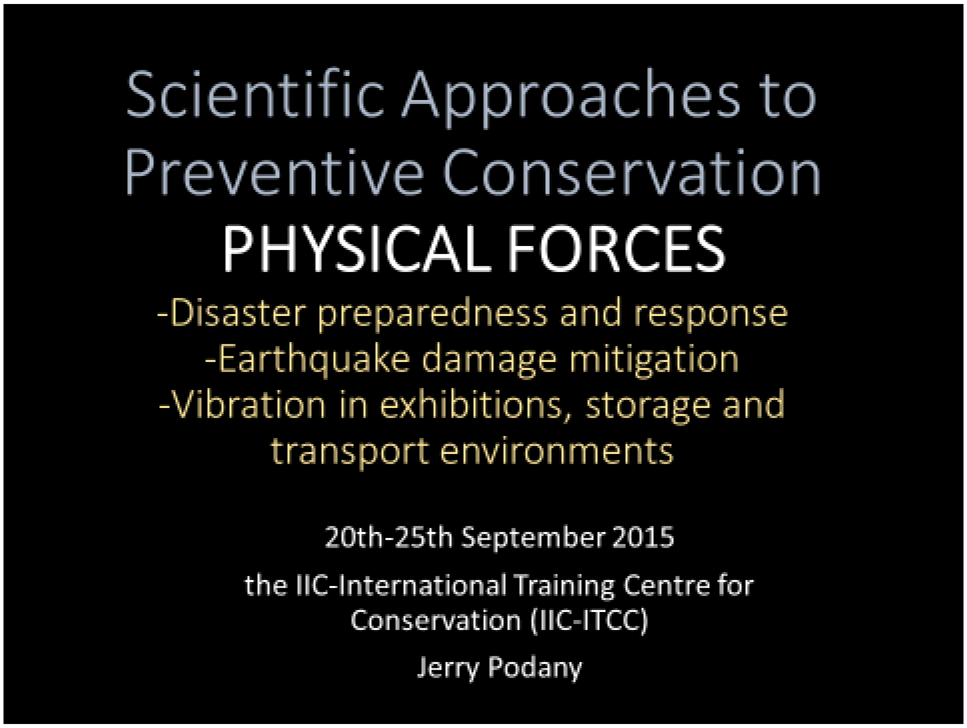


I have been asked to discuss physical forces and their role in damaging heritage collections, specifically the role of vibration and earthquakes. And then to address emergency and disaster preparedness for cultural institutions like museums.

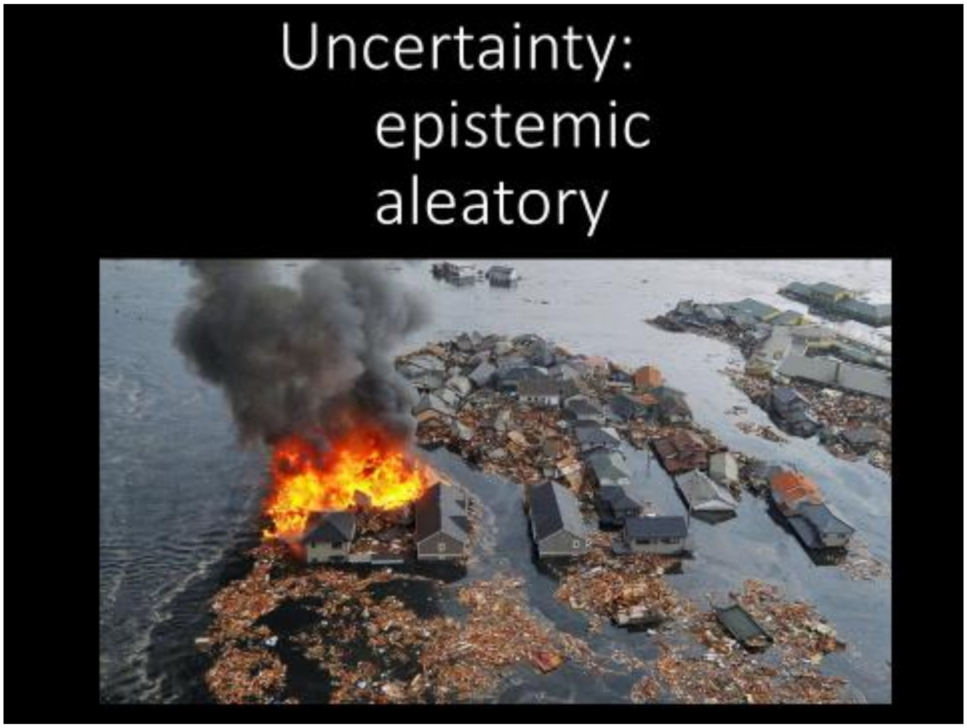
There are a few overall concepts and comments that I think are suitable to start with.

The first is that in the discussions about vibration and seismic events there will be some demand placed on you to absorb a few principles of physics and engineering. These are necessary if you are to gain a sufficient appreciation of why certain forces occur, how they can be damaging to works in collections, and how they, or at least the damage they produce, can be mitigated. None of us here are engineers or physicists or necessarily fully conversant in calculus or probability theory, but like chemistry it is essential that at least the basics be reviewed since such concepts are crucial to effective preventive conservation. I have for this course, kept it very much to the basics. You will, I hope, come away from today having a sense that this chart (slide) showing the root square mean acceleration of a crate in transit indicates that the trucks were less than efficient at transport and that handling at the docks must be improved.

