8.0 SEISMIC RESTRAINTS

8.1 Standard Catalog Restraints

Standard catalog restraints are load rated components, listed in vendor catalogs, that can be readily procured and used “off the shelf”. They can be divided into three categories of hardware:

(1) Attachment of restraint to pipe: pipe clamps, clevis, pipe rings, U-bolt, U-hook, riser clamps, etc.

(2) Restraint member: strut, rod, snubber, sway brace, spring, saddle, roller, vibration spring, etc.

(3) Restraint attachment to the building or structural steel: ceiling flange, beam attachment, beam clamps, concrete inserts, etc.

Figure 8.1-1 illustrates a standard catalog spring hanger assembly, with pipe clamp, spring can and rods, and beam clamp. Figure 8.1-2 illustrates a pair of standard catalog sway braces. Figure 8.1-3 illustrates a wall-mounted strut with pipe clamp or fingers, standard catalog items commonly used in supporting small bore piping and tubing. Figure 8.1-4 illustrates a U-bolt arrangement, where the U-bolt is a standard catalog item with commonly listed tensile capacity (upward resistance in Figure 8.1-4) and side resistance (lateral horizontal in Figure 8.1-4) usually available from manufacurer tests.

Standard supports are illustrated in MSS-SP standards [MSS-SP-69, MSS-SP-90, MSS-SP-127]. For fire protection sprinkler systems, standard supports are listed in NFPA [NFPA-13], with qualification or rating requirements specified in reference documents, such as those issued by Factory Mutual or UL.

Seismic wire rope (cable bracing) is also available as catalog items for use in bracing piping systems, suspended ceilings, HVAC ducts and components. They are generally manufactured from steel wires braided into cables.

For the seismic restraint of equipment and piping used for heating, refrigeration and air conditionning, ASHRAE recommends the use of seismic “snubbers” (side bumpers at floor level) and restrained spring isolators which are available as standard catalog items [ASHRAE].

8.2 Steel Frames

Steel frames and racks are often used as pipe supports or intervening members between standard catalog pipe supports and the building structure. Such steel frames are typically made from welded steel shapes (I-beams, channels, structural tubing, etc.). They can provide uni-directional or bi-directional restraint (Figure 8.2-1), or can be used as full anchors restraining the pipe against translation and rotation (Figure 8.2-2).

Steel frame members and welds are designed and sized in accordance with structural design standards [AISC, AISI] and reference design manuals [Blodgett]. Steel frames can be sized by hand calculations or modeled and analyzed by computer. Often times the piping analysis codes do include support frame analysis modules. The steel frame can also be modeled as part of the piping system, but this complicates the piping system model, and is seldom necessary.

The seismic design should not take credit for the friction force between pipe and support, which tends to reduce seismic motion of the pipe. However, pipe-support friction caused by thermal expansion or contraction should be accounted for as an applied load in designing the support.

8.3 Concrete Anchor Bolts

8.3.1 Types of Concrete Anchor Bolts

Concrete anchor bolts are commonly used to secure pipe support and restraint base plates to the building. They can be grouped into two categories: shell and non-shell anchor bolts (Figure 8.3.1-1).

(1) Shell Anchors

Shell anchors are concrete anchor bolts in which the bolt penetrates a shell that is expanded tightly against the concrete. There are three categories of shell anchors:

(1.1) Self-Drilling: The shell is the drill bit. Once the hole is drilled, it is cleaned and a plug is placed into the hole. The shell is reinserted, expanding over the plug.

(1.2) Non-Drill: Same as self-drill, but the shell is hammered over the plug.

(1.3) Drop-In: The hole is drilled and the shell hammered into place. A setting tool expands the shell against the concrete.

(2) Non-Shell Anchors

Non-shell anchors are concrete anchors that penetrate directly the concrete, without a shell surrounding the bolt. There are two categories of non-shell anchors:

(2.1) Wedge: As the nut is torqued, the bolt pulls up, expanding the clip.
Sleeve: Same as a wedge anchor, but the expanding clip is replaced by an expanding sleeve.

