Volume 2012, Issue 7 July 15, 2012

PV Newsletter

Monthly Publication from CoDesign Engineering Academy

How do Vessels Fail?

Pressure vessels may fail in service for a variety of reasons. Consideration of the types of failure that may occur is one of the criteria which should be used on pressure vessel design. Failure may result from excessive elastic of plastic deformation or from creep. As a result of such deformation, the pressure vessel may fail to perform its specified function without rupture or may fail catastrophically with rupture. Failure of pressure vessels can be classified in one of the following categories:

1) Excessive elastic deformation
2) Elastic instability
3) Plastic instability
4) Brittle rupture
5) Creep
6) corrosion

Excessive Elastic Deformation

Elastic deformation is induced by a load such that when the load is removed, the part resumes its original shape. Under service conditions, various parts of pressure vessel will be subjected to a variety of induced stresses. These are generally classified as tensile, compressive, shear, bending and torsion. These stresses may be result simply of weight of pressure vessel, or may be caused by loads resulting from fluid pressure, external forces, wind or earthquake moments, and so on.

Induced stresses result in corresponding induced elastic deformations. The deformations may interfere with the functional operation of the pressure vessel. A common example is found in the use of excessively thin flanges for a bolted closure with a gasket. Tightening of the flange bolts in an attempt to seat the gasket in such a way that it will contain the internal pressure may result in excessive elastic bending of the flange between the bolts without transfer of bolt loads to the gasket.

In order to avoid such situations, sufficient rigidity must be incorporated into the design of the part (in this case, a flange) to restrict the amount of deformation to a permissible value. Parts in simple tension or compression, such as those that exist in axial loading, deform in the elastic region in direct proportion to the induced stress and in inverse proportion to the modulus of elasticity of the material of construction. Deflection of a part subjected to forces which produce bending is a more complex phenomenon. In such cases, the amount of deflection is inversely proportional to the modulus of elasticity and the moment of inertia of the part.

Elastic Instability

Elastic instability is a phenomenon associated with pressure vessel parts having limited rigidity and subjected to compression, bending, torsion, or a combination of such combination loadings. It is a condition in which the shape of the part is altered as a result of insufficient stiffness. It is often the controlling factor when compressive loads are involved. A typical example of elastic instability is the buckling of a cylindrical vessel under an external pressure as a result of vacuum operation. Elastic instability in pressure vessels is usually associated with the use of thin shells.

The simplest type of elastic instability occurs in the "column" action of an axial, end-loaded compression member. The critical stress for these members is the load per unit area at which incipient buckling occurs. This is not the maximum stress developed as a very slight increase in $P_{critical}$ will result in a considerable amount of deflection and a rapid increase in stress until failure by buckling ensues. For design, an allowable stress appreciably less than the critical stress is used to provide a margin of safety against buckling.

In the design of vessels, the relationship for the elastic stability of a curved plate subjected to an axial compressive load is of interest because this condition commonly exists in the shell of vertical cylindrical vessels. Timoshenko in *Theory of Elastic Stability* has given the derivation of the following relationship:

$$f_{critical} = \frac{E}{\sqrt{3(1-\mu^2)}}\left(\frac{t}{r}\right) \qquad \text{(Equation 1)}$$

$$= 0.6E\left(\frac{t}{r}\right) \qquad (\text{for } \mu = 0.3)$$

where t = shell thickness
r = shell radius
μ = Poisson's ratio

Experimental tests carried out on the axial compression of thin cylinders have resulting in buckling loads which are about 40% of that predicted by Equation 1). It is found that the safe compressive stress that can be imposed on a steel cylindrical shell without failure by buckling can be expressed as follows:

$$f_{allowable} = 1.5\ x\ 10^6\left(\frac{t}{r}\right) \quad \leq \tfrac{1}{3}\text{ yield point}$$

Plastic Instability

The most widely used criterion in the design of vessels is that of maintaining the induced stresses within the elastic region of the material of construction in order to avoid plastic deformation resulting from exceeding the yield point. These stresses must be limited to a permissible value that is accepted as being safe for the particular application. Ductile materials such as hot rolled mild steel have two significant stress values, the yield point and the ultimate tensile strength.

