit to outer surface repairs	10% to structural, no limit to outer surface repairs	Debond tests required prior to inner surface repairs

GENERAL NOTES:
(a) Above acceptance criteria apply to condition of laminate after repair.
(b) Noncatalyzed resin is not permissible to any extent in any area of the laminate.
(c) See Nonmandatory Appendix C for guidance on repairs.

Chapter 5
Fabrication, Assembly, and Erection

5-1 GENERAL

Manufactured FRP piping materials and components are assembled and joined by one or more of the methods covered in this Chapter. The materials used shall be as defined in Chapter 3. Only manufacturing processes as defined in Chapter 1 shall be used.

5-2 BONDING

Bonding shall conform to paras. 5-2.1 through 5-2.6 and shall comply with other applicable requirements of this Standard.

5-2.1 Bonding Responsibility

Each employer is responsible for the bonding done by its personnel and, except as provided in paras. 5-2.2 and 5-2.3, shall conduct the required performance qualification tests to qualify the Bonding Procedure Specifications (BPSs) and bonders.

5-2.2 Bonding Qualifications

5-2.2.1 Qualification Requirements

(a) Qualification of the BPS to be used and of the bonders' performance is required. Qualification of a BPS requires that all tests and examinations specified therein and in para. 5-2.2.5 be completed successfully.

(b) In addition to the procedure for making the bonds, the BPS shall include the following information:

(1) all materials and supplies (including storage requirements)

(2) tools and fixtures (including instructions for proper care and handling)

(3) environmental requirements (e.g., temperature, humidity, and methods of measurement)

(4) joint preparation (e.g., joint type, cleanliness of joint surfaces, sealed cut surfaces, required surface profile)

(5) dimensional requirements and tolerances (e.g., squareness of ends, gap width, offset and angular alignment, strap thickness and width)

(6) required cure time

(7) methods for protection of work

(8) tests and examinations other than those required by para. 5-2.2.5

(9) acceptance criteria for the completed test assembly

(c) A separate BPS is required when one or any combination of the following thermoset resins is used:

(1) polyester

(2) vinyl ester

(3) epoxy

5-2.2.2 Procedure Qualification by Others. Subject to the specific approval of the Inspector, a BPS qualified by an organization other than the employer may be used provided

(a) the Inspector verifies that the proposed qualified BPS has been prepared and executed by a responsible recognized organization with expertise in the field of bonding

(b) by signature, the employer accepts as its own both the BPS and Procedure Qualification Record

(c) the employer currently employs at least one bonder who, while working for the employer, has satisfactorily passed a performance qualification test using the proposed qualified BPS

5-2.2.3 Performance Qualification by Others. Without the Inspector's specific approval, an employer shall not accept a performance qualification test made by a bonder for another employer. If approval is given, it is limited to work on piping using the same or equivalent BPS. An employer accepting such performance qualification tests shall obtain a copy of the performance qualification test record from the previous employer showing the name of the employer by whom the bonder or bonding operator was qualified, the date of such qualification, and the date the bonder or bonding operator last bonded pressure piping under such performance qualification.

5-2.2.4 Qualification Records. The employer shall maintain a self-certified record, available to the owner or owner's agent and to the Inspector, showing the BPS used, the bonders or bonding operators employed, and the dates and results of BPS qualifications and bonding performance qualifications.

5-2.2.5 Qualification Tests. Tests shall be performed to qualify each BPS and the performance of each bonder. Test assemblies shall conform to (a), and the test method shall be in accordance with either (b) or (c).

(a) Test Assembly. The test assembly shall be fabricated in accordance with the BPS and shall contain at least one of each different type of joint identified in the BPS. More than one test assembly may be prepared if necessary to accommodate all of the joint types or to ensure that at least one of each joint type is loaded in both circumferential and longitudinal directions. Test assemblies shall not have been pretested or pre-stress-relieved prior to first loadings and testing. The size of pipe and fittings in the test assembly shall be as follows:

(1) When the largest size to be joined is DN 100 (NPS 4) or smaller, the test assembly shall be the largest size to be joined.

(2) When the largest size to be joined is greater than DN 100 (NPS 4) and less than or equal to DN 1200 (NPS 48), the size of the test assembly shall be between 25% and 100% of the largest piping size to be joined, but shall be a minimum of DN 100 (NPS 4).

(3) When the largest size to be joined is greater than DN 1200 (NPS 48), the size of the test assembly shall be agreed upon between the owner and the employer.

(b) Burst Test Method. The test assembly shall be subjected to a burst test in accordance with ASTM D1599, Procedure B. The burst pressure shall be, as a minimum, 6 times pipe rated pressure. The time to burst may be extended as indicated in ASTM D1599.

(c) Hydrostatic Test Method. The test assembly shall be subjected to a hydrostatic pressure, P_T, for not less than 1 h with no leakage or separation of joints.

(1) P_T shall be 3 times design pressure for the components being joined.

(2) The test shall be conducted so that the joint is loaded in both the circumferential and longitudinal directions. All joints tested shall be unrestrained.

5-2.2.6 Performance Requalification. Renewal of a bonding performance qualification shall be performed when

(a) a bonder has not used the specific bonding process for a period of 6 months or more, or

(b) there is specific reason to question the individual's ability to make bonds that meet the BPS

5-2.3 Bonding Materials and Equipment

5-2.3.1 Materials

(a) Thermoset Resins

(1) The resin shall be checked to ensure that it is the product ordered. The resin shall be properly labeled.

(2) The resin shall be within the manufacturer's recommended usable viscosity range. It shall be of normal color and clarity, and free from solid or gelled particles and dirt as determined by visual examination. There shall be no layering or separation of the resin.

(3) The resin shall be within the manufacturer's specification for room-temperature gel time as determined by the manufacturer's prescribed method.

(b) Glass Reinforcement

(1) The glass shall be checked to ensure that it is the product ordered. The glass shall have proper labeling.

(2) The glass shall be dry and clean. It shall be kept in its packaging container until time of use.

(c) Curing Agents

(1) Curing agents shall be checked to ensure they are the products ordered. They shall have proper labeling.

(2) Curing agents shall have no layering or separation.

5-2.3.2 Equipment. Fixtures and tools used in making joints shall be in such condition as to perform their functions satisfactorily. Fixtures, tools, equipment, and other devices used to hold or apply forces to the pipe shall function in a way that does not damage the pipe surface.

5-2.4 Preparation for Bonding

Preparation shall be defined in the BPS and shall specify the following requirements at minimum:

(a) cutting
(b) cleaning
(c) preheat
(d) end preparation
(e) fit-up

5-2.5 Bonding Requirements

5-2.5.1 General

(a) Production joints shall be made only in accordance with a written BPS that has been qualified in accordance with para. 5-2.2. Manufacturers of piping materials, bonding materials, and bonding equipment should be consulted in the preparation of the BPS. When joints are accessible, an interior joint liner shall be considered, and for nonaccessible joints, a liner capping at the cut piping edges shall be considered based on fluid service.

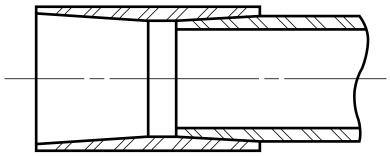
(b) Production joints shall be made only by qualified bonders who have appropriate training or experience in the use of the applicable BPS and have satisfactorily passed a performance qualification test that was performed in accordance with a qualified BPS.

(c) Each qualified bonder shall be assigned an identification symbol. Unless otherwise specified in the engineering design, each pressure-containing bond or adjacent area shall be stenciled or otherwise suitably marked with the identification symbol of the bonder. Identification stamping shall not be used, and any marking paint or ink shall not be detrimental to the piping material. In lieu of marking the bond, the bonder may be identified on appropriate quality control records.

(d) Qualification in one BPS shall not qualify a bonder for any other bonding procedure.

(e) Longitudinal joints shall not be used.

Figure 5-2.5.2-1 Adhesive Joint



GENERAL NOTE: Figure is for illustrative purposes only.

5-2.5.2 For Adhesive Joints

(a) Procedure. Adhesive joints shall be made in accordance with the qualified BPS. Application of adhesive to the surfaces to be joined and assembly of these surfaces shall produce a continuous bond between them and shall seal over all cuts to protect the reinforcement from the fluid service. See Figure 5-2.5.2-1.

(b) Branch Connections. The cut edges of the hole in the run pipe shall be sealed with adhesive at the same time the saddle or branch pipe is bonded to the run pipe.

5-2.5.3 For Wrapped Joints. Wrapped joints shall be made in accordance with the qualified BPS. Application of plies of reinforcement saturated with catalyzed resin to the surfaces to be joined shall produce a continuous structure with them. Cuts shall be sealed to protect the reinforcement from the fluid service. See Figure 5-2.5.3-1. A fabricated branch connection shall be made by inserting the branch pipe into a hole in the run pipe and applying reinforcement to the run pipe and attachment lay-up to the branch pipe.

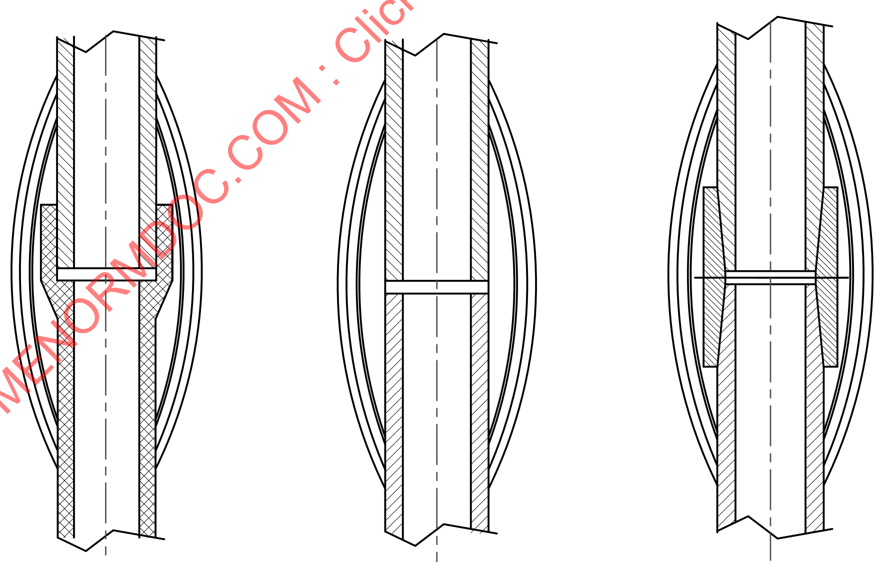
5-2.6 Bonding Repair

Defective material, joints, and other workmanship that fail to meet the requirements of this Standard and of the engineering design shall be repaired or replaced, and the new work shall be examined to the same extent and by use of the same methods and acceptance criteria as were required for the original work.

5-2.7 Seal Bonds

Threaded joints may be seal bonded only to prevent leakage of a joint and only if it has been demonstrated that there will be no deleterious effect on the materials bonded. The work shall be done by qualified bonders, and all exposed threads shall be covered by the seal bond.

Figure 5-2.5.3-1 Wrapped Joints



(a) Overwrapped Bell-and-Spigot Joint (b) Butt and Wrapped Joint (c) Overwrapped Tapered Joint

GENERAL NOTE: Figure is for illustrative purposes only.

5-3 ASSEMBLY AND ERECTION

5-3.1 Tolerances and Alignment

5-3.1.1 Piping Distortions. Any alignment of pipe that produces detrimental strain in equipment or piping components shall not be permitted.

5-3.1.2 Linear, Angular, and Rotational Tolerances

5-3.1.2.1 The tolerances on linear dimensions (intermediate or overall) shall apply to the face-to-face, face-to-end, and end-to-end measurements of fabricated straight pipe and headers; center-to-end or center-to-face measurements of nozzles or other attachments; or center-to-face measurements of bends, as illustrated in Figure 5-3.1.2.1-1. These tolerances shall not be cumulative.

5-3.1.2.2 When fittings or flanges are joined without intervening pipe segments, deviations greater than those specified in Figure 5-3.1.2.1-1 may occur due to the cumulative effects of tolerances on such components; these deviations are acceptable.

5-3.1.2.3 Angularity tolerances across the face, end preparation, and rotation of flanges are shown in Figure 5-3.1.2.1-1.

(20) **5-3.1.2.4 Flange face tolerances** Flange face drawback and waviness shall not exceed 0.8 mm ($^1\!/_{32}$ in.) as measured at or inside the bolt circle. No reverse drawback is permitted. See Figure 5-3.1.2.4-1.

5-3.1.3 Closer Tolerances. When closer tolerances than those given in paras. 5-3.1.2.1 through 5-3.1.2.3 are necessary, they shall be subject to agreement between the designer and the fabricator.

5-3.1.4 Flanged Joints. Unless otherwise specified in the engineering design, flanged joints shall be aligned as follows:

(a) Before bolting, mating gasket contact surfaces shall be aligned to each other within 1 mm/200 mm ($^1\!/_{16}$ in./ft) measured across any diameter.

(b) The flanged joint shall be capable of being bolted such that the gasket contact surfaces bear uniformly on the gasket.

(c) Flange bolt holes shall be aligned within 3 mm ($^1\!/_8$ in.) maximum offset.

5-3.1.5 Irregularities. Irregularities (i.e., gap, angular deflection, and misalignment) between two field-connected pipes and/or alignment of flange facings shall be within the tolerances as set in the engineering documentation and approved by the owner.

5-3.2 Flanged and Mechanical Joints

The preferred flanged joint assembly shall be one with two flat-face flanges with full-face gaskets having a 50 to 70 Shore A durometer. When other combinations of flanges and gaskets are used, the additional requirements of para. 5-3.2.5 shall be considered.

Mechanical joints that are not flanged shall be assembled in accordance with the manufacturer's requirements and as shown on engineering documents.

Bolting torque sequence and limits shall be specified by the manufacturer for a particular flange and approved by the designer. Type of compound or lubricant shall directly relate to specified torqueing values and gasket material.

5-3.2.1 Preparation for Assembly. Any damage to the gasket seating surface that would prevent gasket seating shall be repaired, or the flange shall be replaced.

5-3.2.2 Bolting Torque

(a) During assembly of flanged joints, the gasket shall be uniformly compressed to the proper design loading.

(b) Bolts shall be tightened to a predetermined torque.

(c) Narrow flat washers (see ASME B18.21.1, Type A) shall be used under all bolt heads and nuts.

5-3.2.3 Bolt Length. Bolt length should consider the presence of washers, nut height, and required thread protrusion. Nuts should engage the bolt threads for the full depth of the nut. The nut may be considered acceptably engaged if the lack of complete engagement is not more than one thread. The use of bolt tensioners requires that the threaded portion of the bolt extend at least one bolt diameter beyond the outside nut face on the tensioner side of the joint. Galvanized or coated bolts may require special tensioner puller sleeves.

5-3.2.4 Gaskets. No more than one gasket shall be used between contact faces in assembling a flanged joint.

5-3.2.5 Nonstandard Flanged Joints. When other than flat-face flanges with full-face gaskets having a 50–70 Shore A durometer are used, the following shall apply:

(a) Consideration shall be given to the strength of the flanges, and to sustained loads, displacement strains, and occasional loads described in Chapter 2.

(b) When mating raised-face to flat-face flanges, the following shall occur:

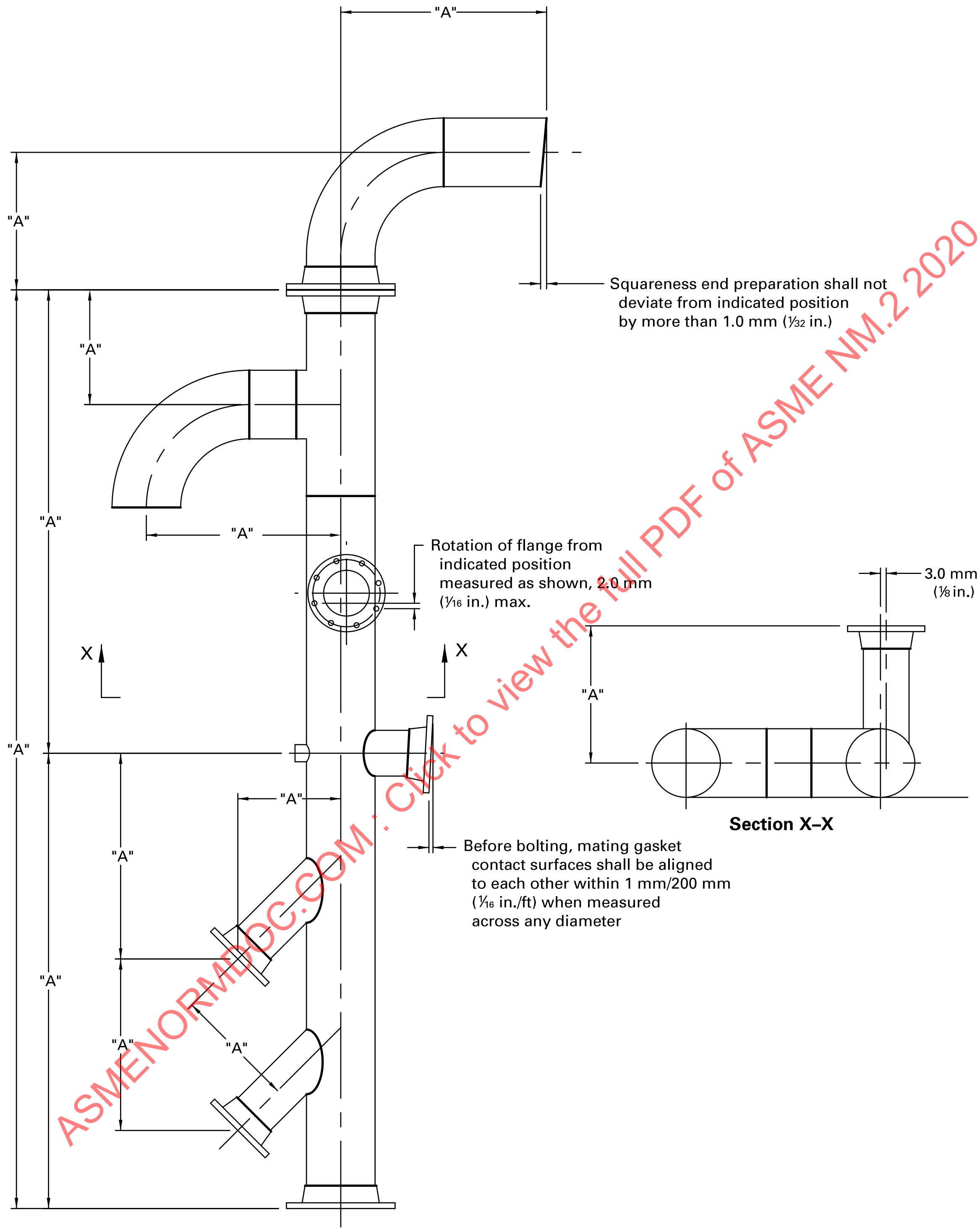
(1) The flange connection shall be designed to withstand the stresses during bolt-up.

(2) The appropriate spacer or filler rings shall be used to prevent overstressing of the flat-face flange.

(c) An appropriate bolt-up sequence shall be specified.

(d) Appropriate bolt-up torque limits specified by the manufacturer shall be approved by the designer, and those limits shall not be exceeded.

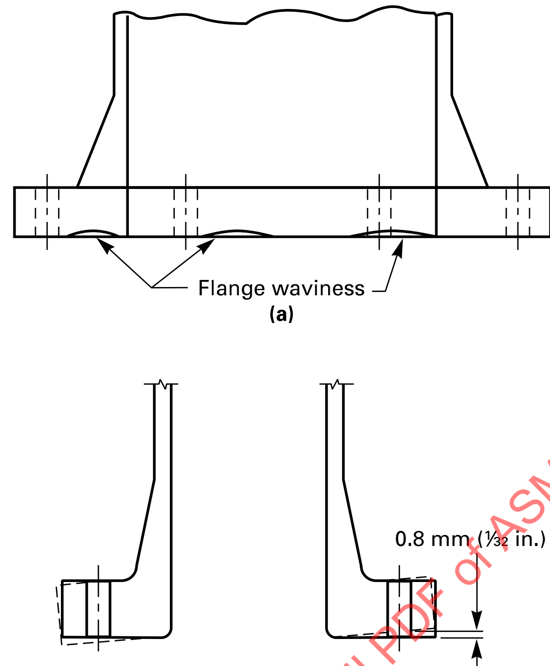
Figure 5-3.1.2.1-1 Assembly Tolerances and Alignment



Pipe Sizes, DN (NPS)	Linear Assembly Tolerances at A, mm (in.)
<300 (12)	±3.0 (±1⁄8)
300 (12) through 600 (24)	±5.0 (±3⁄16)
650 (26) through 900 (36)	±6.0 (±1⁄4)
>900 (36)	±6.0 (±1⁄4) deviating ±2.0 (±1⁄16) for each 300 mm (12 in.) in diameter over 900 mm (36 in.)

GENERAL NOTE: Figure adapted from PFI ES-3, Figure 1, by permission of the Pipe Fabrication Institute, New York, NY.

Figure 5-3.1.2.4-1 Flange Tolerances (20)



5-3.3 Threaded Joints

Where threads may be exposed to fluids that can attack the reinforcing material, threads shall be coated with sufficient resin to cover the threads and completely fill the clearance between the pipe and the fitting.

Threaded joints shall conform to the following:

(a) External threads shall be factory cut or molded on special thick-walled pipe ends.

(b) Matching internal threads shall be factory cut or molded in the fittings.

(c) Threading of plain ends is not permitted, except where such threads are limited to the function of a mechanical lock to matching internal threads factory cut or molded in the bottom portions of fittings with deep sockets.

(d) Factory-cut or factory-molded threaded nipples, couplings, or adapters bonded to plain-end pipe and fittings may be used where it is necessary to provide connections to threaded metallic piping.

5-3.3.1 Thread Compound or Lubricant. Compound or lubricant shall be used on threads, shall be suitable for the service conditions, and shall not react unfavorably with either the fluid service or the piping material. The type of compound or lubricant directly relates to specified torqueing values.

5-3.3.2 Joints for Seal Bonding. A threaded joint to be seal bonded shall be made up without thread compound. A joint containing thread compound that leaks during leak testing may be seal bonded in accordance with para. 5-2.7, provided all compound is removed from exposed threads.

5-3.3.3 Tools. Either strap wrenches or other full-circumference wrenches shall be used to tighten threaded pipe joints. Tools, equipment, and other devices used to hold or apply forces to the pipe shall function in a manner that does not score or deeply scratch the pipe surface.

5-3.4 Special Joints

5-3.4.1 General. Special joints shall be installed and assembled in accordance with the manufacturer's instructions, as modified by the engineering design. Care shall be taken to ensure adequate engagement of joint members.

5-3.4.2 Packed Joints. If a packed joint is used to absorb thermal expansion, proper clearance shall be provided at the bottom of the socket to permit this movement.

5-3.4.3 Flexible Elastomeric-Sealed Joints. Assembly of flexible elastomeric-sealed joints shall be in accordance with the manufacturer's recommendations and the following:

(a) Seal and bearing surfaces shall be free from injurious imperfections.