In both the measurement and mitigation of vibration, like the measurement and damage mitigation associated with earthquakes, you as conservation professionals will need to work with allied professionals, like engineers, to do an effective job. In most cases, these allied professionals speak a very different technical language than you do and have very different ways to looking at objects or buildings. So it is important that together we make the effort to unfolded these basic concepts related to physical forces.

There are two concepts I would like you to at least consider because they play a very important role in the topics we are going to cover:

These are the two types of uncertainty, **Aleatory and Epistemic.**



Epistemic is uncertainty due to lack of knowledge

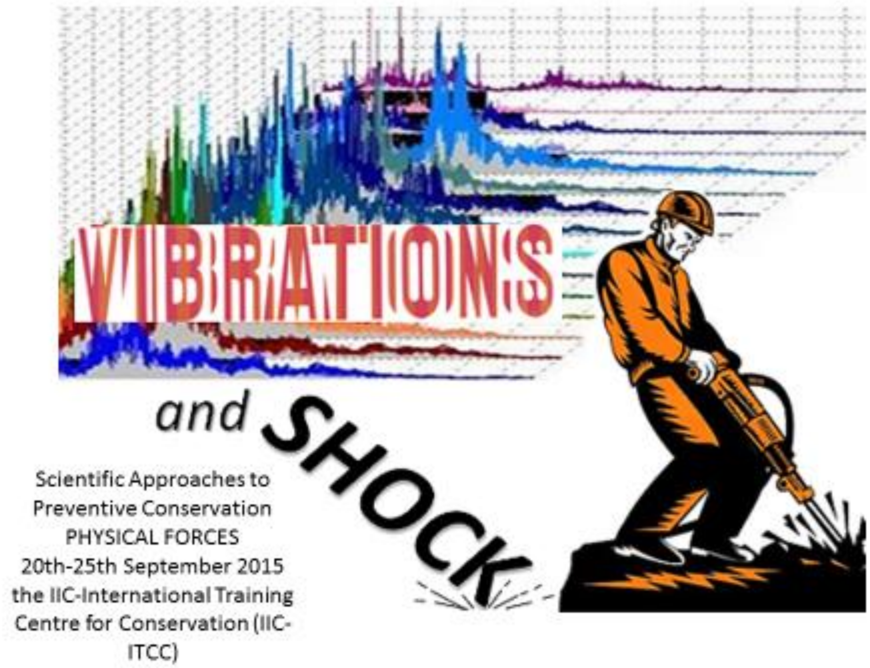
Aleatory is uncertainty due to the randomness of nature

Putting aside the almost philosophical view that there really isn't anything such as randomness, since that kind of uncertainty just reflects our lack of sufficient knowledge to understand the order behind what we perceive as random unpredictable events, we will keep this distinction for convenience.

What these lectures will address are events which have considerable unknowns associated with them. In both cases we know quite a lot about the way in which physical forces occur, their mechanisms. But we often do not know exactly when or how the material we are protecting from harm will respond to or be effected by these forces. And of course when they will occur, or how strong they might be, can also be a significant unknown, often random in nature.

And lastly a sort of disclaimer and confession. Some decades ago a spent a great deal of time lecturing and teaching about the topic of emergency and disaster response and preparedness. It is without a doubt a very important topic. But the amount of information that is now available regarding response and preparedness is very large and there are some especially thorough guides to the process. So my discussion with you on this topic will be more of an overview and an encouragement to realize that you may not be given the kind of access, time or resources you wish you would have, or that you planned for, when the event occurs. I am going to suggest to you that such planning is really a way of eliminating all the various things that would interfere with effectively thinking in the moment, albeit a very stressful moment. I want to stress this point right at the beginning, as I will again in the end of this session, that it should be your goal to have to do very little when you respond because of all that you did beforehand to mitigate the level of damage.

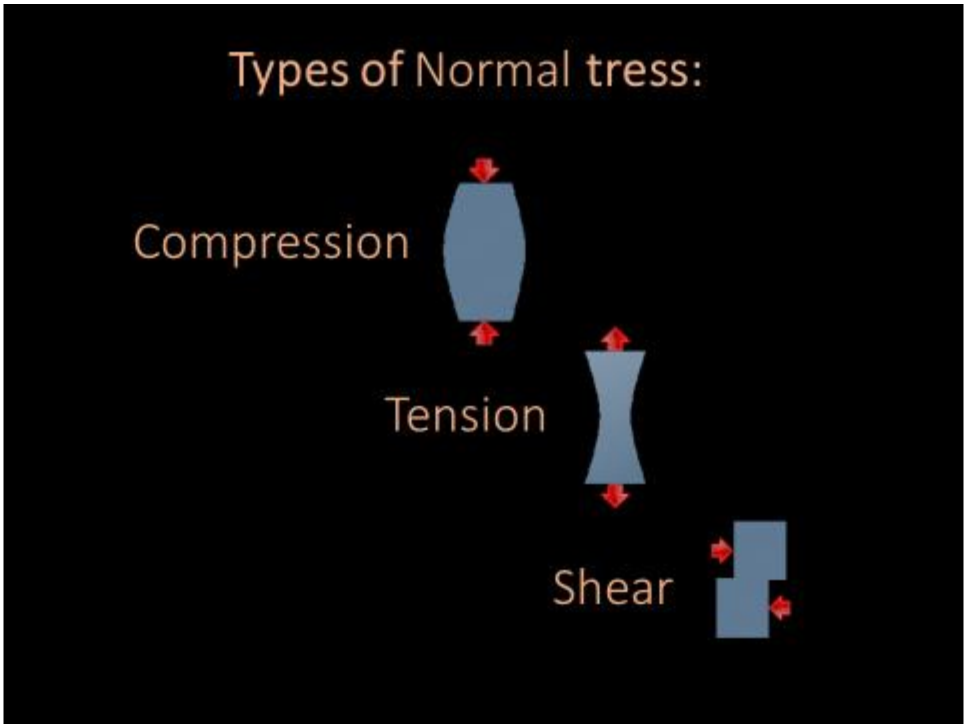
PHYSICAL FORCES



Physical forces damage object's by several mechanisms: Impact, shock and vibration (which brings abrasion)