(2.2) Cast-in-place concrete anchor bolts are bolts that are placed in position and the concrete is then poured around the bolt, as the concrete cures the bolt is cast into position. There are two categories of cast-in-place concrete anchor bolts:

(2.2.1) Headed Stud: A straight bolt with head (typically at least 1.5D) embedded in concrete or grout.

(2.2.2) L- or J-Bolt: A steel bar L or J shaped embedded in concrete. 3/8" to 1" bolts have typically a 3D radius, while larger bolts have a 4D radius.

8.3.2 Bolt Materials

Anchor bolts are typically made of high strength carbon steel, with a yield stress of 75 to 115 ksi and an ultimate strength of 90 to 150 ksi. Material specifications for anchor bolts include ASTM A 193, A 307, A 325, A 354, A 449, A 490 and A 687. Cast-in-place rods may be high strength steel or carbon steel with a yield stress of 36 to 46 ksi and an ultimate strength of 58 to 70 ksi. Material specifications include ASTM A 36, A 572, A588, A 1554. High strength rods can be made with a yield stress of 105 ksi and an ultimate strength of 125 ksi (ASTM A 193 and A 1554 Gr.105). Concrete anchor bolts can be protected against corrosion by galvanizing (zinc coating) or by epoxy coating.

8.3.3 Qualification of Anchor Bolts

The seismic qualification of concrete anchor bolts is accomplished in three steps: First, the calculation of seismic demand (applied load) on each anchor; second, the calculation of the tensile and shear capacity of the anchor bolt; and third, the comparison of demand to capacity.

The codes and standards applicable to the design and qualification of concrete anchor bolts include: International Building Code [IBC]; American Concrete Institute [ACI].

(1) Calculation of Seismic Demand

The calculation of seismic demand (applied load) on individual anchor bolts consists of two steps: (1) distribution of load applied by the pipe to individual base plates, and (2) distribution of the base plate load to each individual bolt, as tension and shear.

The first step, distribution of load on individual base plates is a classic statics problem, and can be resolved by hand calculations and, for more complex or statically indeterminate configurations by a model of the support structure.

The second step typically involves a lateral load F applied at a certain height above the base plate (Figure 8.3.3-1). The applied load F is reacted by the base plate anchors as a shear (simply equal to F/N where N is the number of anchor bolts), and a tension T given by T X = F L where L is the eccentricity (height) of F above the base plate. The distance X depends on the assumed mode of compressive reaction at the base plate. If the base plate is stiff (for example, a base plate with a thickness at least equal to the bolt size) X can be taken as the distance between the two bolts (case (a) in Figure 8.3.3-1), or X may be based on a triangular compression of the concrete, with a resultant compressive reaction at 2/3 the distance from the centerline of the plate to its edge. If the plate is thinner, it could bend and pry the bolts in tension, and the moment arm would be based on a compressive reaction as indicated in (c) (this is the shortest moment arm and therefore would lead to the largest tension) or (d).

(2) Calculation of Capacity

The total capacity of an anchor bolt in tension and in shear is equal to a nominal value multiplied by penalty factors, where applicable, to account for embedment length, anchor spacing, edge distance, concrete strength and concrete cracks.

$$P = P_N (X_{EM} X_{AS} X_{ED} X_{CS} X_{CC})$$
$$V_C = V_N (Y_{EM} Y_{AS} Y_{ED} Y_{CS} Y_{CC})$$

P_C = tensile capacity, lb
P_N = nominal tensile capacity, lb
V_C = shear capacity, lb
V_N = nominal shear capacity, lb
X_{EM} , Y_{EM} = embedment length penalty factors for tension and shear
X_{AS} , Y_{AS} = anchor spacing penalty factors for tension and shear
X_{ED} , Y_{ED} = edge distance penalty factors for tension and shear
X_{CS} , Y_{CS} = concrete strength penalty factors for tension and shear
X_{CC} , Y_{CC} = concrete cracking penalty factors for tension and shear

The penalty factors are often specified in anchor bolt vendor catalogs.

Anchor bolts are tested to failure under tensile (pullout) and shear loads. The bolt manufacturer may gain approval of bolt capacities from ICBO, UL, FM and city or state jurisdictions.

(2.1) Nominal Capacity: The nominal capacities are then set at a fraction of the ultimate load

$$P_N = P_U / SF$$
$$V_N = V_U / SF$$

The safety factor may be established by regulations, contract or by the design agency. It is typically in the order of 4 to 5.