(b) Any lubricant used to facilitate joint assembly shall be compatible with the joint components and the intended service.

(c) Proper joint clearances and piping restraints (if not integral in the joint design) shall be provided to prevent joint separation when expansion can occur due to thermal and/or pressure effects.

5-3.5 Handling of Piping

FRP piping shall be handled and supported in a manner that prevents scratching of and mechanical damage to the piping. Any scratched or chipped components shall be examined or inspected for compliance with applicable acceptance criteria defined in this Standard.

5-3.6 Cleaning of Piping

Piping shall be cleaned per the manufacturer's recommendation.

5-3.7 Identification of Piping

Each pipe section, fitting, and accessory shall be clearly marked with the following information:

(a) manufacturer's name or trademark and identity code

(b) date of manufacturing

(c) nominal pipe size, pipe classification, and diameter series

(d) pressure class

(e) manufacturer's examination mark

See also para. 5-2.5.1(c).

Chapter 6
Inspection, Examination, and Testing

6-1 INSPECTION

This Standard distinguishes between examination (see section 6-2) and inspection. Inspection applies to functions performed for the owner by the owner's Inspector or the Inspector's delegates. References in this Standard to the "Inspector" are to the owner's Inspector or the Inspector's delegates.

6-1.1 Responsibility for Inspection

It is the owner's responsibility, exercised through the Inspector, to verify that all required examinations and testing have been completed and to inspect the piping to the extent necessary to be satisfied that it conforms to all applicable examination requirements of this Standard.

6-1.2 Rights of the Owner's Inspector

The owner's Inspector and the Inspector's delegates shall have access to any place where work is being performed. This work shall include manufacture, fabrication, assembly, erection, installation, examination, and testing of the piping. They shall have the right to audit any examination, to inspect the piping using any examination method specified by the engineering design, and to review all certifications and records necessary to satisfy the owner's responsibility stated in para. 6-1.1.

6-1.3 Qualifications of the Owner's Inspector

(a) The Inspector shall be designated by the owner and shall be the owner, an employee of the owner, an employee of an engineering or scientific organization, or an employee of a recognized insurance or inspection company acting as the owner's agent. The Inspector shall not represent nor be an employee of the piping manufacturer, fabricator, or erector unless the owner is also the manufacturer, fabricator, or erector.

(b) The owner's Inspector shall have not less than 10 yr of experience in the design, fabrication, examination, and inspection of FRP pressure piping. An individual may count each satisfactorily completed year of an ABET-accredited engineering degree program as 1 yr of experience, up to a maximum of 4 yr.

(c) Alternatively, the Inspector shall meet the Inspector qualifications of the National Board Inspection Code (NBIC), Part 2, Supplement 4, S4.5.

6-2 EXAMINATION

Examination applies to quality control functions performed by the manufacturer (for components only), fabricator, or erector. Reference in this Standard to an examiner shall be to a person who performs quality control examinations.

6-2.1 Responsibility for Examination

Inspection shall not relieve the manufacturer, fabricator, or erector of the responsibility for

(a) providing materials, components, and workmanship in accordance with the requirements of this Standard and of the engineering design

(b) performing all required examinations

(c) preparing suitable records of examinations and tests for the Inspector's use

6-2.2 Examination Requirements

6-2.2.1 General. Prior to initial operation, each piping installation, including components and workmanship, shall be examined in accordance with the applicable requirements of section 6-2. The type and extent of any additional examination required by the engineering design, and the acceptance criteria to be applied, shall be specified. Joints not included in examinations required by para. 6-2.3 or by the engineering design may be accepted if they pass the leak test required by section 6-3.

6-2.2.2 Acceptance Criteria

(a) The acceptance criteria for imperfections in bonds shall be as listed in Table 6-2.2.2-1.

(b) Acceptance criteria should be defined in the engineering design or other agreement with the owner. For cases in which failure or substantial leakage of the piping could pose high risk to the health or safety of personnel or cause significant economic loss, acceptance criteria should comply with para. 6-2.7.2(c)(3).

6-2.2.3 Defective Components and Workmanship

(a) An examined item with one or more defects (imperfections) of a type or magnitude exceeding the acceptance criteria of this Standard shall be repaired or replaced.

(b) The new work shall be examined to the same extent and by use of the same methods and acceptance criteria as required for the original work.

Table 6-2.2.2-1 Acceptance Criteria for Bonds

Type of Imperfection	Acceptance Criteria
Cracks	None permitted
Unfilled areas in joint	None permitted
Unbonded areas in joint	None permitted
Inclusions of foreign material	None permitted
Protrusion of adhesive into pipe bore, % of total pipe wall thickness	25%
Incomplete joint makeup	None permitted

6-2.2.4 Progressive Sampling for Examination. When required spot or random examination reveals a defect, the following steps shall be used:

Step 1. Two additional samples of the same kind (if bonded joints, by the same bonder) shall be given the same type of examination.

Step 2

(a) If the items examined as required by Step 1 are acceptable, the defective item shall be repaired or replaced. The repaired or replaced item shall be reexamined as specified in para. 6-2.2.3, and all items represented by these two additional samples shall be accepted.

(b) If any of the items examined as required by Step 1 reveals a defect, a double number of further samples of the same kind shall be examined for each defective item found by that sampling.

Step 3

(a) If all the items examined as required by Step 2(b) are acceptable, the defective item(s) shall be repaired or replaced. The repaired or replaced item shall be reexamined as specified in para. 6-2.2.3, and all items represented by the additional sampling shall be accepted.

(b) If any of the items examined as required by Step 2(b) reveals a defect, all items represented by the progressive sampling shall be either

(1) repaired or replaced and reexamined as required, or

(2) fully examined and repaired or replaced as necessary, and reexamined as necessary to meet the requirements of this Standard

Step 4. If any of the defective items are repaired or replaced and then reexamined, and a defect is again detected in the repaired or replaced item, continued progressive sampling in accordance with Steps 1, 2(b), and 3 shall not be required based on the defects found in the repair. The defective item(s) shall be repaired or replaced. The repaired or replaced item shall be reexamined until acceptance as specified in para. 6-2.2.3. Spot or random examination (whichever is applicable) shall then be performed on the remaining unexamined joints.

6-2.3 Extent of Examination

6-2.3.1 Required Examination. Piping and piping components shall be examined to the extent specified herein or to any greater extent specified in the engineering design. Acceptance criteria shall be as stated in para. 6-2.2.2 unless otherwise specified.

(a) Visual Examination. Visual examination in accordance with para. 6-2.7.2 shall include the following at minimum:

(1) examination of materials and components, selected at random, to satisfy the examiner that they conform to specifications and are free from defects.

(2) examination of at least 20% of fabrication. For bonds, each type of bond made by each bonder shall be represented.

(3) examination of 100% of fabrication for bonds other than circumferential.

(4) random examination of the assembly of threaded, bolted, and other joints to satisfy the examiner that they conform to the applicable requirements of section 5-3. When pneumatic testing is to be performed, all threaded, bolted, and other mechanical joints shall be examined.

(5) random examination during erection of piping, including checking of alignment, supports, and cold spring.

(6) examination of erected piping and assembled joints for evidence of defects that would require repair or replacement, and for other evident deviations from the intent of the design.

(b) Other Types of Examination

(1) Not less than 5% of all bonded joints shall be examined by in-process examination in accordance with para. 6-2.7.4.

(2) The joints to be examined shall be selected to ensure that the work of each bonder and bonding operator making the production joints is examined.

(c) Certifications and Records

(1) The examiner shall be assured, by examination of certifications, records, and other evidence, that the materials and components are of the specified grades and that they have received the required manufacturing processes, examination, and testing.

(2) The examiner shall provide the Inspector with a certification that all the quality control requirements of this Standard and of the engineering design have been carried out.

6-2.3.2 Additional Required Examination. Piping systems and associated piping components designated in the governing Code as requiring examination beyond that specified in para. 6-2.3.1 shall be examined to the extent necessary to satisfy the examiner that components, materials, and workmanship conform to the requirements of this Standard, the governing Code, and the engineering design.

6-2.4 Supplementary Examination

6-2.4.1 General. Any applicable method of examination described in para. 6-2.7 may be specified by the engineering design to supplement the examination required by para. 6-2.3. The extent of supplementary examination to be performed and any acceptance criteria that differ from those in para. 6-2.2.2 shall be specified in the engineering design.

6-2.4.2 Examinations to Resolve Uncertainty. Any method of examination may be used to resolve uncertainty of results from the required examinations. Acceptance criteria shall be those for the required examination.

6-2.5 Examination Personnel

6-2.5.1 Personnel Qualification and Certification

(a) Examiners shall have training and experience commensurate with the needs of the specified examinations.

(b) The employer shall certify records of the examiners employed, showing dates and results of personnel qualifications, and maintain them and make them available to the Inspector.

6-2.5.2 Personnel for In-Process Examinations. In-process examinations shall be performed by personnel other than those performing the production work.

6-2.6 Examination Procedures

(a) Any examination shall be performed in accordance with a written procedure that conforms to one of the methods specified in para. 6-2.7, including special methods defined in para. 6-2.7.1(b).

(b) The employer shall certify records of the examination procedures employed, showing dates and results of procedure qualifications, and maintain them and make them available to the Inspector.

6-2.7 Types of Examination

6-2.7.1 General

(a) Methods Specified in This Standard. Except as provided in (b), any examination required by this Standard, the engineering design, or the Inspector shall be performed in accordance with one of the methods specified herein.

(b) Methods Not Specified in This Standard. If a method not specified herein is to be used, it and its acceptance criteria shall be specified in the engineering design in enough detail to permit qualification of the necessary procedures and examiners.

6-2.7.2 Visual Examination

(a) Definition. Visual examination is observation of the portion of components, joints, and other piping components that are or can be exposed to view during fabrication, assembly, erection, examination, or testing. This examination includes verification of materials, components, dimensions, joint preparation, alignment, bonding, bolting, threading, or other joining method, supports, assembly, and erection.

(b) Method. Visual examination shall be performed in accordance with the following:

(1) During the course of fabrication, assembly, or erection, the examiner shall make all such checks necessary to ensure that laminate imperfections (as defined in Table 4-3.2-1) are within the requirements of this Standard.

(2) The Quality Control Program shall include procedures and forms to be used to control the ongoing process of lamination so as to ensure that imperfections are within required tolerances prior to the final inspection.

(3) Visual examination shall be made before an exterior pigmented coating or insulation is applied to the piping system and/or components. If exterior pigmentation or insulation has been specified, the fabricator, owner, and Inspector shall discuss and agree on visual methods and arrange for closely timed and scheduled inspections.

(c) Acceptance Criteria

(1) The visual acceptance criteria shall be as stated in Table 4-3.2-1.

(2) In general, the acceptable quality level should be Level 2, as defined in Table 4-3.2-1.

(3) For cases in which failure or substantial leakage of the piping could pose high risk to the health or safety of personnel or cause significant economic loss, the designer or owner should consider specifying the acceptable quality level as Level 1, as defined in Table 4-3.2-1.

(d) Records. Records of individual visual examinations shall not be required, except for those of in-process examination as specified in para. 6-2.7.4.

6-2.7.3 Degree of Cure

(a) Method. The degree of cure shall be determined by Barcol hardness in accordance with ASTM D2583.

(b) Criteria. The reported Barcol hardness value shall be at least 90% of resin manufacturer's specified hardness for the cured resin.

6-2.7.4 In-Process Examination

(a) Definition. In-process examination shall comprise, but not be limited to, examination of the following:

(1) joint preparation and cleanliness

(2) fit-up, joint clearance, and internal alignment prior to joining

(3) materials specified by the joining procedure

(4) appearance of the finished joint

(b) Method. The in-process examination shall be a visual examination in accordance with para. 6-2.7.2 unless additional methods are specified in the engineering design.

6-3 TESTING

6-3.1 Required Leak Test

Prior to initial operation, each piping system shall be tested to ensure tightness. The test shall be a hydrostatic leak test in accordance with para. 6-3.4, except as provided herein.

(a) At the owner's option, a piping system may be subjected to an initial service leak test in accordance with para. 6-3.6 in lieu of the hydrostatic leak test.

(b) If the owner considers a hydrostatic leak test impracticable, a pneumatic test in accordance with para. 6-3.5 may be substituted. When such tests are performed, consideration shall be given to the hazard of energy stored in compressed gas. FRP piping tests carry much higher risks than those for metallic pipe because FRP material by its nature possesses less ductility than steel.

NOTE: See ASME PCC-2, Article 501 for detailed guidance on pneumatic testing.

(c) Lines open to the atmosphere, such as vents or drains downstream of the last shutoff valve, should be closed with temporary end closures and leak tested.

6-3.2 General Requirements for Leak Test

6-3.2.1 Limitations on Pressure

(a) Pressure Limits. Test pressure limits shall be as indicated in para. 2-2.3.8(b) or as agreed to by the owner and the contractor.

(b) Test Fluid Expansion. If a pressure test is to be maintained for a period of time and the test fluid in the system is subject to thermal expansion, precautions shall be taken to avoid excessive pressure.

(c) Preliminary Pneumatic Test. A preliminary test using air at no more than 70 kPa (10 psi) gauge pressure may be made prior to hydrostatic testing to locate major leaks.

6-3.2.2 Other Test Requirements

(a) A leak test shall be maintained for no less than 10 min, after which time all joints and connections shall be examined for leaks.

(b) The possibility of brittle fracture shall be considered when leak tests are conducted at low temperature.

6-3.2.3 Special Provisions for Testing

(a) Piping Subassemblies, Segments of System, and Full System. The full piping system may be tested as a whole, or subassemblies or segments of the system may be tested individually.

(b) Flanged Joints. Flanged joints used to connect piping components and subassemblies that have previously been tested, and flanged joints at which a blank or blind is used to isolate equipment or other piping during a test shall not be required to be retested in accordance with para. 6-3.1.

(c) Closure Bonds. The final bond connecting piping systems or components that have been successfully tested in accordance with section 6-3 shall not be required to be tested provided the bond is examined in-process in accordance with para. 6-2.7.4.

6-3.2.4 Externally Pressured Piping. Unjacketed piping designed for external pressure shall be tested at an internal gauge pressure 1.5 times the external differential pressure but not at less than 105 kPa (15 psi).

6-3.2.5 Repairs or Additions After Leak Testing. If repairs or additions are made following the leak test, the affected piping shall be retested, except that for minor repairs or additions the owner may waive retest requirements when precautionary measures are taken to ensure sound construction.

6-3.2.6 Test Records. The following information shall be recorded for each piping system tested:

(a) date of test
(b) identification of piping system tested
(c) test fluid
(d) test pressure
(e) certification of results by examiner

These records need not be retained after completion of the test if the owner retains the Inspector's certification that the piping has satisfactorily passed the pressure testing required by this Standard.

6-3.3 Preparation for Leak Test

6-3.3.1 Joints Exposed

(a) All joints and bonds (including structural and attachment bonds to pressure-containing components) shall be left uninsulated and exposed for examination during leak testing, except that joints and bonds previously tested in accordance with this Standard may be insulated or covered.

(b) All joints and bonds may be primed and painted prior to leak testing unless a sensitive leak test (see para. 6-3.7) is required.

6-3.3.2 Temporary Supports. Piping designed for vapor or gas shall be provided with additional temporary supports, if necessary, to support the weight of test liquid.

6-3.3.3 Piping With Expansion Joints

(a) Unrestrained expansion joints depend on external main anchors to resist pressure thrust forces. Except as limited in (c), a piping system containing unrestrained expansion joints shall be leak tested without any temporary restraints in accordance with section 6-3 up to 150% of the expansion joint design pressure. If the required test pressure exceeds 150% of the expansion joint design pressure and the main anchors are not designed to resist the pressure thrust forces at the required test pressure, for that portion of the test when the pressure exceeds 150% of the expansion joint design pressure, either the expansion joint shall be temporarily removed or temporary restraints shall be added to resist the pressure thrust forces.

(b) Except as limited in (c), a piping system containing self-restrained expansion joints shall be leak tested in accordance with section 6-3.

(1) A self-restrained expansion joint previously shop tested by the manufacturer in accordance with applicable provisions of ASME B31.3, Appendix X, may be excluded from the system to be leak tested, except when a sensitive leak test in accordance with para. 6-3.7 is required.

(2) Restraint hardware for all types of expansion joints shall be designed for the pressure thrust forces at the test pressure.

(c) When a bellows expansion joint is installed in a piping system that is subject to a leak test and the leak test pressure determined in accordance with section 6-3 exceeds the pressure of the test performed by the manufacturer in accordance with applicable provisions of ASME B31.3, Appendix X, the required leak test pressure shall be reduced to the manufacturer's test pressure.

6-3.3.4 Limits of Tested Piping. Equipment that is not to be tested shall be either disconnected from the piping or isolated by blinds or other means during the test. A valve may be used provided the valve (including its closure mechanism) is suitable for the test pressure.

6-3.4 Hydrostatic Leak Test

6-3.4.1 Test Fluid. The test fluid for a hydrostatic leak test shall be water unless there is the possibility of damage due to freezing or to adverse effects of water on the piping or the process. In those cases, another suitable nontoxic liquid that is compatible with the pipe material may be used.

6-3.4.2 Test Pressure. Except as provided in para. 6-3.4.3, the hydrostatic test pressure at any point in the piping system shall not be less than 1.33 times the design pressure.

6-3.4.3 Hydrostatic Test of Piping With Vessels as a System. The following provisions do not affect the pressure test requirements of any applicable vessel code:

(a) If the test pressure of piping attached to a vessel is the same as or less than the test pressure for the vessel, the piping may be tested with the vessel at the piping test pressure.

(b) If the test pressure of the piping exceeds the vessel test pressure, and it is not considered practicable to isolate the piping from the vessel, the piping and the vessel may be tested together at the vessel test pressure, provided the owner approves and the vessel test pressure is not less than 77% of the piping test pressure calculated in accordance with ASME B31.3, para. 345.4.2(b).

6-3.5 Pneumatic Leak Test

(a) Pneumatic leak tests shall be permitted only with the owner's approval and as allowed by the referenced code.

(b) In general, with the exception of testing low-pressure piping systems, pneumatic testing should be avoided.

(c) For gas fluid requirements and limitations, see section 2-6.

6-3.5.1 Precautions

(a) Pneumatic testing involves the hazard that energy stored in compressed gas could be released.

(b) Particular care shall be taken to minimize the chance of brittle failure during a pneumatic leak test.

(c) Material properties and test temperature shall be considered when the hazards associated with pneumatic testing are evaluated.

(d) See also paras. 6-3.1(b) and 6-3.2.2(b).

NOTE: See ASME PCC-2, Article 501 for more detailed guidance on pneumatic testing.

6-3.5.2 Pressure Relief Device. A pressure relief device having a set pressure not higher than the test pressure shall be provided.

6-3.5.3 Test Fluid. The gas used as test fluid, if not air, shall be nonflammable, noncombustible, and nontoxic.

6-3.5.4 Test Pressure. Unless otherwise defined by the governing code, the test pressure shall not be less than 1.1 times the design pressure and shall not exceed 1.33 times the design pressure.

6-3.5.5 Procedure

Step 1. The pressure shall be gradually increased until a gauge pressure that is the lesser of one-half the test pressure or 105 kPa (15 psi) is attained, at which time a preliminary check shall be made, including examination of joints in accordance with para. 6-2.4.1.

Step 2. The pressure shall be gradually increased in steps until the test pressure is reached; at each step, the pressure shall be held long enough to equalize piping strains.

Step 3. The test pressure should be maintained as indicated in para. 6-3.2.2(a).

Step 4. The pressure shall then be reduced to the design pressure before the system is examined for leakage in accordance with para. 6-3.2.2(a).

6-3.6 Initial Service Leak Test

An initial service leak test shall be applicable only when specifically allowed by the governing code and at the owner's option [see para. 6-3.1(a)].

6-3.7 Sensitive Leak Test

(a) The test pressure shall be in accordance with the following:

(1) The test pressure shall be at least the lesser of 105 kPa (15 psi) gauge or 25% of the design pressure.

(2) The pressure shall be gradually increased until a gauge pressure the lesser of one-half the test pressure or 105 kPa (15 psi) is attained, at which time a preliminary check shall be made. Then the pressure shall be gradually increased in steps until the test pressure is reached; at each step, the pressure shall be held long enough to equalize piping strains.

(b) Options of one or more of the test methods from ASME BPVC, Section V, Article 10, which allow the engineering design to modify specified requirements of the Mandatory Appendices V and VI test methods (such as acceptability limits for system leak tightness), may be used. Such options may be exercised only to make these requirements more sensitive or more conservative.

(c) The design specification shall identify the acceptance criteria for the specified sensitive leak testing techniques.

6-4 RECORDS

6-4.1 Responsibility

It shall be the responsibility of the piping designer, manufacturer, fabricator, and erector, as applicable, to prepare the records required by this Standard, the governing code, and the engineering design.

6-4.2 Retention of Records

Unless otherwise specified by the engineering design, the following records shall be retained for at least 5 yr after the record is generated for the project:

(a) examination procedures
(b) examination personnel qualifications
(c) examination data

MANDATORY APPENDIX I
DESIGN OF INTEGRAL FLAT-FACE FLANGES

I-1 SCOPE

This Appendix provides a design method for integral flat-face FRP flanges that use full-face gaskets. These requirements may be used to design flanges having ASME B16.5 or ASME B16.47 bolt circle and bolt hole diameters or to custom design flanges not meeting those standards.

NOTE: The design method herein is derived from a design method given in ASME BPVC, Section X, and Section VIII, Division 1, Mandatory Appendix 2.

I-2 LIMITATIONS

I-2.1 Size and Pressure

There is no size or pressure limitation for this design method, but in a larger flange at higher pressures the spot facing for the washers on the back side of the flange may thin out the hub more than 1.5 mm (0.06 in.), which is unacceptable. For custom designs of such flanges, the use of stress analysis procedures such as finite element analysis, found in ASME BPVC, Section VIII, Division 2, Part 2, using the allowable stresses for FRP given in ASME NM.3.3 shall be considered.

I-2.2 Hardness

Only full-face, soft elastomeric-type gaskets with or without reinforcement and with a maximum hardness of Shore A60 + 5 shall be used for flanges designed per section I-3. Harder gaskets are acceptable only if stress analysis methods are used to design the flange and empirical testing is used to verify leak tightness.

NOTE: When the flange is assembled, the guidelines outlined in ASME PCC-1 should be followed.

I-2.3 Construction

Flange construction shall be of either of the following styles:

(a) Flanges may be integral with the pipe neck where the flange is built up with laminate coming from the back side of the flange onto the pipe and forming a secondary bonded tapered hub on the back side to both attach the flange to the pipe and to provide the required flange thickness. The face of the flange is then covered with several plies of mat and one or more plies of surfacing veil extending from the outside diameter (O.D.) of the flange to the inside of the pipe. See Figure I-2.3-1, illustration (a).

(b) Flanges also may be integrally molded, including a pipe neck. See Figure I-2.3-1, illustration (b).