Impact: something hits the object or the object collides with something else. Impact is short lived but highly concentrated

Shock: an abrupt strong impact force resulting in large deformations and strain



Reminder: stress is force and strain is deformation due to that force. Types of stress are:

Normal Stress: Stress that acts perpendicular to a surface.

Compression: Stress that acts to shorten an object.

Tension: Stress that acts to lengthen an object.

Shear: Stress that acts parallel to a surface. It can cause one object, or plain, to slide over another. The most general definition is that shear acts to change the angles in an object.

Shock is an abrupt strong impact force resulting in large deformations and strain. Intensity is measured in units of *g*, 1*g* is the force of gravity.

Shock intensity
measured in “g” force
1g = gravity

Newton’s second law:
F=Ma
(dynamic loading)


AXIOMATA
SIVE
LEGES MOTUS

Is something weighs 50 pounds and is subjected to a 10*g* force then the force acting on it if it falls or collides with something else is 500lbs of force. The Newtonian law of Force=Mass X acceleration. Shock is brief but intense, lasting only milliseconds. It is especially dangerous for brittle materials.

Shock results in the production vibration, fracture in brittle materials and deformation (in more elastic materials).

Vibration: is the oscillating motion of an object relative to a fixed point.

For the purpose of this discussion vibration can be considered the cyclic oscillating motion of an object from the positon of rest, or its neutral position, to some extreme displacement either side of that neutral position.

Sources of Vibration:

Earthquakes

Explosions

Conflicts/civil unrest

Handling

Transport

Construction

Machinery/building systems

Traffic

Pedestrian traffic

Kinds of vibration:

Continuous vibration

steady road traffic, machinery, continuous construction

Impulsive vibration

Occasional loading and unloading

Intermittent vibration

Passing heavy vehicles, jack hammers

Four forces determine the characteristics of vibration :

- The exciting force
- The mass of the vibrating object (M)
- The stiffness of the vibration object (K)
- The damping characteristics of the object (C)

The first of these characteristic, the source, causes the vibration. The other three influence or resist the vibration.

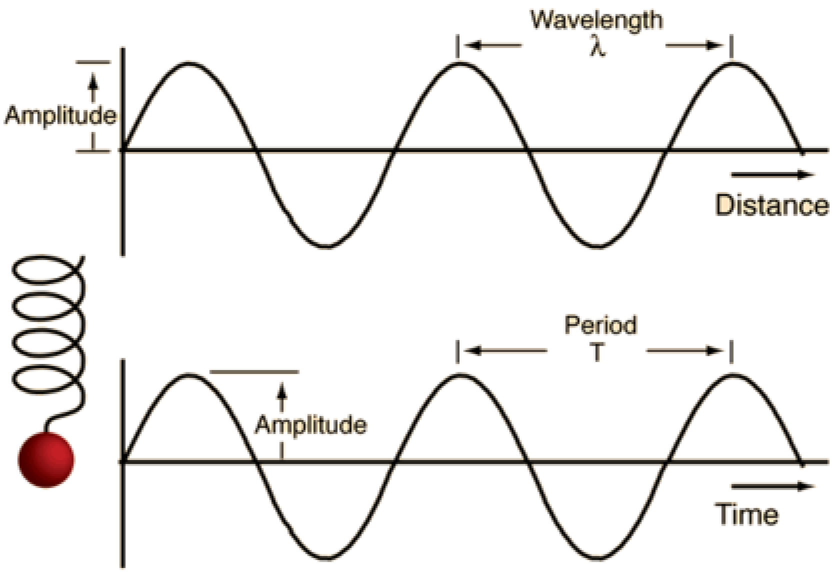
Vibration is measured by units of velocity mm/sec but more useful is displacement so that stress can be determined. But velocity, mm/sec, is standard.

Characteristics which define vibration are:

- Frequency
- Displacement
- Velocity
- Acceleration
- Phase

But before going further let’s look at how we visualize vibration:

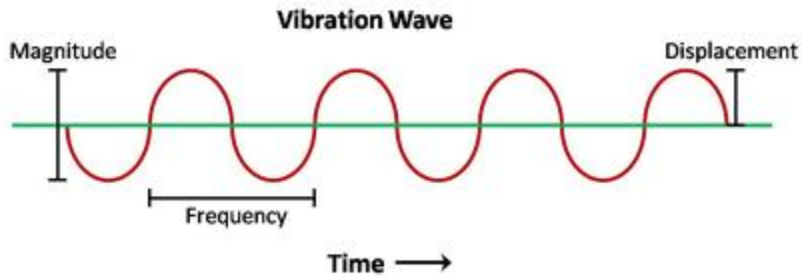
The most common is Waveform: A waveform is a graphical representation of how the vibration level changes with time.

