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Vibrations in buildings are of increasing importance as stronger building materials and more refined and sophisticated designs result in lighter structures that are more prone to vibrations than earlier, heavier ones. This Digest presents various aspects of building vibrations and ways of avoiding or alleviating vibration-related problems. Effects of blasting,[1] earthquake resistant design,[2] and floor vibrations[3] have been discussed in previous Digests and will therefore not be covered in detail here.

Building vibrations fall into two categories: those that arise from internal sources and those that arise from external sources. Most vibrations generated inside buildings originate from machines (cranes, trollies, elevators, fans, pumps, drop hammers, punching presses) and from the activities of people (walking, jumping, dancing, running). Externally generated vibrations commonly arise from road and rail traffic, subways, construction activities (pile driving, blasting, excavation and compacting of soil), sonic booms, strong winds, and earthquakes. The resulting vibrations in buildings may cause annoyance to the occupants, impaired function of instruments, or structural damage.

Basic Considerations

The parameters of primary importance in structural vibrations are natural frequencies, mode shapes, and damping. The natural frequencies of a building or a component are those at which continuing free oscillations occur after the excitation has stopped. The structure or component assumes a mode shape when it vibrates freely at a natural frequency. When an excitation frequency coincides with or is close to a natural frequency, large vibration amplitudes can result. This is called resonance and, in general, should be avoided. Damping capacity is the ability to absorb vibration energy. This property is inherent in all materials to some degree. In most cases, increasing the damping capacity results in reduced vibration amplitudes. Thus, components or buildings that have low damping capacity tend to vibrate more than those with high capacity. Energy is dissipated in the materials, joints and connections. Damping can be increased by the use of dashpots, friction devices, or by the addition of special damping materials.

Most vibration problems can be described in terms of the source, the transmission path, and the receiver. This provides a convenient subdivision of the overall problem and a simpler approach to many remedial measures. These three components can usually be treated in isolation, although sometimes all three have to be considered together in order to find a satisfactory solution to unacceptable vibration levels.

When vibrations are transmitted from the source through the soil into the building foundations, they propagate sideways and upwards throughout the building. The soil has a strong influence on the intensity of the vibrations received in the building. Under similar excitations at the vibration source, soft soils result in larger amplitude vibrations than hard or rock-like materials. However, soft soils attenuate the vibrations somewhat more rapidly with distance. The type of foundation selected for the building is also important. A foundation extending down to firmer layers can reduce vibration amplitudes due to exterior sources. The transmission path can also be entirely within the building, for instance when the source is a machinery room at the top of the building, or a person jumping in an adjacent room.

The "receiver" is a person, the contents, or the building itself that is affected by the vibrations. The sensitivity of humans varies with body position (sitting, standing, lying), the direction of the vibration (vertical, horizontal, rotational) and the type of activity being performed. When vibrations are accompanied by noise, a complex psychological interaction occurs, which tends to increase the annoyance that people experience.

Instruments can also be adversely affected by vibrations. They can be must more sensitive than humans since their operation will be impaired before the vibrations are felt by the operators. Microbalances, electron microscopes, and other sensitive instruments require a relatively vibration-free environment for proper functioning. As a general rule, the best location within a building for these instruments is on a slab on grade. Data processing equipment and computers, on the other hand, are less sensitive to vibrations.

Buildings also are governed by certain vibration tolerance levels. Old buildings are often less tolerant than new constructions because of archaic building materials or structural systems. Other factors include deterioration of mortar and settlement of foundations. Properly constructed and maintained buildings are quite resistant to low vibration levels that are tolerated by human occupants. Pressure pulses in the air from the supersonic boom of aircraft or from blasting can cause damage to brittle components such as windows and plaster on walls or ceilings. Some studies suggest that long-term exposure causes cumulative damage, but this has not been clearly demonstrated. Ground-transmitted vibrations from blasting and construction activity can cause cracking of plaster, masonry or concrete if safe levels are exceeded.[1] The motions induced by earthquakes can result in damage ranging from superficial cracking to major structural damage.[2]

Annoying vibrations from footsteps may arise when light and flexible floor structures and large areas without partitions are employed.[3] For dynamic floor loads that occur in gymnasia, dance floors, and sports arenas, the coordinated rhythmic motions of people can cause large amplitude vibrations that can range from simple annoyance to structural damage in extreme cases. To minimize this effect, the floor should have sufficient stiffness, and a coincidence of the excitation frequencies and the natural frequencies of the floor has to be avoided.[4]

Vibration Criteria and Guidelines

Criteria and guidelines for acceptable vibration limits are useful when designing buildings or evaluating the adequacy of existing structures. Unfortunately, they are not always available in sufficient detail, or for the situation under consideration. Extrapolation from similar cases or a trial-and-error approach of successive improvements may be necessary.

