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DESIGN AGAINST IN-STUCTURE SHOCK IN HIGH HAZARD FACILITIES

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Abstract

When a structure is subjected to a very short lived impact or blast at one location, a pulse of energy is transmitted through the structure. This energy pulse manifests itself as displacement, velocity and acceleration within the structure. The overall effect is known as In Structure Shock (ISS). Although this shock has a very short duration and is attenuated as it passes through the structure, it theoretically has the potential to disrupt equipment resting on or anchored to the building structure. The paper will examine how to deal with such shock transmission, using the example of a facility built from multi-cellular concrete shear walls. The findings are applicable to all high hazard facilities where such shock transmission can occur.

The paper will examine how the effects of shock loading may be modelled within the building. It will compare and contrast the techniques available for shock loading with those commonly used for seismic loading, and discusses the differences associated with the extremely short duration of loading.

The use of spectra for shock typically shows significant accelerations for frequencies greater than 20Hz; with very high accelerations (many multiples of g) at the peak, which is in the region of 100 to 300 Hz. The dynamic deflections associated with these accelerations are small (typically less than 1mm) at frequencies of 15 to 25 Hz, with even smaller deflections at higher frequencies. The paper will discuss how these effects can be allowed for. The consequence of these high strain rates on material properties will also be considered.

The duration of the pulse is of the order of 10 ms to 100 ms. In this timescale the energy absorbed is small, and as such, if the structure system or component (SSC) was to yield and a mechanism form, then only a very limited amount of plastic deformation would occur. Collapse would only occur if a brittle fracture occurred in the few milliseconds of the pulse. In this time scale, even failure from conventional brittle failure modes such as buckling and shear will not occur in steel. Failure modes are limited to components shaking loose; failure of brittle materials; and other similar modes.

Based upon the above, the paper will examine for the structure in question, a number of different techniques that were adopted to deal with the various SSCs. These were:

- Comparison with seismic spectra
- Adequate Margin
- Ductility
- Use of shock fragility data in accordance with UFC 3-340-01, 2002
- Provision of vibration isolation

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Introduction

A Design Basis Accident (DBA) within a building is an explosion; impact; or other sudden release of energy causing a sudden shock loading. It results in a pulse of energy being transmitted through the building, and affects all structures, systems and components (SSCs).

This very short lived pulse of energy is characterised by displacement / velocity / acceleration through a structure and is known as In-Structure Shock (ISS). Although this shock has a very short duration and is attenuated as it passes through the structure, it theoretically has the potential to disrupt equipment resting on or anchored to the building structure. However, the small movements associated with ISS are such that few ductile structures are at risk of collapse, and consequentially it may be inappropriate to spend a large amount of resources on examining it in detail.

This paper discusses a number of approaches that can be adopted for determining the adequacy of structures and systems to withstand ISS whilst minimising the work involved.

Analysing In-Structure Shock

The following section discusses the approach that can be taken to rigorously analyse ISS, in order that it may be appreciated what ISS is. However, as discussed later in the paper such a rigorous approach may not be warranted in many cases.

The initial shock loading is in the form of a pulse load lasting a few milliseconds. This pulse loading can be applied at a node or patch in a finite element model of the structure, and using a time history analysis the acceleration can be determined at any other node in the structure. Care must be taken if this load is applied to a building model with the ground included that appropriate transmitting boundary conditions are utilised. There may be the need to examine within this model upper and lower bound ground conditions; material properties; and boundary conditions. This can lead to a significant number of different modes that need to be investigated.

Once the analysis has been completed, the resulting time history can be converted to a response spectra in a similar manner to that used for a seismic analysis. A typical acceleration response spectrum for a DBA in a structure consisting of multiple concrete boxes with an enveloping overall concrete box is shown in figure 1. The multiple lines