I-2.4 Material

Flanges greater than or equal to DN 100 (NPS 4) shall be constructed of Type II laminates using alternate plies of chopped-strand mat and woven roving. Flanges less than DN 100 (NPS 4) may be constructed of Type I all-mat laminates or Type II laminates. Compression molding, filament winding, or tape winding shall not be used to manufacture flanges designed in accordance with this Appendix.

I-2.5 Adhesives

Flanges that require the use of adhesives shall not be permitted.

I-2.6 Hub Reinforcement

For all flanges manufactured using Type II laminates, the hub reinforcement shall consist of alternating layers of mat and woven roving that are continuous from the hub to the O.D. of the flange.

I-2.7 Ring Plies

For all types of flange construction, the ring plies from the O.D. to the inside diameter (I.D.) of the flange shall be interspersed between the reinforcement plies that extend from the hub to the O.D. of the flange.

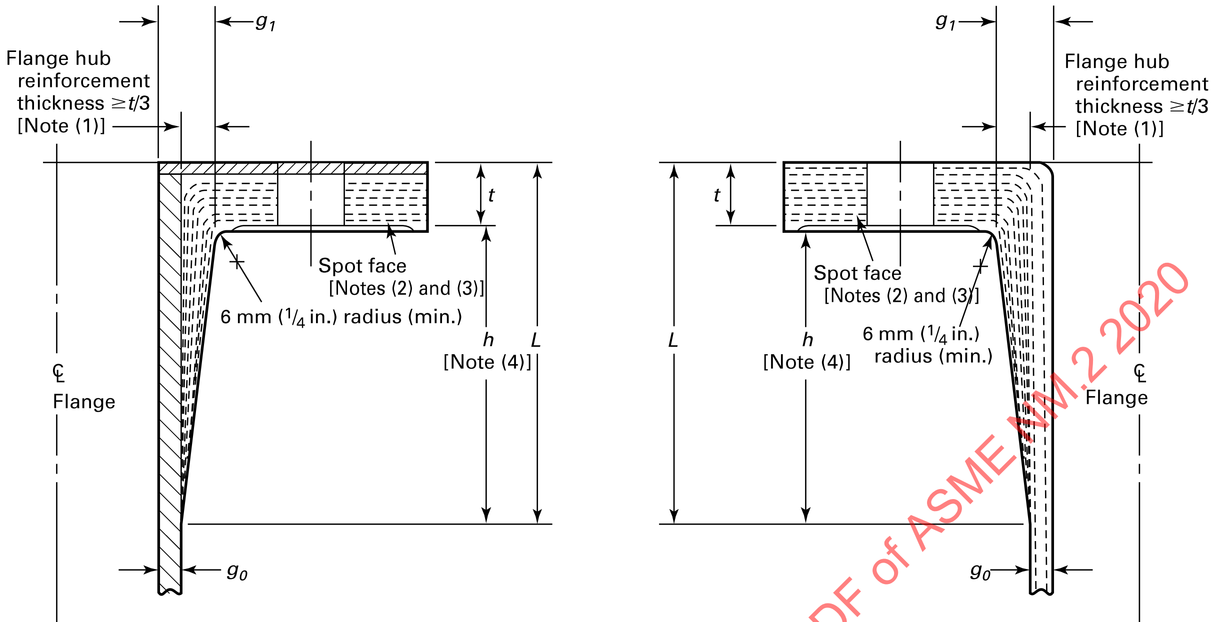
I-3 DESIGN OF FLANGES

I-3.1 Nomenclature (20)

The following symbols are used in the equations for the design of flat-face flanges employing full-face gaskets (see Figure I-3.3-1):

A = outside diameter of flange, mm (in.)
A_m = total required cross-sectional area of bolts; the greater of W_{m1}/S_b or W_{m2}/S_a, mm^2 (in.^{2})
B = inside diameter of flange, mm (in.)
b = effective gasket width or joint-contact-surface seating width, mm (in.)
C = diameter of bolt circle, mm (in.)

(20) **Figure I-2.3-1 Typical Flange Designs**



(a) Typical Integral Flange on Pipe Design (b) Typical Integrally Molded Flange Design

NOTES:
(1) Hub reinforcement thickness shall be calculated, but in no case shall it be less than $t/3$.
(2) Spot face for washers per ASME B18.21.1 Type A narrow plain washers. Spot facing should not cut into the hub thickness g_1 by more than 1.5 mm (0.06 in.). If this is unavoidable, then reinforcement shall be added to the flange inner diameter to compensate.
(3) The minimum flange thickness t shall be taken from the flange face to the surface of the spot face with a tolerance of +3 mm (−0 + $^1\!/_8$ in.). Flange thickness includes corrosion barrier
(4) Hub length, h, shall be greater than or equal to $3t$ and shall have a minimum 3:1 slope.

d = shape factor for integral-type flanges
= $\left|(U/V)h_0g_0^2\right|$
d_1 = bolt hole diameter, mm (in.)
e = shape factor
= F/h_0
F = shape factor (see Figure I-3.3-3)
f = hub stress correction factor (see Figure I-3.3-4)
= 1 for calculated values less than 1
G = diameter of gasket load reaction, mm (in.)
g_0 = thickness of hub at small end, mm (in.)
g_1 = thickness of hub at back of flange, mm (in.)
H = hydrostatic end force, N (lb)
h = length of hub, mm (in.)
h_0 = factor
= $(Bg_0)^{0.5}$
H_D = hydrostatic end force on area inside of flange, N (lb)
h_D = radial distance from bolt circle to circle on which H_D acts, mm (in.)
H_G = difference between bolt load and hydrostatic end force, N (lb)
h_G = radial distance from bolt circle to circle on which H_G acts, mm (in.)
h'_G = radial distance from bolt circle to gasket load reaction, mm (in.)
h''_G = flange lever arm, mm (in.)
H_{Gy} = bolt load for gasket yielding, N (lb)
= $b\pi Gy$
H'_{Gy} = compression load required to seat gasket outside G diameter, N (lb)
H_p = total joint-contact-surface compression load, N (lb)
= $2b\pi Gmp$
H'_p = total adjusted joint-contact-surface compression for full-face gasketed flange, N (lb)
= $(h_G/h'_G)H_p$
H_T = difference between total hydrostatic end force and the hydrostatic end force area inside of flange, N (lb)
= $H - H_D$
h_T = radial distance from bolt circle to circle on which H_T acts, mm (in.)
K = ratio of inside flange diameter to outside flange diameter

L = length of flange including hub, mm (in.)
M = unit load, operating, N (lb)
= M_{max}/B
m = gasket factor
= 0 to 0.50 for soft gaskets; use manufacturer's recommendations
M_0 = total moment
M_a = moment under bolt-up conditions
M_D = component of moment due to H_D
M_G = component of moment due to H_G
M_{max} = max(M_0, M_G)
M_T = component of moment due to H_T
N = number of bolts
p = design pressure, kPa (psi)
R = radial distance from bolt circle to point of intersection to hub and back of flange, mm (in.)
= $(C - B)/2 - g_1$
S_a = allowable bolt stress at ambient temperature, kPa (psi)
S_b = allowable bolt stress at design temperature, kPa (psi)
S_{Fa} = allowable flange stress at ambient temperature, kPa (psi)
S_{Fo} = allowable flange stress at design temperature, kPa (psi)
S_H = longitudinal hub stress, kPa (psi)
S_R = radial flange stress, kPa (psi)
S_{RAD} = radial stress at bolt circle, kPa (psi)
S_T = tangential flange stress, kPa (psi)
T = shape factor (see Figure I-3.3-5)
t = flange thickness, mm (in.)
U = shape factor (see Figure I-3.3-5)
V = shape factor (see Figure I-3.3-2)
W_a = flange design bolt load for operating conditions or gasket seating as may apply, N (lb)
W_{m1} = minimum bolt loading for design conditions, N (lb)
W_{m2} = minimum bolt loading for bolt-up conditions, N (lb)
Y = shape factor (see Figure I-3.3-5)
y = gasket unit seating load, kPa (psi)
= 345 kPa to 1 379 kPa (50 psi to 200 psi) for soft gaskets; use manufacturer's recommendations
Z = shape factor (see Figure I-3.3-5)

I-3.2 Allowable Flange Stress

The flange thickness shall be designed such that the allowable stress does not exceed the allowable flexural stress given in ASME NM.3.3.

(20) I-3.3 Calculation Procedure

Calculation procedures are as follows (see also Figures I-3.3-1 through I-3.3-5, and Table I-3.3-1):

(a) Determine design conditions, material properties, and dimensions of flange, bolts, and gasket.

(b) Determine the lever arms of the inner and outer parts of the gasket:

$$h_G = \frac{(C - B)(2B + C)}{6(B + C)} \tag{I-3-1}$$

$$h'_G = \frac{(A - C)(2A + C)}{6(C + A)} \tag{I-3-2}$$

(c) Determine the gasket dimensions:

$$G = C - 2h_G \tag{I-3-3}$$

$$b = (C - B)/4 \tag{I-3-4}$$

(d) Determine loads:

$$H = G^2 \pi p/4 \tag{I-3-5}$$

$$H_p = 2b\pi Gmp \tag{I-3-6}$$

$$H'_p = (h_G/h'_G)H_p \tag{I-3-7}$$

$$W_{m1} = H_p + H + H'_p \tag{I-3-8}$$

$$H_{Gy} = b\pi Gy \tag{I-3-9}$$

$$H'_{Gy} = (h_G/h'_G)H_{Gy}$$

$$W_{m2} = H_{Gy} + H'_{Gy} \tag{I-3-10}$$

(e) Determine the bolting requirements:

$$A_1 = W_{m1}/S_b \tag{I-3-11}$$

$$A_2 = W_{m2}/S_a \tag{I-3-12}$$

A_m = greater of A_1 or A_2.
W_a = 1.25 (greater of W_{m1} or W_{m2}).

NOTE: To ensure that the flange is not overstressed, the bolts shall be tightened using a procedure that controls torque in a manner that ensures W_a is not exceeded.

(f) Determine flange load, moments, and lever arms:

$$H_D = \pi B^2 p/4 \tag{I-3-13}$$

$$H_T = H - H_D \tag{I-3-14}$$

$$h_D = R + 0.5g_1 \tag{I-3-15}$$

$$h_T = 0.5(R + g_1 + h_G) \tag{I-3-16}$$

$$M_D = H_D h_D \tag{I-3-17}$$

$$M_T = H_T h_T \tag{I-3-18}$$

$$M_0 = M_D + M_T \tag{I-3-19}$$

(g) Determine flange moment at gasket seating condition:

$$H_G = W_a - H \tag{I-3-20}$$

$$h''_G = \frac{h_G h'_G}{h_G + h'_G} \tag{I-3-21}$$

$$M_G = H_G h''_G \tag{I-3-22}$$

(h) Assume a flange thickness, t.

(i) Calculate stress and compare to allowable stress:

$$S_{RAD} = \frac{6M_G}{t^2(\pi C - Nd_1)} < \text{allowable} \tag{I-3-23}$$

$$S_H = fM/\lambda g_1^2 < \text{allowable} \tag{I-3-24}$$

$$S_R = \beta M/\lambda t^2 < \text{allowable} \tag{I-3-25}$$

$$S_T = \left(MY/t^2\right) - ZS_R < \text{allowable} \tag{I-3-26}$$

where f, β and λ are defined in Figure I-3.3-1 and $M = M_{max}/B$.

Figure I-3.3-1 Design of Flat-Face Integral Flanges

(20)

Design Conditions				Gasket and Bolting Calculations		
Design pressure, p			kPa (psi)	Gasket details	G	$C - 2h_G$
Design temp.			°C (°F)		b	$(C - B)/4$
Atmospheric temp.			°C (°F)	Facing details	y	
Flange material					m	
Bolting material				$h_G = \dfrac{(C-B)(2B+C)}{6(B+C)} =$	$h'_G = \dfrac{(A-C)(2A+C)}{6(C+A)} =$	
$A =$	$B =$	$C =$				
Allowable bolt stress	Oper. temp.	S_b	kPa (psi)	$H_p = 2b\pi Gmp =$	$H_{Gy} = b\pi Gy =$	
	Atm. temp.	S_a	kPa (psi)	$H = \dfrac{G^2\pi p}{4} =$	$H'_{Gy} = \left(\dfrac{h_G}{h'_G}\right) H_{Gy} =$	
Allowable flange stress	Oper. temp.	S_{Fo}	kPa (psi)	$H'_p = \left(\dfrac{h_G}{h'_G}\right) H_p =$	$W_{m2} = H_{Gy} + H'_{Gy} =$	
	Atm. temp	S_{Fa}	kPa (psi)	$W_{m1} = H_p + H + H'_p =$		

Bolting requirement	$A_m =$ greater of $\dfrac{W_{m1}}{S_b}$ and $\dfrac{W_{m2}}{S_a} =$	$A_B =$	$W_a = 1.25$ (greater of W_{m1} or W_{m2})

Flange Moment at Operating Conditions

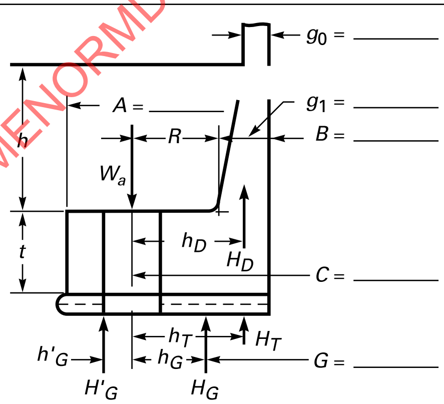
Flange Loads (Operating Condition)	Lever Arms	Flange Moments (Operating Condition)
$H_D = \pi B^2 p/4 =$	$h_D = R + 0.5g_1 =$	$M_D = H_D \times h_D =$
$H_T = H - H_D =$	$h_T = 0.5(R + g_1 + h_G) =$	$M_T = H_T \times h_T =$
		$M_0 = M_D + M_T =$

Flange Moment at Gasket Seating Conditions

Flange Load (Bolting-Up Condition)	Lever Arm	Flange Moment (Bolting-Up Condition)
$H_G = W_a - H =$	$h''_G = h_G h'_G/(h_G + h'_G) =$	$M_G = H_G \times h''_G =$

M_{max} = greater of M_0 or $M_a \times \dfrac{S_{Fo}}{S_{Fa}}$	(Equivalent to checking for M_0 at allowable flange stress of S_{Fo} and separately for M_a at allowable flange stress of S_{Fa})	$M = \dfrac{M_{max}}{B} =$

Stress Calculation	Shape Constants		
Longitudinal hub stress $S_H = fM/\lambda g_1^2$	$K = A/B =$		$h_0 = \sqrt{Bg_0} =$
Radial flange stress $S_R = \beta M/\lambda t^2$	$T =$	=	$h/h_0 =$
Tangential flange stress $S_T = (MY/t^2) - ZS_R$	$Z =$	=	$F =$
Greater of $0.5(S_H + S_R)$ or $0.5(S_H + S_T)$	$Y =$	=	$V =$
Radial stress at bolt circle $S_{RAD} = \dfrac{6M_G}{t^2(\pi C - Nd_1)}$	$U =$	=	$f =$
	$g_1/g_0 =$		$e = F/h_0$

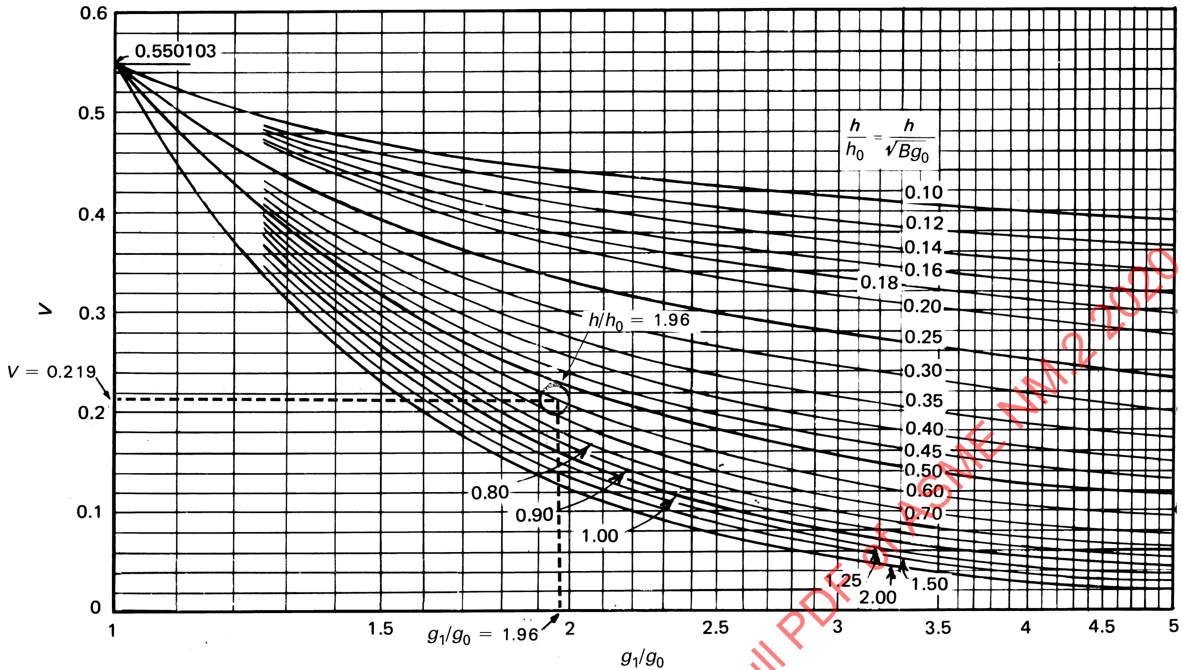


$d = \dfrac{U}{V} h_0 g_0^2 =$			
t (assumed)			
$\alpha = te + 1$			
$\beta = {}^4/_3 te + 1$			
$\gamma = \alpha/T$			
$\delta = t^3/d$			
$\lambda = \gamma + \delta$			

N = No. bolts = ______
d_1 = Dia. bolt holes = ______

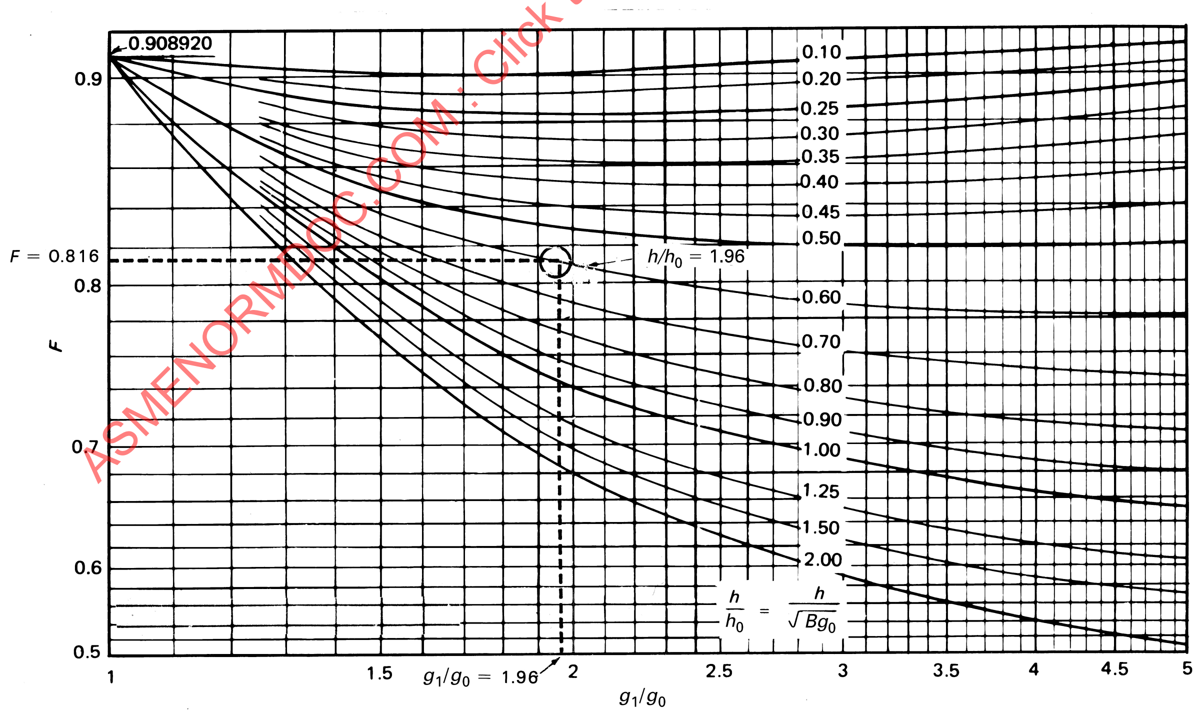
GENERAL NOTE: See Table I-3.3-1 for equations.

Figure I-3.3-2 Values of *V* (Integral Flange Factor)



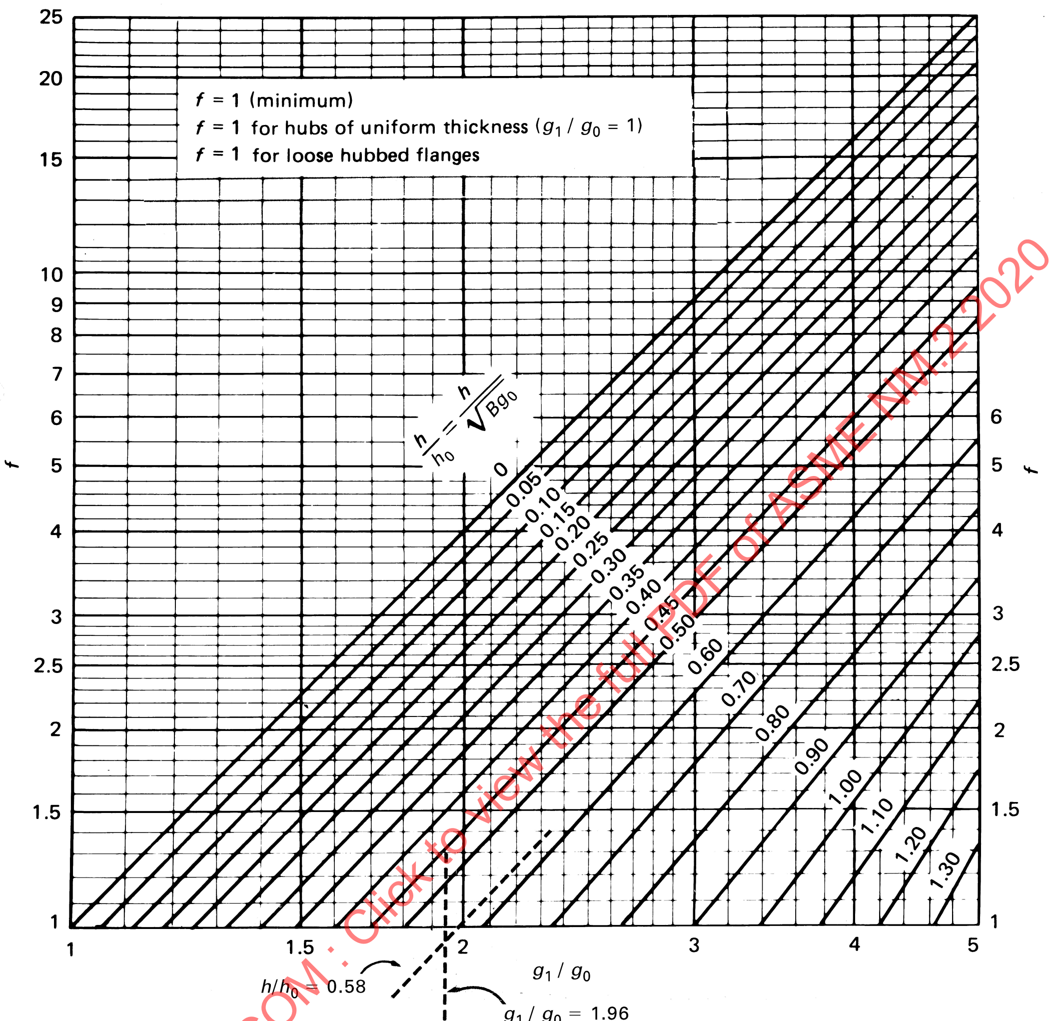
GENERAL NOTE: See Table I-3.3-1 for equations.