Criteria for acceptable vibration limits have been derived from experiments, practical experience, and judgement. They undergo continual study and development and are periodically changed to incorporate new information. Vibration criteria may be developed for the benefit of the occupants, for sensitive instruments (or other contents), or for the building itself.

Vibration criteria for occupants have been published by the International Standards Organization (ISO). Vibration limits are presented as a function of frequency and exposure time for the transverse (front-to-back) and longitudinal (foot-to-head) directions.[5] This standard has been adopted in the United States[6] and the United Kingdom,[7] but has not yet been adopted as a national standard in Canada. Some vibration design guidelines have also been discussed in a previous Digest on floor vibrations.[3] Vibration standards for occupational health and safety also exist, but these are outside the scope of this Digest.

Some sensitive instruments can be adversely affected by vibrations of the support structure. The tolerance limits should be available from the manufacturer. If not, experience with similar instruments has to be relied upon.[8] Because of instrument sensitivity, the vibration criteria for standards laboratories are particularly severe.[9]

Deflection criteria are sometimes specified as a means of limiting vibration amplitudes that are detrimental to the building or its contents. For instance, clearances between adjacent buildings or between the structural frame and the partitions might need to be preserved (in the event of seismic or wind-induced vibrations). Deflection criteria are also a means of limiting the allowable stress or strain in a brittle or low-strength material (such as plastered ceilings). Conformance to an allowable deflection ratio under static loads, however, may not always adequately insure the absence of vibration problems as far as human annoyance, serviceability or resonance is concerned.

Although overloading of building components as a result of vibrations is relatively rare, it can occur as a result of resonance conditions, intense impacts, blasts and earthquakes. The allowable stresses will depend on the material and whether a loss (or gain) of strength has occurred because of other factors (ageing, weathering, corrosion or other chemical reactions). Relatively small vibration loads may add to the built-in stresses and lead to unexpected cracking of concrete, masonry or plaster. This sometimes occurs in buildings near construction blasting even if the vibration levels are below the recommended limits.

Loss of strength from repeated loadings, or fatigue failure, may occur when stress levels are high in relation to the strength of the material and the number of load cycles is large. This is not normally a serious concern because the induced stresses are generally very low. Exceptions include wind-induced vibrations of structural members and other excitations at resonance frequencies. Although fatigue behaviour is reasonably well understood for steel, it is not as well known for other common construction materials. Long-term observations, however, have not shown any alarming tendency of brick, concrete or wood to suffer from fatigue under commonly encountered vibration levels.

In old buildings, materials may be weathered and weakened, foundation movements may have induced high stresses in the structure and some cracks may already be present. The structural system may be complex and difficult or impossible to assess and materials with little-known strength characteristics may have been used. In addition old buildings sometimes contain features that are difficult to repair or replace once damage has occurred. Therefore, allowable vibration levels for these structures should be set only after careful consideration of the circumstances. In some European countries vibration limits for historic structures have been established. They range from 10 to 20% of the limits applicable to new constructions. This could be used as a guide in limiting vibrations in old buildings.[10]

To gauge the adequacy of an existing building for a proposed use or occupancy or to evaluate a complaint, the existing vibrations are measured and then compared to the appropriate criteria or acceptable limits. If these limits are exceeded, then remedial measures are indicated. The measurement and interpretation of vibrations is a specialized discipline that requires experienced operators and suitable equipment. The latter can include vibration sensors, signal conditioners, recording devices, and possibly a spectrum analyzer or computer for evaluating the results.

