MANDATORY APPENDIX XIII
DESIGN BASED ON STRESS ANALYSIS

ARTICLE XIII-1000
GENERAL REQUIREMENTS

XIII-1100  SCOPE

This Appendix is applicable for the design of metallic items when specifically permitted by the applicable Section III Subsection. This Appendix uses Division 1 terminology. When this Appendix is referenced by other divisions, (a) through (c) are applicable.

(a) The terms Service Loadings versus Operating Loadings, vessel versus containment, pressure boundary versus containment boundary, etc. shall be considered as identical in the application of these rules for Division 3 components.

(b) The stress limits for Class 1 components are also applicable for Division 5, Class A components.

(c) The stress limits for Class 2 components are also applicable for Division 5, Class B components.

XIII-1200  DESIGN ACCEPTABILITY

XIII-1210  REQUIREMENTS FOR DESIGN ACCEPTABILITY

The requirements for the acceptability of a design are as follows:

(a) The design shall be such that the stresses shall not exceed the limits described in this Appendix.

(b) For configurations where compressive stresses occur, in addition to the requirement in (a), the critical buckling stress shall be taken into account.

(c) The requirements for material, design, fabrication, examination, and testing of the applicable Subsection shall be met.

XIII-1220  BASIS FOR DETERMINING STRESSES

The theory of failure used in the rules of this Appendix is the maximum shear stress theory. The maximum shear stress at a point is equal to one-half the difference between the algebraically largest and the algebraically smallest of the three principal stresses at the point.

XIII-1300  TERMS RELATING TO STRESS ANALYSIS

Terms used in this Appendix relating to stress analysis are defined in (a) through (ak) below.

(a) Bending Stress. Bending stress is the component of normal stress that varies across the thickness. The variation may or may not be linear. The bending component of primary stress for piping is the stress proportional to the distance from the centroid of the pipe cross section.

(b) Collapse Load — Lower Bound. If, for a given load, any system of stresses can be found that everywhere satisfies equilibrium, and nowhere exceeds the material yield strength, the load is at or below the collapse load. This is the lower bound theorem of limit analysis, which permits calculations of a lower bound to the collapse load.

(c) Creep. Creep is the special case of inelasticity that relates to the stress-induced, time-dependent deformation under load. Small time-dependent deformations may occur after the removal of all applied loads.

(d) Deformation. Deformation of a component part is an alteration of its shape or size.

(e) Equivalent Linear Stress. Equivalent linear stress is defined as the linear stress distribution that has the same net bending moment and net force as the actual stress distribution.

(f) Expansion Stresses. Expansion stresses are those stresses resulting from restraint of free end displacement of the piping system.

(g) Fatigue Strength Reduction Factor. Fatigue strength reduction factor is a stress intensification factor that accounts for the effect of a local structural discontinuity (stress concentration) on the fatigue strength. Values for some specific cases, based on experiment, are given in the applicable Subsection. A theoretical stress concentration factor or stress index may be used. A fatigue strength reduction factor or stress index may also be determined using the procedures in Mandatory Appendix II.

(h) Free End Displacement. Free end displacement consists of the relative motions that would occur between a fixed attachment and connected piping if the two members were separated and permitted to move.
(i) Gross Structural Discontinuity. Gross structural discontinuity is a geometric or material discontinuity that affects the stress or strain distribution through the entire wall thickness. Gross discontinuity-type stresses are those portions of the actual stress distributions that produce net bending and membrane force resultants when integrated through the wall thickness. Examples of a gross structural discontinuity are head-to-shell junctions, flange-to-shell junctions, nozzles, and junctions between shells of different diameters or thicknesses.

(j) Inelasticity. Inelasticity is a general characteristic of material behavior in which the material does not return to its original shape and size after removal of all applied loads. Plasticity and creep are special cases of inelasticity.

(k) Limit Analysis. Limit analysis is a special case of plastic analysis in which the material is assumed to be ideally plastic (non-strain-hardening). In limit analysis, the equilibrium and flow characteristics at the limit state are used to calculate the collapse load. The two bounding methods used in limit analysis are the lower bound approach, which is associated with a statically admissible stress field, and the upper bound approach, which is associated with a kinematically admissible velocity field. For beams and frames, the term mechanism is commonly used in lieu of kinematically admissible velocity field.