NEHRP-97, Section 9.2 recommends a nominal capacity established based on 10 specimen tests, as

$$P_N = k(P_U - \sigma)$$

P_N = nominal pullout strength, lb
k = 0.80 for ductile (bolt steel) failure and 0.65 for brittle (concrete) failure
P_U = mean measured strength, lb
σ = standard deviation of measured strengths, lb

(2.2) Embedment Depth: When a concrete expansion anchor is subject to a pullout load, two things happen: (1) the bolt steel itself is placed in tension and (2) the concrete around the bolt is also placed in tension. Failure can occur from either excessive tensile elongation, necking than rupture of the steel bolt (ductile failure) or from sudden concrete fracture (brittle failure).

The tensile ductile failure of the bolt steel occurs when

$$P_U = A_b S_U$$

P_U = tensile load at failure, lb
A_b = minimum cross section of the bolt, in^2
S_u = ultimate strength of the bolt material, psi

The tensile brittle failure of the concrete occurs when the tensile load reaches a limit equal to

$$P_U = 4 \Phi A_C (f'_C)^{0.5}$$

Φ = strength reducton factor [ACI 349]
P_U = tensile load at failure, lb
A_C = area of base of 45^o cone emanating at bolt tip, in^2
f_C' = concrete strength, psi

with

$\Phi = 0.65$, except that $\Phi = 0.85$ if:
(a) Embedments anchored beyond the member far face reinforcement, or
(b) Embedments anchored in a compression zone of a member, or
(c) Embedment anchored in a tension zone of a member where the uncracked concrete tension stress at the surface is less than $5\ (f_C')^{0.5}$.

Ductile steel failure by tensile rupture will happen before brittle concrete failure, if the concrete strength exceeds the steel bolt strength

$$4 \Phi A_C (f'_C)^{0.5} > A_b S_U$$

Since the area A_C at the base of a 45^o cone of height L_E is $A_C = \pi L_E^2$

$$L_E > \{A_b S_U / [\Phi \pi (f'_C)^{0.5}]\}^{0.5} / 2$$

Vendor catalogs will typically provide minimum embedment length for each anchor bolt. The vendor information may have the format of Table 8.3.3-1.

Head Style	Catalog No.	Bit Dia.	Bolt Dia.	Bolt Length	Thick. Mat'l	Emb. depth	P_U Kips	V_U Kips
Hex	ABC	¾"	5/8"	2.5"	0.25"	2.25"	6470	13071
Nut		¾"	5/8"	4"	1.75"	2.25"	6470	13071
		¾"	5/8"	6.25"	4"	2.25"	6470	13071

Table 8.3.3-1 Example of Anchor Bolt Capacity Table

Note that, in this case, the minimum embedment depth is approximately 4 times the bolt diameter.

(2.3) Anchor Spacing: If the spacing between adjacent anchors is more than 10D (where D is the anchor bolt diameter) then X_{AS} = 1.0 (no penalty). If the spacing is 10D down to 5D then X_{AS} must be reduced from 1.0 to 0.5. Y_{AS} is 1.0 if the anchor bolt spacing is larger than 2D.

(2.4) Edge Distance: If the distance from anchor bolt to the free edge of concrete, with no concrete reinforcement, is over 10D than $X_{ED} = Y_{ED} = 1.0$. From 10D down to 5D, X_{ED} must be reduced from 1.0 to0.5, and Y_{ED} varies as $(d/10)^{1.5}$ where d is the edge distance.

(2.5) Concrete Strength: For concrete strength above 4000 psi X_{CS} = 1.0, from 4000 down to 2000 X_{CS} varies as f_C'/4000 where f_C' is the concrete strength. For concrete strength above 3500 psi Y_{CS} = 1.0, from 3500 down to 2000 Y_{CS} varies as 0.65 + (f_C'/10,000).

(2.6) Concrete Crack: Cracks in concrete: If there are no cracks passing through the anchor bolt, X_{CC} = 1.0. For cracks not wider than approximately 10 mils, X_{CC} = 0.75, between 10 and 20 mils, X_{CC} = 0.5. Unless the crack is a gross rupture of concrete, Y_{CC} = 1.0.