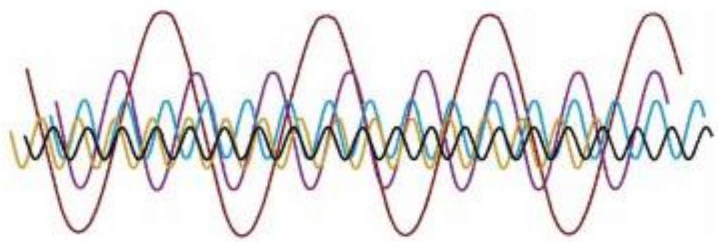


The other was is by the production of spectra which will be described a bit latter

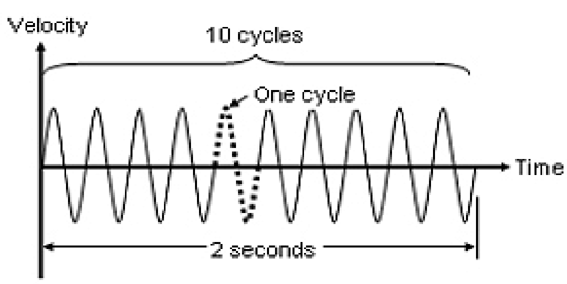
FREQUENCY: describes the oscillation rate, it is the number of wave cycles that occur in one second, which might be 20 or might be 0.2.

The **PERIOD** of a vibration is the amount of time it takes to complete one full wave cycle. Frequency is the inverse of period. So if the period of time to complete one full cycle is 1/60 of a second (0.0166) then the frequency is 60 cycles per second (CPS) or 60 Hertz (Hz).





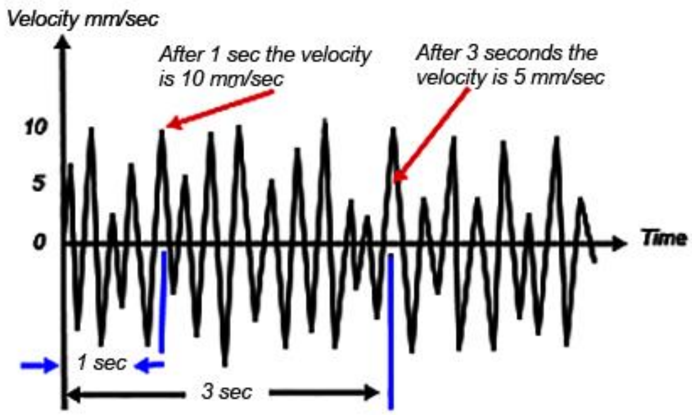
In most cases however vibration is a mixed range of frequencies and amplitudes.



The frequency in this case is 5 cycles per second or 5 Hz

AMPLITUDE describes the severity or magnitude of the vibration. Large vibration amplitude means large, fast, or forceful vibratory movements. The larger the amplitude, the more movement or stress is experienced by the object. It can be a measure of the displacement, velocity or acceleration of a vibration motion. Commonly acceleration is measured but often in the construction industry the amplitude is expressed as particle velocity, High amplitudes of vibration displacement can cause brittle materials to fail by cracking. This often occurs below 60 Hz(600 CPM)

Amplitude changes over time:



Amplitude depends upon

- the size of the vibratory movement
- the speed of the movement
- the force associated with the movement

That is to say, Displacement, Velocity and Accleraiton

Displacement is how far something moves from its position of rest. Displacement is a good measure at lower frequencies especially less than 5 Hz. The failure mode is generally the “stress” caused due to the displacement, such as in the case of fatigue.

Velocity is how fast it is traveling at any given instant. Construction vibration amplitude is normally expressed as particle velocity. Because that is what effects buildings the most due to the effect of inertial forces and momentum (Newton’s 1st law states that what is at rest prefers to stay at rest and what is in motion prefers to stay in motion. If a building is in motion, it can be quite difficult to stop it especially if it has gained velocity). The speed of the wave which tends to correspond better to damage observed. Velocity measures how often the displacement is being applied in a given time period. It is related to the fatigue mode of failure. Velocity amplitude unit is a good measure in the range of 5-2000 Hz frequency. Even at small displacement amplitude the repeated motion can cause fatigue failure. Measured in inch/sec or mm/sec

The damaging potential of vibration depends not only on frequency but on displacement is illustrated by the fact that most failures due to vibration are because of the fatigue of the material. Everyone at one time or another has bent a wire back and forth until it broke, so think of that bending occurring at a higher rate, higher frequency, and with greater displacement and one can clearly see how vibration can fatigue a material to the point of figure. Thus the severity of vibration is dependent on the frequency and displacement.

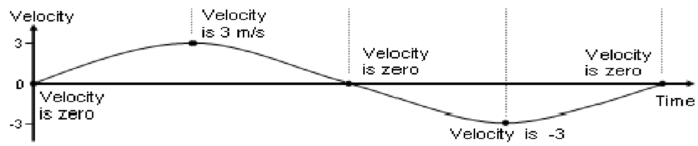
Velocity: a measure of velocity is a direct measure of fatigue since for something to travel a certain distance in a given time it needs to travel at a certain speed.

Fatigue=displacement X frequency

Velocity = displacement X frequency

Thus velocity = fatigue

So, velocity is the measure of the speed by which an object or surface goes through an oscillating motion. But the speed is always changing.