(l) Limit Analysis — Collapse Load. The methods of limit analysis are used to compute the maximum load that a structure assumed to be made of ideally plastic material can carry. At this load, which is termed the collapse load, the deformations of the structure increase without bound.

(m) Load-Controlled Stress. Load-controlled stress is the stress resulting from application of a loading, such as internal pressure, inertial loads, or gravity, whose magnitude is not reduced as a result of displacement.

(n) Local Primary Membrane Stress. Cases arise in which a membrane stress produced by pressure or other mechanical loading and associated with a discontinuity would, if not limited, produce excessive distortion in the transfer of load to other portions of the structure. Conservatism requires that such a stress be classified as a local primary membrane stress even though it has some characteristics of a secondary stress.

A stressed region may be considered local if the distance over which the membrane stress intensity exceeds 1.1$S_m$ (see XIII-2200) does not extend in the meridional (longitudinal) direction more than $1.0/\sqrt{R}$, where $R$ is the minimum midsurface radius of curvature and $t$ is the minimum thickness in the region considered. Regions of local primary stress intensity involving axisymmetric membrane stress distributions that exceed 1.1$S_m$ shall not be closer in the meridional (longitudinal) direction than $2.5/Rt$, where $R_h$ is defined as $(R_1 + R_2)/2$ and $t_2$ is defined as $(t_1 + t_2)/2$ (where $t_1$ and $t_2$ are the minimum thicknesses at each of the regions considered, and $R_1$ and $R_2$ are the minimum midsurface radii of curvature at these regions where the membrane stress intensity exceeds 1.1$S_m$). Discrete regions of local primary membrane stress intensity, such as those resulting from concentrated loads acting on brackets, where the membrane stress intensity exceeds 1.1$S_m$, shall be spaced so that there is no overlapping of the areas in which the membrane stress intensity exceeds 1.1$S_m$.

Examples of local primary membrane stress include:

1. Membrane stress in a shell produced locally by an external load
2. Membrane stress in a shell at a permanent support or nozzle location
3. Circumferential membrane stress at the intersection of a cylindrical shell with a conical shell due to internal pressure, as illustrated in Figure XIII-1300-1.

Local stressed area may also include areas of local wall thinning. The requirements of XIII-3770 shall be applied for these cases.

(o) Local Structural Discontinuity. Local structural discontinuity is a geometric or material discontinuity that affects the stress or strain distribution through a fractional part of the wall thickness. The stress distribution associated with a local discontinuity causes only very localized deformation or strain and has no significant effect on the shell-type discontinuity deformations. Examples are small fillet radii, small attachments, and partial penetration welds.

(p) Membrane Stress. Membrane stress is the component of normal stress that is uniformly distributed and equal to the average stress across the thickness of the section under consideration.

(q) Nonreversing Dynamic Loads. Nonreversing dynamic loads (see Figure XIII-1300-2) are those loads that do not cycle about a mean value; examples include the initial thrust force due to sudden opening or closure of valves and waterhammer resulting from entrapped water in two phase flow systems. Reflected waves in a piping system due to flow transients are classified as nonreversing dynamic loads.

(r) Normal Stress. Normal stress is the component of stress normal to the plane of reference. This is also referred to as direct stress. Usually the distribution of normal stress is not uniform through the thickness of a part, so this stress is considered to have two components, one uniformly distributed and equal to the average stress across the thickness under consideration, and the other varying from this average value across the thickness.
Figure XIII-1300-1
Example of Acceptable Local Primary Membrane Stress Due to Pressure

Legend:
- $P$ = pressure
- $P_L$ = primary local membrane stress intensity limit applies within the local region
- $P_m$ = primary general membrane stress intensity limit applies outside the local region
- $R$ = minimum midsurface radius of curvature
- $t$ = minimum thickness in stressed region considered
- $V_1$ and $V_2$ = meridional forces
- $S_{m}$ = design stress intensity for the material at service temperature
- $SI_{max}$ = maximum stress intensity
- $SI_{max}$ = maximum stress intensity
- $t$ = minimum thickness in stressed region considered
- $V_1$ and $V_2$ = meridional forces

GENERAL NOTE: See XIII-1300(n) and XIII-3120 for limits.
ARTICLE XIII-3000
STRESS LIMITS FOR OTHER THAN BOLTS

(19) XIII-3100 PRIMARY STRESS INTENSITY LIMITS

(a) Design Loadings. The stress intensity limits that are to be satisfied at the Design Temperature for the Design Loadings stated in the Design Specification are given in XIII-3110 through XIII-3130.