Some typical stress strain curves for various materials are shown in the Figure 1. Of these, only the curve for hot-rolled mild steel has a well-defined yield point which occurs at about 30,000 psi. The functional service of a member may be lost if the induced stresses exceed the yield point. Thus the allowable stresses in such applications should be kept below yield point.

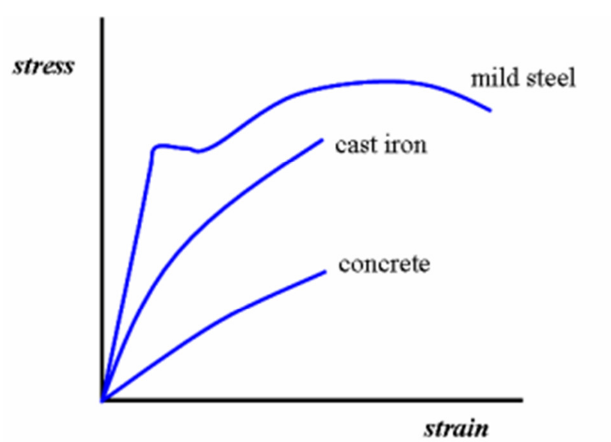

Figure 1: Typical Stress-Strain Curves for Various Materials

If part of the cross section is subjected to elastic strain and the remainder of the cross section undergoes plastic deformation, residual stresses and strains will remain in the cross section upon removal of the load condition. If the portion undergoing plastic deformation is small in comparison with the portion undergoing elastic deformation, the residual strain will be imperceptible. Thus the prevention of significant plastic deformation does not require all calculated elastic stresses to be below the yield point since appreciable plastic deformation can occur only if the material yields across the entire area.

Such a loading condition exists where local stress concentrations (which are non-uniform across the cross section) occur, as at the junction of vessel shell and heads. Because the major part of the cross section is in elastic strain, the small amount of plastic strain relieves the high stress without serious deformation. Also the mean stress across the elastic-plastic zone may be sufficiently below the yield point to allow an adequate margin of safety. Thus such a condition may have advantages in relieving high local stresses but may become undesirable if excessive repeated loading and unloading occur. Such a cyclic operation may result in strain hardening with corresponding loss in ductility and subsequent failure by rupture.

Brittle Rupture

The current trend toward the use of higher strength steels having lower ductility increases the possibility of failure by rupture. Figure 2 shows failure by excessive plastic deformation in a pressure vessel purposely tested to destruction. Such failure can occur only if high stress is distributed over a large area. Local stresses can never produce great plastic deformation because small plastic deformation serves to relieve these stresses. This type of failure seldom occurs in a properly designed vessel.

Figure 2: Failure by Excessive Plastic Deformation in Vessel Purposely Tested to Destruction

Figure 3 shows the fragments of a 5000 psi monobloc vessel purposely tested to destruction. The fragmentation is typical of brittle rupture. Brittle rupture may result from: the use of brittle materials, “notch brittleness”, strain hardening of ductile materials, and strain hardening resulting from local overstressing in repeated cyclic loading.

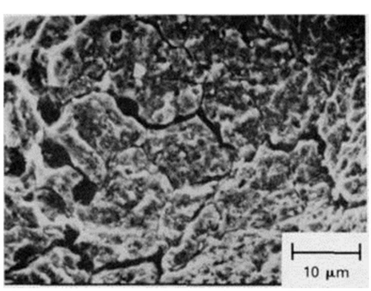

Figure 3: Brittle Fracture in a Pressure Vessel

What is "notch brittleness"?

Mild steels show high elongation in simple tensile tests and are normally considered to be ductile materials. Such materials can fail with little or no evidence of plastic strain if the material contains a crack or a notch and if the material is at a service temperature below the "transition temperature" of the material. This type if failure is known as "notch brittleness".