Design Considerations

The incorporation of vibration criteria in the design process can be a complex undertaking. The uncertainty of the nature of the vibration source the behaviour of the various interacting elements, and the complexity of the analysis may make an accurate prediction of vibration levels of the various components virtually impossible. Nevertheless, design guides for some specific dynamic loadings are available,[1, 3, 4, 10] and certain decisions at the design stage can improve the overall vibrational environment of buildings. When feasible, buildings should be located away from known vibration sources, or the vibration source relocated away from the building. For vibration-sensitive occupancies, the structural system should be selected on the basis of known vibration response characteristics (i.e., massive construction versus lightweight, shear wall or braced versus pure frame construction, low rise versus high rise). In tall buildings, wind-induced vibrations can lead to the discomfort of occupants, cracking of cladding, partitions or windows and creaking noises resulting from the building motion. Design guidelines are presented in Ref. (11). When anticipated motions exceed tolerable levels, the building has to be either stiffened or supplied with active devices such as electro-hydraulically controlled mass dampers, or passive devices such as friction joints, tuned-mass-dampers or viscoelastic damping layers. These devices can also be employed as remedial measures to vibration problems. Before selecting a site for a building that has a vibration-sensitive occupancy, it may be desirable to establish the type, level and frequency content of vibrations that exist or are likely to exist at the site. This would require a site measurement and analysis program.

Buildings housing sensitive instrumentation require careful consideration of the location of the building, the choice of structural system, and the location, layout, and possible isolation of instruments within the building. The choice and isolation of machinery (for instance air handling and elevators) and the vibrations caused by people walking and slamming doors may also be important.

Remedial Measures

Remedial measures for vibration problems can be considered for the source, the transmission path, or the receiver. At the source, the aim is to reduce the vibrations that are being generated. For road traffic, this can be achieved by reducing the speed and weight of vehicles, smoothing the road surface and improving the road bed. For surface and subway rail, isolation pads can be used between the rail and the subgrade. Rubber tires (instead of steel wheels) also reduce vibration levels. Machinery that is a source of vibration should be isolated from its mountings by springs or spring-like pads or located where it is less prone to transmitting vibrations. Reciprocating and rotating machinery should be properly balanced.

The transmission path can reduce vibrations by introducing barriers to the waves that reach a building. When surface waves predominate, deep trenching (which may be backfilled with bentonite) is an effective method. Piles in properly selected patterns also reduce transmitted vibrations. Another promising method is isolating the entire building during construction, or as a remedial measure. Elastomeric pads are introduced at the basement level of every column to reduce the magnitude of vibrations in the remainder of the building.

When the vibration problem concerns a portion or a component of a building such as a floor or a beam, other measures may be effective. These include stiffening the component to change its resonance frequency, adding damping to reduce the amplitude of vibration, and adding mass to reduce the response to impulsive loads. The exact nature of the remedial measures must be analyzed carefully, to avoid making the vibration problem worse.

Concluding Remarks

An awareness of the nature of vibrations can help avoid or alleviate vibration-related problems. It is advantageous and sometimes less costly to consider the effects of vibration on the building and its contents during the design process. Although specific guidelines for design are not always available, some do exist. A detailed consideration of vibration problems in buildings is a complex matter, however, and usually requires the assistance of specialists.

References

1. Northwood, T.D. and Crawford, R., "Blasting and Building Damage in Canada". National Research Council Canada, Division of Building Research, **Canadian Building Digest 63**, March 1965.

2. Rainer, J.H. and Northwood, T.D., "Earthquakes and Buildings in Canada". National Research Council Canada, Division of Building Research, **Canadian Building Digest 208**, October 1979.
3. Allen, D.E. and Rainer, J.H., "Floor Vibrations". National Research Council Canada, Division of Building Research, **Canadian Building Digest 173**, September 1975.
4. Supplement to the National Building Code of Canada, 1985 Edition, Commentary A, "Serviceability Criteria for Deflections and Vibrations".
5. "Guide for the Evaluation of Human Exposure to Whole-Body Vibration". International Standards Organization, ISO 2631-1978, Geneva, 1978.
6. "Guide to the Evaluation of Human Exposure to Vibration in Buildings". American National Standard, Acoustical Society of America, ANSI S3.29-1983, New York, 1983.
7. "Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)", British Standards Institution BS 6472, London, 1984.
8. Ferahian, R.H. and Ward, H.S., "Vibration Environment in Laboratory Buildings", National Research Council Canada, Division of Building Research, Technical Paper No. 329, 1970.
9. "Recommended Environments for Standards Laboratories, Recommended Practice". Instrument Society of America, RP52.1-75, 1975.
10. Rainier, J.H., "Effect of Vibrations on Historic Buildings: An Overview", APT Bulletin, Vol. XIV, No. 1, 1982, p 2-10.
11. Supplement to the National Building Code of Canada, 1985 Edition, Commentary B, "Wind Loads".