(b) Level A, Level B, Level C, and Level D Service Limits. The primary stress intensity limits that must be satisfied at the coincident material temperature for any Level A, Level B, Level C, or Level D loadings stated in the Design Specification are those given in XIII-3110 through XIII-3130. For piping, additional requirements are provided in XIII-3140.

(c) Testing Limits. XIII-3600 includes primary stress intensity limits for testing.

(d) The provisions of XIII-3200 may provide relief from certain of these stress limits if plastic analysis techniques are applied.

XIII-3110 GENERAL PRIMARY MEMBRANE STRESS INTENSITY

This stress intensity is derived from $P_m$ in Figure XIII-2100-1 and is calculated using the average value across the thickness of a section of the general primary stresses [see XIII-1300(n)] produced by

(a) Design Pressure and other specified Design Mechanical Loads

(b) coincident pressure and mechanical loads associated with the Service or Operating Loadings specified in the Design Specification, but excluding all secondary and peak stresses.

Averaging is to be applied to the stress components prior to determination of the stress intensity values. The allowable values of this stress intensity are tabulated in Table XIII-3110-1.

XIII-3130 PRIMARY MEMBRANE (GENERAL OR LOCAL) PLUS PRIMARY BENDING STRESS INTENSITY

This stress intensity is derived from $(P_m + P_L)$ in Figure XIII-2100-1 and is calculated using the highest value across the thickness of a section of the general or local primary membrane stresses plus primary bending stresses produced by

(a) Design Pressure and other specified Design Mechanical Loads

(b) coincident pressure and mechanical loads associated with the Service or Operating Loadings specified in the Design Specification, but excluding all secondary and peak stresses.

For solid rectangular sections, the allowable values of this stress intensity are tabulated in Table XIII-3110-1. For other than solid rectangular sections, a value of $\alpha$ times the limit on $P_m$ established in Table XIII-3110-1 may be used, where the factor $\alpha$ is defined as the ratio of the load set producing a fully plastic section to the load set producing initial yielding in the extreme fibers of the section. In the evaluation of the initial yield and fully plastic section capacities, the ratios of each individual load in the respective load set to each other load in that load set shall be the same as the respective ratios of the individual loads in the specified Design Load set. The value of $\alpha$ shall not exceed the value calculated for bending only ($P_m = 0$). In no case shall the value of $\alpha$ exceed 1.5. The $\alpha$ factor is not permitted for Level D Service Limits when inelastic component analysis is used as permitted in Mandatory Appendix XXVII. The propensity for buckling of the part of the section that is in compression shall be investigated.

For piping, primary bending stress is proportional to the distance from the centroid of the pipe cross section.

XIII-3140 PRIMARY STRESS LIMITS FOR PIPING

For Class 1 piping components operating within the temperature limits of the applicable Subsection, the requirements of XIII-3141 through XIII-3144 shall apply.
XIII-3141 Design Limits

The stress intensity limits for Class 1 components in Table XIII-3110-1 shall be satisfied.

XIII-3142 Level B Service Limits

(a) For Service Loadings for which Level B Service Limits are designated that do not include reversing dynamic loads [see XIII-1300(aa)] or that have reversing dynamic loads combined with nonreversing dynamic loads [see XIII-1300(q)], the stress intensity limits for Class 1 components in Table XIII-3110-1 shall be satisfied.

(b) For Service Loadings for which Level B Service Limits are designated that include reversing dynamic loads that are not required to be combined with nonreversing dynamic loads, the reversing dynamic loads shall meet the requirements of (a) above. The reversing dynamic loads shall meet the requirements of XIII-3420 and XIII-3520 as a unique load set. The reversing dynamic loads are not required to meet (a) above.

