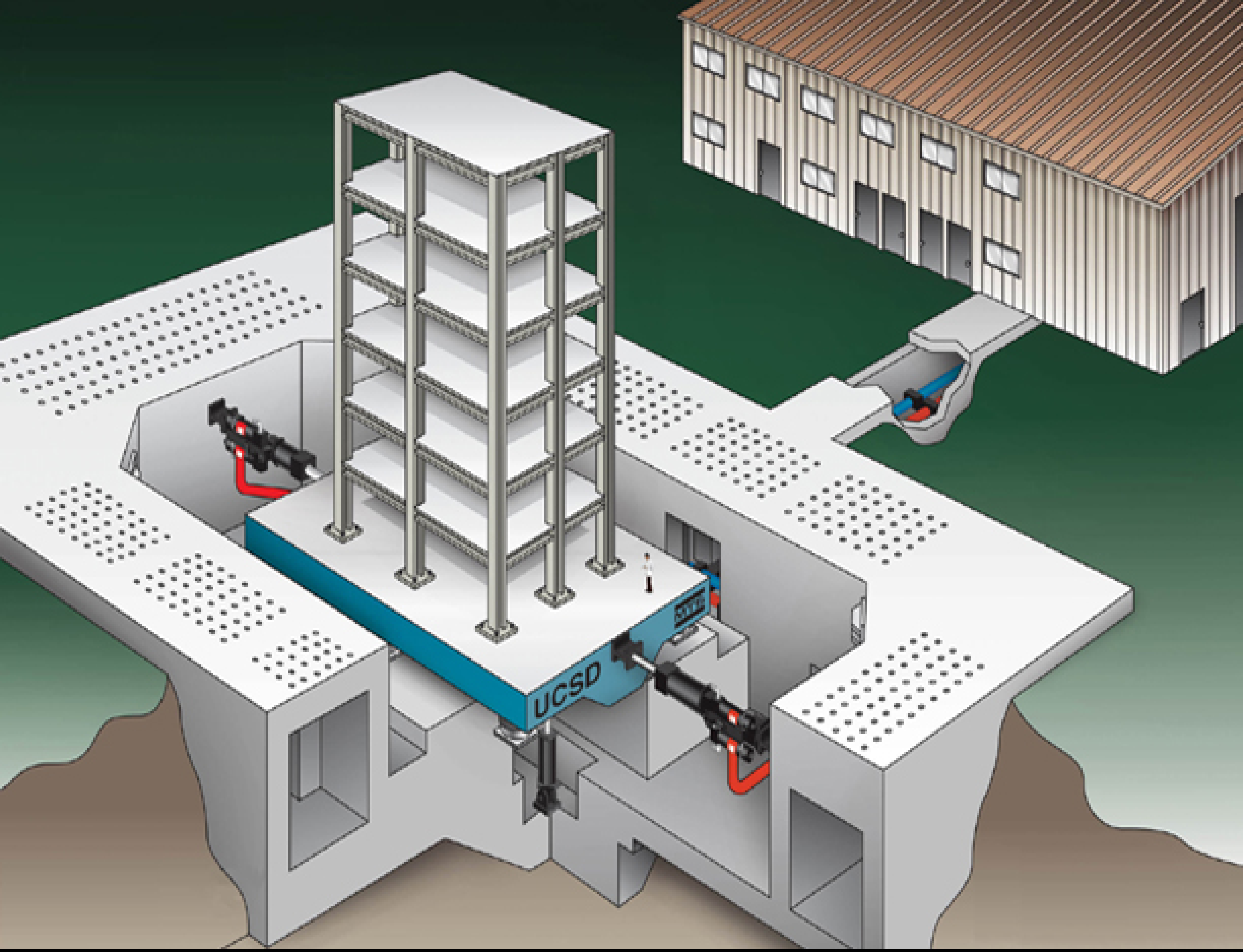

Advanced Earthquake Engineering

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Chapter 1

Introduction to Earthquake Engineering

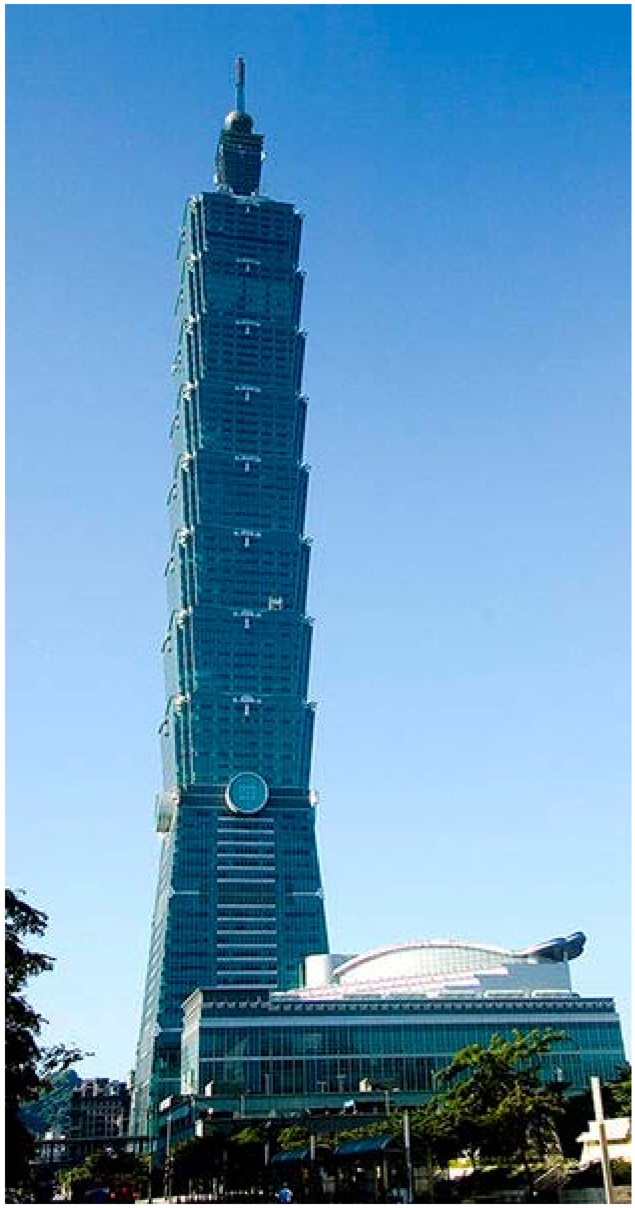
Earthquake engineering is the study of the behavior of buildings and structures subject to seismic loading. It is a subset of both structural and civil engineering.

The main objectives of earthquake engineering are:

- Understand the interaction between buildings or civil infrastructure and the ground.
- Foresee the potential consequences of strong earthquakes on urban areas and civil infrastructure.
- Design, construct and maintain structures to perform at earthquake exposure up to the expectations and in compliance with building codes.

A properly engineered structure does not necessarily have to be extremely strong or expensive.

Shake-table crash testing of a regular building model (left) and a base-isolated building model (right) at UCSD



Taipei 101, equipped with a tuned mass damper, is the world's second tallest skyscraper.

The most powerful and budgetary tools of earthquake engineering are vibration control technologies and, in particular, base isolation.

Seismic loadings

Seismic loading means application of an earthquake-generated agitation to a structure. It happens at contact surfaces of a structure either with the ground, or with adjacent structures, or with gravity waves from tsunami. Seismic loading depends, primarily, on:

The Last Day of Pompeii

- Anticipated earthquake's parameters at the site
- Geotechnical parameters of the site
- Structure's parameters
- Characteristics of the anticipated gravity waves from tsunami (if applicable).

Ancient builders believed that earthquakes were a result of wrath of gods (in Greek mythology, e.g., the main "Earth-Shaker" was Poseidon) and, therefore, could not be resisted by humans. Nowadays, the people's attitude has changed dramatically though the seismic loads, sometimes, exceed ability of a structure to resist them without being broken, partially or completely.

Due to their mutual interaction, seismic loading and seismic performance of a structure are intimately related.

Seismic performance evaluation

Engineers need to know the quantified level of an actual or anticipated seismic performance associated with the direct damage to an individual building subject to a specified ground shaking.

The best way to do it is to put the structure on a shake-table that simulates the earth shaking and watch what may happen next. Such kinds of experiments were performed still more than a century ago

Shake-table of a 6-story non-ductile concrete building destructive testing

Another way is to evaluate the earthquake performance analytically.

Seismic performance analysis

Seismic performance analysis or, simply, seismic analysis is a major intellectual tool of earthquake engineering which breaks the complex topic into smaller parts to gain a better understanding of seismic performance of building and non-building structures. The technique as a formal concept is a relatively recent development.