(2.7) Cast-In-Place: An example of approximate pullout and shear capacities of headed studs is shown in table 8.3.3-2 [LANL].

Bolt Dia. (in)	Pullout (Kips)	Shear (Kips)	Min. Embed't. (in)	Min. Spacing (in)	Min. Edge Dist (in)
3/8	3	1	3-3/4	4-3/4	3-3/8
1/2	6	3	5	6-1/4	4-3/8
5/8	10	5	6-1/4	7-7/8	5-1/2
3/4	15	7	7-1/2	9-1/2	6-5/8
1	26	13	10	12=5/8	8-3/4

Table 8.3.3-2 Example of Load capacity of Headed Studs

(3) Comparing Demand and Capacity

Having established the demand (applied pullout *P* and shear *V*) and the capacity P_C *and* V_C , including penalty factors, we must now compare demand to capacity. The general form of the acceptance criterion can be written as

$$(P / P_C)^n + (V / V_C)^n < 1$$

P = applied pullout, lb
V = applied shear, lb
P_C = pullout capacity of bolt, lb
V_C = shear capacity of bolt, lb
n = exponent

The value of the exponent *n* depends on the applicable reference, for example in ACI 318 Appendix D "Anchoring to Concrete" n = 5/3.

8.3.4 Quality of Installation

An essential aspect of the seismic adequacy of concrete anchor bolts is the quality of their installation. The following is of particular importance:

(a) Concrete anchor bolts should be installed by personnel trained in accordance with the anchor vendor's recommendations.
(b) The installation should follow the vendor's instructions.
(c) Concrete anchor bolts should be installed in cured concrete.
(d) The drilled hole should be of the right depth, diameter and should be cleaned.
(e) The anchor should not be welded, unless it is of a weldable steel grade.
(f) The installer should follow the Designer's torque requirement.
(g) Avoid conditions leading to capacity penalties (spacing, edge distance, concrete strength, cracks) unless the penalties have been accounted for in design.
(h) Rebar cutting should be pre-approved by civil engineering.

Newly installed expansion anchors may be checked for tightness at 80% to 100% unless specified otherwise by the manufacturer.

Verification of seismic adequacy of existing expansion anchors should include a tightness check at ~ 20% of the installation torque, such as indicated by the torque check values of Table 8.3.4-1.

Bolt size	Installation torque ft-lb	20% torque ft-lb
3/8"	25 – 35	5 – 7
½"	45 – 65	9 – 13
5/8"	80 – 90	16 – 18
¾"	125 – 175	25 – 35