The transition temperature is defined as the temperature above which ductile type of failure occurs. Below the transition temperature, a transition range may exist in which the material has semi-brittle properties. At still lower temperature the material becomes completely brittle. Below this temperature of complete embrittlement, brittle fracture may occur even though no notches or cracks exist in the material.

How does repeated cyclic loading result in brittle rupture?

Brittle rupture can occur without appreciable plastic deformation as a result of local high stresses and repeated cyclic loading. Such failure may occur near limited areas of stress concentration, near defects in the plate, or near weld joints. Failure by rupture usually begins by the formation of a tiny crack after the vessel has been in service for a considerable period of time with cyclic loading operation. These small cracks continue to propagate with time. The material surrounding the cracks becomes strain-hardened and brittle. The extension of the cracks continues through the strain hardened area and stops when ductile material is encountered. After continued stress cycles, the material at the root of the cracks becomes strain hardened and the cracks progress further. The continued strain hardening and progression of the crack result in eventual failure by brittle fracture.

What is hydrogen embrittlement?

Hydrogen will diffuse into steel under certain conditions. The action of hydrogen at high temperatures and pressures differs from that at low temperatures and pressures. When steel is exposed to hydrogen at high temperatures and pressures, the steel loses its tensile strength, becomes brittle and often cracks or blisters. The mechanism of diffusion of hydrogen into steel at high temperatures and pressures is believed to result from the dissociation of hydrogen molecules to monoatomic hydrogen. The partial pressure of monoatomic hydrogen causes the hydrogen to diffuse into the steel. As the hydrogen diffuses into the steel at high temperatures, it reacts with the carbon to form methane. The methane does not diffuse out of steel and accumulates to form cracks and blisters.

At low temperatures and pressures, the mechanism of hydrogen diffusion is believed to be associated with the formation of hydrogen ions as a result of corrosive attack. The hydrogen ions are converted to monoatomic hydrogen by means of electron exchange.

The embrittlement caused in a vessel by hydrogen diffusion is temporary. If the equipment is shut down for a period of time, the hydrogen will diffuse from the steel. If the equipment is cooled slowly, the rate of hydrogen diffusion from the steel will greatly increase. Many process plants operate normally without giving any particular consideration to hydrogen embrittlement. However, blistering and cracking is a serious problem with vessels handling hydrogen at high temperatures and pressures.

Creep

So far we have assumed that strain under load does not vary with time. This assumption is true for ferrous materials under load at temperatures up to about 650^{o}F. However, beyond this temperature range, the material "creeps" under the load causing an increase in strain with time. An increasing rate of creep is encountered as the service temperature is increased. The rate of creep depends upon the prior history of the material and the stress as well as upon the temperature.

Corrosion

The extent to which corrosion will occur in a pressure vessel depends upon the nature of the films that form on the surface of it parts. The excellent corrosion resistance of copper and its alloys, for example, is the result of their ability to form thin protective films on their surface. These films may be the result of simple oxidation or may be composed of insoluble salts. To be protective the coating should be thin, adherent, continuous and relatively insoluble. Vessels operating under conditions that allow formation of a uniform protective film generally corrodes slowly and may last for a great many years.

Following is a brief description of various types of corrosion encountered in pressure vessels:

Uniform Corrosion:

When corrosion occurs at surface of the vessel by the formation of soluble salts, a uniform thinning of the vessel wall occurs. This kind of corrosion is encountered in acid solutions (particularly those containing oxygen), in waters carrying a high oxygen or CO_2 content (such as mine water), and in solutions having a solvent action on the corrosion products (such as those containing ammonium hydroxide, which dissolve the corrosion products from copper alloys).

Impingement Attack:

Under normal loading conditions, certain localized areas of the vessel may be exposed to the destructive forces of a relatively high velocity circulating medium. Corrosion under such conditions is described as “impingement attack”. Turbulence of the fluids causes a rapid and repeated destruction of the protective film with subsequent corrosion of the exposed metal.