In general, seismic analysis is based on the methods of structural dynamics. For decades, the most prominent instrument of seismic analysis has been the earthquake response spectrum method which, also, contributed to the proposed building code's concept of today.

However, those spectra are good, mostly, for single-degree-of-freedom systems. Numerical *step-by-step integration* proved to be a more effective method of analysis for multi-degree-of-freedom structural systems with several non-linearity under a substantially transient process of kinematic excitation.

Basically, numerical analysis is conducted in order to evaluate the seismic performance of buildings. Performance evaluations is generally carried out by using nonlinear static pushover analysis or full direct nonlinear time history analysis. In these analysis process, first nonlinear modeling of building components such as beams, columns, beam-column joints, shear walls etc. are required. It is essential that nonlinear response of these components should be validated by the experimental results in order to ensure the accuracy of the analysis. After validating all components of buildings with experimental results, these components are assemble to create a full nonlinear model of the structure. Thus created model are analyzed to evaluate the performance of buildings.

One of the important thing in seismic evaluation of the building is also the computational platform. There are several commercially available Finite Element Analysis software's such as CSI-SAP2000/CSI-PERFORM-3D / CSI-ETABS which can be used to for seismic performance evaluation of buildings. Moreover, there are research based finite element analysis software such as OpenSees(Open Source)/RUAUMOKO/DRAIN-3D for the seismic evaluation of the buildings.

Research for earthquake engineering

Shake-table testing of Friction Pendulum Bearings at EERC

Research for earthquake engineering means both field and analytical investigation or experimentation intended for discovery and scientific explanation of earthquake engineering related facts, revision of conventional concepts in the light of new findings, and practical application of the developed theories. The National Science Foundation (NSF) is the main United States government agency that supports fundamental research and education in all fields of earthquake engineering. In particular, it focuses on experimental, analytical, and computational research on design and performance enhancement of structural systems.

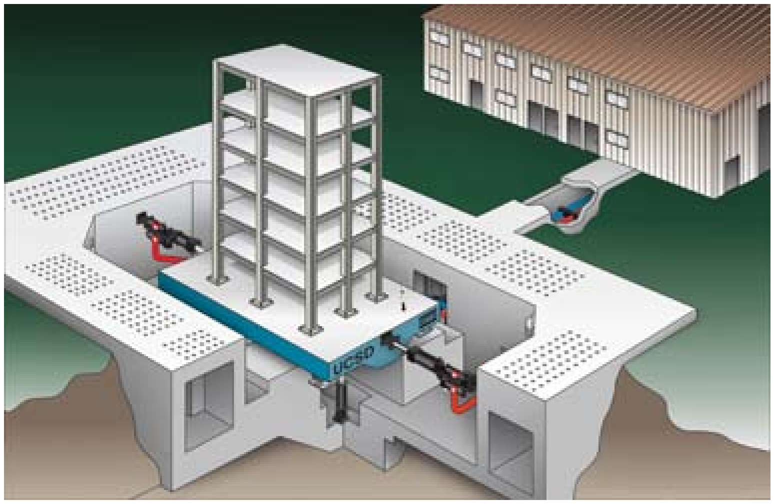
E-Defense Shake Table

The Earthquake Engineering Research Institute (EERI) is a leader in dissemination of earthquake engineering research related information both in the U.S. and globally.

A definitive list of earthquake engineering research related shaking tables around the world may be found in Experimental Facilities for Earthquake Engineering Simulation Worldwide. The most prominent of them is now E-Defense Shake Table in Japan.