Figure I-3.3-3 Values of *F* (Integral Flange Factor)



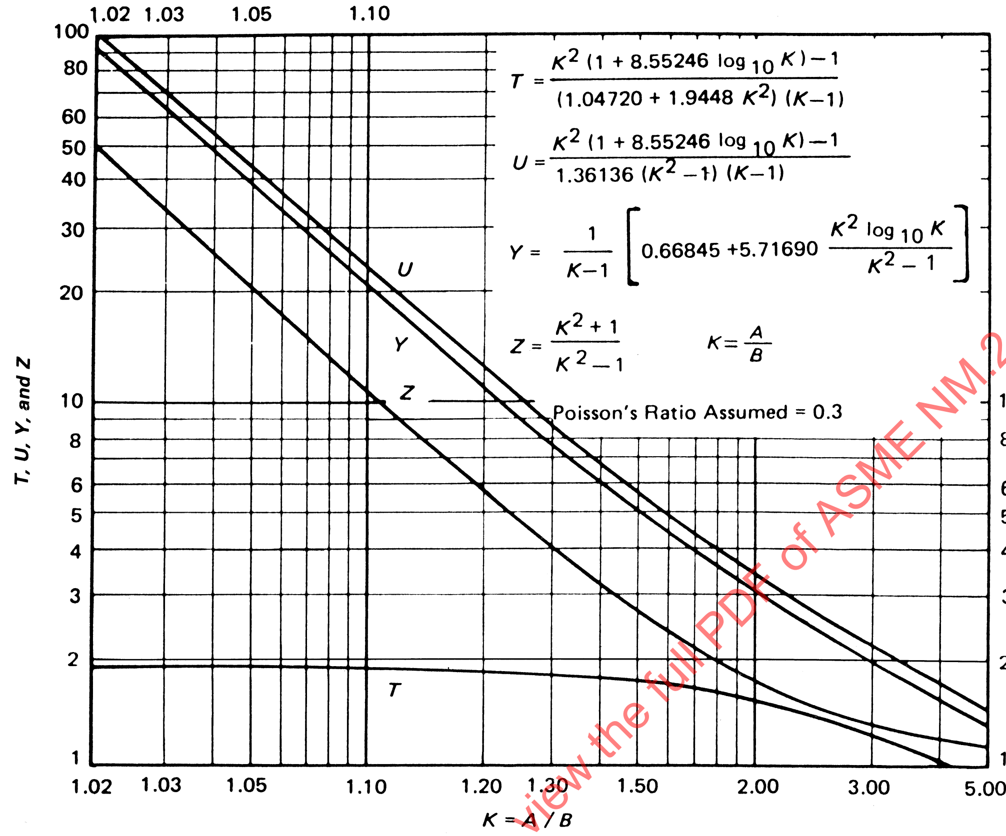
GENERAL NOTE: See Table I-3.3-1 for equations.

Figure I-3.3-4 Values of *f* (Hub Stress Correction Factor)



GENERAL NOTE: See Table I-3.3-1 for equations.

Figure I-3.3-5 Values of *T*, *U*, *Y*, and *Z* (Terms Involving *K*)



GENERAL NOTE: See Table I-3.3-1 for equations.

Table I-3.3-1 Flange Factors in Formula Form

Integral Flange

Factor V per Figure I-3.3-2 is then solved by

$$V = \frac{E_4}{\left(\frac{2.73}{C_0}\right)^{1/4} (1 + A_0)^3}$$

Factor F per Figure I-3.3-3 is then solved by

$$F = \frac{E_6}{\left(\frac{C_0}{2.73}\right)^{1/4} \frac{(1 + A_0)^3}{C_0}}$$

Factor f per Figure I-3.3-4 is then solved by

$$f = \frac{C_{36}}{(1 + A_0)}$$

The values used in the above equations are solved using eqs. (1) through (45) below based on the values g_1, g_0, h, and h_0 as defined by para. I-3.1. When $g_1 = g_0$, F = 0.908920, V = 0.550103, and f = 1; thus eqs. (1) through (45) need not be solved.

Equations

(1) $A_0 = (g_1/g_0) - 1$

(2) $C_0 = 43.68(h/h_0)^4$

(3) $C_1 = 1/3 + A_0/12$

(4) $C_2 = 5/42 + 17A_0/336$

(5) $C_3 = 1/210 + A_0/360$

(6) $C_4 = 11/360 + 59A_0/5\,040 + (1 + 3A_0)/C_0$

(7) $C_5 = 1/90 + 5A_0/1\,008 - (1 + A_0)^3/C_0$

(8) $C_6 = 1/120 + 17A_0/5\,040 + 1/C_0$

(9) $C_7 = 215/2\,772 + 51A_0/1\,232 + (60/7 + 225A_0/14 + 75A_0^2/7 + 5A_0^3/2)/C_0$

(10) $C_8 = 31/6\,930 + 128A_0/45\,045 + (6/7 + 15A_0/7 + 12A_0^2/7 + 5A_0^3/11)/C_0$

(11) $C_9 = 533/30\,240 + 653A_0/73\,920 + (1/2 + 33A_0/14 + 39A_0^2/28 + 25A_0^3/84)/C_0$

(12) $C_{10} = 29/3\,780 + 3A_0/704 - (1/2 + 33A_0/14 + 81A_0^2/28 + 13A_0^3/12)/C_0$

(13) $C_{11} = 31/6\,048 + 1\,763A_0/665\,280 + (1/2 + 6A_0/7 + 15A_0^2/28 + 5A_0^3/42)/C_0$

(14) $C_{12} = 1/2\,925 + 71A_0/300\,300 + (8/35 + 18A_0/35 + 156A_0^2/385 + 6A_0^3/55)/C_0$

(15) $C_{13} = 761/831\,600 + 937A_0/1\,663\,200 + (1/35 + 6A_0/35 + 11A_0^2/70 + 3A_0^3/70)/C_0$

(16) $C_{14} = 197/415\,800 + 103A_0/332\,640 - (1/35 + 6A_0/35 + 17A_0^2/70 + A_0^3/10)/C_0$

(17) $C_{15} = 233/831\,600 + 97A_0/554\,400 + (1/35 + 3A_0/35 + A_0^2/14 + 2A_0^3/105)/C_0$

(18) $C_{16} = C_1C_7C_{12} + C_2C_8C_3 + C_3C_8C_2 - (C_3^2C_7 + C_8^2C_1 + C_2^2C_{12})$

Table I-3.3-1 Flange Factors in Formula Form (Cont'd)

Equations (Cont'd)
(19) $C_{17} = [C_4C_7C_{12} + C_2C_8C_{13} + C_3C_8C_9 - (C_{13}C_7C_3 + C_8{}^2C_4 + C_{12}C_2C_9)]/C_{16}$
(20) $C_{18} = [C_5C_7C_{12} + C_2C_8C_{14} + C_3C_8C_{10} - (C_{14}C_7C_3 + C_8{}^2C_5 + C_{12}C_2C_{10})]/C_{16}$
(21) $C_{19} = [C_6C_7C_{12} + C_2C_8C_{15} + C_3C_8C_{11} - (C_{15}C_7C_3 + C_8{}^2C_6 + C_{12}C_2C_{11})]/C_{16}$
(22) $C_{20} = [C_1C_9C_{12} + C_4C_8C_3 + C_3C_{13}C_2 - (C_3{}^2C_9 + C_{13}C_8C_1 + C_{12}C_4C_2)]/C_{16}$
(23) $C_{21} = [C_1C_{10}C_{12} + C_5C_8C_3 + C_3C_{14}C_2 - (C_3{}^2C_{10} + C_{14}C_8C_1 + C_{12}C_5C_2)]/C_{16}$
(24) $C_{22} = [C_1C_{11}C_{12} + C_6C_8C_3 + C_3C_{15}C_2 - (C_3{}^2C_{11} + C_{15}C_8C_1 + C_{12}C_6C_2)]/C_{16}$
(25) $C_{23} = [C_1C_7C_{13} + C_2C_9C_3 + C_4C_8C_2 - (C_3C_7C_4 + C_8C_9C_1 + C_2{}^2C_{13})]/C_{16}$
(26) $C_{24} = [C_1C_7C_{14} + C_2C_{10}C_3 + C_5C_8C_2 - (C_3C_7C_5 + C_8C_{10}C_1 + C_2{}^2C_{14})]/C_{16}$
(27) $C_{25} = [C_1C_7C_{15} + C_2C_{11}C_3 + C_6C_8C_2 - (C_3C_7C_6 + C_8C_{11}C_1 + C_2{}^2C_{15})]/C_{16}$
(28) $C_{26} = -(C_0/4)^{1/4}$
(29) $C_{27} = C_{20} - C_{17} - 5/12 + C_{17}C_{26}$
(30) $C_{28} = C_{22} - C_{19} - 1/12 + C_{19}C_{26}$
(31) $C_{29} = -(C_0/4)^{1/2}$
(32) $C_{30} = -(C_0/4)^{3/4}$
(33) $C_{31} = 3A_0/2 - C_{17}C_{30}$
(34) $C_{32} = 1/2 - C_{19}C_{30}$
(35) $C_{33} = 0.5C_{26}C_{32} + C_{28}C_{31}C_{29} - (0.5C_{30}C_{28} + C_{32}C_{27}C_{29})$
(36) $C_{34} = 1/12 + C_{18} - C_{21} - C_{18}C_{26}$
(37) $C_{35} = -C_{18}(C_0/4)^{3/4}$
(38) $C_{36} = (C_{28}C_{35}C_{29} - C_{32}C_{34}C_{29})/C_{33}$
(39) $C_{37} = [0.5C_{26}C_{35} + C_{34}\ C_{31}C_{29} - (0.5C_{30}C_{34} + C_{35}C_{27}C_{29})]/C_{33}$
(40) $E_1 = C_{17}C_{36} + C_{18} + C_{19}C_{37}$
(41) $E_2 = C_{20}C_{36} + C_{21} + C_{22}C_{37}$
(42) $E_3 = C_{23}C_{36} + C_{24} + C_{25}C_{37}$
(43) $E_4 = 1/4 + C_{37}/12 + C_{36}/4 - E_3/5 - 3E_2/2 - E_1$
(44) $E_5 = E_1(1/2 + A_0/6) + E_2(1/4 + 11A_0/84) + E_3(1/70 + A_0/105)$
(45) $E_6 = E_5 - C_{36}(7/120 + A_0/36 + 3A_0/C_0) - 1/40 - A_0/72 - C_{37}(1/60 + A_0/120 + 1/C_0)$

MANDATORY APPENDIX II
CALCULATION OF PHYSICAL AND MECHANICAL PROPERTIES USING THE LAMINATE ANALYSIS METHOD

(20)

II-1 SCOPE

This Appendix details the use of micromechanics and classical lamination theory (CLT) analysis methods to calculate the laminate properties needed for design. The application of the principals of micromechanics allows the physical and mechanical properties of a lamina to be determined based on its constituent materials. The CLT method consists of integrating the physical and mechanical properties of each lamina through the thickness of the laminate allowing the physical and mechanical properties of the laminate to be determined. Once the properties of the laminate have been determined, the laminate can be analyzed for various load inputs. The analysis allows the stresses and strains to be determined, and the computation of the strength ratios of each lamina using the Tsai-Wu interaction criteria.

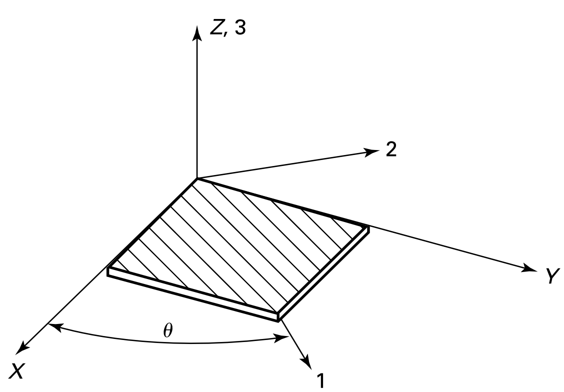
II-2 COORDINATE SYSTEMS

Two coordinate systems, as illustrated in Figure II-2-1, are used in the application of micromechanics and CLT of flat plates. When relating to the local coordinates of a material, the principal axes are identified as directions 1, 2, and 3. Within the local coordinate system, direction 1 is aligned along the length of the fiber, direction 2 is perpendicular to direction 1, and within the plane of the lamina. Direction 3 is normal to the 1–2 plane. Notations for in-plane shear are commonly simplified to direction 6.

The second coordinate system relates to the global, or structural coordinate system. While referencing the global coordinate system, the principal axes are identified as x, y, and z. Within the global coordinate system, axes x and y represent the laminate in-plane directions, and z is oriented through the thickness of the lamina or laminate. Axes x and y can be oriented for convenience; however, it is typical in the analysis of cylinders that x is aligned with the axial direction, and y with hoop.

The material coordinate system can be related to the global coordinate system by conducting a rotation through the angle theta. Using the conventions described above for the orientations of the global coordinate system on a cylinder, a unidirectional layer oriented at an angle of 0 deg would represent an axial reinforcement; an orientation of 90 deg would therefore represent a hoop reinforcement.

Figure II-2-1 Coordinate System



Legend:

1, 2, 3 = material coordinates
x, y, z = piping coordinates

II-3 DETERMINATION OF LAMINA PROPERTIES

The physical properties of a lamina can be determined by testing or when test data is not available, the physical properties of a lamina can be predicted by the application of micromechanics. This section details the methods that are to be used to predict the properties of a lamina in the absence of test data.

II-3.1 Volume and Weight Fractions

(a) General. Two conditions typically exist when defining a lamina; either

(1) the thickness and the fiber weight fraction are known (such as the application of a unidirectional roving), or

(2) the thickness and reinforcement weight are known (such as a layer of woven roving or chopped strand mat)

In both cases, information such as the lamina thickness, fiber density, and the matrix (resin) density must be known to predict the properties of the lamina. The lamina thicknesses shall be based on measurement unless the lamina has not yet been produced. In such cases it will be necessary to estimate the expected thickness. Thicknesses shall, however, be confirmed once the lamina has been produced.

(b) In cases where the lamina thickness and fiber weight fraction are known [(a)(1)], the following approach is used:

Step 1. First, determine the volume fractions from the following equations:

$$V_f = \frac{W_f \rho_m}{\rho_f - W_f \rho_f + W_f \rho_m}$$

$$V_m = 1 - V_f$$

where

V_f = volume fraction of the fiber, dimensionless
V_m = volume fraction of the matrix, dimensionless
W_f = weight fraction of the reinforcing fiber, dimensionless
ρ_m = density of the matrix, kg/mm^3 (lb/in.^{3})
ρ_f = density of the reinforcement, kg/mm^3 (lb/in.^{3})

Step 2. Next, determine the volume per unit area of the constituent materials from the following equations:

$$v_{Af} = V_f(t_k A_u)$$

$$v_{Am} = t_k A_u - v_{Af}$$

where

A_u = unit area, mm^2/mm^2 (144 in.^{2}/ft^2)
t_k = thickness of the layer k, mm (in.)
v_{Af} = volume of the reinforcing fibers per unit area, mm^3/mm^2 (in.^{3}/ft^2)
v_{Am} = volume of the matrix per unit area, mm^3/mm^2 (in.^{3}/ft^2)

Step 3. Then, determine the reinforcement weight, W, kg/mm^2 (lb/ft^2)

$$W = v_{Af} \rho_f$$

(c) In cases where the thickness and the reinforcement weight are known [(a)(2)], the following approach is used:

Step 1. First, determine the volume per unit area of the constituent materials

$$v_{Af} = \frac{W}{\rho_f}$$

$$v_{Am} = t_k A_u - v_{Af}$$

Step 2. Next, the volume fractions are determined

$$V_f = \frac{v_{Af}}{v_{Af} + v_{Am}}$$

$$V_m = 1 - V_f$$

Step 3. Then the fiber weight fraction is determined

$$W_f = \frac{V_f \rho_f}{V_f \rho_f + (1 - V_f)\rho_m}$$

(d) Determining Density of the Lamina. Once the above computations have been completed, the density of the lamina, ρ_c, kg/mm^3 (lb/in.^{3}), can be determined

$$\rho_c = \rho_m(1 - V_f) + V_f \rho_f$$

II-3.2 Mechanical Properties for a Lamina With Unidirectional Reinforcement

II-3.2.1 Elastic Properties

(a) The formulas necessary to determine the elastic properties of a lamina with unidirectional reinforcement are included herein. It should be noted that it is assumed that a uniform fiber orientation and distribution exists throughout the thickness of the lamina.

(1) Knowing the mechanical properties of the constituent materials, the plane strain bulk moduli are first computed. These are

The plane strain bulk modulus for isotropic fibers, MPa (psi)

$$K_f = \frac{E_f}{2(1 - \nu_f - 2{\nu_f}^2)}$$

The plane strain bulk modulus for an isotropic matrix, MPa (psi)

$$K_m = \frac{E_m}{2(1 - \nu_m - 2{\nu_m}^2)}$$

where

E_f = the modulus of elasticity of the fiber, MPa (psi)
E_m = the modulus of elasticity of the matrix, MPa (psi)
ν_f = the Poisson's ratio of the fiber, dimensionless
ν_m = the Poisson's ratio of the matrix, dimensionless

If the shear moduli of the constituent materials are not available, and they can be assumed to be isotropic, then the following relations can be used:

The shear modulus of the fiber, MPa (psi)

$$G_f = \frac{E_f}{2(1-\nu_f)}$$

The shear modulus of the matrix, MPa (psi)

$$G_m = \frac{E_m}{2(1-\nu_m)}$$

(2) Next, the following relations must be determined:
The plane strain bulk modulus for the lamina, MPa (psi)

$$K_{\text{star}} = \frac{V_m \cdot K_m \cdot \left(K_f + G_m\right) + V_f \cdot K_f \cdot (K_m + G_m)}{V_m \cdot \left(K_f + G_m\right) + V_f \cdot (K_m + G_m)}$$

To simplify the remainder of the analysis the following are used:

$$\gamma = \frac{G_f}{G_m}$$

$$\eta_m = 3 - 4\nu_m$$

$$\eta_f = 3 - 4\nu_f$$

$$A = 3 \cdot V_f \cdot V_m{}^2 \cdot (\gamma - 1) \cdot \left(\gamma + \eta_f\right) + \left[\gamma \cdot \eta_m + \eta_f \cdot \eta_m - \left(\gamma \cdot \eta_m - \eta_f\right) \cdot V_f{}^3\right] \cdot \left[V_f \cdot \eta_m \cdot (\gamma - 1) - (\gamma \cdot \eta_m + 1)\right]$$

$$B = -3 \cdot V_f \cdot V_m{}^2 \cdot (\gamma - 1) \cdot \left(\gamma + \eta_f\right) + \frac{1}{2}\left[\gamma \cdot \eta_m + (\gamma - 1) \cdot V_f + 1\right] \cdot \left[(\eta_m - 1) \cdot \left(\gamma + \eta_f\right) - 2 \cdot \left(\gamma \cdot \eta_m - \eta_f\right) \cdot V_f{}^3\right] + \frac{V_f}{2} \cdot (\eta_m + 1) \cdot (\gamma - 1) \cdot \left[\gamma + \eta_f + \left(\gamma \cdot \eta_m - \eta_f\right) \cdot V_f{}^3\right]$$

$$C = 3 \cdot V_f \cdot V_m{}^2 \cdot (\gamma - 1) \cdot \left(\gamma + \eta_f\right) + \left[\gamma \cdot \eta_m + (\gamma - 1) \cdot V_f + 1\right] \cdot \left[\gamma + \eta_f + \left(\gamma \cdot \eta_m - \eta_f\right) \cdot V_f{}^3\right]$$

(3) Finally, the mechanical properties of the lamina can be determined by the following:
The modulus of elasticity in the fiber direction, MPa (psi)

$$E_{11} = E_m \cdot V_m + E_f \cdot V_f + \frac{4 \cdot (\nu_f - \nu_m)^2 \cdot V_m \cdot V_f}{\frac{V_m}{K_f} + \frac{V_f}{K_m} + \frac{1}{G_m}}$$

The major in-plane Poisson's ratio, mm/mm (in./in.)

$$\nu_{12} = \nu_m \cdot V_m + \nu_f \cdot V_f + \frac{(\nu_f - \nu_m) \cdot \left(\frac{1}{K_m} - \frac{1}{K_f} \right) \cdot V_m \cdot V_f}{\frac{V_m}{K_f} + \frac{V_f}{K_m} + \frac{1}{G_m}}$$

The in-plane shear modulus, MPa (psi)

$$G_{12} = G_m + \frac{V_f}{\frac{1}{\left(G_f - G_m\right)} + \frac{V_m}{2 \cdot G_m}}$$

The transverse interlaminar shear modulus, MPa (psi)

$$G_{23} = \frac{-G_m \cdot \left[\sqrt{4 \cdot B^2 - 4 \cdot A \cdot C} + 2 \cdot B \right]}{2 \cdot A}$$

The modulus of elasticity transverse to the fiber direction, MPa (psi)

$$E_{22} = \frac{4 \cdot K_{\text{star}} \cdot G_{23}}{K_{\text{star}} + \left(1 + \frac{4 \cdot K_{\text{star}} \cdot {\nu_{12}}^2}{E_{11}} \right) \cdot G_{23}}$$

The minor in-plane Poisson's ratio, mm/mm (in./in.)

$$\nu_{21} = \frac{E_{22}}{E_{11}} \cdot \nu_{12}$$

Properties normal to the plane of the lamina can also be computed using the following:
The modulus of elasticity through the thickness of the lamina, MPa (psi)

$$E_{33} = E_{22}$$

The fiber direction interlaminar shear modulus, MPa (psi)

$$G_{13} = G_{12}$$

The fiber direction interlaminar Poisson's ratio, mm/mm (in./in.)

$$\nu_{13} = \nu_{12}$$

The transverse interlaminar Poisson's ratio, mm/mm (in./in.)

$$\nu_{23} = \frac{K_{\text{star}} - \left(1 + \frac{4 \cdot K_{\text{star}} \cdot {\nu_{12}}^2}{E_1} \right) \cdot G_{23}}{K_{\text{star}} + \left(1 + \frac{4 \cdot K_{\text{star}} \cdot {\nu_{12}}^2}{E_1} \right) \cdot G_{23}}$$

The minor out-of-plane Poisson's ratio, mm/mm (in./in.)

$$\nu_{31} = \nu_{21}$$

The transverse interlaminar Poisson's ratio, mm/mm (in./in.)

$$\nu_{32} = \nu_{23}$$

II-3.2.2 Thermal Mechanical Properties. The formulas necessary to determine the thermal mechanical properties of a lamina with unidirectional reinforcement are included herein. As indicated in para. II-3.2.1, it is assumed that a uniform fiber orientation and distribution exists throughout the thickness of the lamina.