At the upper and lower limits of travel the velocity is zero. That is to say from where it starts to where it reaches its maximum travel and must pause before it begins its journey back through the neutral position and toward the opposite extreme point of travel. Since it is constantly changing the peak is used. Velocity is expressed in inches per second peak (in/sec-pk) or mm/sec-pk

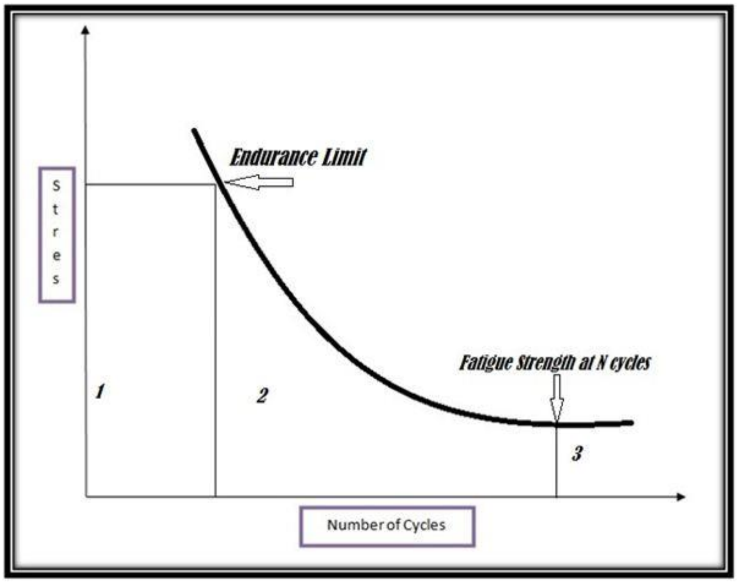
Acceleration is the change in velocity. Measurements of the acceleration suffer from a serious limitation and can only indirectly be used for assessing risk of damage. Generally, acceleration is a measure of the inertial force acting on an object subjected to vibration or shock. The superposition of all forces present produces deformation in the object which can be characterized by strain **-** a relative dimensional change. The strain depends, on the one hand, on the magnitude and frequency of the resulting force applied, while, on the other, it depends on the material characteristics of the object, like rigidity and mass. When strain goes beyond a certain critical level, characteristic of a material or object, mechanical damage occurs. Above the 2000 Hz the failure is normally force related. Acceleration is measure of the likelihood of force being the mode of failure.

As mentioned the speed or velocity is continually changing. Each time an object comes to one of the limits of travel it must stop, but when it leaves that limit it must speed up, it must accelerate and change direction (both a definition of acceleration: the change of speed and direction). As the velocity increase the rate of change often decreases. Velocity increases acceleration decreases. Since the rate of acceleration is constantly changing in vibration then just as with velocity it is measured as peak acceleration. So acceleration is measured in in/sec^2 or mm/sec^2 But normally expressed in g's which is the force exerted by gravity at sea level. 980.665 cm/sec/secor 386.087 in/sec/sec or 32.1739 ft/sec/sec

Humans perceive vibration over a relatively large range of frequencies, from a slow as 0.1-0.5 mm/sec at 5-30 Hz and at a steady state 0.03 in/sec. We find it disturbing at 0.1 -0.2 inch/sec usually above 10Hz We are most sensitive to the range of 5-30 Hz but we can perceive from 1 hz to 20k Hz which happens to be the range most common for construction activities.

http://www.sensorsmag.com/sensors/acceleration-vibration/a-practical-approach-vibration-detection-and-measurement-par-951

Vibration is a cyclic loading. So not only will frequency and amplitude be important to determining if damage potential is high but duration will play a crucial role. Fatigue of the material.

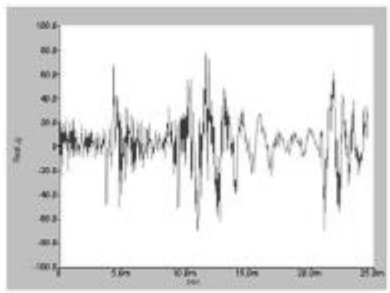


Wöhler curve (after the 19th century German engineer August Wöhler) also known as the SN curve S= cyclic stress or load and N= duration in numbers of cycles on the X axis. So if you know the stress level you can draw a horizontal line and vertically down. Where it intersects the curve will be the number of cycles before failure (fracture). The right side of the x axis represents many millions of cycles.

Many materials have a fatigue limit. So it may take many loads well below the strength of the material to fail, but it will eventually fail since the effect of vibration is cumulative

Vibration can be quantified by several descriptors:

The raw signal, (often recorded and used) such as in the light line which is an instantaneous vibration velocity which fluctuates from positive to negative around a zero line. The maximum velocity point is the peak particle velocity. Often used in construction monitoring. Because velocity is of greater concern due to inertial forces and momentum. But most often the vibration is random and mixed.

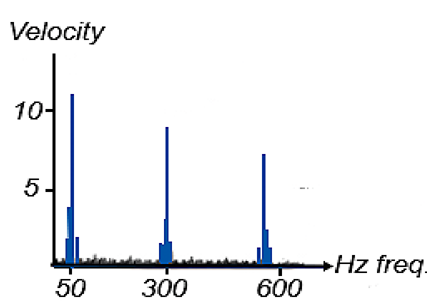


Typical acceleration signal from an RS vibration system

Spectrum

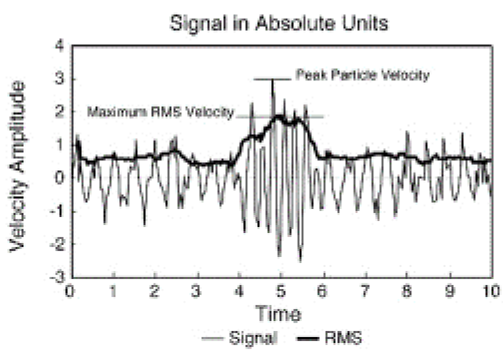
Another kind of display commonly used by vibration analysts is the spectrum. A spectrum is a graphical display of the frequencies at which a source or object is vibrating, together with the amplitudes of the component at these frequencies. In contrast to waveform spectra which displays the overall effect, the spectra display the individual frequencies at which vibration occur. With the exception of a few specialized cases, spectra (and not waveforms) are usually the primary tool for analyzing object or source vibration.

