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PV Newsletter

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Pressure Vessel Design Criteria

The modes of failure assumed for the design of pressure vessel are either a) elastic failure, which is governed by theory of elasticity, or b) plastic failure, which is governed by theory of plasticity. For thin-walled pressure vessels, elastic failure is used for pressure vessel design by ASME Boiler & Pressure Vessel codes.

The most commonly used theories of failure are:

- Maximum principal stress theory

  According to this theory, failure occurs when one of the three principal stresses reaches a stress value of elastic limit as determined from a uniaxial tension test. This theory is meaningful for brittle fracture applications.

- Maximum shear stress theory

  According to this theory, the maximum shear equals the shear stress at the elastic limit as determined from the uniaxial tension test. Here the maximum shear stress is one half the difference between the largest (say σ_1) and the smallest (say σ_3) principal stresses. This is also known as the Tresca criterion, which states that yielding takes place when

  $$\frac{(\sigma_1-\sigma_3)}{2} = \pm\frac{\sigma_y}{2}$$

- Maximum distortion energy theory

  This theory considers failure to have occurred when the distortion energy accumulated in the component under stress reaches the elastic limit as determined by the distortion energy in a uniaxial tension test. This is also known as von Mises criterion, which states that yielding takes place when

  $$\frac{1}{\sqrt{2}}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2] = \pm\sigma_y$$

The difference between the Tresca and von Mises criteria can be highlighted by considering a simplified case of bi-axial stress state, where we assume that the principal stress σ_3 is zero.

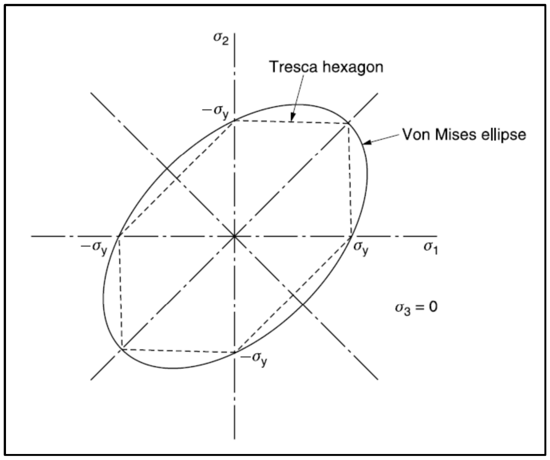

Figure 1:
Tresca and von Mises Theories of Failure

In Figure 1 on the left, it is assumed that the material strength is equal in magnitude when in tension or in compression. According to Tresca criterion, the values of σ_1 and σ_2 falling on the hexagon and outside would cause yielding. According to von Mises criterion, the points falling on or outside of the ellipse would cause yielding.

Theories of Failure used in ASME Section VIII Codes

ASME Section VIII, Division 1 (ASME VIII-1) uses the maximum principal stress theory. Although this theory is more appropriate for materials such as cast iron at room temperature, and for mild steels at temperatures below the nil ductility temperature (NDT), the reason it finds favor with ASME VIII-1 is because it is simple and reduces the amount of analysis. However, it does necessitate a large factor of safety.

ASME VIII-2 uses the maximum distortion energy theory (von Mises criterion). As can be seen from Figure 1, this theory results in continuous (ellipse) function (as opposed to discontinuous - hexagon - function for Tresca criterion) and is easily adaptable for calculations using computers.

Allowable Stress Limits in the ASME Section VIII Codes

The modes that are most likely to cause a failure in pressure vessels are:

- Excessive elastic deformation including elastic instability - This failure mode is generally related to functional requirements. The aspect of elastic instability deals with the propensity of buckling in thin shells.
- Excessive plastic deformation - This failure mode leads to complete collapse in pressure vessels.
- Brittle fracture - The failure mode associated with brittle fracture is related to fracture toughness.
- Stress rupture or creep deformation (inelastic) - This failure mode is associated with pressure vessels operating at high temperatures.
- Plastic instability and incremental collapse - This failure mode is due to ratcheting that causes progressive growth due to cyclic load application
- High strain and low cycle fatigue - The high strain and low cycle fatigue is an important consideration for cycle thermal loads.
- Stress corrosion and corrosion fatigue - These failure modes are related to the environmental considerations as well as mode of operation.