The coefficient of thermal expansion along the direction of the fiber, mm/mm/°C (in./in./°F)

$$\alpha_{11} = \frac{V_f E_f \alpha_f + \left(1 - V_f\right) E_m \alpha_m}{V_f E_f + \left(1 - V_f\right) E_m}$$

The coefficient of thermal expansion transverse to the direction of the fiber, mm/mm/°C (in./in./°F)

$$\alpha_{22} = V_f \alpha_f \left(1 + \nu_f\right) + \left(1 - V_f\right) \alpha_m (1 + \nu_m) - \alpha_{11} \nu_{12}$$

where

α_f = the coefficient of thermal expansion of the fiber, mm/mm/°C (in./in./°F)

α_m = the coefficient of thermal expansion of the matrix, mm/mm/°C (in./in./°F)

II-3.3 Mechanical Properties for a Lamina With Randomly Oriented Reinforcement

When a lamina is reinforced with randomly oriented fibers, the in-plane properties can be considered isotropic. To determine the properties of a lamina with randomly oriented reinforcements, it is necessary to first compute the properties of a representative lamina with unidirectional reinforcements. The approach detailed herein assumes that the properties of the representative lamina with unidirectional reinforcements have already been determined.

II-3.3.1 Elastic Properties for Lamina With Randomly Oriented Reinforcements. The formulas necessary to determine the elastic properties of a lamina with randomly oriented reinforcement are included herein. It is important to note that in order for the formulas to remain valid, the following conditions must be met:

(a) The elastic properties of the representative lamina with unidirectional reinforcement must be of the same constituent materials and weight fractions of the intended lamina with randomly oriented reinforcements.

(b) The lengths of the glass reinforcement exceed the critical fiber length [approximately 10 mm (0.40 in.) with 2.76 GPa (400 ksi) strength in the fiber] and exceed 1.4 MPa (200 psi) shear strength at the fiber to resin interface.

The in-plane modulus of elasticity, MPa (psi)

$$E = \frac{E_{22}{}^2 + 2 \cdot E_{22} \cdot E_{11} + 4 \cdot E_{22} \cdot G_{12} \cdot \Delta + E_{11}{}^2 + 4 \cdot E_{11} \cdot G_{12} \cdot \Delta - 4 \cdot \nu_{12}{}^2 \cdot E_{22}{}^2 + 8 \cdot \nu_{12} \cdot E_{22} \cdot G_{12} \cdot \Delta}{(3 \cdot E_{22} + 3 \cdot E_{11} + 2 \cdot \nu_{12} \cdot E_{22} + 4 \cdot G_{12} \cdot \Delta) \cdot \Delta}$$

The in-plane shear modulus, MPa (psi)

$$G = \frac{1}{8} \cdot \frac{E_{11}}{\Delta} + \frac{1}{8} \cdot \frac{E_{22}}{\Delta} - \frac{1}{4} \cdot \frac{\nu_{12} \cdot E_{22}}{\Delta} + \frac{1}{2} \cdot G_{12}$$

The in-plane Poisson's ratio, mm/mm (in./in.)

$$\nu = \frac{E_{11} + E_{22} - 4 \cdot G_{12} \cdot \Delta + 6 \cdot \nu_{12} \cdot E_{22}}{3 \cdot E_{22} + 3 \cdot E_{11} + 2 \cdot \nu_{12} \cdot E_{22} + 4 \cdot G_{12} \cdot \Delta}$$

where

$\Delta = 1 - \nu_{12} \nu_{21}$

II-3.3.2 Thermal Mechanical Properties for Lamina With Randomly Oriented Reinforcements. The coefficient of thermal expansion for a lamina with randomly oriented reinforcements, α mm/mm/°C (in./in./°F), can be determined by the following. The conditions detailed in para. II-3.3.1 must be satisfied for the formula below to be valid.

$$\alpha = \frac{\alpha_{11} + \alpha_{22}}{2} + \frac{\alpha_{11} - \alpha_{22}}{2} \left(\frac{E_{11} - E_{22}}{E_{11} + (1 + 2\nu_{12}) E_{22}} \right)$$

II-3.4 Stress-Strain Relations for an Orthotropic Lamina

In the proceeding section the stress and strain behavior of an orthotropic lamina will be discussed. It is important to note that the results of this analysis are applicable only to flat laminates subject to a state of plane stress. It is possible to adapt this analysis for curved surfaces; however, it is the responsibility of the designer to ensure the deformations are appropriate for the surface under review.

The response of an orthotropic lamina subject to a three-dimensional stress tensor is described by the equation below:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix}_k = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix}_k \times \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix}_k$$

Subscript k denotes that the relation applies to layer "k." In the analysis of flat laminated thin plates, the loadings are simplified to a condition of plane stress, i.e., σ_{33}, τ_{23} and τ_{13} all equal zero. The equation above is then simplified to the equations below:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{bmatrix}_k = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix}_k \times \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix}_k$$

$$\varepsilon_{33_k} = S_{13_k}\sigma_{11_k} + S_{23_k}\sigma_{22_k}$$

The 3 × 3 matrix above is commonly known as the reduced compliance matrix. The second equation is necessary to maintain a condition of plane stress.

Typically, the strains are known, and the stresses are desired. Therefore, the equation above is then re-arranged to the following:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix}_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}_k \times \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{bmatrix}_k$$

The 3 × 3 matrix above is commonly known as the reduced stiffness matrix and it is the inverse of the reduced compliance matrix.

The reduced stiffness coefficients, Q_{ij}, MPa (psi), from the equations above can be related to Engineering constants by the following:

$$Q_{11} = \frac{E_{11}}{(1 - \nu_{12}\nu_{21})}$$

$$Q_{22} = \frac{E_{22}}{(1 - \nu_{12}\nu_{21})}$$

$$Q_{12} = \nu_{12}Q_{22}$$

$$Q_{66} = G_{12}$$

The approach detailed above can be used to relate the stresses and strains of a lamina within its principal material coordinate system. It is typical for laminates to be comprised of several layers each with their own material coordinate system. As a result, it is necessary to define an arbitrary global coordinate system. This allows the laminate, and comprising lamina, to be evaluated within a common coordinate system.

The stress resultants from the material coordinate system can be rotated to the global coordinate system, and vice versa, by applying a transformation matrix as defined below:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix}_k = [T]_k \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k$$

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k = [T]_k \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix}_k$$

where

$$[T] = \begin{bmatrix} \cos\theta^2 & \sin\theta^2 & 2\cos\theta\sin\theta \\ \sin\theta^2 & \cos\theta^2 & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos\theta^2 - \sin\theta^2 \end{bmatrix}$$

The following is produced by applying the transformation matrix to the reduced stiffness matrix. The 3 × 3 matrix below is known as the transformed reduced stiffness matrix.

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k = \begin{bmatrix} Q_{bar_{11}} & Q_{bar_{12}} & Q_{bar_{16}} \\ Q_{bar_{12}} & Q_{bar_{22}} & Q_{bar_{26}} \\ Q_{bar_{16}} & Q_{bar_{26}} & Q_{bar_{66}} \end{bmatrix}_k \times \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix}_k$$

The transformed reduced stiffness coefficients, Q_{barij}, MPa (psi), can be determined by the following:

$$Q_{bar_{11}} = Q_{11}\cos\theta^4 + Q_{22}\sin\theta^4 + 2(Q_{12} + 2Q_{66})\cos\theta^2\sin\theta^2$$

$$Q_{bar_{12}} = (Q_{11} + Q_{22} - 4Q_{66})\cos\theta^2\sin\theta^2 + Q_{12}\left(\cos\theta^4 + \sin\theta^4\right)$$

$$Q_{bar_{22}} = Q_{11}\sin\theta^4 + Q_{22}\cos\theta^4 + 2(Q_{12} + 2Q_{66})\cos\theta^2\sin\theta^2$$

$$Q_{bar_{16}} = Q_{11}\cos\theta^3\sin\theta - Q_{22}\cos\theta\sin\theta^3 + (Q_{12} + 2Q_{66})\left(\cos\theta\sin\theta^3 - \cos\theta^3\sin\theta\right)$$

$$Q_{bar_{26}} = Q_{11}\cos\theta\sin\theta^3 - Q_{22}\cos\theta^3\sin\theta + (Q_{12} + 2Q_{66})\left(\cos\theta^3\sin\theta - \cos\theta\sin\theta^3\right)$$

$$Q_{bar_{66}} = (Q_{11} + Q_{22} - 2Q_{12})\cos\theta^2\sin\theta^2 + Q_{66}\left(\cos\theta^2 - \sin\theta^2\right)^2$$

II-4 CLASSICAL LAMINATION THEORY

The methods and equations detailed herein allows the response of a multilayered laminate subject to a state of plane stress to be quantified. The results of this analysis are only applicable to a thin flat laminate subject to a state of plane stress resulting from a uniformly distributed load. It is possible to adapt the analysis for curved surfaces; however, it is the responsibility of the designer to ensure the deformations are appropriate for the surface under review. Other methods of laminate analysis may be used in place of the equations herein, but it is the responsibility of the designer to prove that they are valid.

In the preceding section the stresses of any lamina within the global coordinate system were found to be related to the strains as detailed below.

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k = \begin{bmatrix} Q_{\text{bar}_{11}} & Q_{\text{bar}_{12}} & Q_{\text{bar}_{16}} \\ Q_{\text{bar}_{12}} & Q_{\text{bar}_{22}} & Q_{\text{bar}_{26}} \\ Q_{\text{bar}_{16}} & Q_{\text{bar}_{26}} & Q_{\text{bar}_{66}} \end{bmatrix}_k \times \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix}_k$$

Knowing that the loads applied to the laminate are uniform, the assessment of the laminate is simplified and conducted on a unit length basis. After applying a series of sums and integrations, the following relationship is established for the laminate.

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \times \begin{bmatrix} \varepsilon_{xx0} \\ \varepsilon_{yy0} \\ \gamma_{xy0} \\ \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{bmatrix}$$

where

N_{xx}, N_{yy}, N_{xy} = the distributed force resultants as illustrated in Figure II-4-1, N/mm (lbf/in.)
M_{xx}, M_{yy}, M_{xy} = the distributed moment resultants as illustrated in **Figure II-4-2**, N/mm/mm (lbf/in./in.)
ε_{xx0}, ε_{yy0}, ε_{xy0} = the midplane strains of the laminate, mm/mm (in./in.)
κ_{xx0}, κ_{yy0}, κ_{xy0} = the midplane curvatures of the laminate, radians/mm (radians/in.)

The matrix containing terms A_{11} through D_{66} describes how a laminate will deform under the various in-plane loadings
A_{ij} = the extensional stiffness coefficients, N/mm (lbf/in.)
B_{ij} = the coupling stiffness coefficients that result in out-of-plane deformations due to in-plane loads, N/mm/mm (lbf in./in.)
D_{ij} = the bending stiffness coefficients, N/mm (lbf/in.)

Figure II-4-1 In Place Force Resultants

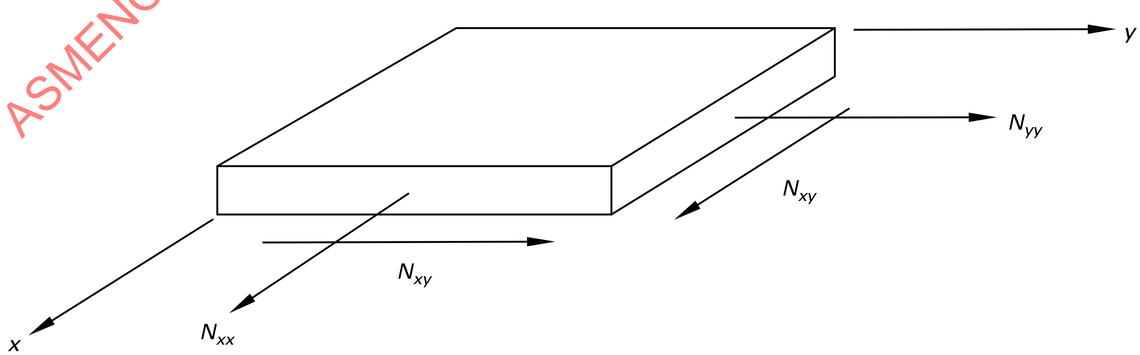
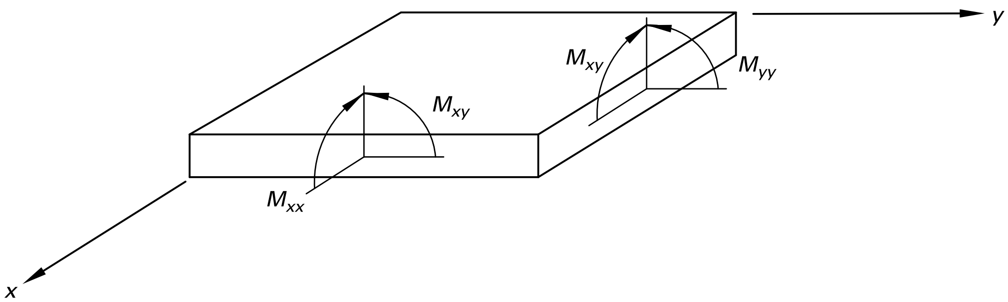


Figure II-4-2 Moment Resultants



The stiffness coefficients of the laminate are determined using the following relations:

$$A_{ij} = \sum_{k=1}^{n} \left[Q_{\text{bar}\, ij_k} [z_k - z_{k-1}] \right]$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} \left[Q_{\text{bar}\, ij_k} \left[{z_k}^2 - {z_{k-1}}^2 \right] \right]$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} \left[Q_{\text{bar}\, ij_k} \left[{z_k}^3 - {z_{k-1}}^3 \right] \right]$$

where

i, and j = 1, 2, and 6

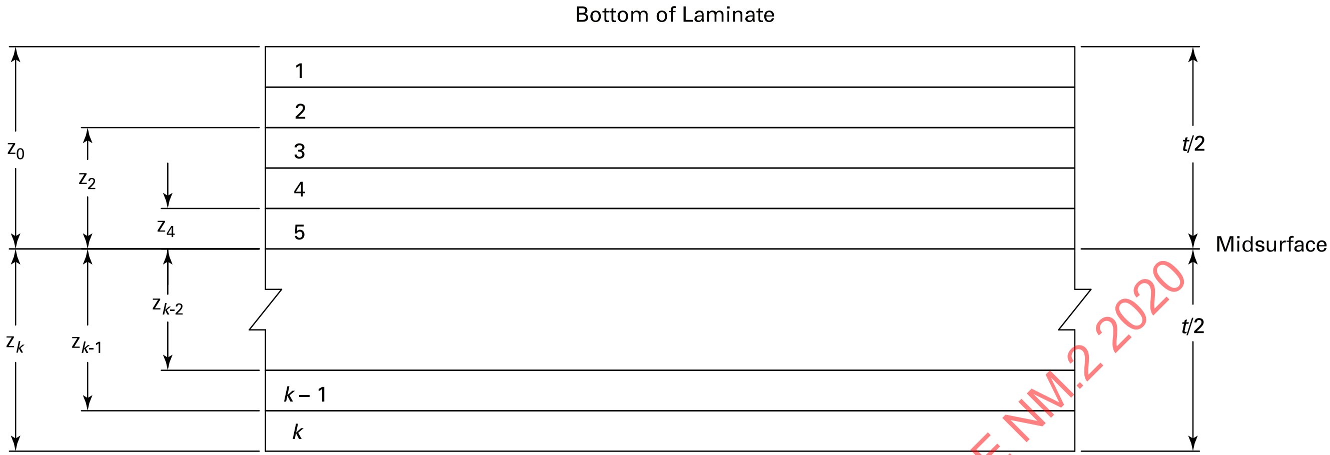
n = the total number of layers

z_k = the distance from the geometric midplane of the laminate to the upper surface of the nth lamina, as detailed in Figure II-4-3. The geometric midplane of the laminate is defined as $z = 0$. Dimension z_0 is the distance from the midplane to the bottom of the laminate and is negative. Conversely the dimension for any lamina located above the geometric midplane is positive.

During the design process the forces and moments are typically known and the strains are desired. It is therefore necessary to invert the 6 × 6 ABD matrix. The result of this operation is detailed below:

$$\begin{bmatrix} \varepsilon_{xx0} \\ \varepsilon_{yy0} \\ \gamma_{xy0} \\ \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \times \begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix}$$

Figure II-4-3 Notations for Ply Positions and Laminate Stacking Sequence (20)



where

$$\begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix}^{-1}$$

Once the midplane strains and curvatures have been quantified, the strains [mm/mm (in./in.)] can be computed for each lamina in the global coordinate system using the relationship below:

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix}_k = \begin{bmatrix} \varepsilon_{xx0} \\ \varepsilon_{yy0} \\ \gamma_{xy0} \end{bmatrix} + \left(z_\kappa + w\frac{t_\kappa}{2} \right) \begin{bmatrix} \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{bmatrix}$$

where w is a term to specify the location within the lamina where the strains are to be computed. Setting w to 0 will allow for the computation of the lamina midplane strains. Setting w to 1 or −1 will allow for the computation of the strains at the upper, and lower surfaces respectively.

Repeated for convenience, the layer stresses in the global coordinate system [MPa (psi)] are then computed using the following:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k = \begin{bmatrix} Q_{bar_{11}} & Q_{bar_{12}} & Q_{bar_{16}} \\ Q_{bar_{12}} & Q_{bar_{22}} & Q_{bar_{26}} \\ Q_{bar_{16}} & Q_{bar_{26}} & Q_{bar_{66}} \end{bmatrix}_k \times \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix}_k$$

The lamina strains in the global coordinate system are then transformed into the material coordinate system using the transformation matrix as follows:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12}/2 \end{bmatrix}_k = \begin{bmatrix} \cos\theta^2 & \sin\theta^2 & 2\cos\theta\sin\theta \\ \sin\theta^2 & \cos\theta^2 & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos\theta^2 - \sin\theta^2 \end{bmatrix}_k \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy}/2 \end{bmatrix}_k$$

And finally, also repeated for convenience, the layer stresses in the material coordinate system [MPa (psi)] are computed as follows:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix}_k = \begin{bmatrix} \cos\theta^2 & \sin\theta^2 & 2\cos\theta\sin\theta \\ \sin\theta^2 & \cos\theta^2 & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos\theta^2 - \sin\theta^2 \end{bmatrix}_k \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix}_k$$

II-4.1 Effective Laminate Elastic Properties

The following relations shall be used to determine the effective elastic properties for a symmetric laminate in the global coordinate system:

The modulus of elasticity in the x direction, MPa (psi)

$$E_{xx} = \frac{1}{ta_{11}}, \; E_{xx}{}^{f} = \frac{12}{t^3 d_{11}}$$

NOTE: This is typically defined as the axial direction for cylinders.

The modulus of elasticity in the y direction, MPa (psi)

$$E_{yy} = \frac{1}{ta_{22}}, \; E_{yy}{}^{f} = \frac{12}{t^3 d_{22}}$$

NOTE: This is typically defined as the hoop direction for cylinders.

The in-plane shear modulus, MPa (psi)

$$G_{xy} = \frac{1}{ta_{66}}$$

The major in-plane Poisson's ratio, mm/mm (in./in.)

$$\nu_{xy} = -\frac{a_{12}}{a_{11}}, \; \nu_{xy}{}^{f} = -\frac{d_{12}}{d_{11}}$$

The minor in-plane Poisson's ratio, mm/mm (in./in.)

$$\nu_{yx} = -\frac{a_{12}}{a_{22}}, \; \nu_{yx}{}^{f} = -\frac{d_{12}}{d_{22}}$$

where

a_{ij}, d_{ij} = the terms from the inverted 6 × 6 ABD matrix

t = the total laminate thickness

Superscript f indicates flexural properties.

For the laminate to be symmetric, the B matrix must be zero. This indicates that there is no coupling between extension and bending.