Shown below is an example of a velocity spectrum.



Usually, it consists of many vibratory motions taking place simultaneously. Because a spectrum shows the frequencies at which vibration occurs, it is a very useful analytical tool. By studying the individual frequencies at which the source or object vibrates, as well as the amplitudes corresponding to those frequencies, we can infer a great deal about the cause or potential cause of damage.

Root mean square (rms) amplitude is used, it is a bit like an average. And produces a smoothed spectral curve like the dark one. RMS is gotten by taking the square root of the average of the squared amplitudes of the signal. This average is usually taken over a one second period. The rms is always lower than the PPV. The rms velocity is normally expressed as inches per second or meters per second.



Raw instantaneous velocity and Vrms (darker line)

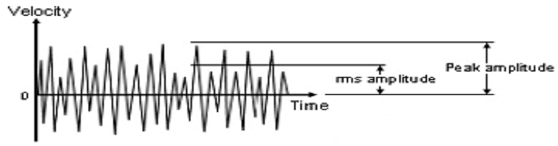
SPECTRAL DENSITY: RMS

When faced with random vibration, mixed amplitudes and frequencies, can often be specified in spectral density (particularly useful for acceleration) or root mean square rms root mean acceleration for example. It is the square root of the area under the ASD curve in the frequency domain.   The peak ground acceleration PGA is the acceleration that exceeds a certain level for a moment in time. The rms shows the main value of shock and vibration. It can illustrate the potential hazard of certain operations. rms is the statistical measure of the magnitude of a varying quantity   Particularly valuable for acceleration and is best used when the vibration is random.

$$g_{rms} = \left(\frac{1}{N} \sum_{1=0}^{N} gi^2 - g^2 \right)^{1/2}$$

Peak Amplitude or Peak-to-peak amplitude

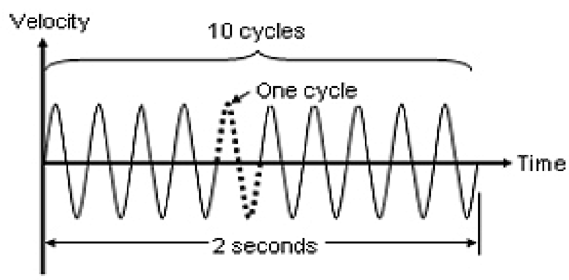
Root Mean Square *RMS (the quadratic mean)*: Is the statistical measure of the magnitude of a varying quantity like acceleration. In statistics it is a measure defined as the **square root** of the **mean** of the squares of a sample.   So if all the accelerations recorded are squared, and the mean of that collection is then calculated followed by the determination of the square root of that mean the result is the rms expressed as g force $\mathbf{g_{rms}}$. The g_{rms} helps to identify the amount of vibration for individual processes (like landing, transport, or offloading etc.

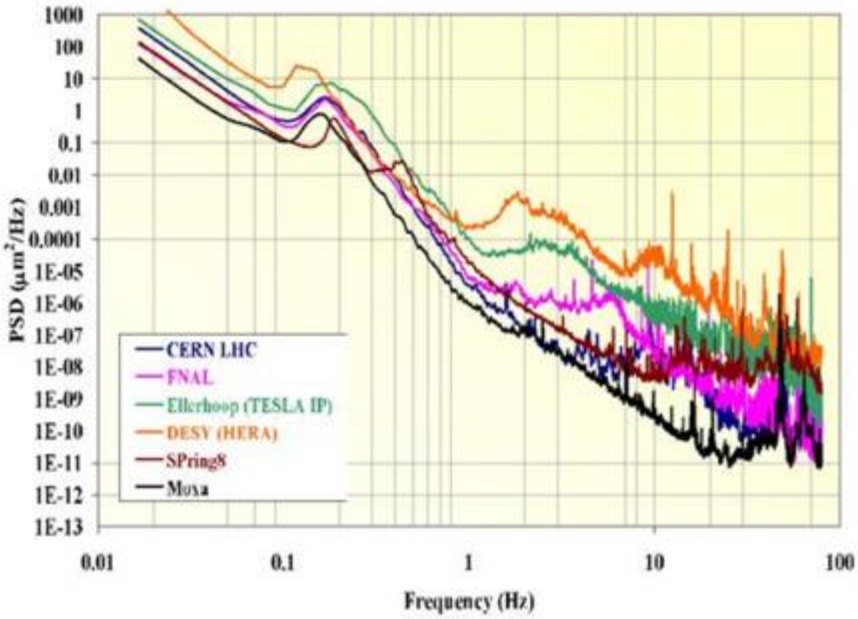


Which one is used is personal choice but should be consistent

http://www.lifetime-reliability.com/free-articles/maintenance-management/Fundamentals_of_Vibration_Measurement_and_Analysis_Explained.pdf