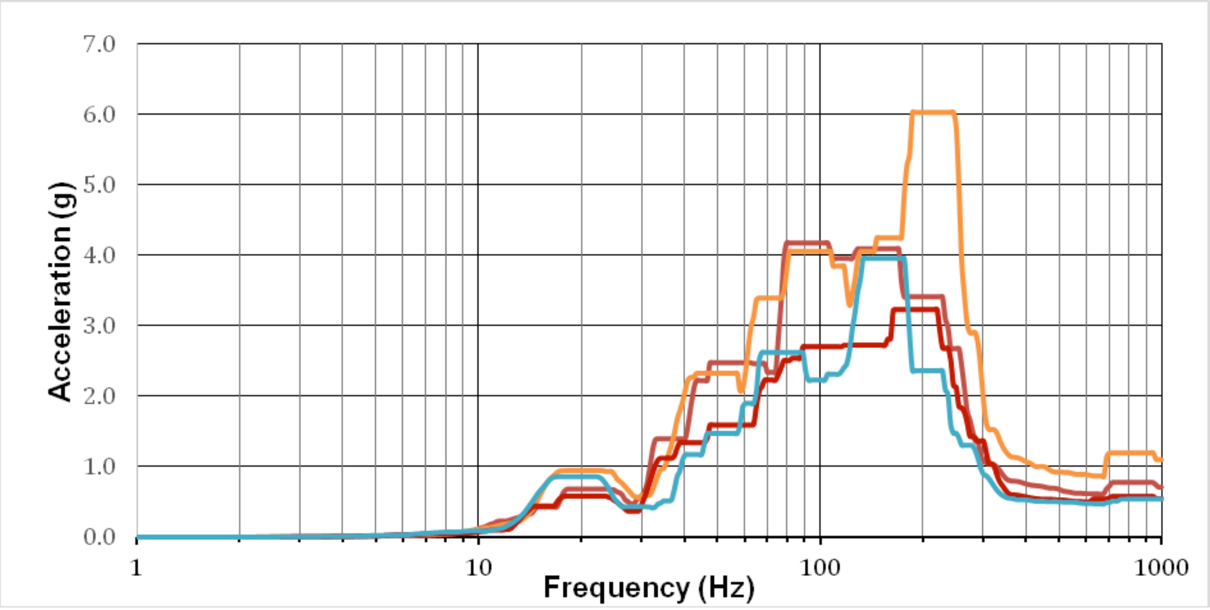

Figure 1. Typical ISS acceleration spectra

represent different locations on the structure. It should be recognised that this plot, and the plots derived from it are based upon a particular DBA; and a particular structure. Nevertheless it gives an appreciation of the sort of response that can be expected.

Figure 1 shows minimal acceleration below 10Hz. The acceleration increases above this frequency, with accelerations above 1g at 20Hz. There are very high accelerations at the peak, which is in the region of 100 to 300 Hz.

The response spectra graphs presented in figure 1 can be expressed as velocities and displacements as follows:

$$S_v = S_a/\omega_n \tag{1}$$

$$S_d = S_a/\omega_n^2 \tag{2}$$

Where S_v is the spectral velocity S_d is the spectral displacement, S_a is the spectral acceleration and ω_n is the natural frequency in rad/s. ($\omega_n = 2\pi f$, where f is he frequency in Hz)

The velocity and displacement spectra associated with figure 1 are shown in figures 2 and 3.