In cases where the laminate is not symmetric, and the laminate is on a curved cylindrical surface, the following relations shall be used:

$$E_{xx} = \frac{A_{11}A_{22} - A_{12}{}^2}{tA_{22}}$$

$$E_{yy} = \frac{A_{11}A_{22} - A_{12}{}^2}{tA_{11}}$$

$$G_{xy} = \frac{A_{66}}{t}$$

$$\nu_{xy} = \frac{A_{12}}{A_{22}}$$

$$\nu_{yx} = \frac{A_{12}}{A_{11}}$$

where
A_{ij} = the terms from the 6 × 6 ABD matrix
t = the total laminate thickness

II-4.2 Effective Laminate Thermal Mechanical Properties

The following relations shall be used to determine the effective thermal mechanical properties for a laminate in the global coordinate system:

Once the thermal mechanical properties for each lamina have been determined it will be necessary to rotate the properties into the global coordinate system. The rotation is conducted by the following:

The coefficient of thermal expansion of a lamina in the global x direction, mm/mm/°C (in./in./°F)

$$\alpha_{xx_k} = \alpha_{11_k}\cos^2(\theta) + \alpha_{22_k}\sin^2(\theta)$$

The coefficient of thermal expansion of a lamina in the global y direction, mm/mm/°C (in./in./°F)

$$\alpha_{yy_k} = \alpha_{11_k}\sin^2(\theta) + \alpha_{22_k}\cos^2(\theta)$$

The coefficient of thermal expansion for in-plane shear of a lamina in the global coordinate system, mm/mm/°C (in./in./°F)

$$\alpha_{xy_k} = 2\cos(\theta)\sin(\theta)(\alpha_{11_k} - \alpha_{22_k})$$

Assuming the perimeter of the laminate is constrained, the loads generated by the application of a unit temperature are determined by the following.

$$N_{xx}^{T_1} = \sum_{k=1}^{n} \left\{\left[Q_{\text{bar}_{11}}\alpha_{xx} + Q_{\text{bar}_{12}}\alpha_{yy} + Q_{\text{bar}_{16}}\alpha_{xy}\right]_k [z_k - z_{k-1}]\right\}$$

$$N_{yy}^{T_1} = \sum_{k=1}^{n} \left\{\left[Q_{bar_{12}}\alpha_{xx} + Q_{\text{bar}_{22}}\alpha_{yy} + Q_{\text{bar}_{26}}\alpha_{xy}\right]_k [z_k - z_{k-1}]\right\}$$

$$N_{xy}^{T_1} = \sum_{k=1}^{n} \left\{\left[Q_{\text{bar}_{16}}\alpha_{xx} + Q_{\text{bar}_{26}}\alpha_{yy} + Q_{\text{bar}_{66}}\alpha_{xy}\right]_k [z_k - z_{k-1}]\right\}$$

$$M_{xx}^{T_1} = \frac{1}{2}\sum_{k=1}^{n} \left\{\left[Q_{\text{bar}_{11}}\alpha_{xx} + Q_{\text{bar}_{12}}\alpha_{yy} + Q_{\text{bar}_{16}}\alpha_{xy}\right]_k \left[z_k^2 - z_{k-1}^2\right]\right\}$$

$$M_{yy}^{T_1} = \frac{1}{2}\sum_{k=1}^{n} \left\{\left[Q_{\text{bar}_{12}}\alpha_{xx} + Q_{\text{bar}_{22}}\alpha_{yy} + Q_{\text{bar}_{26}}\alpha_{xy}\right]_k \left[z_k^2 - z_{k-1}^2\right]\right\}$$

$$M_{xy}^{T_1} = \frac{1}{2}\sum_{k=1}^{n}\left\{\left[Q_{\mathrm{bar}_{16}}\alpha_{xx} + Q_{\mathrm{bar}_{26}}\alpha_{yy} + Q_{\mathrm{bar}_{66}}\alpha_{xy}\right]_k\left[z_k^2 - z_{k-1}^2\right]\right\}$$

If the perimeter of the laminate is free to displace and the loads from above are applied to the laminate, then the resulting strains, and coefficients of thermal expansion, can be determined by the following:

The coefficient of thermal expansion for the laminate in the global x direction, mm/mm/°C (in./in./°F)

$$\alpha_{xx} = N_{xx}^{T_1}a_{11} + N_{yy}^{T_1}a_{12} + N_{xy}^{T_1}a_{16} + M_{xx}^{T_1}b_{11} + M_{yy}^{T_1}b_{12} + M_{xy}^{T_1}b_{16}$$

The coefficient of thermal expansion for the laminate in the global y direction, mm/mm/°C (in./in./°F)

$$\alpha_{yy} = N_{xx}^{T_1}a_{12} + N_{yy}^{T_1}a_{22} + N_{xy}^{T_1}a_{26} + M_{xx}^{T_1}b_{21} + M_{yy}^{T_1}b_{22} + M_{xy}^{T_1}b_{26}$$

The coefficient of thermal expansion for the laminate for in-plane shear in the global coordinate system, mm/mm/°C (in./in./°F)

$$\alpha_{xy} = N_{xx}^{T_1}a_{16} + N_{yy}^{T_1}a_{26} + N_{xy}^{T_1}a_{66} + M_{xx}^{T_1}b_{61} + M_{yy}^{T_1}b_{62} + M_{xy}^{T_1}b_{66}$$

II-5 LAMINA FAILURE PREDICTION

In general, a lamina has five independent uniaxial ultimate strengths; tensile and compressive strengths in the direction of the fiber, tensile and compressive strengths in the direction transverse to the fiber, and shear strength with respect to a pure shear stress in the principal directions. Furthermore, the five strengths can be unequal.

Each lamina within the laminate is to be analyzed separately based on computing the lamina stresses resulting from the midplane deformations of the laminate. If any lamina is found to fail the criteria, then the corresponding load on the laminate shall not be allowed.

The interaction between the in-plane stresses and lamina strengths is performed using the Tsai-Wu interaction criteria, shown below:

$$\mathrm{FI} = \sigma_{11}F_1 + \sigma_{22}F_2 + \sigma_{11}{}^2F_{11} + \sigma_{22}{}^2F_{22} + \tau_{12}{}^2F_{66} + 2F_{12}\sigma_{11}\sigma_{22}$$

If the failure index (FI) is ≥ 1.0 then failure of the lamina is expected. It is useful to note that each of the terms in the above equation can be used to assess the relative influence that each stress term has on the index.

To achieve the minimum strength ratios that are detailed in Chapter 2, it is necessary to modify the Tsai-Wu interaction criteria to report a strength ratio, rather than a failure index. To do so, each stress in the Tsai-Wu interaction criteria is divided by the strength ratio to yield:

$$[\sigma_{11}F_1 + \sigma_{22}F_2]R + \left[\sigma_{11}{}^2F_{11} + \sigma_{22}{}^2F_{22} + \tau_{12}{}^2F_{66} + 2F_{12}\sigma_{11}\sigma_{22}\right]R^2 - 1 = 0$$

The strength ratio for each lamina is then determined by the following:

$$R = \frac{-H \pm \sqrt{H^2 + 4G}}{2G}$$

where

$$G = \sigma_{11}{}^2F_{11} + \sigma_{22}{}^2F_{22} + \tau_{12}{}^2F_{66} + 2F_{12}\sigma_{11}\sigma_{22}$$

$$H = \sigma_{11}F_1 + \sigma_{22}F_2$$

The strength interaction terms are detailed below:

The fiber direction second order term, 1/MPa (1/psi)

$$F_1 = \frac{1}{\sigma_{11}{}^T} - \frac{1}{\sigma_{11}{}^C}$$

The fiber direction fourth order term, $1/MPa^2$ ($1/psi^2$)

$$F_{11} = \frac{1}{\sigma_{11}{}^{T}\sigma_{11}{}^{C}}$$

The transverse direction second order term, 1/MPa (1/psi)

$$F_2 = \frac{1}{\sigma_{22}{}^{T}} - \frac{1}{\sigma_{22}{}^{C}}$$

The transverse direction fourth order term, $1/MPa^2$ ($1/psi^2$)

$$F_{22} = \frac{1}{\sigma_{22}{}^{T}\sigma_{22}{}^{C}}$$

The fourth order in-plane shear term, $1/MPa^2$ ($1/psi^2$)

$$F_{66} = \frac{1}{(\tau_{12}{}^{S})^2}$$

The F_{12} coupling term [$1/MPa^2$ ($1/psi^2$)] is approximated by the following expression but it is the responsibility of the designer to ensure it is applicable for the lamina under evaluation:

$$F_{12} = -\frac{1}{2}\sqrt{F_{11}F_{22}}$$

The strength terms may be determined from a test or predicted from the relations below. It is important to note that it is assumed that the tensile and compressive moduli are equal in the relations below.

The ultimate in-plane shear strength, MPa (psi)

$$\tau_{12}{}^{S} = \gamma_{12}{}^{S}G_{12}$$

The ultimate tensile strength in the fiber direction, MPa (psi)

$$\sigma_{11}{}^{T} = \varepsilon_{11}{}^{T}E_{11}$$

The ultimate compressive strength in the fiber direction, MPa (psi)

$$\sigma_{11}{}^{C} = \varepsilon_{11}{}^{C}E_{11}$$

The ultimate tensile strength transverse to the fiber direction, MPa (psi)

$$\sigma_{22}{}^{T} = \varepsilon_{22}{}^{T}E_{22}$$

The ultimate compressive strength transverse to the fiber direction, MPa (psi)

$$\sigma_{22}{}^{C} = \varepsilon_{22}{}^{C}E_{22}$$

If test data is not available, then the following strain limits may be used:

Strain Direction	Randomly Oriented Fibers	Oriented Fiber
$\varepsilon_{11}{}^{T}$	0.0150	0.0200
$\varepsilon_{11}{}^{C}$	0.0200	0.0120
$\varepsilon_{22}{}^{T}$	0.0150	0.00150
$\varepsilon_{22}{}^{C}$	0.0200	0.0080
$\gamma_{12}{}^{S}$	0.0268	0.0268

It can be seen from the table above that the permissible transverse strain limits for an oriented fiber are lower than the limits along the direction of the fiber. As a result, if a laminate comprising of angled laminae is subject to a load that places some of the laminae in a state of transverse stress it is likely that those laminae will govern the analysis. In such cases, if the governing stress state for the remaining adjacent laminae is along the direction of the fiber, and the strength ratios for these laminae comply with the requirements of Chapter 2, then the lamina under transverse stress may be exhibiting a state of resin crazing. This type of response is common with woven roving, axial/hoop laminates, and FW laminates, and it is permitted.

With these types of responses, it is permissible to analyze the laminate using macro layers. A macro layer is one where the properties of two or more lamina are combined into a single layer. To use a macro layer, the designer must demonstrate that the layer is able to achieve the predicted load-carrying capacity for the stress state under review.

MANDATORY APPENDIX III
STRESS INTENSIFICATION FACTORS, FLEXIBILITY FACTORS, AND PRESSURE STRESS MULTIPLIERS

III-1 SCOPE

This Appendix provides methods for determining the stress intensification factors, flexibility factors, and pressure stress multipliers needed to predict stresses and deformation in piping components other than pipe. These factors are applied to the results calculated for pipe to find relevant values for piping components. Specifically, the calculated stiffness of a pipe needs to be adjusted by the appropriate flexibility factor, k, to determine the stiffness of the component; the calculated bending moment on a pipe needs to be multiplied by the appropriate stress intensification factor (SIF), i, to determine the bending stress of the component; and the pressure stress of a pipe needs to be multiplied by the pressure stress multiplier, m, to determine the pressure stress of the component.

III-1.1 Definitions

flexibility factor, k: the ratio of the bending flexibility of a component to the bending flexibility of an equivalent pipe. It is used to predict the magnitude of the deformation of the component relative to that of the equivalent pipe under the same loading.

stress intensification factor (SIF), i: the ratio of the peak stress in a component to the peak stress in an equivalent pipe. It is used to predict the magnitude of the peak stress in the component relative to that in the equivalent pipe under the same loading.

pressure stress multiplier, m: the ratio of the pressure stress in a component to that in an equivalent pipe. It is used to predict the pressure stress in the component relative to that in an equivalent pipe under the same pressure loading.

III-1.2 Sources of Factors

Appropriate values for k, i, and m can be determined by several methods, including

(a) testing
(b) finite element analysis (FEA)
(c) methods detailed in this Appendix

In addition, historical values for fittings that have been documented to have provided successful performance for a minimum of 5 yr may be used for fittings of similar material, construction, and geometry.

These values shall then be incorporated in a pipe stress analysis in accordance with section 2-4.

III-2 ELBOWS

III-2.1 Flexibility Factors for Elbows

(a) Due to the ovalization of an elbow that occurs when the elbow is exposed to a bending moment, the flexibility of an elbow is typically greater than that of an equivalent pipe.

(b) The flexibility factor, k, of an elbow is defined by the following equation, and is not less than 1.0:

$$k = \theta_E/\theta_P \tag{III-2-1}$$

where

θ_E = rotation of an elbow when the elbow is exposed to a bending moment, rad
θ_P = rotation of an equivalent pipe (see Note) when the pipe is exposed to the same bending moment, rad
= $\frac{R_1 \alpha}{EI} M$
E = axial modulus of elasticity of total wall, MPa (psi)
I = moment of inertia of total wall, mm^4 (in.^{4})
M = bending moment, N·mm (lb-in.)
R_1 = radius of bend, mm (in.); R_1 > the inside diameter of the pipe, D
α = angle of elbow in radians (e.g., π/2)

NOTE: An equivalent pipe is one that has the same modulus of elasticity, E, the same second moment of area, I, and the same midline length, $L = R \times \alpha$, as the elbow that it is intended to represent. These properties are the properties that should be entered into a pipe stress analysis.

(c) The same pipe properties that are intended to be used to represent the elbow in a pipe stress analysis shall be used in eq. (III-2-1) to determine the elbow's flexibility factor, k.

(d) In the absence of more directly applicable data, the flexibility factor for elbows may be determined as described in paras. III-2.1.1 through III-2.1.3.

III-2.1.1 Type I and Type II Elbows. The equations below may be used to calculate the flexibility factor, k, for Type I and Type II long-radius elbows that comply with the following criteria:

(a) The diameter-to-total-thickness ratio is not greater than 140.

(b) The pipe size does not exceed 1 200 mm (48 in.) diameter.

(c) The butt joint between the elbow and the pipe is a Type II laminate, and the connected pipe is Type II or filament-wound laminate.

For Type I elbows

$$k = 0.22\gamma\left(\frac{D}{t_e}\right)\left(\frac{t_i}{t_e}\right)^{-1.04} \quad \text{(III-2-2)}$$

For Type II elbows

$$k = \gamma\left[0.2\left(\frac{D}{t_e}\right) - 0.7\right]\left(\frac{t_i}{t_e}\right)^{-0.98} \quad \text{(III-2-3)}$$

where

D = inside diameter of pipe, mm (in.)

t_e = thickness of the total wall of the elbow measured at the extrados [including a corrosion-barrier thickness of at least 2.8 mm (0.11 in.)], mm (in.)

t_i = thickness of the total wall of the elbow measured at the intrados [including a corrosion barrier thickness of at least 2.8 mm (0.11 in.)], mm (in.)

γ = correction factor for reduction in flexibility due to internal pressure

$= \left(1 + 2.53\frac{Pr}{E_h t_e} \times R_1{}^{0.333}\frac{r}{t_e{}^{1.333}}\right)^{-1}$

E_h = hoop modulus of the elbow, MPa (psi)

P = pressure, MPa (psi)

R_1 = radius of the bend, mm (in.)

= $1.5D$

r = inside radius of the elbow, mm (in.)

NOTE: k shall not be taken as less than 1.0.

III-2.1.2 Elbows Other Than Type I and Type II. In the absence of more directly applicable data, the flexibility factor, k, for elbows other than Type I and Type II shall be taken as 1.0.

III-2.1.3 Flanged Elbows. The flexibility factor for flanged elbows shall be reduced by multiplying k by one of the following factors, c:

(a) For elbows with one flanged end

$$c = \left(\frac{t_e R_1}{\left(\frac{D}{2}\right)^2}\right)^{1/6} \quad \text{(III-2-4)}$$

(b) For elbows with two flanged ends

$$c = \left(\frac{t_e R_1}{\left(\frac{D}{2}\right)^2}\right)^{1/3} \quad \text{(III-2-5)}$$

where

D = inside diameter of pipe, mm (in.)

R_1 = radius of bend, mm (in.)

= $1.5D$

t_e = thickness of the total wall of the elbow measured at the extrados, mm (in.)

NOTE: k shall not be taken as less than 1.0.

III-2.2 Stress Intensification Factors for Elbows

(a) Due to the ovalization of an elbow that occurs when the elbow is exposed to a bending moment, the maximum bending stress in an elbow is typically greater than that of an equivalent pipe.

(b) The SIF, i, of an elbow is defined as follows, and is not less than 1.0:

$$i = \sigma_E/\sigma_P \quad \text{(III-2-6)}$$

where

σ_E = maximum stress in an elbow when the elbow is exposed to a bending moment, MPa (psi)

σ_P = stress in an equivalent pipe (see Note) when the pipe is exposed to the same bending moment, MPa (psi)

= M/Z_s

M = bending moment, N·mm (in.-lb)

Z_s = section modulus, mm^4 ($in.^4$)

NOTE: An equivalent pipe is one that has the same section modulus, Z_s, as the elbow that it is intended to represent. This is the section modulus that should be entered into a pipe stress analysis.

(c) The same section modulus that is intended to be used to represent the elbow in a pipe stress analysis shall be used in eq. (III-2-6) to determine the elbow's SIF, i.

(d) The magnitudes of SIFs typically depend on direction of the applied moment, i.e., in-plane, out-of-plane, or torsional, and are typically determined for both the hoop and axial directions.

(e) In the absence of more directly applicable data, the SIFs for elbows may be determined as described in paras. III-2.2.1 through III-2.2.3.

III-2.2.1 Type I and Type II Elbows

(a) The following equation shall be used to calculate i for Type I and Type II long-radius elbows for which the diameter-to-structural-thickness ratio is not greater than 140, and for which the pipe size does not exceed 1 200 mm (48 in.) diameter:

$$i = \frac{\alpha_2 \gamma}{h^{0.667}} \quad \text{(III-2-7)}$$

where

h = flexibility characteristic

$= \frac{t_{es} R_1}{r^2}$

r = inside radius of the elbow, mm (in.)

R_1 = radius of the bend, mm (in.)

= 1.5D where D is the inside diameter of the pipe

t_{es} = thickness of the structural wall of the elbow measured at the extrados, mm (in.)

α_2 = correction factor for reduction in SIF due to increased thickness at the intrados compared to the extrados; see (c) below

γ = correction factor for reduction in SIF due to internal pressure

$= \left(1 + 2.53\frac{Pr}{E_h t_e} \times R_1^{0.333}\frac{r}{t_e^{1.333}}\right)^{-1}$

E_h = hoop modulus of the elbow, MPa (psi)

P = pressure, MPa (psi)

t_e = thickness of the total wall of the elbow measured at the extrados [including a corrosion-barrier thickness of at least 2.8 mm (0.11 in.)], mm (in.)

(b) Five SIFs are required to quantify the stresses in an elbow.

(1) longitudinal SIF due to in-plane moment, i_{ix}.

(2) longitudinal SIF due to out-of-plane moment, i_{ox}.

(3) hoop SIF due to in-plane moment, i_{ih}.

(4) hoop SIF due to out-of-plane moment, i_{oh}.

(5) shear stress SIF due to torsional moment, i_t. For Type I and Type II elbows, i_t may be taken to be 1.0.

(c) FRP elbows are often manufactured such that the thickness varies uniformly around the circumference of the elbow from a minimum at the extrados to a maximum at the intrados. An elbow with this additional thickness will have lower SIFs than an elbow that has a uniform thickness around its entire circumference. For Type I and Type II long-radius elbows, this reduction in SIF may be accounted for using the following values of α_2:

(1) Type I Elbows

(-a) For i_{ih}

$$\alpha_2 = 3.59 - 1.30 \times \left(\frac{t_{is}}{t_{es}}\right)$$
$$= 1.64 \text{ if } \frac{t_{is}}{t_{es}} > 1.50$$

(-b) For i_{oh}

$$\alpha_2 = 2.37 - 0.78 \times \left(\frac{t_{is}}{t_{es}}\right)$$
$$= 1.20 \text{ if } \frac{t_{is}}{t_{es}} > 1.50$$

(-c) For i_{ix} and i_{ox}

$$\alpha_2 = 2.15 - 0.74 \times \left(\frac{t_{is}}{t_{es}}\right)$$
$$= 1.04 \text{ if } \frac{t_{is}}{t_{es}} > 1.50$$

where

t_{es} = thickness of the structural wall measured at the extrados, mm (in.)

t_{is} = thickness of the structural wall measured at the intrados, mm (in.)

(2) Type II Elbows

(-a) For i_{ih}

$$\alpha_2 = 3.03 - 1.02 \times \left(\frac{t_{is}}{t_{es}}\right)$$
$$= 1.50 \text{ if } \frac{t_{is}}{t_{es}} > 1.50$$

(-b) For i_{oh}

$$\alpha_2 = 1.70 - 0.50 \times \left(\frac{t_{is}}{t_{es}}\right)$$
$$= 0.95 \text{ if } \frac{t_{is}}{t_{es}} > 1.50$$

(-c) For i_{ix} and i_{ox}

$$\alpha_2 = 1.62 - 0.52 \times \left(\frac{t_{is}}{t_{es}}\right)$$
$$= 0.84 \text{ if } \frac{t_{is}}{t_{es}} > 1.50$$

III-2.2.2 Elbows Other Than Type I and Type II. For elbows other than Type I and Type II long-radius elbows, the SIFs shall be determined by testing or FEA, or by using historical values that have been documented to have been used successfully for a minimum of 5 yr.

III-2.2.3 Flanged Elbows. The SIFs for flanged elbows may be reduced by multiplying i by one of the following factors, c:

(a) For elbows with one flanged end

$$c = \left(\frac{t_{es} R_1}{\left(\frac{D}{2} \right)^2} \right)^{1/6} \quad \text{(III-2-8)}$$

(b) For elbows with two flanged ends

$$c = \left(\frac{t_{es} R_1}{\left(\frac{D}{2} \right)^2} \right)^{1/3} \quad \text{(III-2-9)}$$

where

D = inside diameter of pipe, mm (in.)
R_1 = radius of bend, mm (in.)
= $1.5D$
t_{es} = thickness of the structural wall of the elbow measured at the extrados, mm (in.)

III-2.3 Pressure Stress Multipliers for Elbows

(a) An elbow will experience higher hoop stresses when exposed to pressure than will an equivalent pipe.

(b) The pressure stress multiplier, m, of an elbow is defined as follows, and is not less than 1.0:

$$m = \sigma_{HE} / \sigma_{HP} \quad \text{(III-2-10)}$$

where

σ_{HE} = maximum hoop stress in an elbow when the elbow is exposed to pressure, MPa (psi)
σ_{HP} = hoop stress in an equivalent pipe (see Note) when the pipe is exposed to the same pressure, MPa (psi)

NOTE: An equivalent pipe is one that has the same structural thickness, t_s, as the elbow that it is intended to represent. This is the structural thickness that should be entered into a pipe stress analysis.

(c) The same thickness that is intended to be used to represent the elbow in a pipe stress analysis shall be used in eq. (III-2-10) for σ_{HP} to determine the elbow's pressure stress multiplier, m.

(d) In the absence of more directly applicable data, the pressure stress multipliers for elbows may be determined as described in paras. III-2.3.1 and III-2.3.2.

III-2.3.1 Type I and Type II Elbows

(a) The following equation may be used to calculate m for Type I and Type II elbows:

$$m = \alpha_3 \left(\frac{4\frac{R_1}{D} - 1}{4\frac{R_1}{D} - 2} \right) \quad \text{(III-2-11)}$$

where

D = inside diameter of elbow, mm (in.)
R_1 = bend radius of the elbow, mm (in.); $R_1 > D$
α_3 = correction factor for reduction in m due to increased thickness at the intrados compared to the extrados; see (b)

(b) FRP elbows are often manufactured such that the thickness varies uniformly around the circumference of the elbow from a minimum at the extrados to a maximum at the intrados. This additional thickness will reduce the maximum hoop pressure stress of the elbow compared to an elbow that has a uniform thickness around the entire circumference. The following values for α_3 may be used for Type I and Type II elbows:

(1) $\alpha_3 = 0.8$ if $t_{is}/t_{es} > 1.25$

(2) $\alpha_3 = [-0.8(t_{is}/t_{es}) + 1.8]$ if $1.0 < t_{is}/t_{es} < 1.25$

where

t_{es} = thickness of the structural wall measured at the extrados, mm (in.)
t_{is} = thickness of the structural wall measured at the intrados (not less than t_{es}), mm (in.)

III-2.3.2 Elbows Other Than Type I and Type II. For elbows other than Type I and Type II, the pressure stress multiplier shall be determined by testing or FEA, or by using historical values that have been documented to have been used successfully for a minimum of 5 yr.

III-3 TEES

III-3.1 Flexibility Factors for Tees

The flexibility factor, k, for tees shall be taken to be 1.0.

III-3.2 SIFs for Tees

In the absence of more directly applicable data, the SIFs, i, for tees may be determined as described in paras. III-3.2.1 and III-3.2.2. In no case shall i be less than 1.0.