XIII-3143 Level C Service Limits

(a) For Service Loadings for which Level C Service Limits are designated that do not include reversing dynamic loads or that have reversing dynamic loads combined with nonreversing dynamic loads, the requirements of XIII-3110, XIII-3120, XIII-3130, XIII-3300, and XIII-3740 shall be satisfied. If the effects of anchor motion due to reversing dynamic loads are not considered in XIII-3142(b), then they shall satisfy the requirements of (b)(5) and (b)(6) below.

(b) As an alternative to (a) above, for piping fabricated from material designated P-No. 1 through P-No. 9 in Section II, Part D, Subpart 1, Table 2A and limited to \( \frac{D_o}{t} \leq 40 \) for Level C Service Limits, that include reversing dynamic loads that are not required to be combined with nonreversing dynamic loads, the requirements of (1) through (6) below shall apply.

(1) The pressure coincident with the reversing dynamic load shall not exceed the Design Pressure.

(2) The requirements of XIII-3110, XIII-3120, XIII-3130, XIII-3300, and XIII-3740 shall be satisfied for all nonreversing dynamic load combinations provided in the Design Specifications.

(3) The stress intensity for primary membrane plus bending stresses, \( (P_m \text{ or } P_L) + P_b \), due to weight loads shall not exceed 0.5\( S_m \).

---

### Table XIII-3110-1

<table>
<thead>
<tr>
<th>Stress Classification</th>
<th>Design</th>
<th>Service Level A</th>
<th>Service Level B</th>
<th>Service Level C</th>
<th>Service Level D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1 Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( P_m )</td>
<td></td>
<td></td>
<td>S_m</td>
<td></td>
<td>1.1S_m</td>
</tr>
<tr>
<td>( P_m ), ferritic material, pressure loadings alone</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>1.2S_m or S_y</td>
</tr>
<tr>
<td>( P_L )</td>
<td>1.5S_m</td>
<td></td>
<td>1.65S_m</td>
<td>1.8S_m or 1.5S_y</td>
<td></td>
</tr>
<tr>
<td>( (P_m \text{ or } P_L) + P_b ) [Note (3)]</td>
<td>1.5S_m</td>
<td>1.65S_m</td>
<td>1.8S_m or 1.5S_y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piping</td>
<td>[Note (4)]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Class 2 and 3 Components |        |                 |                 |                 |                 |
|\( P_m \) |                 | S_m | S_m | 1.1S_m | 1.2S_m | 2S_m [Note (5)] |
|\( P_L \) | 1.5S_m | 1.5S_m | 1.65S_m | 1.8S_m | 3S_m [Note (5)] |
|\( (P_m \text{ or } P_L) + P_b \) [Note (3)] | 1.5S_m | 1.5S_m | 1.65S_m | 1.8S_m | 3S_m [Note (5)] |

| Class SC Components |        |                 |                 |                 |                 |
|\( P_m \) |                 | S_m | S_m | ... | 1.2S_m | [Note (6)] |
|\( P_L \) | 1.5S_m | 1.5S_m | ... | 1.8S_m | |
|\( (P_m \text{ or } P_L) + P_b \) [Note (3)] | 1.5S_m | 1.5S_m | ... | 1.8S_m | |

**NOTES:**

(1) The values of \( S_m \) and \( S_y \) are given by XIII-2200.

(2) There are no specific primary stress limits for Level A Service Conditions.

(3) For other than solid rectangular sections, see XIII-3130(b).

(4) Paragraph XIII-3140 provides additional requirements for piping.

(5) As an alternative, the stress limits of Mandatory Appendix XXVII may be applied.

(6) Mandatory Appendix XXVII shall be applied. As an alternative, the requirements of WC-3700 may be used to evaluate inelastic component responses to energy-limited dynamic events.
(4) The stress intensity for primary membrane plus bending stresses, \((P_m + P_L) + P_b\), resulting from the combination of pressure, weight, and reversing dynamic loads shall not exceed the following:
   
   (-a) in elbows and bends: \(3.1S_m\)
   
   (-b) in tees and branches: \(3.1S_m\)
   
   (-c) in all other components: \(2.1S_m\)

(5) The stress intensity range of secondary stresses, \(Q\), resulting from anchor motion effects due to reversing dynamic loads shall not exceed \(4.2S_m\).