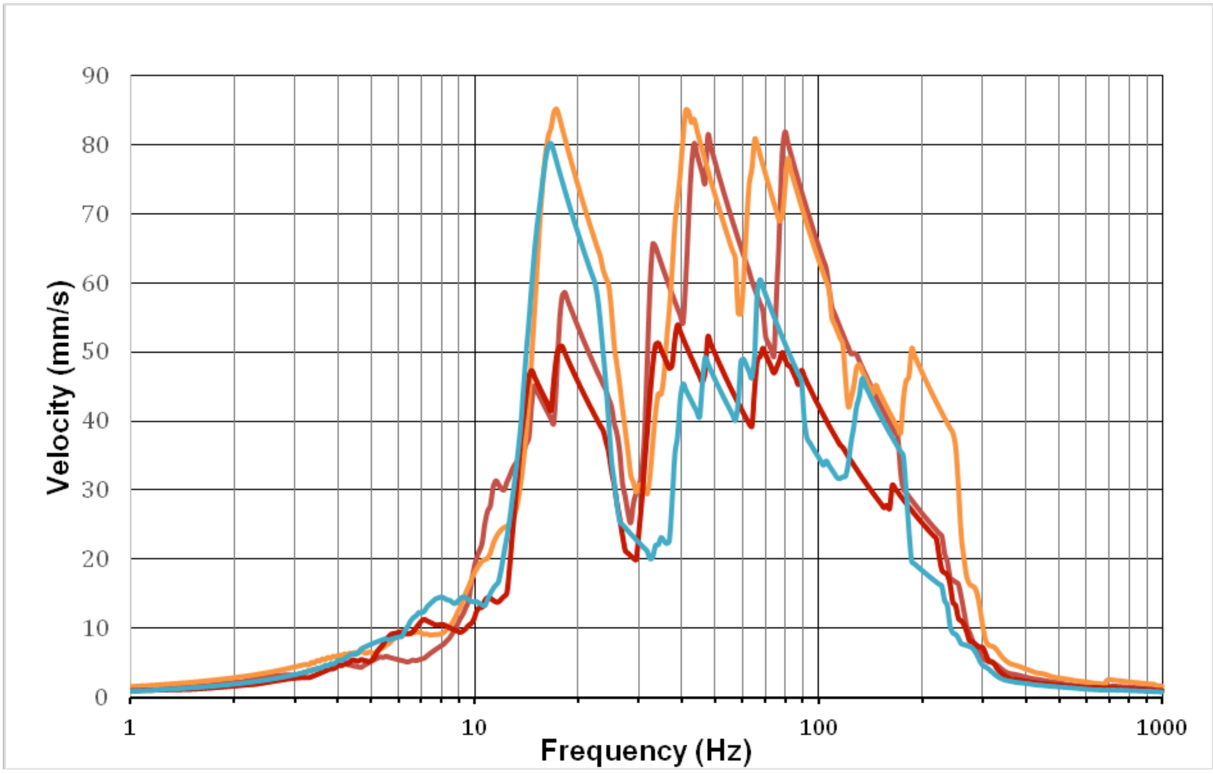

Figure 2. Typical ISS velocity spectra

Figure 2 shows that the peak velocities occur in the range of 10 to 100Hz. However, whilst the accelerations were high (6g peak), because of the high frequencies the peak velocities are relatively small at 80 mm/s.