In order for sustained loads to produce full collapse in a structure, it is necessary that the loads produce full plasticity over the cross section bearing the load. The stresses produced from sustained loads are designated primary stresses (P_m). In order to avoid gross distortion, it is necessary to avoid a significant portion of the wall of the vessel from becoming fully plastic. For an elastic-perfectly plastic stress strain law (Figure 2), such a vessel would be fully plastic when the membrane stress reaches the yield stress. A safety factor of 1.5 is provided to avoid this situation. The allowable design stress (primary membrane) is limited to a stress limit typically two-third of the yield stress.

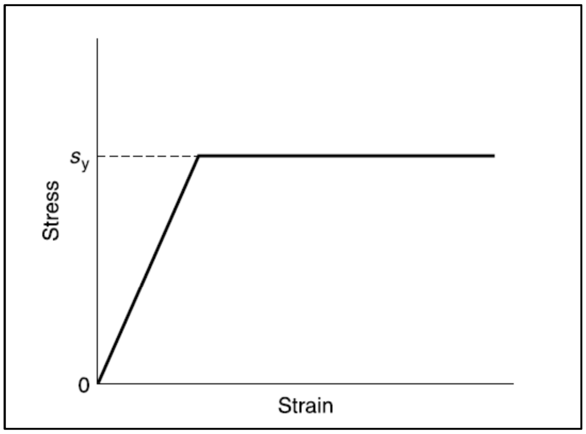

Figure 2: Stress-strain Characteristics for an Elastic-perfectly Plastic Material

Large bending moments acting over the full cross section can also produce structural collapse. The set of bending stresses generated by sustained bending moments are termed primary bending stresses, P_b. The mode of collapse is bending, as opposed to extension, and the collapse will take place only when there is complete plastic yielding of the net cross section. The pattern of plasticity so formed consists of the part of the cross section becoming plastic in tension and the remainder of the section becoming plastic in compression.

When there are both direct (membrane) as well as bending stresses, the avoidance of gross distortion in a pressure vessel is treated in the same way as direct and bending stresses in a rectangular beam. If such a beam is loaded in bending, collapse does not occur until the load has been increased by a factor known as the “shape factor” of the cross-section. The shape factor of a rectangular section in bending is 1.5. When the primary stress in a rectangular section consists of a combination of bending and axial tension, the value of the limit load depends on the ratio between the tensile and bending loads.

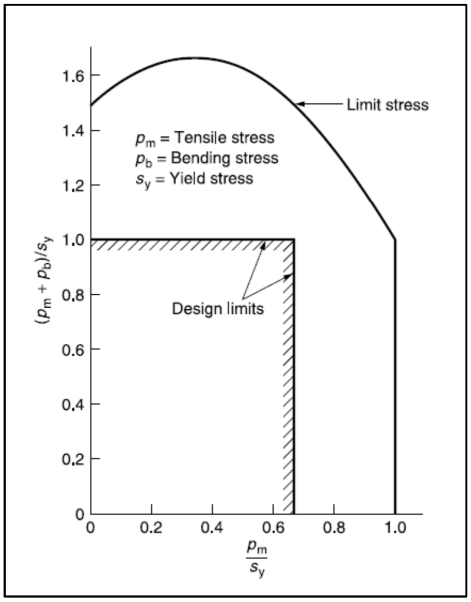

Figure 3: Membrane plus Bending versus membrane stress for a rectangular beam

Figure on the left shows the value of the maximum calculated stress at the outer fiber of a rectangular section required to produce a plastic collapse plotted against the average tensile stress across the section, with both values expressed as multiples of the yield stress, S_y. When the average tensile stress P_m is zero, the failure stress for bending is $1.5S_y$. The ASME Code limits the combination of the membrane and bending to the yield stress.

Service Limits

The loading conditions that are generally considered for the design of pressure vessels include pressure, dead weight, piping reaction, seismic, thermal expansion, and loadings due to wind. The ASME Code delineates the various loads in terms of the following conditions:

1. Design

   ASME VIII-1 sets following limits on the design stress values (From UG-23).

   - Induced maximum general primary membrane stress shall not exceed the maximum allowable stress value in tension.
   - For the combination of earthquake loading, or wind loading with other loading in UG-22, general primary membrane stress shall not exceed 1.2 times the maximum allowable stress. Earthquake loading and wind loading need not be considered to act simultaneously.
   - Combined maximum primary membrane stress plus primary bending stress across the thickness shall not exceed 1.5 times the maximum allowable stress in tension. Pressure vessels with such loadings may have high localized discontinuity stresses; however, design rules have been written to generally limit these stresses to a safe level consistent with experience.