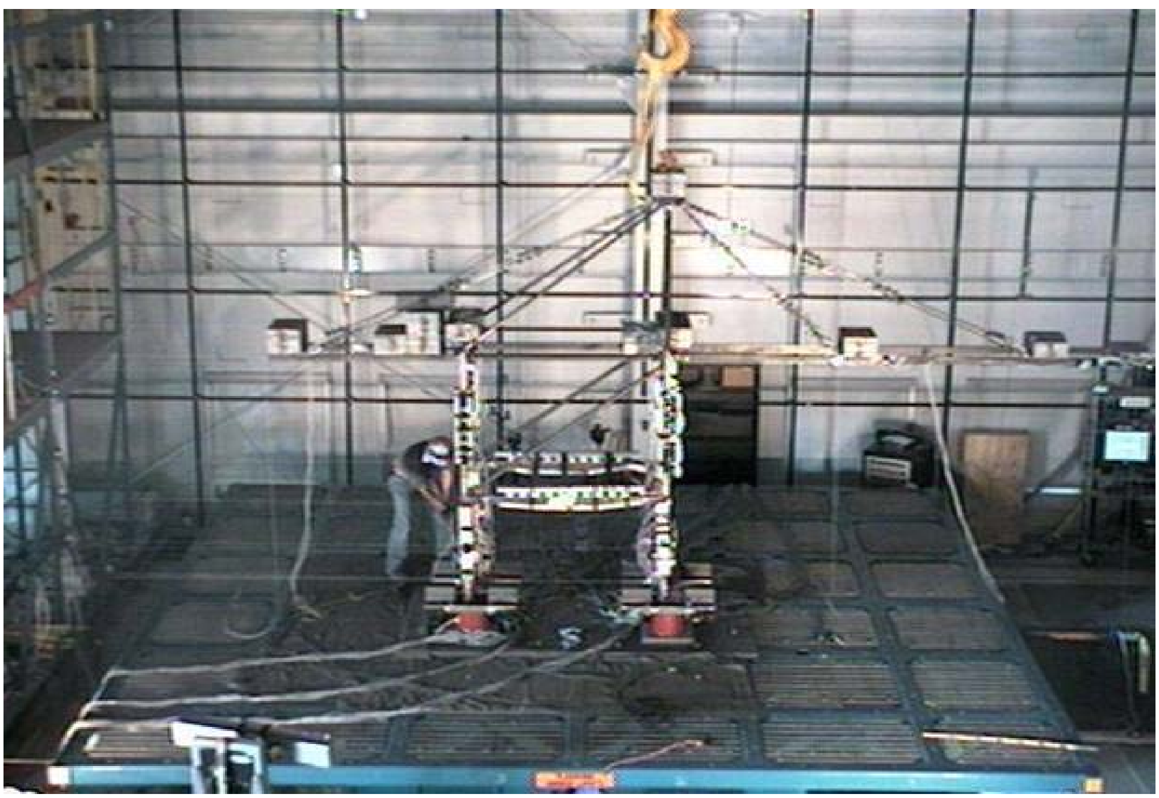
Major U.S. research programs

The NSF Hazard Mitigation and Structural Engineering program (HMSE) supports research on new technologies for improving the behavior and response of structural systems subject to earthquake hazards; fundamental research on safety and reliability of constructed systems; innovative developments in analysis and model based simulation of structural behavior and response including soil-structure interaction; design concepts that improve structure performance and flexibility; and application of new control techniques for structural systems.



Large High Performance Outdoor Shake Table, UCSD, NEES network

NSF also supports George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) that advances knowledge discovery and innovation for earthquakes and tsunami loss reduction of the nation's civil infrastructure, and new experimental simulation techniques and instrumentation.



NEES@Buffalo testing facility

The NEES network features 14 geographically-distributed, shared-use laboratories that support several types of experimental work: geotechnical centrifuge research, shake-table tests, large-scale structural testing, tsunami wave basin experiments, and field site research. Participating universities include: Cornell University; Lehigh University; Oregon State University; Rensselaer Polytechnic Institute; University at Buffalo, SUNY; University of California, Berkeley; University of California, Davis; University of California, Los Angeles; University of California, San Diego; University of California, Santa Barbara; University of Illinois, Urbana-Champaign; University of Minnesota; University of Nevada, Reno; and the University of Texas, Austin.

The equipment sites (labs) and a central data repository are connected to the global earthquake engineering community via the NEEShub, a website that it more than a website. The NEES website is powered by HUBzero software developed at Purdue University specifically to help the scientific community share resources and collaborate. The cyberinfrastructure, connected via Internet2, provides interactive simulation tools, a simulation tool development area, a curated central data repository, animated presentations, user support, telepresence, mechanism for uploading and sharing resources and statistics about users, and usage patterns.

This cyberinfrastructure allows researchers to: securely store, organize and share data within a standardized framework in a central location; remotely observe and participate in experiments through the use of synchronized real-time data and video; collaborate with colleagues to facilitate the planning, performance, analysis, and publication of research experiments; and conduct computational and hybrid simulations that may combine the results of multiple distributed experiments and link physical experiments with computer simulations to enable the investigation of overall system performance.

