

6.0 QUALIFICATION

6.1 Operating Conditions

The qualification of the piping system for operating conditions such as pressure, expansion, weight, must comply with the requirements of the applicable ASME B31 code.

6.2 Seismic Qualification

6.2.1 System Qualification

The seismic analysis output typically consists of:

- (a) Loads (forces and moments) at model points along the piping systems.
- (b) Total longitudinal stress at the same points.
- (c) Displacements and rotations at the same points.

The piping is qualified for seismic loads if:

- (a) The stresses in the pipe are within allowable limits.
- (b) The loads at equipment nozzles are within vendor allowable limits.
- (c) Pipe supports and restraints have been qualified.
- (d) The loads or deflections at specialty mechanical joints are within the vendor limits.
- (e) The acceleration and loads on valve operators or other acceleration sensitive components or instruments are within vendor limits, or limits established by test or analysis.
- (f) Where required, the operability of active components (components that have to change state or have moving parts, such as valve actuators or pumps) is established, by testing, analysis or based on earthquake experience.
- (g) Seismic interactions have been evaluated and credible and significant interactions have been eliminated.

6.2.2 IBC Qualification Options

The International Building Code (IBC) exempts certain systems from seismic qualification, as follows:

If $I = 1$, only pipe supports need to be seismically designed (IBC 1621.3.10). If $I > 1$ then the piping systems “themselves” must be seismically designed, but IBC provides no explicit requirements to qualify the “pipe itself”.

For fire sprinkler systems, the seismic design techniques of NFPA 13 are acceptable provided 1.4 times the NFPA “seismic design force and displacement” are not less than those prescribed by IBC.

For pressure piping, the seismic design techniques of the applicable ASME B31 code, except ASME B31.9, are acceptable.

For piping other than sprinkler systems (NFPA-13) and pressure piping (ASME B31), IBC provides design rules for strength design of concrete anchorage (1621.1.7, 1913), but no explicit rules apply for pipe supports or the pipe itself.

6.2.3 Allowable Stress

The ASME B31.1 code provides an explicit equation for stresses due to occasional loads [B31.1-2001]

$$\frac{PD}{4t} + 0.75i \frac{M_A + M_B}{Z} \leq kS_h$$

P = internal design pressure, psi

D = outside diameter of pipe, in

i = stress intensification factor

M_A = resultant moment due to sustained loads (such as weight), in-lb

M_B = resultant moment due to occasional loads (in our case, seismic), in-lb

Z = pipe section modulus, in³

k = 1.15 for occasional loads acting for no more than 8 hrs at any one time and no more than 800 hr/year, or 1.2 for occasional loads acting for no more than 1 hr at any one time and no more than 80 hr/year. Therefore, in the case of an earthquake, k = 1.2.

S_h = code allowable stress, psi

ASME B31.3 does not provide an explicit equation for calculating the longitudinal stress, but specifies that it should be limited to 1.33 times the code allowable stress S for earthquake design. The pipeline codes [B31.4, B31.8] do not explicitly address seismic design.

The ASME Boiler & Pressure Vessel Code, Section III, Div.1, Subsection NC-3600, specifies the following stress equation for “reverse dynamic loads” (which includes earthquake loads) if the system is to remain functional (deliver and regulate flow)

$$i \frac{M_R}{Z} \leq 2S_A$$

M_R = range of resultant moment due to inertia and anchor motion effects, in-lb

S_A = allowable stress = f(1.25 S_C + 0.25 S_h), psi

f = cycle dependent factor, 1 for less than 7000 cycles

S_C = code allowable stress at ambient temperature, psi

S_h = code allowable stress at operating temperature, psi

If functionality is not required, but leak tightness and position retention are required, then the “level D” rules of NC-3600 would apply

$$B_1 \frac{P_D D}{2t} + B_2' \frac{M_E}{Z} \leq 3S_m$$

B_1 = primary stress index from Table NC-3673.2(b)-1 of ASME III Div.1, NC-3600

P_D = system pressure during the earthquake, psi

B_2' = primary stress index from Table NC-3673.2(b)-1 of ASME III Div.1, NC-3600 and section NC-3655.