Table 8.3.4-1 Example of Torque Check Values

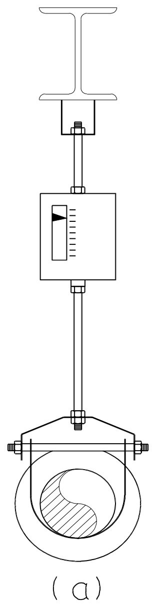

Figure 8.1-1 Spring Hanger

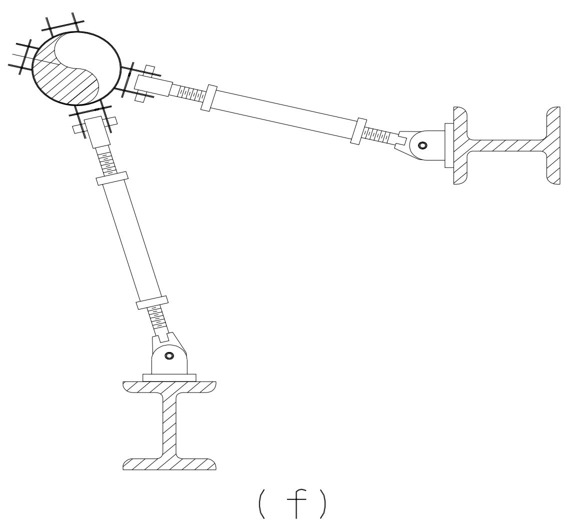

Figure 8.1-2 Rigid Struts Sway Braces

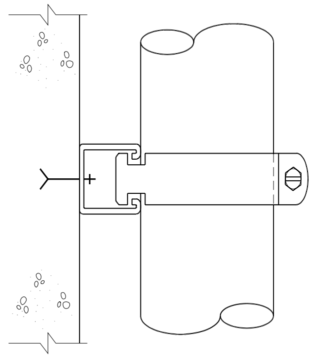

Figure 8.1-3 Wall Mounted Strut with Pipe Clamp

Figure 8.1-4 U-Bolt Arrangement

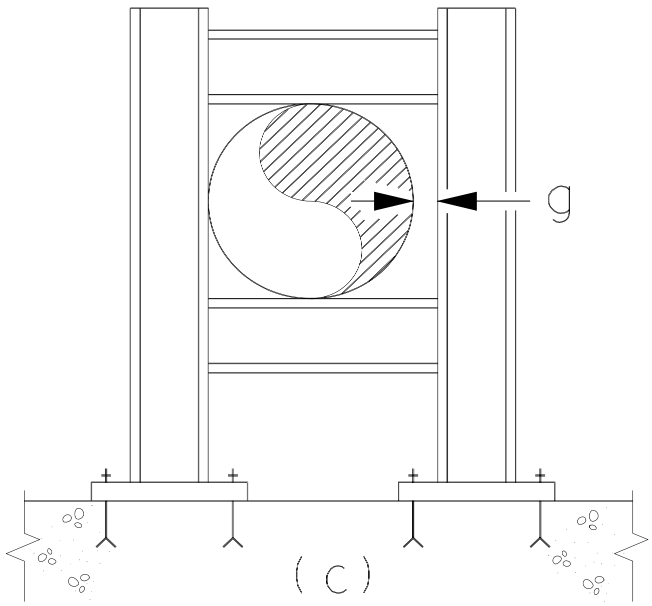

Figure 8.2-1 Rigid Frame as a Lateral Seismic Support

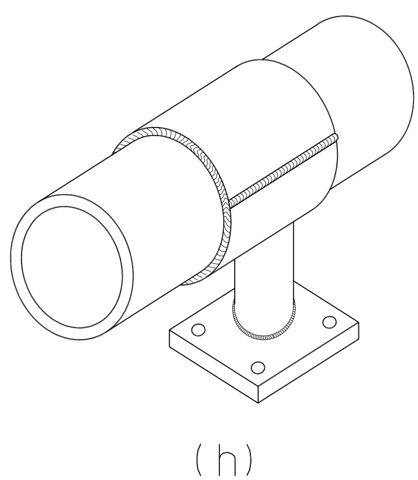

Figure 8.2-2 Steel Pipe Anchor

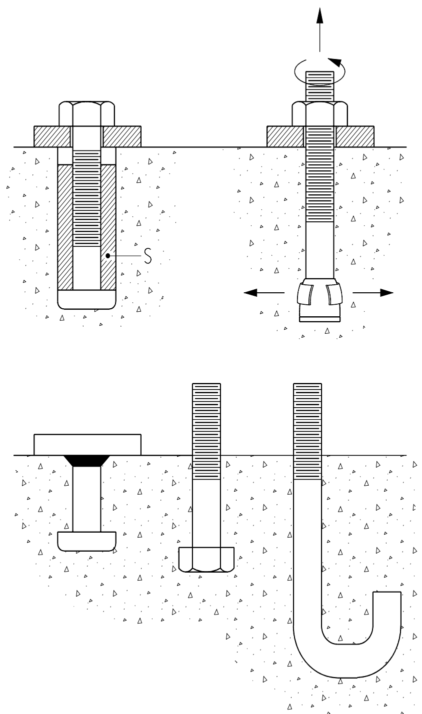

Figure 8.3.1-1 Shell Anchor (top right), Non-Shell Anchor (top left), Cast-in-Place (bottom)