These resources jointly provide the means for collaboration and discovery to improve the seismic design and performance of civil and mechanical infrastructure systems.

Earthquake simulation

The very first **earthquake simulations** were performed by statically applying some *horizontal inertia forces* based on scaled peak ground accelerations to a mathematical model of a building. With the further development of computational technologies, static approaches began to give way to dynamic ones.

Dynamic experiments on building and non-building structures may be physical, like shake-table testing, or virtual ones. In both cases, to verify a structure's expected seismic performance, some researchers prefer to deal with so called "real time-histories" though the last cannot be "real" for a hypothetical earthquake specified by either a building code or by some particular research requirements. Therefore, there is a strong incentive to engage an earthquake simulation which is the seismic input that possesses only essential features of a real event.

Sometimes, earthquake simulation is understood as a re-creation of local effects of a strong earth shaking.

Structure simulation

Theoretical or experimental evaluation of anticipated seismic performance mostly requires a **structure simulation** which is based on the concept of structural likeness or similarity. Similarity is some degree of analogy or resemblance between two or more objects. The notion of similarity rests either on exact or approximate repetitions of patterns in the compared items.

Concurrent experiments with two building models which are *kinematically equivalent* to a real prototype.

In general, a building model is said to have similarity with the real object if the two share *geometric similarity*, *kinematic similarity* and *dynamic similarity*. The most vivid and effective type of similarity is the *kinematic* one. *Kinematic similarity* exists when the paths and velocities of moving particles of a model and its prototype are similar.

The ultimate level of *kinematic similarity* is *kinematic equivalence* when, in the case of earthquake engineering, time-histories of each story lateral displacements of the model and its prototype would be the same.

Seismic vibration control

Seismic vibration control is a set of technical means aimed to mitigate seismic impacts in building and non-building structures. All seismic vibration control devices may be classified as *passive*, *active* or *hybrid* where:

- *passive control devices* have no feedback capability between them, structural elements and the ground;
- *active control devices* incorporate real-time recording instrumentation on the ground integrated with earthquake input processing equipment and actuators within the structure;
- *hybrid control devices* have combined features of active and passive control systems.

When ground seismic waves reach up and start to penetrate a base of a building, their energy flow density, due to reflections, reduces dramatically: usually, up to 90%. However, the remaining portions of the incident waves during a major earthquake still bear a huge devastating potential.

After the seismic waves enter a superstructure, there are a number of ways to control them in order to soothe their damaging effect and improve the building's seismic performance, for instance:

- to dissipate the wave energy inside a superstructure with properly engineered dampers;

- to disperse the wave energy between a wider range of frequencies;

- to absorb the resonant portions of the whole wave frequencies band with the help of so called *mass dampers*.

Mausoleum of Cyrus, the oldest base-isolated structure in the world

Devices of the last kind, abbreviated correspondingly as TMD for the tuned (*passive*), as AMD for the *active*, and as HMD for the *hybrid mass dampers*, have been studied and installed in high-rise buildings, predominantly in Japan, for a quarter of a century.

However, there is quite another approach: partial suppression of the seismic energy flow into the superstructure known as seismic or base isolation.

For this, some pads are inserted into or under all major load-carrying elements in the base of the building which should substantially decouple a superstructure from its substructure resting on a shaking ground.

The first evidence of earthquake protection by using the principle of base isolation was discovered in Pasargadae, a city in ancient Persia, now Iran: it goes back to 6th century BCE. Below, there are some samples of seismic vibration control technologies of today.

Dry-stone walls control

Dry-stone walls of Machu Picchu Temple of the Sun, Peru

People of Inca civilization were masters of the polished **dry-stone walls**, called ashlar, where blocks of stone were cut to fit together tightly without any mortar. The Incas were among the best stone masons the world has ever seen and many junctions in their masonry were so perfect that even blades of grass could not fit between the stones.

Peru is a highly seismic land, and for centuries the mortar-free construction proved to be apparently more earthquake-resistant than using mortar. The stones of the dry-stone walls built by the Incas could move slightly and resettle without the walls collapsing which should be recognized as an ingenious passive structural control technique employing both the principle of energy dissipation and that of suppressing resonant amplifications.

Lead Rubber Bearing

LRB being tested at the UCSD Caltrans-SRMD facility

Lead Rubber Bearing or LRB is a type of base isolation employing a heavy damping. It was invented by Bill Robinson, a New Zealander.