M_E = amplitude of resultant inertial seismic and weight moment, in-lb

S_m = ASME B&PV Code Section III Div.1 allowable stress for class 1 materials, at operating temperature, psi

In addition, seismic anchor motion shall satisfy the following stress equation

$$C_2 \frac{M_{AM}}{Z} < 6S_m$$

$$\frac{F_{AM}}{A_{AM}} < S_m$$

C_2 = secondary stress index from ASME III Div.1, NB-3681(a)-1

M_{AM} = range of resultant seismic anchor motion moment, in-lb

F_{AM} = amplitude of longitudinal force due to seismic anchor motion, lb

A_{AM} = cross-sectional area of metal, in²

For a piping system operating at nearly steady state conditions (no significant temperature gradients), the alternating stress intensity is

$$S_{alt} = K_e \frac{S_P}{2}$$

$$S_P = K_1 C_1 \frac{P_o D}{2t} + K_2 C_2 \frac{M_i}{Z}$$

S_{alt} = alternating stress intensity, psi

K_e = factor, from ASME III Div.1, NB-3653.6

S_P = peak stress intensity, psi

K_i = local stress indices, from ASME III Div.1 Table NB-3681(a)-1

C_i = secondary stress index from ASME III Div.1, NB-3681(a)-1

P_o = operating pressure, psi

M_i = resultant range of (1) all load ranges plus the seismic amplitude or (2) seismic range alone, in-lb

The alternating stress intensity is then used with the fatigue curves of ASME III Appendix I, Figures I-9.0 to obtain the number of allowable cycles N , which is compared to the number of actual cycles n ($n = 100$ cycles of full amplitude response may be used for earthquake). The

usage factor from earthquake is n/N , which should be less than 1. If there are other cyclic loads (such as heat-up and cool-down) their usage factor should also be added so that

$$\sum \frac{n_i}{N_i} \leq 1$$

The fatigue curves (S_a vs. N) in ASME III Appendix I are based on smooth bar specimen tested in air (no corrosion effects), they reflect crack initiation and propagation to a certain point in the smooth bar specimen, with a safety factor of two on stress and 20 on cycles.

Tests on actual carbon steel pipe (as opposed to smooth bar specimen) indicate that failure (crack initiation and propagation through-wall) follows the law [Markl]

$$iS_{\text{ampl}} = 245,000 / N^{0.2}$$

S_{ampl} = amplitude of the elastically calculated applied cyclic stress, psi

6.3 Seismic Qualification by Testing

6.3.1 Seismic Testing

The most direct method to seismically qualify an active component that must perform a function during or after an earthquake is through shake table testing.

The Designer specifies the 5% damped “required response spectrum” (RRS) for which the equipment must be qualified. The test laboratory develops then the artificial seismic input motion $x(t)$ which envelopes the RRS. This time history $x(t)$ is programmed into the servo-mechanism of a shake table. The designer also prepares drawing details of how the equipment will be installed and anchored in the field. The equipment is mounted on the shake table accordingly, and then subject to the seismic excitation. The equipment integrity and operation may be verified during and after the test. Seismic testing is particularly well suited to qualify electrical equipment and “active” mechanical equipment, which must operate during or following the earthquake.

A seismic test must be well planned and entrusted to a test facility experienced in applying seismic testing and test standards [ICBO AC156, IEEE-344, IEEE-382].

6.3.2 Planning the Seismic Test

Step 1 – Select testing method: Equipment is seismically tested and qualified by one of three methods: Proof testing (test the equipment to a test response spectrum (TRS) equal to or slightly larger than the RRS). Generic testing (test the equipment to a larger RRS than required by the DBE). Fragility testing (test with steadily increasing input excitation, until failure of the equipment or until the table capacity is reached).

Step 2 – Decide whether to test the assembly or a device. When testing an assembly such as a pump skid, the test arrangement must accurately simulate the equipment mounting and its attachments. When testing a device, such as a valve actuator alone without the valve, the test arrangement must accurately simulate the amplification of seismic input that will take place through the pipe span and the valve stem.

Step 3 – Specify the test input. The applicable test standard, such as ICBO AC156, will normally specify the type of test: single frequency, sine sweep or response spectrum test. The single frequency test is suitable for equipment with single dominant frequency and excitation with a narrow range of frequencies, typical of input to in-line mounted components. The test should be sufficiently long, in the order of 30 seconds (10 seconds to ramp up, 10 seconds at full capacity, and 10 seconds to ramp down). The sine-sweep test consists of a sinusoidal input with varying frequency, sweeping the frequency range of the spectrum. The table dwells on certain frequencies, for example 4 dwell points between 2-4-8-16-32 Hertz. The test is valuable in identifying the equipment natural frequencies. The response spectrum test is a test at the specified 5% damped Required Response Spectra (RRS) in each direction. The test facility will have to provide a plot of the measured Test Response Spectra (TRS) at 5% damping, showing that they equal or exceed the RRS.