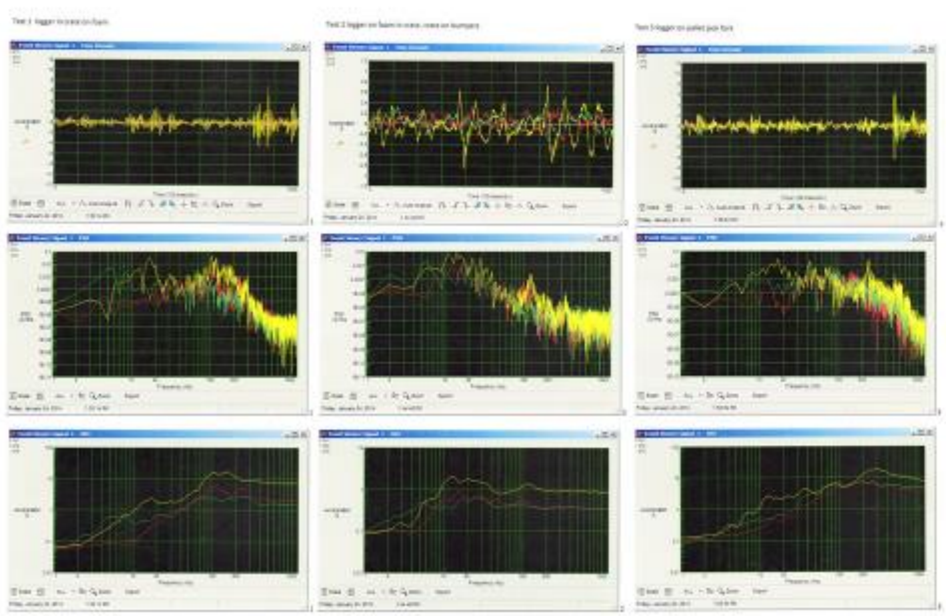
Power Spectral Density (PSD) reveals the energy distribution of the g_{rms} in a aprticualr frequency band of choice. It is a bit like the response spectra or equal hazard response spectra. It represents the level of energy per vibrational frequency





Power Spectral Density shows the energy distribution of the g_{rms} within a given frequency band.

Indirect effect of vibration: objects move and fall, loose parts collide, stress builds in vulnerable parts and they become more susceptible to damage, abrasion



Typical record of vibration

How do object vibrate?

Because of geometry, mass and elasticity most objects can vibrate at many different frequencies. The lowest frequency is called the natural frequency. All of these frequencies can be called resonant frequencies but this is usually refers to the higher ones.

There are several responses objects can have:

Transmission: object will vibrate at same frequency and amplitude as the source if the vibrational frequency of the source is lower than the objects natural frequency of vibration

Attenuation: if the source vibration frequency is greater (higher) than the object the object seems to be still. This is like isolation.

Resonance: if the source natural frequency matches the natural frequency of the source, the amplitude of the resonant frequency vibration will increase. This is resonance of the object.

The concept of damping.

To determine the degree of damping in any system:

$$\xi = -\frac{1}{2\pi n}\ln\left(\frac{Z_n}{Z_0}\right)$$

Where:

ξ is the damping

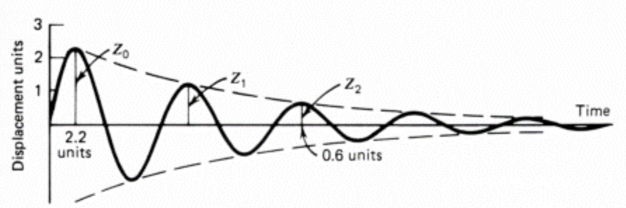
n is the number of cycles being considered

Z_n is the amplitude of the last cycle considered

Z_0 is the amplitude of the first cycle considered

Ln is the natural log

$$\zeta = -\frac{1}{2\pi n}\ln\left(\frac{Z_n}{Z_0}\right)$$



Damped harmonic vibration.

MEASURING:

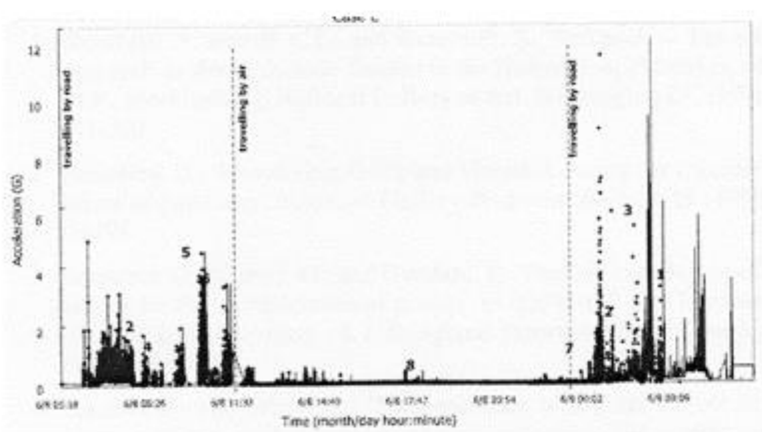
Types and Sources of vibration:

Continuous vibration
Machinery, steady road traffic, continuous construction activity (such as tunnel boring machinery).

Impulsive vibration
Infrequent: Activities that create up to 3 distinct vibration events in an assessment period, e.g. occasional dropping of heavy equipment, occasional loading and unloading.

Intermittent vibration
Trains, nearby intermittent construction activity, passing heavy vehicles, forging machines, impact pile driving, jack hammers. Where the number of vibration events in an assessment period is three or fewer this would be assessed against impulsive vibration criteria

Accelerations can be 8-10 g during handling while more like 1 – 1.3g in truck on highway…but it varies.