III-3.2.1 Type I and Type II Tees

(a) For Type I and Type II tees and reducing tees for which the diameter does not exceed 600 mm (24 in.), the SIF, i, is a function of the pipe factor, λ_t. The pipe factor, λ_t, is defined as follows:

$$\lambda_t = \frac{2t_R}{D_R} \quad \text{(III-2-12)}$$

where

D_R = inside diameter of the main run structural wall, mm (in.)
t_R = thickness of the structural layer of the main run of the tee, mm (in.)

(b) The longitudinal SIFs shall be determined by

$$i_{ix} = i_{ox} = 0.66(\lambda_t)^{-0.5} \quad \text{(III-2-13)}$$

(c) The hoop SIFs, i_{ih} and i_{oh}, may be taken to be 0.0.

(d) The torsional SIF, i_t, may be taken to be 1.5.

III-3.2.2 Tees Other Than Type I and Type II. For other than Type I and Type II tees, the SIFs shall be determined by testing or FEA, or by using historical values that have been documented to have been used successfully for a minimum of 5 yr.

III-3.3 Pressure Stress Multipliers for Tees

In the absence of more directly applicable data, the pressure stress multiplier for tees may be determined as described in paras. III-3.3.1 and III-3.3.2. In no case shall m be less than 1.0.

III-3.3.1 Type I and Type II Tees

(a) For Type I and Type II tees and reducing tees for which the diameter does not exceed 600 mm (24 in.), the pressure stress multiplier, m, is a function of the pipe factor, λ_t. The pipe factor, λ_t, is defined as follows:

(1) For equal tees, $D_B = D_R$

$$\lambda_t = \frac{2t_R}{D_R} \quad \text{(III-2-14)}$$

(2) For reducing tees, $D_B < D_R$

$$\lambda_t = \left(\frac{2t_B}{D_B}\right)^2 \times \frac{D_R}{2t_R} \quad \text{(III-2-15)}$$

where

D_B = inside diameter of the branch structural wall, mm (in.)
D_R = inside diameter of the main run structural wall, mm (in.)
t_B = thickness of the structural layer of the branch of the tee, mm (in.)
t_R = thickness of the structural layer of the main run of the tee, mm (in.)

(b) The pressure stress multiplier, m, shall be determined by

$$m = 1.4(\lambda_t)^{-0.25} \quad \text{(III-2-16)}$$

III-3.3.2 Tees Other Than Type I and Type II. For other than Type I and Type II tees, the pressure stress multiplier, m, shall be determined by testing or FEA, or by using historical values that have been documented to have been used successfully for a minimum of 5 yr.

III-4 CONCENTRIC REDUCERS

The minimum length for concentric reducers is 2.5 times the difference in diameters.

III-4.1 Flexibility Factors for Concentric Reducers

The flexibility factor, k, for concentric reducers shall be taken to be 1.0.

III-4.2 SIFs for Concentric Reducers

In the absence of more directly applicable data, the SIFs, i, for concentric reducers may be determined as described in paras. III-4.2.1 and III-4.2.2. In no case shall i be less than 1.0 except that the hoop SIFs, i_{ih} and i_{oh}, may be taken to be 0.0.

III-4.2.1 Type I and Type II Concentric Reducers. The following values for SIFs may be used for Type I and Type II concentric reducers for which the diameter-to-structural-thickness ratio is not greater than 120, and for which the pipe size does not exceed 1 200 mm (48 in.) diameter:

Concentric Reducer Type	SIF: Large Diameter End	SIF: Small Diameter End
I	2.5	1.3
II	2.5	1.3

III-4.2.2 Concentric Reducers Other Than Type I and Type II. For other than Type I and Type II concentric reducers, the SIFs shall be determined by testing or FEA, or by using historical values that have been documented to have been used successfully for a minimum of 5 yr.

III-4.3 Pressure Stress Multipliers for Concentric Reducers

The pressure stress multiplier, m, for concentric reducers shall be taken to be 1.0.

III-5 FLANGES

III-5.1 Flexibility Factors for Flanges

Flanges shall be considered to be rigid elements.

III-5.2 SIFs for Flanges

In the absence of more directly applicable data, the SIFs, i, for flanges may be determined as described in paras. III-5.2.1 and III-5.2.2. In no case shall i be less than 1.0 except that the hoop SIFs, i_{ih} and i_{oh}, may be taken to be 0.0.

III-5.2.1 Type I and Type II Flanges. For Type I or Type II flanges designed in accordance with Mandatory Appendix I, the SIF may be taken to be 1.0.

III-5.2.2 Flanges Other Than Type I and Type II. For other than Type I and Type II flanges, the SIFs shall be determined by testing or FEA, or by using historical values that have been documented to have been used successfully for a minimum of 5 yr.

III-5.3 Pressure Stress Multipliers for Flanges

The pressure stress multiplier, m, for flanges shall be taken to be 1.0.

MANDATORY APPENDIX IV SPECIFICATION FOR 55-deg FILAMENT-WOUND GLASS-FIBER-REINFORCED THERMOSETTING-RESIN (FRP) PIPE

IV-1 SCOPE

(a) This Appendix covers pipe fabricated by filament winding and made of a commercial-grade polyester resin. Included are requirements for materials, properties, construction, dimensions, tolerances, workmanship, and appearance. This Appendix applies to 55-deg machine filament-wound pipe described as Type III pipe in ASME NM.3.3.

(b) This Appendix covers pipe made from both polyester and vinyl ester resins and glass-fiber-reinforcing materials. See para. IV-5.2 for reinforcing materials allowed in the corrosion barrier.

NOTE: For the purposes of this Appendix, the term "polyester resin" includes both polyester and vinyl ester resins.

IV-2 SAFETY

This specification does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

IV-3 REFERENCED STANDARDS

ASTM C581, Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service

ASTM D638, Standard Test Method for Tensile Properties of Plastics

ASTM D790, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

ASTM D883, Standard Terminology Relating to Plastics

ASTM D1599, Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings

ASTM D1600, Standard Terminology for Abbreviated Terms Relating to Plastics

ASTM D2105, Standard Test Method for Longitudinal Tensile Properties of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube

ASTM D2412, Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading

ASTM D2583, Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor

ASTM D2584, Standard Test Method for Ignition Loss of Cured Reinforced Resins

ASTM D3039/D3039M, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

ASTM D3567, Standard Practice for Determining Dimensions of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Pipe and Fittings

ASTM F412, Standard Terminology Relating to Plastic Piping Systems

Publisher: American Society for Testing and Materials (ASTM International), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959 (www.astm.org)

IV-4 TERMINOLOGY

IV-4.1 General

Definitions are in accordance with ASTM D883 and ASTM F412, and abbreviations are in accordance with ASTM D1600, unless otherwise indicated.

IV-4.2 Definitions

complete cover: two layers of winding, one at the plus winding angle and one at the minus winding angle.

fiberglass pipe: a tubular product containing glass-fiber reinforcements embedded in or surrounded by cured thermosetting resin.

filament winding: a process used to manufacture tubular goods by winding continuous fibrous glass-strand roving, saturated with liquid resin or pre-impregnated with partially cured resin, onto the outside of a mandrel in a predetermined pattern under controlled tension. The inside diameter (I.D.) of the pipe is fixed by the mandrel diameter, and the outside diameter (O.D.) of the pipe is determined by the amount of material that is wound on the mandrel.

helical winding: filament winding where the reinforcement is placed at a specified angle (other than 0 deg or 90 deg) to the axis of rotation.

interior layer: resin-rich layer that is between the surfacing veil and the structural layers of a reinforced plastic laminate.

polyester: resin produced by the polycondensation of dihydroxy glycols and dibasic organic acids or anhydrides, where at least one component contributes ethylenic unsaturation, yielding resins that can react with styrol monomers to give highly cross-linked thermoset copolymers.

structural layer: the portion of the laminate construction providing the primary mechanical strength.

surfacing veil: a thin mat of fine fibers used primarily to produce a smooth, corrosion-resistant, resin-rich surface on a reinforced plastic laminate.

vinyl ester: resin characterized by reactive unsaturation located predominately in terminal positions that can react with styrol monomers to give highly cross-linked thermoset copolymers.

IV-5 MATERIALS AND MANUFACTURE

IV-5.1 Resin System

IV-5.1.1 Resin

(a) The resin used shall be a commercial-grade, corrosion-resistant polyester that has been determined to be acceptable for the service by either test (see ASTM C581) or previous documented service.

(b) Where service conditions have not been evaluated, a suitable resin may also be selected by agreement between the manufacturer and the purchaser.

(c) The use of one resin in the corrosion barrier and a different resin in the structural layer (see section IV-7) is permitted if acceptable to the purchaser.

IV-5.1.2 Additives

(a) Additives such as thixotropic agents or flame retardants may be used when agreed upon by both the manufacturer and the purchaser.

(b) Additional styrene may be added to the resin for viscosity control.

(c) No material shall be added to the resin used in the filament winding for the sole purpose of changing the color or translucency of the resin.

NOTES:

(1) The addition of flame retardants and thixotropic agents can affect laminate properties and visual inspection of laminate quality.

(2) The catalyst/promoter system, diluents, flame retardants, or thixotropic agents used in the resin can affect its chemical resistance.

(3) Antimony compounds or other fire-retardant agents may be added to halogenated resins for improved fire resistance, if agreed to by the manufacturer and the purchaser. These compounds usually impact the translucency of the resin and do not improve the flame retardancy of nonhalogenated resins.

IV-5.1.3 Additives for Abrasion Resistance

(a) Additives may be added to the interior and/or exterior corrosion barrier to increase abrasion resistance as agreed upon between the manufacturer and the purchaser.

(b) Additives to enhance abrasion resistance may be added to the resin, up to 5% by weight of the resin system in the filament winding, without impacting allowable stresses per ASME NM.3.3.

IV-5.2 Fiber Reinforcements

IV-5.2.1 Surfacing Veil

(a) The surfacing veil used in a laminate shall be a chemical-resistant glass or organic fiber determined to be acceptable for the chemical service by either ASTM C581 or verified case history.

(b) The surfacing veil shall be a minimum of 0.254 mm (10 mils) in dry thickness.

IV-5.2.2 Chopped-Strand Reinforcements

(a) Chopped-strand reinforcements shall be E-type or E-CR-type glass fibers 25 mm to 50 mm (1 in. to 2 in.) long, applied in a uniform layer with random orientation.

(b) The fibers shall have a sizing compatible with the selected resin.

(c) Chopped-strand reinforcements may be applied as a mat or as continuous strand roving that is chopped into short lengths and sprayed onto the laminate in a process known as "spray up." Either form is most commonly applied in layers weighing 460 g/m^2 (1.5 oz/ft^2), although other weights are available and may be used.

IV-5.2.3 Continuous Roving

(a) Continuous roving shall be E-type or E-CR-type glass roving, with a maximum 4 400 tex (minimum yield of 110 yd/lb).

(b) The sizing on the roving shall be compatible with the resin.

IV-6 LAMINATES

IV-6.1 Laminate Construction

The pipe wall shall consist of a corrosion barrier (comprising an inner surface and interior layer), a structural layer, and an outer surface.

IV-6.1.1 Erosion Allowance

(a) An erosion allowance shall be specified to suit the service conditions.

(b) The erosion allowance consists of the portion of the corrosion barrier (see para. IV-6.1.2) that is assumed to corrode or erode away during the service life of the pipe.

(c) The thickness of the erosion allowance shall not be included in the pipe wall thickness calculation and may be less than the thickness of the corrosion barrier but shall not exceed the thickness of the corrosion barrier.

IV-6.1.2 Corrosion Barrier. The corrosion barrier consists of the specified inner surface and interior layers.

IV-6.1.2.1 Inner Surface

(a) The inner surface exposed to the chemical environment shall be resin rich and reinforced with at least one layer of a suitable surfacing veil in accordance with para. IV-5.2.1.

(b) Some chemical environments necessitate the use of multiple layers of surfacing veil.

(c) This resin-rich inner surface shall contain less than 10% by weight of reinforcing material and have a thickness between 0.25 mm to 0.50 mm (0.010 in. and 0.020 in.) per layer.

NOTE: The primary chemical resistance of the reinforced thermosetting-resin pipe is provided by the resin. In combination with the cured resin, the surfacing veil helps determine the thickness of the resin-rich layer and reduces microcracking.

IV-6.1.2.2 Interior Layer(s)

(a) The inner surface layer shall be followed with a layer composed of resin reinforced only with noncontinuous glass fiber.

(b) This reinforcement shall be applied as chopped-strand mat or as chopped roving (spray-up process), in accordance with para. IV-5.2.2, resulting in a minimum reinforcement weight of 460 g/m^2 (1.5 oz/ft^2).

(c) The combined thickness of the inner surface and interior layer shall not be less than specified by design.

(d) Depending on the chemical environment, multiple layers of 460-g/m^2 (1.5-oz/ft^2) chopped strand applied as mat or spray-up may be used.

(e) When multiple layers are used, each ply of mat or pass of chopped roving shall be well rolled to eliminate entrapped air prior to the application of additional reinforcement.

(f) The reinforcement content of the inner surface and the interior layer combined shall be 22% to 32% by weight of the reinforcement and resin, when tested in accordance with para. IV-9.1.

IV-6.1.3 Structural Layer

(a) The structural reinforcement shall be helical filament winding per para. IV-4.2, using resin per para. IV-5.1 and continuous-roving reinforcement per para. IV-5.2.3.

(b) The required parameters for the winding process shall be as follows:

(1) The winding angle shall be 55 deg ± 2 deg.

(2) The reinforcement content of the filament-wound layers shall be 60% to 75% by weight for a resin with a cured specific gravity of 1.1.

(3) The rovings of each layer shall be placed parallel and close together with little or no gap.

(-a) No single gap within the band or between adjacent bands shall exceed 3 mm ($^1/_8$ in.).

(-b) During winding, if more than 5% of the rovings in the winding band break or if two adjacent rovings break, the winding shall be interrupted to replace the broken rovings.

(4) The winding pattern shall be consistent and shall produce a uniform laminate without voids or unreinforced resin pockets that exceed acceptance criteria. See para. IV-6.2.

(5) The winding pattern of each cover shall be complete, with the pattern closing at the conclusion of the cover.

(6) The structural layer shall consist of a minimum of two complete covers.

IV-6.1.4 Outer Surface

(a) The outer (exterior) surface shall be smooth with no exposed fibers or sharp projections and shall be resin rich to prevent fiber prominence.

(b) A surfacing mat or similar reinforcement may be specified by the purchaser.

(c) Surface resin may be sealed by the addition of paraffin wax or with a sprayed, wrapped, or overlaid film (as required or approved by the resin manufacturer), to ensure proper cure.

IV-6.1.5 Ultraviolet Exposure. Piping used for outdoor service or otherwise subject to ultraviolet exposure shall incorporate provisions to minimize ultraviolet degradation. Suitable methods may include the following:

(a) ultraviolet absorbers or screening agents

(b) opaque pigments in the resin-rich outer-surface layer

(c) the use of resins inherently resistant to ultraviolet degradation

IV-6.2 Workmanship, Finish, and Appearance

The minimum acceptable level for workmanship and finish of the finished laminate shall be specified by the purchaser.

NOTE: A representative laminate sample may be used for determination of an acceptable surface finish and an acceptable level of visual defects. See Table 4-3.2-1 for acceptance criteria

IV-7 ACCEPTANCE CRITERIA

IV-7.1 Proof of Design

(a) A test pipe fitted with free-end closures to ensure loading in both the hoop and axial directions shall be pressure tested in accordance with ASTM D1599 except that

(1) only one specimen needs to be tested

(2) the pipe may be tested using water at ambient temperature [10°C to 25°C (50°F to 77°F)] as a test medium in lieu of the conditions required by the test method

(b) The test pipe shall be made with the same laminate type and resin used on the production pipe and shall include any required barrier layers.

(c) The minimum diameter of the test pipe shall be the lesser of the largest diameter required for the project or 100 mm (4 in.) and shall have a structural wall consisting of a minimum of two complete covers.

(d) The test pipe shall withstand 4 times the design pressure for 1 h without leaking or cracking of the corrosion barrier; testing to destruction is not required.

(1) When pipe with a corrosion barrier is tested, the test pressure shall be increased to stress the structural wall as if there were no corrosion barrier.

(2) The adjusted test pressure may be determined by use of lamination theory or the rule of mixtures as shown in eqs. (IV-7-1) through (IV-7-3).

$$t_{TOT} = (t_{CB} + t_S) \quad \text{(IV-7-1)}$$

$$E_{TOT} = [(t_{CB} \times E_{CB}) + (t_S \times E_S)]/t_{TOT} \quad \text{(IV-7-2)}$$

$$P_{TEST} = 4 \times P_D(t_{TOT} \times E_{TOT})/(t_S \times E_S) \quad \text{(IV-7-3)}$$

where

E_{CB} = corrosion-barrier modulus of elasticity, MPa (psi)
E_S = structural wall modulus of elasticity, MPa (psi)
E_{TOT} = total laminate modulus of elasticity, MPa (psi)
P_D = design pressure, kPa (psi)
P_{TEST} = adjusted test pressure, kPa (psi)
t_{CB} = corrosion-barrier thickness, mm (in.)
t_S = structural wall (filament winding) thickness, mm (in.)
t_{TOT} = total thickness, mm (in.)

(e) Results from previously manufactured and tested pipe may be accepted by the purchaser provided such pipe was manufactured with the same resin, laminate type, and thickness range within the previous 5 yr.

IV-7.2 Degree of Cure

(a) The degree of cure of the laminate shall be determined from the Barcol hardness test specified in ASTM D2583.

(b) The minimum Barcol hardness shall be 90% of the resin manufacturer's published value.

NOTES:
(1) The use of organic reinforcing materials can reduce the Barcol hardness readings without necessarily indicating undercure.
(2) Due to the size of the Barcol impressor, taking Barcol readings on the inside surface of small pipe sizes is frequently not possible.
(3) A convenient check for the surface cure of polyester resins is an acetone sensitivity test. Remove mold release or paraffin wax, if present, and wipe the surface clean of dust. Then rub four or five drops of acetone on the laminate surface until it evaporates. Any resulting tackiness or softening of the surface is an indication of undercure.

IV-8 DIMENSIONS AND TOLERANCES

IV-8.1 Standard Diameters

(a) Standard diameters, based on nominal measurements, shall be as follows. Other diameters may be produced.

Pipe Diameter, DN (NPS)	Pipe Diameter, DN (NPS)
25 (1)	350 (14)
40 (1½)	400 (16)
50 (2)	450 (18)
80 (3)	500 (20)
100 (4)	600 (24)
150 (6)	750 (30)
200 (8)	900 (36)
250 (10)	1 000 (40)
300 (12)	1 200 (48)

(b) The tolerance on the inside diameter including out-of-roundness shall be ±1.5 mm (±1⁄16 in.) for pipe up to and including DN 150 mm (NPS 6) and ±6.5 mm (±1⁄4 in.) or ±1%, whichever is greater, for pipe sizes exceeding DN 150 (NPS 6). This measurement shall be made at the point of manufacture with the pipe in an unstrained horizontal position.

IV-8.2 Wall Thickness

(a) For pipe walls less than 32 mm (1.25 in.) thick, the minimum wall thickness at any point shall not be less than 90% of the specified thickness. For pipe walls 32 mm

(1.25 in.) or thicker, the minimum thickness at any point shall not be less than 3 mm (0.125 in.) less than the specified wall thickness.

(b) Wall thickness shall be measured in accordance with ASTM D3567.

IV-8.3 Length

The length of each piece of plain end pipe shall not vary more than 50 mm (2 in.) from the ordered length unless arrangements are made to allow for trim in the field.

IV-8.4 Squareness of Ends

Pipe shall be cut square with the axis of the pipe within 3 mm ($^1\!/_8$ in.) for all diameters up to and including 600 mm (24 in.) and within 5 mm ($^3\!/_{16}$ in.) for all diameters greater than 600 mm (24 in.).

IV-9 TEST METHODS

The purchaser shall specify which test methods, if any, are required.

IV-9.1 Glass Reinforcement Content

When required by the purchaser, the glass content shall be determined in accordance with ASTM D2584.

IV-9.2 Hoop Tensile Strength

(a) Hoop tensile strength shall be determined by testing in accordance with ASTM D1599. Specimens shall be tested with unrestrained end closures (which provide biaxial pressure loading).

(b) The pipe may be tested at ambient temperature using water at ambient temperature [10°C to 25°C (50°F to 77°F)] as a test medium in lieu of the conditions required by ASTM D1599.

IV-9.3 Hoop Flexural Modulus

Hoop flexural modulus shall be determined by testing in accordance with ASTM D790 or ASTM D2412 or by lamination analysis.

IV-9.4 Axial Tensile Strength

(a) Axial tensile strength shall be determined by testing in accordance with ASTM D638, ASTM D2105, or ASTM D3039.

(b) The actual laminate thickness shall be tested.

IV-10 MARKING

Pipe shall be marked at least once per section with the following information in such a manner that it remains legible under normal handling and installation practices:

(a) ASME NM.2, with which the pipe complies

(b) nominal pipe size [e.g., "300 mm (12 in.) diameter"]

(c) pressure rating [e.g., "1 000 kPa (150 psi)"]

(d) resin identification (trade name and number)

(e) manufacturer's name or trademark

For example, a 300-mm (12-in.) diameter pipe with a pressure rating of 1 000 kPa (150 psi) would have the following marking: "ASME NM.2 300 mm (12 in.) Dia. 1 000 kPa (150 psi) Polyeverlast 1234, XYZ Manufacturing Co."

IV-11 CERTIFICATION

(a) The seller or manufacturer shall furnish a certificate of compliance when such certification is specified by the purchaser.

(1) A signature is not required on the certificate of compliance, but the document shall be dated and shall clearly identify the organization submitting the document.

(2) Notwithstanding the absence of a signature, the certifying organization is responsible for the contents of the document.

(b) The certificate of compliance shall consist of a copy of the manufacturer's test report or a statement by the seller (accompanied by a copy of the test results) that the material has been sampled, tested, and inspected in accordance with the provisions of the applicable specification.

(c) If the original identity of the material cannot be established, certification can be based only on the sampling procedure provided in this Appendix.

MANDATORY APPENDIX V
INSPECTIONS AND TESTING OF REINFORCEMENT MATERIALS

V-1 GENERAL

(a) All inspections and tests specified in this Appendix shall be performed by manufacturer personnel or an independent testing laboratory on the reinforcement materials.

(b) Reinforcement materials include

(1) fiberglass surfacing veil (mat)
(2) organic fiber surfacing veil (mat)
(3) carbon fiber veil (mat)
(4) fiberglass chopped-strand mat
(5) fiberglass spray-up roving
(6) filament winding roving
(7) fiberglass woven-roving fabric
(8) fiberglass unidirectional fabric
(9) fiberglass nonwoven biaxial fabric
(10) fiberglass milled fibers

V-2 FIBERGLASS SURFACING VEIL (MAT), ORGANIC FIBER SURFACING VEIL (MAT), CARBON FIBER VEIL (MAT), AND FIBERGLASS CHOPPED-STRAND MAT

V-2.1 Introduction

This section specifies the minimum inspections and tests that shall be performed on the rolls of fiberglass surfacing veil, organic fiber surfacing veil, and fiberglass chopped-strand mat used to fabricate glass-fiber-reinforced thermosetting-resin piping systems to this Standard.