Step 4 – Choose whether the test will be single-axis or multi-axis. In a single-axis test, the equipment is shaken in a single direction. It is a useful test for detailed studies and research on fundamental seismic behavior, because the response is not complicated by multi-directional input. The bi-axial test consists of a horizontal direction run simultaneously with the vertical direction then rotated 90° horizontally and repeated. The tri-axial test consists of statistically independent input in all three directions, and in practice it is used for most qualification tests.

Step 5 – Specify interface requirements. These include mounting and hold-down details, wiring, piping loads at equipment nozzles.

Step 6 - Specify Inspections. The designer should specify the desired function during and/or after testing, and what to inspect at the test facility, prior to, during and following the test.

For example, for manual valves, pre-test inspections may include: Visual inspection for damage; mounting and pipe spools conformance to drawings; free movement when opening and closing; no body leakage at pressure; no through-leakage across the seat (or leak-through within certain limits) when closed, under a specified pressure differential. During test, the inspections may include flow through when tested open; seat tightness when tested closed. Post-test inspections would repeat the pre-test inspections plus a detailed inspection for damage.

For motor or air operated valves, pre-test inspections may include visual inspection for damage; mounting and pipe spools conformance to drawings; verify movement when opening and closing on signal; verify current and resistance (motor operated) and trip pressure to open or close (air operated); verify actuator torque; no body leakage at pressure; no through-leakage (or leak-through within certain limits) when closed, under a specified pressure differential. During test, the inspections may include flow through when tested open; seat tightness when tested closed;

opening and closing during test. Post-test inspections would repeat the pre-test inspections plus a detailed inspection for damage.

For pumps, pre-test inspections may include visual inspection for damage; mounting and pipe spools conformance to drawings; verify voltage, current, RPM; measure operating vibration. During test, the inspection may include testing the pump running and de-energized; starting the pump during test if required; recording voltage during test. Post-test inspections would repeat the pre-test inspections plus a detailed inspection for damage.

Step 7 – Specify instrumentation and records. Typically, the test instrumentation includes accelerometers on the table, to record the table input and confirm that the required input (RRS) is enveloped by the test response spectra (TRS), over a certain frequency range (such as 1 Hz to 100 Hz).

Step 8 – Specify the contents of the test report. The applicable standard will normally specify the contents of the test report. The results must be “readable” and easy to interpret, accompanied by photographs (or, better yet, video footage) of the test. The test report will normally include pre-, during and post-test inspections. Results of the functional test. Photos, drawings of test setup. Plots of RRS vs. TRS at same damping (typically 5%). Report of anomalies. Certification.

6.4 Seismic Interaction Review

6.4.1 Types of Seismic Interactions

Seismic interactions are an important part of seismic qualification for two reasons:

- (1) Earthquake experience indicates that many failures are caused by the failure of overhead or adjacent components that, in turn, fail the piping system by interaction.
- (2) It is not uncommon for the costs of upgrades resulting from interaction reviews to exceed the cost of seismic qualification of the piping system itself.

There are two types of seismic interactions: spatial interactions and system interactions. Spatial interactions can in turn be divided into falling interactions, swing interactions, and spray interactions.

(1) Spatial Interactions

(1.1) Falling interaction: A falling interaction is an impact on a critical component due to the fall of overhead or adjacent equipment or structure.

(1.2) Swing interactions: A swing interaction is an impact due to the swing or rocking of adjacent component or suspended system.

(1.3) Spray interactions: A spray interaction is due to the leakage of overhead or adjacent piping or vessels.

(2) System interactions: System interactions are spurious or erroneous signals resulting in unanticipated operating conditions, such as the spurious start-up of a pump or closure of a valve.

6.4.2 Interaction Source and Target

Interaction source: An interaction source is the component or structure that could fail and interact with a target.

Interaction target: An interaction target is a component that is being impacted, sprayed or spuriously activated.

6.4.3 Credible and Significant Interactions

Credible interaction: A credible interaction is one that can take place.

Significant interaction: A significant interaction is one that can result in damage to the target.

6.4.4 Interaction Review

Having clearly identified the interaction targets, an interaction review consists of a walk-down, photographic record, and supporting calculations to document credible and significant sources of interactions.