In transport the sources of vibration are random, a combination of frequencies and amplitudes will be:

Truck:1-200 Hz (not air ride)ASTM standard 4169 suggested that a 0.5g sinusoidal input over a frequency range of 3-100 Hz is a reasonable expectation of an overland truck performance on average roads. But these are low magnitude and random (discouraging resonance). Marcon indicated that vibration frequencies of 2.5 – 100 Hz were typically observed for trucks traveling over a variety of road surfaces. Stolov [9] in contrast indicated 70 – 200 Hz as a typical range for the highway travel

Trains: 1-500 Hz at a maximum of 0.2 G

Airplane: 100-1000Hz 1g at landing,

Ships: 1-100 Hz typically 1.5 G due to slamming of the bow after rising into large waves

The National Gallery used the Wanderer and a unit designed by Cambridge University. They found discrete shock of up to 2.2g in handling and loading and 0.2 to 0.3g during transport with occasional 0.5 g. But later trips had almost doubled that. They concluded air ride vehicles background noise was between 0.5 and 1 g. The Getty has been using the ACR sensor/data logger which was also used by the Tokyo National Museum.

Ambient background for most buildings is between 0.02 inch/sec and 0.1 inches/sec occasionally spiking to around s/sec

Threshold damage is around 2-3 in/sec (hairline crack sin drywall), minor damage is 4-5 in/sec (hairline crack sin masonry) and major structural damage is greater than 5 in/sec (cracking or shifting of foundation) a recommended safety threshold is 0.5 in/sec at below 10Hz higher than that usually is not felt by the building.

On a truck vibrations can occur from 1.5 – 3 in/sec sustained. British Museum reported damage to artworks at 0.6-1.8 in/sec. but there was pre existing weaknesses.

Limit generally agreed upon is 0.1in/sec

Ref:Esser, K. (2012). *Transport of unfixed paint layers on paper within an institution.* In: Moving Collections: Processes and Consequences. (ed: Ida Antonia Tank Bronken, Susan Braovac, Tone Marie Olstad, Anne Apalnes Ørnhøi). Archetype Publications. pp. 91-98

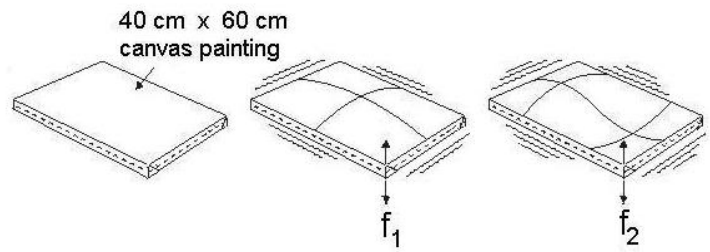
HOW DO OBJECTS MOVE AND HOW IS THAT RELATED TO DAMAGE DUE TO VIBRATION

Fracture/distortion

Fatigue: for fatigue to occur the critical threshold must occur which may be in the range of millions of cycles, but it is very hard to quantify.

Abrasion: Occurs whenever two surfaces, under a degree of compressive load, move relative to one another across the plane of contact. Things rub against one another. The degree of damage due to abrasion depends upon pressure, surface durability and the surface topography.

As Paul Markon has shown a canvass under normal tension can have several vibration frequencies. 24 Hz and 32 Hz is shown here:



Fragility factors:

Approximate fragility of typical packaged articles.

Extremely Fragile	15 - 25 g's	Precision electronic test equipment (plaster, highly fragile glass)
Very Delicate	25 - 40 g's	Scientific instruments, ray equipment (unfired clay, glass)
Delicate solid	40 - 60 g's	Computer display terminals, electric typewriters, most state electronic equipment (clay low fired ware)
Moderately Delicate drives	60 - 85 g's	Stereo equipment, televisions, computer floppy disk (weak flaking paint)
Moderately Rugged	85 - 110 g's	Major appliances, furniture (brittle paint)
Rugged	Over 110 g's	Table saws, sewing machines, machinery (boxed works)

As an objects mass increases so does the force it imposes in a collision under acceleration

Vibration from building

Thicket at BM measured damaging vibrations levels due to the building work, expressed as acceleration, were between 0.2 and 0.6 g and compared to the background levels between 0.006 g and 0.15 g induced by day-to-day activities

https://repository.si.edu/bitstream/handle/10088/8127/mci_Art_in_Transit_Handbook_for_Packing_and_Transporting_Paintings.pdf?sequence=1&isAllowed=y

Wei notes that 2mm/sec could be considered safe for robust objects over a time frame of for several months. But this depends upon vibration amplitude and frequency, and velocity….1 mm/sec is safer

https://www.academia.edu/10047861/Baseline_limits_for_allowable_vibrations_for_objects

Building a crate:

It is essential when designing and building a transport package (box or create) that the characteristics of the environment which this will be sent into are defined and the material characteristics of the object, as well as its fragility factor, be defined as much as possible.

Environment: the most severe shocks will occur in the handling phases. The smaller the package the higher the likely drop, though not necessarily the highest impact, the bigger the package the lower the potential drop (but the heavier the package so mass and acceleration might play a role).

So if a packed object is exposed to vibration there are three possible outcomes:

1. Transmission: if the source vibration frequency is lower than the natural frequency of the object/cushion the object will vibrate with the same frequency as the source
2. Resonance: if the source vibration frequency matches the object/cushion frequency then there will be resonance. And the amplitude of the object vibration will be greater than the source vibration
3. Attenuation: if the source vibration frequency is greater than the object cushion then the object will remain still.

The natural frequency of a cushioned object is the square root of cushion stiffness divided by mass of the object

$$fr = \sqrt{\frac{cushion\ stiffness}{mass\ of\ object}}$$