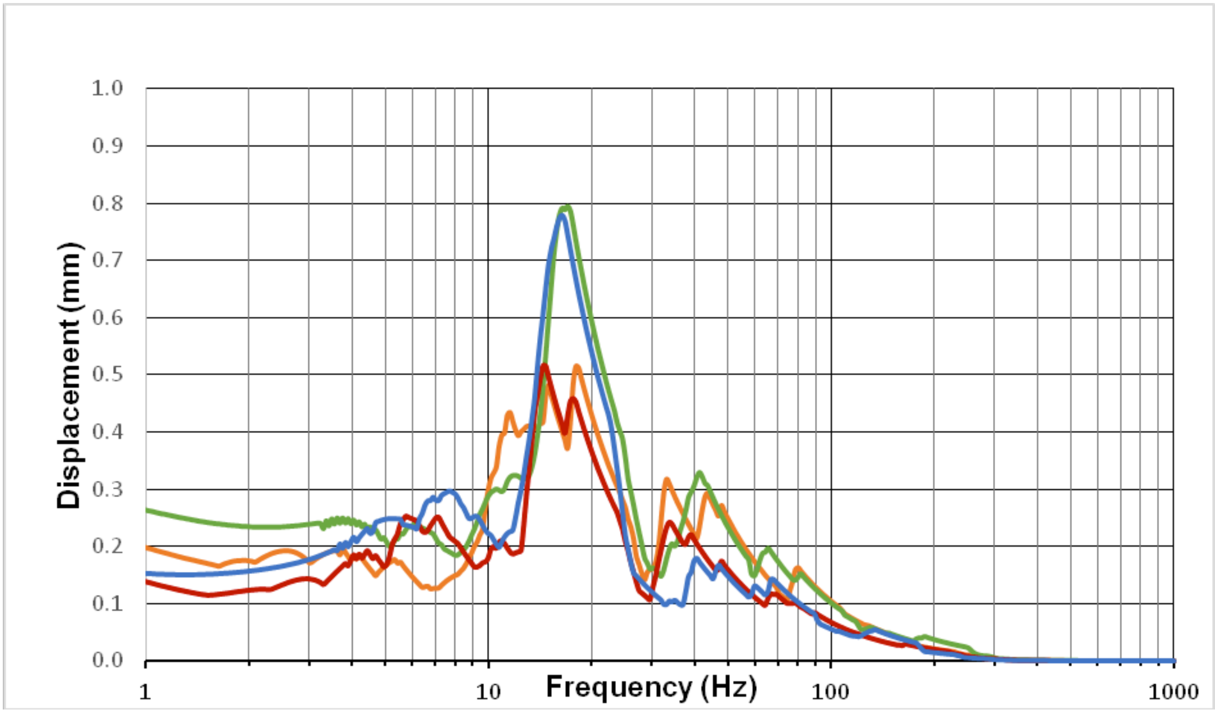

Figure 3. Typical ISS displacement spectra

It can be seen from figure 3 that the largest displacements (all peaks less than 0.8mm in this case) take place below 20 Hz. Frequencies above 60 Hz have associated displacements of less than 0.2mm.

Figure 4 shows the envelope of the information shown in figures 1 to 3. It allows comparison to be made about the occurrence of the peaks for displacement, velocity, and acceleration.

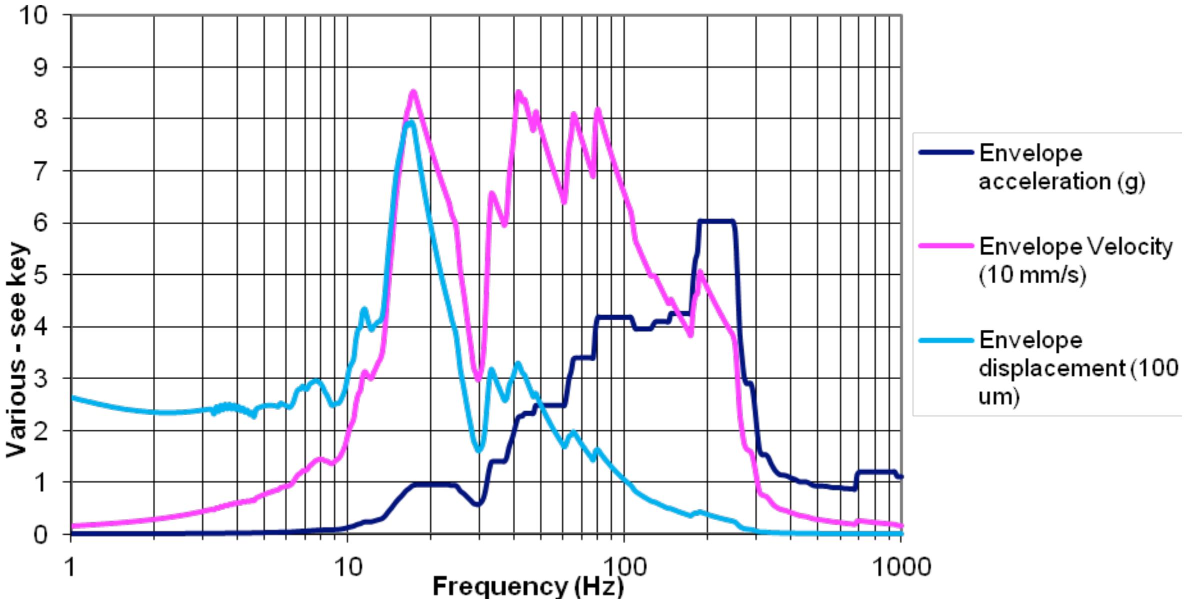

Figure 4. Enveloped ISS displacement, velocity, and acceleration spectra

As with seismic loading, ISS can act in all three directions – two horizontal and vertical. The overall response may be combined in a similar manner to seismic loading i.e. by the square root of the sum of the squares method; or the 100:40:40 rule.

The temptation is to treat the response spectra from an ISS analysis in a similar manner to that used in seismic assessment. Whilst mathematically they are similar, this can lead to undertaking a large amount of analysis that may be unnecessary. This is because the duration of the transmitted shock is much shorter duration than that of an earthquake, and as a result the energy input is significantly reduced.

In the UK the design earthquake has a duration of the order of 12 seconds. However, a typical shock response has a duration of 10 to 100 milliseconds, and this means that the response of the structure is different, even accounting for the difference in frequency response.