V-2.2 Acceptance Inspection

(a) Acceptance inspection of the rolls shall include the following:

(1) Proper Packaging and Identification. This acceptance inspection shall be conducted on the unopened roll. Acceptance requirements and limits shall be as defined in para. V-2.4.1.

(2) Imperfections and Contamination. This inspection shall be conducted during use of the rolled goods. Acceptance requirements and limits shall be as defined in paras. V-2.4.2. If the inspected roll or rolls fail the inspection criteria of para. V-2.4.2, then each roll in the lot shall be inspected.

(3) Unit Weight. At least one roll shall be inspected for measurement of unit weight per ASQ Z1.4 criteria. If the inspected roll or rolls fail the inspection criteria of para. V-2.4.3, then each roll in the lot shall be inspected.

(b) Form V-2.2-1 or a similar form that contains the provisions to record the results of these required inspections and certifications, if applicable, shall be used by the manufacturer and shall be retained in the inspection records.

(1) A separate form shall be used for each mat constituent material manufacturer, mat nomenclature, mat treatment, and mat unit weight.

(2) In lieu of performing the inspections required in paras. V-2.4.2 and V-2.4.3, the fabricator may obtain and accept from the constituent material manufacturer a certificate of compliance with the requirements and limits defined in paras. V-2.4.2 and V-2.4.3. However, the fabricator shall conduct the receiving inspections required in para. V-2.4.1.

(3) The certificate of compliance described in (2) shall ensure that materials were manufactured, inspected, and tested in accordance with the appropriate specifications.

V-2.3 Equipment and Measuring Tools Required

V-2.3.1 Inspection Table and Lights. An inspection table and adequate overhead lighting that are suitable for the inspection and testing of the mat shall be provided. The equipment used shall not introduce contamination to the mat during the inspection and testing process.

V-2.3.2 Linear Measuring Tools. A standard linear measuring tool (longer than the width of the rolls) that measures the roll widths with minimum accuracy of ±3 mm (±$^1/_8$ in.) shall be used. A 305 mm ± 1 mm (12 in. ±$^1/_{32}$ in.) square template shall be used to measure the samples of mat for inspection.

V-2.3.3 Laboratory Balance. A laboratory balance that measures to 0.1 g and has an accuracy of ±0.05 g shall be used to weigh the samples of mat.

V-2.4 Procedures and Acceptance Limits

V-2.4.1 Roll Identification and Package Inspection

(a) The mat shall be packaged as shipped from the mat constituent material manufacturer's factory.

(b) If repackaging is required, the manufacturer shall ensure that a material certificate of compliance traceable to the original material is provided. The original labels may be modified in regard to number and width of rolls only. All other documentation shall remain unchanged.

(c) The mat rolls, as identified by the mat constituent material manufacturer, shall be verified as having the same nomenclature as the mat specified to produce the laminate.

(d) The packaging of the mat shall be examined for damage that renders the mat unusable.

(e) Acceptable rolls shall be indicated by recording the date of the inspection and the inspector's name in Form V-2.2-1, column 4.

(f) For packaged mats that are found to be acceptable for further inspection and tests, the reinforcement production date and lot number shall be entered in Form V-2.2-1, columns 2 and 3, respectively.

V-2.4.2 Visual Inspection of Mat

(a) As the mat is used during fabrication, it shall be visually inspected for imperfections and contamination. The date of the inspection and the inspector's name shall be recorded in Form V-2.2-1, column 8.

(b) The mat shall be uniform in color, texture, and appearance. Imperfections and contaminants shall be removed in a manner that does not damage the mat, or the section of the mat containing the defects may be removed by making two parallel cuts across the width of the mat and discarding the affected section. White or light gray binder spots shall not be considered contaminants.

NOTE: Examples of imperfections are holes, cuts, thin spots, and delaminations, i.e., separation of the mat into layers during unrolling. Examples of contaminants are dirt, oil, grease, and foreign objects.

(c) Rolls having any of the following defects shall not be used in laminates made to this Standard:

(1) wet spots
(2) water contamination
(3) bar marks
(4) lengthwise wrinkles exceeding 1.5 m (5 ft)

V-2.4.3 Weight per Square Foot of Mat

(a) From the leading edge of each roll of mat that will be inspected in accordance with para. V-2.2, a 0.09-m^2 (1-ft^2) mat or 0.92-m^2 (10-ft^2) surfacing veil sample shall be cut using the template specified in para. V-2.3.2.

(b) If the roll is less than 304.8 mm (12 in.) wide, the full width of the roll shall be used, but the length of the sample shall be adjusted (use the linear measuring tool specified in para. V-2.3.2).

(c) Any property measurement shall be conducted by unrolling only the quantity of material required to conduct the test.

(d) The sample of mat shall be placed on the laboratory balance (see para. V-2.3.3) and weighed to the nearest 0.1 g.

NOTE: Convert the grams to ounces, if needed, by multiplying by 0.0352.

(e) If the sample from a roll falls outside the mat constituent material manufacturer's specified weight range, the roll of mat shall be rejected.

(f) The values of weighed samples for acceptable and unacceptable rolls shall be entered in Form V-2.2-1, column 6. The rejected rolls shall be identified by the word "rejected" written next to the recorded weight.

V-3 FIBERGLASS SPRAY-UP ROVING AND FILAMENT-WINDING ROVING

V-3.1 Introduction

This section specifies the minimum inspections and tests that shall be performed on fiberglass spray-up roving and filament-winding roving used to fabricate glass-fiber-reinforced thermosetting-resin piping systems to this Standard.

V-3.2 Acceptance Inspections

(a) Acceptance inspection of roving shall include the following:

(1) *Proper Packaging and Identification.* This acceptance inspection shall be conducted on the unopened roll. Acceptance requirements and limits shall be as defined in para. V-3.4.1.

(2) *Imperfections and Contamination.* This inspection shall be conducted during use of the roving balls. Acceptance requirements and limits shall be as defined in para. V-3.4.2.

(3) *Roving Yield.* Selected rolls shall be inspected for measurement of roving yield per ASQ Z1.4 criteria. Acceptance requirements and limits shall be as defined in para. V-3.4.3.

(b) Form V-3.2-1 or a similar form that contains the provisions to record the results of inspections shall be used by the manufacturer and retained in the inspection records.

(1) A separate form shall be used for each roving constituent material manufacturer, roving nomenclature, and roving yield.

(2) In lieu of performing the inspections required in paras. V-3.4.2 and V-3.4.3, the fabricator may obtain and accept from the constituent material manufacturer a certificate of compliance with the requirements defined in paras. V-3.4.2 and V-3.4.3. However, the fabricator shall conduct the receiving inspections required in para. V-3.4.1.

(3) The certificate of compliance described in (2) shall ensure that materials were manufactured, inspected, and tested per the material supplier's specifications.

V-3.3 Equipment and Measuring Tools Required

V-3.3.1 Wrap Reel. Equipment that provides a sample at least 5 486.4 mm (6 yd) long, measured and cut under sufficient tension to keep the strand taut, shall be used. A standard 914.4-mm (1-yd) or 1 371.6-mm (1.5-yd) yarn reel with adjustable-transverse, four-skein capacity should be used.

V-3.3.2 Laboratory Balance. A laboratory balance that measures to 0.1 g and has an accuracy of ±0.05 g shall be used to weigh the roving samples.

V-3.4 Procedures and Acceptance Limits

V-3.4.1 Roving Identification and Package Inspection

(a) The roving shall be packaged as shipped from the constituent material manufacturer's factory.

(b) The roving shall not be repackaged in the distribution of the material after the constituent material manufacturer has shipped the roving.

(c) The roving balls, as identified by the constituent material manufacturer, shall be verified as having the same nomenclature as the roving required.

(d) The packaging of the roving shall be inspected for damage that renders the roving unusable.

(e) Acceptable roving shall be indicated by recording the date of the inspection and the name of the person performing the inspection in Form V-3.2-1, column 4.

(f) For packaged rovings that are found to be acceptable for further inspection and tests, the reinforcement production date and lot number for each ball shall be entered in Form V-3.2-1, columns 2 and 3, respectively.

V-3.4.2 Visual Inspection of Roving

(a) The roving ball shall be visually inspected for imperfections and contamination prior to use by the manufacturer.

(1) The date of the inspection and the inspector's name shall be recorded in Form V-3.2-1, column 7.

(2) If any roving ball is rejected, the reason shall be recorded in the "Comments" section of Form V-3.2-1.

(b) Roving balls having any of the following defects shall not be used for laminates made to this Standard:

(1) contamination from foreign matter such as dirt, oil, grease, waste glass fiber, or beads of glass such that it would detract from the performance or appearance of the finished product

(2) water contamination

V-3.4.3 Measurement of Roving Yield

(a) From one roving ball per shipment, a sample of roving at least 5 486.4 mm (6 yd) long (length A) shall be obtained as required by para. V-3.3.1.

(1) Roving shall be pulled from the same side of the package as used in the manufacturer's process.

(2) If the roving is pulled from the outside of the package, sufficient material shall be removed and discarded so that the sample will be taken from undisturbed material.

(3) The sample shall be removed from the wrap reel.

(4) The sample shall be doubled several times and tied with a single knot.

(b) The sample shall be placed on the laboratory balance (see para. V-3.3.2) and weighed to the nearest 0.1 g.

NOTE: Convert grams to ounces, if needed, by multiplying by 0.0352.

(1) Two specimens from each package shall be weighed, and the average of the two weights calculated.

(2) The average weight shall be recorded as weight A.

(c) The yield, in yards per pound, shall be calculated from the following equation:

$$\text{yield, yd/lb} = \frac{16\ \text{oz/lb} \times \text{length, yd}}{\text{weight}\ A,\ \text{oz}} \tag{V-3-1}$$

(d) The yields of acceptable and unacceptable balls of roving shall be entered in Form V-3.2-1, column 5.

(e) If the yield of the ball of roving is outside the constituent material manufacturer's specification, the remaining balls in the shipment shall be inspected per ASQ Z1.4 criteria, following the procedure specified in (a) through (d).

(f) Balls whose yield is outside the constituent material manufacturer's specification shall not be used for laminates made to this Standard.

(g) The rejected roving balls shall be identified by the word "rejected" written next to the yield in Form V-3.2-1, column 5.

(h) The date of the yield measurement and the name of the person who took the measurement shall be recorded in Form V-3.2-1, column 6.

V-4 FIBERGLASS WOVEN ROVING FABRIC, FIBERGLASS NONWOVEN BIAXIAL FABRIC, AND FIBERGLASS UNIDIRECTIONAL FABRIC

V-4.1 Introduction

This section specifies the minimum inspections and tests that are to be performed on rolls of fiberglass woven roving fabric, fiberglass nonwoven biaxial fabric, and fiberglass unidirectional fabric used to fabricate glass-fiber-reinforced thermosetting-resin piping systems to this Standard.

V-4.2 Acceptance Inspections

(a) Acceptance inspection of fabric rolls shall include the following:

(1) Proper Packaging and Identification. This inspection shall be conducted on the unopened roll. Acceptance requirements and limits shall be as defined in para. V-4.4.1.

(2) Imperfections and Contamination. This inspection shall be conducted during use of the rolled goods. Acceptance requirements and limits shall be as defined in para. V-4.4.2.

(3) Width, Unit Weight, and Construction. Selected rolls shall be inspected for measurement of width and unit weight and for construction of fabric per ASQ Z1.4 criteria. Acceptance requirements and limits shall be as defined in paras. V-4.4.3 through V-4.4.5.

(b) Form V-4.2-1 or a similar form that contains the provisions to record the results of these required inspections shall be used by the manufacturer and retained in the inspection records. A separate form shall be used for each fabric constituent material manufacturer, fabric nomenclature, fabric unit weight (in ounces per square yard), and fabric construction.

(c) In lieu of performing the inspections required in paras. V-4.4.2 and V-4.4.3, the fabricator may obtain and accept from the constituent material manufacturer a certificate of compliance with the requirements defined in paras. V-4.4.2 and V-4.4.3. However, the fabricator shall conduct the receiving inspections required in para. V-4.4.1.

V-4.3 Equipment and Measuring Tools Required

V-4.3.1 Inspection Table and Lights. An inspection table and adequate overhead lighting that are suitable for the inspection and testing of the fabric shall be used. The equipment used shall not introduce contamination to the fabric during inspection and testing.

V-4.3.2 Linear Measuring, Marking, and Cutting Tools

(a) A standard linear measuring tool (longer than the width of the roll) that measures the roll widths with minimum accuracy of ±3.275 mm (±1⁄8 in.) shall be used. A 76.3 mm ± 0.79 mm (3 in. ± 1⁄32 in.) square template shall be used to measure the samples for inspection.

(b) A fine-point felt-tip pen and scissors shall be used to mark and cut the samples.

V-4.3.3 Laboratory Balance. A laboratory balance that measures to 0.1 g with an accuracy of ±0.05 g shall be used to weigh the samples.

V-4.4 Procedures and Acceptance Limits

V-4.4.1 Roll Identification and Package Inspection

(a) The fabric shall be packaged as shipped from the constituent material manufacturer's factory.

(b) The fabric shall not be repackaged in the distribution of the material after the constituent material manufacturer has shipped the fabric.

(c) The fabric rolls, as identified by the constituent material manufacturer, shall be verified as having the same nomenclature as the fabric required.

(d) The packaging of the fabric rolls shall be examined for damage that renders the fabric unusable.

(e) Acceptable rolls shall be indicated by recording the date of the inspection and the name of the person performing the examination in Form V-4.2-1, column 4.

(f) For packaged rolls that are found to be acceptable for further inspection and tests, the fabric production date and lot number shall be entered in Form V-4.2-1, columns 2 and 3, respectively.

V-4.4.2 Visual Inspection of Fabric

(a) General. As fabric is used, it shall be visually inspected for imperfections and contaminations by the manufacturer.

(1) The date of the inspection and the inspector's name shall be recorded in Form V-4.2-1, column 9.

(2) If a roll is rejected, the reason shall be recorded under the "Comments" section on Form V-4.2-1.

(b) Fiberglass Woven Roving and Fiberglass Nonwoven Biaxial Fabric

(1) Fabric shall be uniform in color, texture, and appearance. The following imperfections and/or contaminations shall be removed from fiberglass woven roving and fiberglass nonwoven biaxial fabric by making two parallel cuts across the width of the fabric and discarding the rectangular sections of fabric containing the defects:

(-a) dirt spots[1] 4.76 mm to 19 mm (3⁄16 in. to 3⁄4 in.) in diameter in excess of one per 3 linear m (10 linear ft)

(-b) missing ends for more than 0.61 consecutive m (2 consecutive ft) in length

(-c) fuzz clumps or loops greater than 25 mm (1 in.) in height from the surface

(2) Fiberglass woven roving and fiberglass nonwoven biaxial fabric having any of the following defects shall not be used for laminates made to this Standard:

(-a) dirt spots[1] in excess of 19 mm (3⁄4 in.) in diameter

(-b) more than 11 missing ends, either individual picks or any combination of individual and multiple (2, 3, 4, or 5) ends, in any 30.48 consecutive linear m (100 consecutive linear ft)

[1] "Dirt spots" are defined as all foreign matter, dirt, grease spots, etc.

(-c) fuzz clumps or loops that prevent the proper lay-down of the fabric and that cannot be easily removed

(-d) water contamination

(c) Fiberglass Unidirectional Fabric

(1) Fiberglass unidirectional fabric shall be uniform in color, texture, and appearance. The following imperfections and/or contaminations shall be removed from the fabric by making two parallel cuts across the width of the fabric and discarding the rectangular sections of fabric containing the defects:

(-a) dirt spots[1] 4.76 mm to 19 mm ($^3\!/_{16}$ in. to $^3\!/_4$ in.) in diameter in excess of one per 3 linear m (10 linear ft)

(-b) more than one missing end per 0.3 linear m (1 linear ft) in any direction

(-c) areas of the fabric less than 152.4 mm (6 in.) where rovings are disoriented or looped less than 25 mm (1 in.) in height from the surface. The number of these areas shall not exceed two per 4.6 linear m (5 linear yd) of fabric. If they do, the roll shall not be used for laminates made to this Standard.

(-d) weft tails greater than 25 mm (1 in.) or less than 3.2 mm ($^1\!/_8$ in.) in length.

(-e) bias exceeding ±10 deg from 0 deg/180 deg in a warp (machine direction) product or from 90 deg/270 deg in a weft (fill direction) product.

(2) Fiberglass unidirectional fabric rolls having any of the following defects shall not be used for laminates made to this Standard:

(-a) dirt spots[1] in excess of 19 mm ($^3\!/_4$ in.) in diameter

(-b) more than one missing end per 0.3 linear m (1 linear ft) in any direction

(-c) areas of the fabric greater than 152.4 mm (6 in.) where rovings are disoriented or looped less than 25 mm (1 in.) in height from the surface

(-d) areas of the fabric where rovings are disoriented or looped greater than 25 mm (1 in.) in height from the surface

(-e) contamination from water or other substances

V-4.4.3 Width Measure of Fabric

(a) The linear measuring tool specified in para. V-4.3.2 shall be used to measure the width of the fabric at a position at least 0.9 m (1 yd) from the beginning (leading) edge of the roll and at two additional positions at least 152.4 mm (6 in.) apart.

(1) Follow the constituent material manufacturer's definition for the width of the particular fabric.

NOTE: Due to the methods of manufacturing fabrics, there are different ways of describing widths of fabrics.

(2) Measure to the nearest 3.175 mm ($^1\!/_8$ in.).

(3) Average the three measurements and enter the measured width of acceptable and unacceptable rolls in Form V-4.2-1, column 5.

(b) Rolls with variations greater than ±12.7 mm (±$^1\!/_2$ in.) shall not be used in laminates made to this Standard.

(c) The rejected rolls shall be identified by the word "rejected" written next to the width in Form V-4.2-1, column 5.

(d) The date of the width, weight, and construction measurements and the name of the person who took the measurements shall be recorded in Form V-4.2-1, column 8.

V-4.4.4 Weight per Square Yard of Fabric

V-4.4.4.1 Measuring Process

(a) The fabric shall be unrolled and laid flat on the inspection table.

(b) One fill pick shall be pulled from the fabric, or a line shall be marked across the width of the fabric.

(c) The linear measuring tool specified in para. V-4.3.2 shall be used to measure a fabric sample 914.4 mm (36 in.) long starting at the pulled pick or marked line specified in (b). A second pick shall be pulled or line marked to indicate the end of the sample.

(d) The 914.4-mm (36-in.) long sample shall be cut, using the scissors specified in para. V-4.3.2, across the width of the fabric.

(e) The width of the fabric shall be measured as described in para. V-4.4.3.

V-4.4.4.2 Weight Determination Process

(a) The sample shall be placed on the laboratory balance (see para. V-4.3.3) and weighed to the nearest 0.1 g.

NOTE: Convert the grams to ounces, if needed, by multiplying by 0.0352.

(b) The weight, in ounces per square yard, shall be calculated from the following equation:

$$\text{weight, oz/yd}^2 = 1{,}296\ \text{in.}^2/\text{yd}^2 \times \frac{\text{sample weight, oz}}{\text{sample width, in.} \times \text{sample length, in.}} \quad \text{(V-4-1)}$$

(c) Rolls whose weight per square yard is outside the constituent material manufacturer's specification shall not be used for laminates made to this Standard.

(d) The weight per square yard of acceptable and unacceptable rolls shall be entered in Form V-4.2-1, column 6. The rejected rolls shall be identified by the word "rejected" written next to the recorded weight.

V-4.4.5 Construction

(a) The following construction process shall be used:

(1) Unroll the fabric on the inspection table and lay flat.

(2) Perform the verification of construction in an area at least 1 yd from the beginning of the roll and one-tenth of the width from the edge of the fabric. For

example, on 1 524-mm (60-in.) material, start at least 152.4 mm (6 in.) from one edge and 914.4 mm (1 yd) from the beginning of the fabric.

(3) Using the template required by para. V-4.3.2, measure a 76.2-mm (3-in.) square and count the number of warp strands (if applicable) to the nearest half strand in the section. Repeat this three times diagonally across the fabric.

(4) Add the total warp strands counted in the three 76.2-mm (3-in.) squares and divide by 9. This will give picks per inch in the warp of the fabric.

(b) The construction process described in (a) shall be repeated for the fill (weft) strands, if applicable.

(c) Rolls whose picks per inch in either warp or fill are outside the constituent material manufacturer's specification shall not be used for laminates made to this Standard.

(d) The picks per inch in the warp and fill of acceptable and unacceptable rolls to the nearest 0.1 picks shall be entered in Form V-4.2-1, column 7.

V-5 FIBERGLASS MILLED FIBERS

V-5.1 Introduction

This section specifies the minimum inspections and tests that shall be performed on packages of fiberglass milled fiber used to fabricate glass-fiber-reinforced thermosetting-resin piping systems to this Standard.

V-5.2 Acceptance Inspections

(a) Acceptance inspections of fiberglass milled fiber shall include inspection of the milled fiber for proper packaging and identification, and visual inspection for contamination.

(b) Acceptance requirements and limits shall be as defined in paras. V-5.4.1 and V-5.4.2.

(c) Form V-5.2-1 or a similar form that contains the provisions to record the results of these required inspections shall be used by the manufacturer and retained in the inspection records. A separate form shall be used for each milled fiber constituent material manufacturer, milled fiber nomenclature, and milled fiber length.

V-5.3 Equipment Required

An inspection table and adequate overhead lighting that are suitable for the inspection of the milled fiber shall be used. The equipment used shall not introduce contamination to the milled fiber during inspection.

V-5.4 Procedures and Acceptance Limits

V-5.4.1 Package Identification and Inspection

(a) The milled fiber shall be packaged as shipped from the constituent material manufacturer's factory.

(b) The milled fiber shall not be repackaged in the distribution of the material after the constituent material manufacturer has shipped the milled fiber.

(c) The milled fiber, as identified by the constituent material manufacturer, shall be verified as having the same nomenclature as the milled fiber required.

(d) Each package of milled fiber shall be examined for damage that renders it unusable.

(e) Acceptable milled fibers shall be indicated by recording the date of the inspection and the name of the person performing the inspection in Form V-5.2-1, column 4.

(f) For packaged milled fiber that is found to be acceptable for further inspection, the reinforcement production date and lot number for each package used shall be entered in Form V-5.2-1, columns 2 and 3, respectively.

V-5.4.2 Visual Inspection of Milled Fiber

(a) As milled fiber is used, it shall be visually inspected for contamination by the manufacturer. The the date of the inspection and the inspector's name shall be recorded in Form V-5.2-1, column 5.

(b) Packages having contamination of the milled fiber evident in the form of water, oil, grease, or clumping together shall be rejected.

(c) The results of the visual inspection of each package of milled fiber shall be recorded in the "Comments" section of Form V-5.2-1.