In practice, it is only necessary to document credible and significant sources of interaction. It is not necessary to list and evaluate every single overhead or adjacent component in the area around the target, only those that could interact and whose interaction could damage the target. In all cases, a photographic record of the interaction walk-down should be maintained.

Because only credible and significant sources of interaction are documented, an important aspect of the interaction review is engineering judgement. As a minimum, a team of two reviewers, each with at least 5 years experience in seismic design, must reach consensus on credible and significant interactions. The review team must be familiar with all three aspects of seismic engineering: analysis, testing and earthquake experience. Where system interactions are of concern, the written input of a system engineer is in order. An owner may also perform an independent third party review to verify the conclusions of the interaction review.

6.4.5 Falling Interactions

In most cases, judgment is sufficient to establish whether a falling object can reach a target and be a credible interaction. Alternatively, one can calculate the radius R of the zone in which a falling object can strike. This zone is called the zone of influence

$$R = V_H \{[(V_V/g)^2 + 2H/g]^{0.5} - V_V/g\}$$

R = radius of the zone of influence, in
V_H = horizontal spectral velocity, in/sec
V_V = vertical spectral velocity, in/sec
g = gravity = 386 in/sec²
H = height of fall, in

The safety factors in a seismic interaction review differ from those used in the seismic design process. When judging whether a source component will rupture and fall, it is not necessary to establish that it has a typical design safety factor of 3 to 5 against rupture. Instead, a safety factor of 1.5 of the interaction source against ductile failure and 2 against non-ductile failure may be sufficient.

Earthquake experience indicates that suspended ceilings and block walls are often a credible and significant source of interaction. They must be explicitly addressed in the interaction review process.

When a falling body of weight W falls from a height h and impacts a target of weight W_b and stiffness k, the impact force and deflection can be calculated based on energy conservation [Pickey]:

$$P = W + W_b + \sqrt{W_b^2 + 2W(W_b + kh)}$$
$$d = d_{st} + \sqrt{d_{st}^2 + 2h(d_{st} - d_s) - d_s^2}$$

P = impact force, lb
W = weight of falling body, lb
W_b = weight of elastic member, lb
k = stiffness of elastic member, at point of impact, lb/in
h = height of free fall, in
d = maximum displacement at impact, in
d_s = static displacement of elastic member due to its own weight, in
d_{st} = static displacement due to weight plus the weight of the falling body, lb

P is an overestimate of the impact force because it does not account for rebound, deformation of the source and friction and heat loss at impact. When the target being hit is a section of pipe, its stiffness k can be calculated by a beam approximation. The stiffness of a cantilevered beam of moment of inertia I, Young's modulus E, and length L, loaded at free end is 3EI/L³. The stiffness of a fixed-fixed beam loaded at a distance a and b from each end is 3EIL³/(a³b³), and the stiffness of a simply supported beam loaded at a distance a and b from each end is 3EIL/(a²b²).

6.4.6 Rocking or Swing Impact

Studies of seismic induced rocking and sliding of unanchored equipment indicate that the potential for sliding, rocking or overturning of free standing, unanchored equipment depends on its slenderness ratio (the height of the equipment's center of gravity relative to the width of its

base), the coefficient of friction between the equipment and floor, and the horizontal and vertical acceleration [Shao, Aslam, Zhu, Gates].

The swing displacement of a suspended system (suspended piping, HVAC, cable trays, etc.) can be estimated by

$$d = 1.3 S_a / \omega^2$$

d = swing amplitude, in

S_a = spectral acceleration at frequency f_a , in/sec²

ω = natural circular of swing motion = $2\pi f_a$ 1/sec

f_a = swing frequency, Hz

The natural frequency f_a of a pendulum of length L is $(g/L)^{0.5} / (2\pi)$.

Credible impacts that are significant must be documented. This includes, as a minimum, any one of the following conditions:

They affect an active component such as a pump or valve.

They affect instruments and impact sensitive components.

The source is a pipe larger than a target pipe.

The source is a portion of a wall or structure.

The source is a heavy component.

The source is an overhead architectural feature or ceiling.

The source is an overhead grating.

6.4.7 Spray Interactions

During an earthquake overhead or adjacent piping can break (severance of the pipe in two, also called “guillotine” break) or leak through a crack. The consequence of such failures can be a liquid, gas or steam spray or jet on critical equipment, loss of contents, and flooding of certain areas in the facility. Non-seismically qualified piping should be assumed to leak or break as a result of the earthquake [SRP].