With the short duration of the pulse, the energy absorbed is small, and as such, if the SSC was to yield and a mechanism form, then only a very limited amount of plastic deformation would occur. Collapse would only occur if a brittle fracture occurred in the few milliseconds of the pulse. In this time scale, even failure from conventional brittle failure modes such as buckling and shear will not occur in steel. Failure modes are limited to components shaking loose; failure of brittle materials; and other similar modes. Failure can also occur in components that cannot absorb a small amount of deformation, such as very short bolts or rivets.

Dealing with In Structure Shock

For the reasons discussed above, the consequence of ISS is only minor movement for most structures and systems. Any one of the following approaches can be adopted to demonstrate that the response to ISS is acceptable.

- Comparison with seismic spectra
- Adequate Margin
- Ductility
- Use of shock fragility data (plant and services only)
- Vibration isolation

These are discussed further below.

The choice should be based upon whichever method is considered to be the most cost effective. Other approaches may be acceptable. In all cases, the designers should confirm that there are no obviously brittle modes such as components shaking loose; or reliance placed on highly brittle materials such as glass, some plastics, etc.

Comparison of ISS with Seismic Spectra

In the nuclear industry, many items which are required to be designed against ISS will also be required to be designed against seismic loads. As a result the natural frequencies may already be known. In such cases, comparison between the seismic spectra and the shock spectra can then be useful.

Figure 5 compares a typical ISS spectra with the seismic spectra at the same location. It is noteworthy that below 15Hz the seismic response dominates; with the ISS response dominating at higher frequencies.

Many structures will have a frequency below 15 Hz, and therefore seismic loads will dominate. However the installed plant may well be relatively stiff with the result that ISS dominates.

It should be noted that if the structure has a number of modes with significant mass participation, then higher frequencies may need to be considered in this comparison.

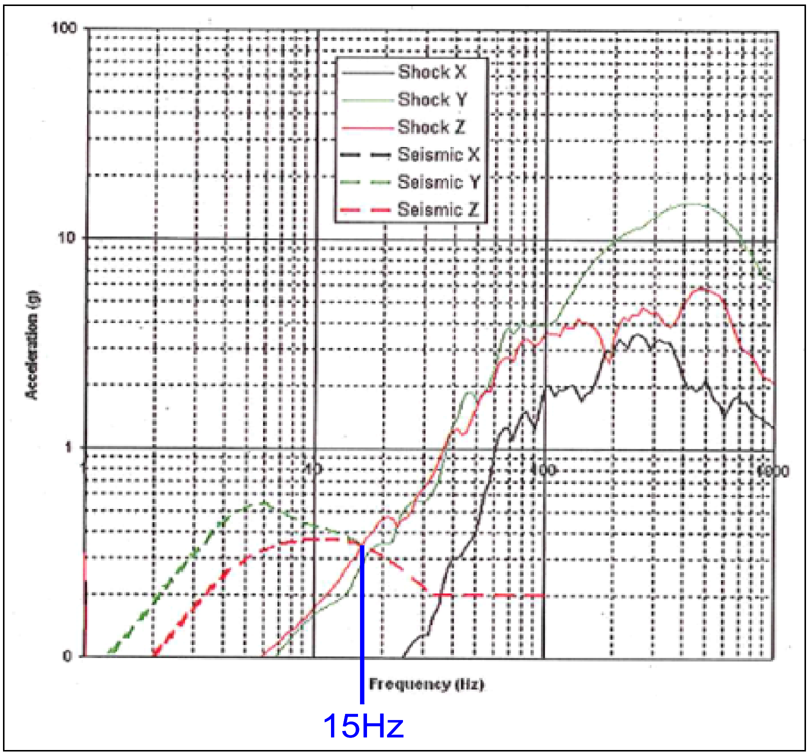

Figure 5 Comparison of seismic and ISS spectra

Adequate margin

In some cases, a finite element model of the structure or system may have already been prepared for other purposes, such as seismic design. In such cases the ISS response spectra can be used as another loading case, and a modal analysis carried out. The response from each natural frequency is combined in the same manner as for seismic loading using approaches such as SRSS (Square Root of Sum of the Squares) or CQC (Complete Quadratic Curvature).

As all three directions have to be considered, in practice there are three different spectra needed, and the output from each direction is combined using the SRSS or 100:40:40 rule.