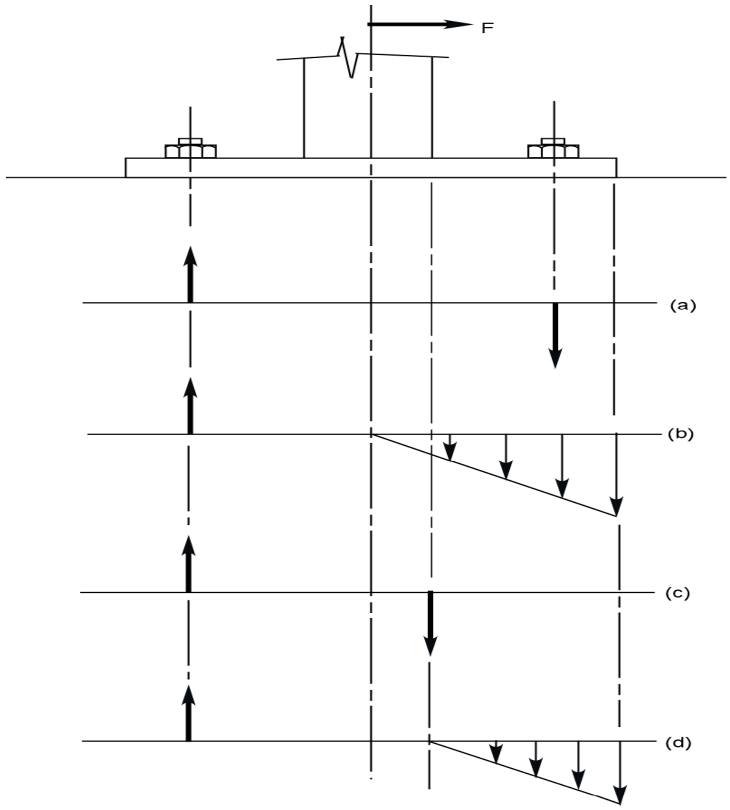

Figure 8.3.3-1 Base Plate reaction to Overturning Moment

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ACRONYM LIST

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
ALA	American Lifeline Alliance
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating and Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
EJMA	Expansion Joints Manufacturers Association
IBC	International Building Code
IEEE	Institute of Electrical and Electronics Engineers
NFPA	National Fire Protection Association
PGA	Peak Ground Acceleration
RRS	Required Response Spectrum
SIF	Stress Intensity Factor
TRS	Test Response Spectrum
ZPA	Zero Period Acceleration

Terms and Definitions

Spectral Displacement - The maximum value of the displacement x(t) of the SDOF oscillator of frequency of natural frequency ω_D and damping ζ subject to an earthquake P(t) is the spectral displacement at frequency $f = \omega_D / 2\pi$ and damping ζ.

Spectral Velocity and Acceleration – The maxima of the first and second derivatives of x(t) are the spectral velocity and acceleration respectively. The spectral acceleration will be noted $a(f,\zeta)$.

Peak Spectral Acceleration – Is the maximum spectral acceleration for a given damping ζ: $a(\zeta) = \max a(f, \zeta)$. In Figure 4.1.2-1 the peak spectral acceleration at 5% damping is approximately 3.2g.

Peak Ground Acceleration (PGA) – Is the maximum seismic acceleration of a SDOF oscillator with infinite frequency $a(f=\infty,\zeta)$ placed on the ground. Note that in the "rigid range" (large frequencies f) the acceleration does not depend much on damping. The maximum acceleration of a rigid SDOF $a(f=\infty,\zeta)$ is the maximum acceleration of the ground since the rigid SDOF does nothing more than follow the ground motion, hence the name "peak ground acceleration". In earthquakes, the "rigid range" typically starts between 20 Hz and 33 Hz. In Figure 4.1.2-1 the peak ground acceleration is approximately 1.0g (the right hand tail of the response spectra curves).

Zero Period Acceleration (ZPA) – Is the spectral acceleration at zero period, i.e. at infinite frequency. At ground level, the ZPA is the PGA. In the case of Figure 4.1.2-1, the ZPA is approximately 1.0g.

Seismic Design Spectra - For a given Design, the plot of SDOF frequency f (or period $T = 1/f$) and damping ζ vs. acceleration $a(f,\zeta)$ is the earthquake's acceleration response spectrum at damping ζ. Over the years, engineers have used a few classical (typical) shapes of the bell shaped spectrum curve (a, f) as seismic response spectra. These classical shapes are then scaled up or down to match the site's peak ground acceleration (PGA) [Housner, Newmark, R.G. 1.60].

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

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

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

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.

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.

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.