(6) The use of the \(6.0S_m\) limit in (5) assumes essentially linear behavior of the entire piping system. This assumption is sufficiently accurate for systems where plastic straining occurs at many points or over relatively wide regions, but fails to reflect the actual strain distribution in unbalanced systems where only a small portion of the piping undergoes plastic strain. In these cases, the weaker or higher-stressed portions will be subjected to strain concentration due to elastic follow-up of the stiffer or lower-stressed portions. Unbalance can be produced by

   (-a) the use of small pipe runs in series with larger or stiffer pipe, with the small lines relatively highly stressed

   (-b) local reduction in size or cross section, or local use of weaker material

In the case of unbalanced systems, the design shall be modified to eliminate the unbalance, or the stress intensity range of secondary stresses, \(Q\), shall be limited to \(2.1S_m\).

XIII-3144 Level D Service Limits

(a) For piping fabricated from material designated P-No. 1 through P-No. 9 in Section II, Part D, Subpart 1, Table 2A and limited to \(D_o/t \leq 40\), if Level D Service Limits are designated, that include reversing dynamic loads that limit the nonreversing dynamic load, then the combining rules defined in XIII-3210, XIII-3220, or XIII-3230 shall apply.

1. The pressure coincident with the reversing dynamic load shall not exceed the Design Pressure.

2. The requirements of Mandatory Appendix XXVII shall be satisfied for all nonreversing dynamic load combinations provided in the Design Specifications.

3. The primary membrane plus bending stresses, \((P_m + P_L) + P_b\), due to weight loads shall not exceed \(0.5S_m\).

4. The primary membrane plus bending stresses \((P_m + P_L) + P_b\), resulting from the combination of pressure, weight, and reversing dynamic loads shall not exceed the following:

   (-a) in elbows and bends: \(4.5S_m\)

   (-b) in tees and branches: \(4.5S_m\)

   (-c) in all other components: \(3.0S_m\)

5. The range of secondary stress, \(Q\), resulting from anchor motion effects due to reversing dynamic loads shall not exceed \(6.0S_m\).

6. The use of the \(6.0S_m\) limit in (5) assumes essentially linear behavior of the entire piping system. This assumption is sufficiently accurate for systems where plastic straining occurs at many points or over relatively wide regions, but fails to reflect the actual strain distribution in unbalanced systems where only a small portion of the piping undergoes plastic strain. In these cases, the weaker or higher-stressed portions will be subjected to strain concentration due to elastic follow-up of the stiffer or lower-stressed portions. Unbalance can be produced by

   (-a) the use of small pipe runs in series with larger or stiffer pipe, with the small lines relatively highly stressed

   (-b) local reduction in size or cross section, or local use of weaker material

In the case of unbalanced systems, the design shall be modified to eliminate the unbalance, or the range of secondary stress, \(Q\), shall be limited to \(3.0S_m\).

(b) For piping systems not meeting the requirements of (a) above, or as an alternative to (a) above, the rules contained in Mandatory Appendix XXVII may be used in evaluating these Service Loadings on piping systems independently of all other Design and Service Loadings. If the effects of anchor motion due to reversing dynamic loads are not considered in XIII-3142(b), they shall satisfy the requirements of (a)(5) and (a)(6).

XIII-3200 APPLICATIONS OF PLASTIC ANALYSIS

The following subsarticles provide guidance in the application of plastic analysis to determine the collapse load \(C_L\) and achieve some relaxation of the basic primary stress limits that is allowed if plastic analysis is used. The limits on general primary membrane stress intensity, local primary membrane stress intensity, and primary membrane plus primary bending stress intensity (see XIII-3130) need not be satisfied at a specific location if it can be shown that the specified loadings do not exceed \(kC_L\) where \(C_L\) is the collapse load determined using the procedure defined in XIII-3210, XIII-3220, or XIII-3230 and the value of \(k\) is specified in Table XIII-3200-1. When one of these rules is used, the effects of plastic strain concentrations in localized areas of the structure, such as the points where hinges form, shall be considered. The effects of the concentrations of strain on the fatigue behavior, ratcheting behavior, or buckling behavior of the structure shall be considered in the design. The design shall satisfy the minimum wall thickness requirements of the applicable Subsection.