Due to the short duration of the loading, the material yield strengths are enhanced. Based upon information contained in UFC 3-340-01, 2002 and ACI 349-13, the material yield strengths may multiplied by the following factors:

Structural Steel	1.1
Reinforcing Steel	1.1
Reinforced Concrete	1.1
Other materials	1.0

As usual, the design is adequate if the utilisation ratio (UR) is less than 1.0, using the codes the design is based upon. If the UR is greater than 1.0, it is preferable to consider the ductility, see below, rather than increase the size of the member.

Ductility

Another way in which performance against ISS can be demonstrated, is showing that there is adequate ductility to withstand ISS deformations without collapse.

The first step is to ascertain the maximum displacements to which the structure might be subjected. In most cases the displacements are small (less than a mm) and it is sufficient to use the peak displacement. The load path to the system is then identified and a judgement made about the ability of the load path to tolerate movement. This assessment may be qualitative, based upon the predicted failure modes, and can make allowance for a time duration of the pulse of 100ms. Many of these arguments can be similar to those used to justify beyond design basis seismic loads.

In most cases, when assessing against a DBA, it is acceptable for small plastic deformations to occur. However, if the ISS is repeated then there may be a need to ensure that the system remains elastic. In such case it may be necessary to assess numerically the response and determine the margin as described above.

As part of the approach to identifying if a system has enough ductility, it is necessary to identify component(s) of the support system load path with the least ability to accept small deflections. Such components might well be short rivets, screws, bolts, brackets and the like. These components are especially vulnerable when made from high strength material with reduced elongation to failure. Other components that might be vulnerable are those made from brittle materials; or those which might fall out or otherwise loose support such as circuit boards; light bulbs; etc.

Use of Fragility data

Fragility data can be used to qualify plant items against ISS when there are a large number of individual items and it is tolerable for a small number to fail. Alternatively, it may be used where equipment is not safety-critical and a high levels of reliability are not required.

UFC 3-340-01, 2002 provides empirical fragility data giving limiting spectral accelerations and velocities for which the probability of failure is 1% or 5%. The peak acceleration and velocity from the spectra is compared with these values. If the associated probability of failure is tolerable, then the design is considered to be acceptable.

Information on the fragility of a large number of different systems is provided in UFC 3-340-01, 2002, but for convenience a limited abstract from this reference is given below in Tables 1 and 2.

Table 1. Failure Rates for HVAC Systems subject to ISS

	Velocity limit (mm/s)		Acceleration limit (g)	
	1% probability of failure	5% probability of failure	1% probability of failure	5% probability of failure
Air Conditioners / Chillers /Coolers	480	730	14.1	29.9
Gauges / Sensors / Controls	450	760	12.7	29.8
Ducting / Dampers / Filters	610	890	12.7	26.8
Piping / valves / fittings / strainers / filters	740	1100	30.4	63.4
Fan / Blowers	730	1020	19.4	34.1

Table 2. Failure Rates for Electrical Systems subject to ISS

	Velocity limit (mm/s)		Acceleration limit (g)	
	1% probability of failure	5% probability of failure	1% probability of failure	5% probability of failure
Switchboards	430	680	9.1	27.0
Circuit breakers	600	1080	14.6	39.3
Relays	770	990	28.3	67.0
Distribution Panels	840	1180	27.4	59.2
Control panels, monitoring and control devices	620	980	16.8	38.2
Lights & light fixtures	520	860	11.2	25.2

Isolation

Another approach to dealing with ISS is to isolate a system from the effects by providing a resilient mount. This may be as simple as a rubber pad under the equipment with a rubber pad under the holding down bolts. The rubber pads accommodate the ISS deformation and isolate the equipment from the effects of the shock.

Care should be used in specifying isolation, as although each pad is relatively inexpensive. if they are used for systems such as ducting the cost can be significant due to the large numbers needed. Further, the use of rubber may affect the life time cost as provision must be made for the need to change the pads as the system ages.

Conclusion

This paper has described what happens when a system is subjected to an In Structure Shock as a result of a Design Basis Accident. It looks at various methods by which it may be considered and acceptability demonstrated. Any of the methods discussed may be used.

In many high hazard facilities, by using the appropriate technique, it is possible to minimise the effort required to demonstrate an acceptable ISS performance against a DBA. More effort may be required if the facility can be subject to repeated incidents.

REFERENCES

UFC 3-340-01, Design and Analysis of Hardened Structures to Conventional Weapons Effects, Jun 2002

ACI 349-13, Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary, American Concrete Institute, 2013