- Combined maximum primary membrane stress plus secondary stresses at discontinuities shall be limited to S_{PS}, where $S_{PS} = 3S$, and S is the maximum allowable stress of the material at temperature

  In lieu of using $S_{PS} = 3S$, a value of $S_{PS} = 2S_Y$ may be used, where S_Y is the yield strength at temperature, provided the following are met:
    - The allowable stress of material S is not governed by time-dependent properties
    - The room temperature ratio of the specified minimum yield strength to the specified minimum tensile strength for the material does not exceed 0.7
    - The value of S_Y can be obtained from Table Y-1 of ASME II-D

2. Testing - Test conditions refer to the hydrostatic tests that are performed on the pressure vessel during its operating life. ASME Codes usually set the test pressures so that the maximum stresses developed during the hydrotest does not exceed 90% of the material yield stress.
3. Level A - These correspond to those of normal operating conditions.
4. Level B - Level B service limits are “upset” conditions where the component must withstand without sustaining damage requiring repair. Typically this includes the operating basis earthquake (OBE) and thermal transients for which the power level changes are on the order of 10 to 20%.
5. Level C - These service limits constitute the emergency conditions in which large deformations in the area of discontinuity are created.
6. Level D - Level D service limits are faulted conditions, for which gross deformation with a loss of dimensional stability is permitted. The component may require repair or removal. Examples are safe shutdown earthquake (SSE), pipe break or combination of such events.

Protection against Fracture

Pressure vessel materials are primarily steels. Steels are generally ductile, but their resistance to brittle fracture diminishes as the temperature is lowered. The lower limit of the operating temperature is determined by the transition point at which there is a change from ductile to brittle fracture. The value of stress at fracture under those situations can be considerably lower than the yield strength. The fracture properties including the transition temperature depend on the composition, heat treatment, prior cold work, and the size of flaws that may be present. As the carbon content is increased from 0.1 to 0.8%, the NDT (nil ductility transition) temperature increases from -45^{o}C to +50^{o}C. Small amount of manganese or niobium can produce large decreases in NDT temperatures. The four design criteria for mild steels can be summarized as follows:

1. NDT design criterion: The maximum principal stress should not exceed 34.5 MPa, to assure fracture arrest at temperatures below NDT temperature.
2. NDT + 17^{o}C design criterion: The temperature of operation must be maintained above an NDT of +33^{o}C, to assure that the brittle fracture will not take place at stress levels up to one-half the yield strength.
3. NDT + 33^{o}C design criterion: The temperature of operation must be maintained above an NDT of +17^{o}C, to assure that the brittle fracture will not take place at stress levels up to the yield strength.
4. NDT + 67^{o}C design criterion: The temperature of operation must be maintained above an NDT of +67^{o}C, to assure that the brittle fracture will not take place at any stress level.

The margin of safety from brittle fracture is therefore dependent on the stress level as well as the expected minimum temperature of operation.

Sources:

1. Pressure Vessels: Design and Practice *by* Somnath Chattopadhyay

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*** **END OF THE ARTICLE** ***

About CoDesign Engineering:

CoDesign Engineering specializes in the core business of providing training and consultancy for design and fabrication of ASME code pressure vessels, and the ecosystem that includes piping, welding, valves, geometric dimensioning and tolerancing, process improvement, and engineering management. Some of the training courses (lasting from two days to five days) that we provide include,

- Design and Fabrication of ASME Section VIII, Div. 1 Pressure Vessels
- Design and Fabrication of ASME Section VIII, Div. 2 Pressure Vessels
- Shell & Tube Heat Exchangers - Thermal and Mechanical Design
- ASME Section IX - Welding Technology
- Engineering Management

We also provide several one-day workshops:

- Know Your Power Piping
- Know Your Process Piping
- Know Your ASME Section VIII Pressure Vessel Code
- Know Your Shell & Tube Heat Exchangers
- A to Z of Pressure Vessels
- Transitioning to ASME Section VIII, Div. 2

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Ramesh Tiwari holds a Master's degree in Mechanical Engineering from Clemson University in South Carolina, and is a registered Professional Engineer from the state of Maryland in the United States. He has over 22 years of experience designing pressure vessels, heat exchangers and tanks. Ramesh is a member of ASME Section VIII Subgroup on Heat Transfer Equipment. He is also an approved pressure vessel instructor at National Thermal Power Corporation (NTPC), a premier thermal power generating company in India.

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