Concentration-cell Attack:

Corrosion may be caused by differential aeration with the formation by concentration cells at the vessel surfaces under certain operating conditions. Cracks, crevices, porous coatings and breaks in protective films are sources of trouble since they trap liquid and set up differences in the concentrations of salts, ions or gases in the circulation medium. As a result of an electrochemical type of concentration-cell action, severe pitting of the metal surface and localized perforation of the material occur. An example of this type of corrosion is the “rusting” of plain carbon steel.

This type of corrosion can be reduced by observation of the following suggestions:

1) Specify butt joints and emphasize the necessity for complete penetration of the weld material to guard against minute crevices.
2) Avoid the use of lap joints, or completely seal them with weld metals.
3) Avoid sharp corners and stagnant areas or other sites favorable to the accumulation of precipitates and other solids.
4) Endeavor to provide uniform flow of liquid with a minimum of turbulence and air entrainment.

Deposit Attack:

When small particles settle out or lodge on the wall of the vessel, part of the metal wall becomes protected by the deposit, and a special type of concentration cell action may take place. Usually the shielded area becomes anodic and intense pitting results. Filtering of the circulating medium and frequent cleaning will minimize the occurrence of deposit attack.

Galvanic Cell Attack:

When dissimilar metals and alloys are in contact with each other in a conducting medium, a galvanic action is set up which results in the dissolution of the less noble or anodic metal. From the electromotive or galvanic series it is possible to predict the tendencies of metals and alloys to form galvanic cells and to predict the probable direction of the galvanic action.

When one is using metals that produce a galvanic action, the relative areas of the two materials have a very important bearing on the extent of corrosion. Usually, the extent of galvanic action will be proportional to the ratio of the area of the metal lower in the series to the area of the metal higher in the list. Thus it is wise to avoid galvanic couples where the exposed area of the cathodic metal is much greater than that of the anodic metal. For example, a steel part in a copper vessel would rapidly corrode, but a copper part in a steel vessel would be relatively safe.

Stress Corrosion:

As a result of the simultaneous action of stresses and certain corrosive conditions, parts may fail by cracking. When the stress is applied externally, the break often is called a "stress-corrosion crack". When residual internal stresses are involved, the resulting break often is called a "season crack". Annealing to relieve residual stresses greatly reduces season cracking.

Sources:

1. Brownell, Lloyd E. and Edwin H. Young, *Process Equipment Design*: 1959

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

About CoDesign Engineering

CoDesign Engineering is involved in providing training and consultancy services as described below:

Training

- Pressure vessel & heat exchanger design (ASME Section VIII, Div. 1)
- Power and process piping design (ASME B31.1 & B31.3)
- Solar PV power plant design

Consultancy

- Engineering solutions related to pressure vessels and heat exchangers
- PMC as well as EPC services for solar PV power plants

We have designed a 3-day training courses for ASME BPVC Section VIII, Div. 1 and for Shell and Tube Heat Exchangers that can be offered at most cities in India. In-house training can also be provided at any location in India or in US upon request. The training is designed as a workshop where the delegates are encouraged to do all calculations using only pencil, paper and calculators. Please contact Ramesh Tiwari at rtiwari123@gmail.com or ramesh.tiwari@codesignengg.com for 2012 training calendar and rates.

Contents of 3-Day Training Course for Pressure Vessels:

- Organization of ASME Pressure Vessel Code
- Design Loads and Stresses in Pressure Vessels
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- Low Temperature Operation
- Joint Efficiencies
- Design of Shell Sections
- Design of Conical Sections
- Design of Formed Heads and Flat Heads
- Openings and Reinforcements
- Nozzle Loads
- Design of Flanges
- Design of Tall Towers
- Design of Column Supports
- Fabrication and Inspection

Contents of 3-Day Training Course for Heat Exchangers:

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- Basic Heat Transfer Principles
- Major Types of Heat Exchangers
- General Description of Shell-and-Tube Heat Exchanger
- Thermal Design of Shell-and-Tube Heat Exchangers
- Major Components of Shell-and-Tube Heat Exchangers
- Mechanical Design of Heat Exchanger Components
- Heat Exchanger Fabrication
- TEMA Standards
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