Heavy damping mechanism incorporated in vibration control technologies and, particularly, in base isolation devices, is often considered a valuable source of suppressing vibrations thus enhancing a building's seismic performance. However, for the rather pliant systems such as base isolated structures, with a relatively low bearing stiffness but with a high damping, the so-called "damping force" may turn out the main pushing force at a strong earthquake. The video shows a Lead Rubber Bearing being tested at the UCSD Caltrans-SRMD facility. The bearing is made of rubber with a lead core. It was a uniaxial test in which the bearing was also under a full structure load. Many buildings and bridges, both in New Zealand and elsewhere, are protected with lead dampers and lead and rubber bearings. Te Papa Tongarewa, the national museum of New Zealand, and the New Zealand Parliament Buildings have been fitted with the bearings. Both are in Wellington, which sits on an active earthquake fault.

Friction pendulum bearing

FPB shake-table testing

Friction Pendulum Bearing (FPB) is another name of **Friction Pendulum System** (FPS). It is based on three pillars:

- articulated friction slider;
- spherical concave sliding surface;
- enclosing cylinder for lateral displacement restraint.

Snapshot with the link to video clip of a shake-table testing of FPB system supporting a rigid building model is presented at the right.

Building elevation control

Transamerica Pyramid building

Building elevation control is a valuable source of vibration control of seismic loading. Pyramid-shaped skyscrapers continue to attract attention of architects and engineers because such structures promise a better stability against earthquakes and winds. The elevation configuration can prevent buildings' resonant amplifications because a properly configured building disperses the shear wave energy between a wide range of frequencies.

Earthquake or wind quieting ability of the elevation configuration is provided by a specific pattern of multiple reflections and transmissions of vertically propagating shear waves, which are generated by breakdowns into homogeneity of story layers, and a taper. Any abrupt changes of the propagating waves velocity result in a considerable dispersion of the wave energy between a wide ranges of frequencies thus preventing the resonant displacement amplifications in the building.

A tapered profile of a building is not a compulsory feature of this method of structural control. A similar resonance preventing effect can be also obtained by a proper *tapering* of other characteristics of a building structure, namely, its mass and stiffness. As a result, the building elevation configuration techniques permit an architectural design that may be both attractive and functional (see, e.g., Pyramid).

Simple roller bearing

Simple roller bearing is a base isolation device which is intended for protection of various building and non-building structures against potentially damaging lateral impacts of strong earthquakes.

This metallic bearing support may be adapted, with certain precautions, as a seismic isolator to skyscrapers and buildings on soft ground. Recently, it has been employed under the name of *Metallic Roller Bearing* for a housing complex (17 stories) in Tokyo, Japan.

Springs-with-damper base isolator

Springs-with-damper close-up

Springs-with-damper base isolator installed under a three-story town-house, Santa Monica, California is shown on the photo taken prior to the 1994 Northridge earthquake exposure. It is a base isolation device conceptually similar to *Lead Rubber Bearing*.

One of two three-story town-houses like this, which was well instrumented for recording of both vertical and horizontal accelerations on its floors and the ground, has survived a severe shaking during the Northridge earthquake and left valuable recorded information for further study.

Hysteretic damper

Hysteretic damper is intended to provide better and more reliable seismic performance than that of a conventional structure at the expense of the seismic input energy dissipation. There are four major groups of hysteretic dampers used for the purpose, namely:

- Fluid viscous dampers (FVDs)
- Metallic yielding dampers (MYDs)
- Viscoelastic dampers (VEDs)
- Friction dampers (FDs)

Each group of dampers has specific characteristics, advantages and disadvantages for structural applications.

Seismic design

Seismic design is based on authorized engineering procedures, principles and criteria meant to design or retrofit structures subject to earthquake exposure. Those criteria are consistent just with the contemporary state of the knowledge about earthquake engineering structures. Therefore, the building design which blindly follows some seismic code regulations does not guarantee safety against collapse or serious damage.

The price of poor seismic design may be enormous. Nevertheless, seismic design has always been a trial and error process no matter it was based upon physical laws or empirical knowledge of the structural performance of different shapes and materials.

Ruin of the $7,000,000 poorly designed San Francisco City Hall by 1906 earthquake and fire

To practice seismic design, seismic analysis or seismic evaluation of new and existing civil engineering projects, an engineer should, normally, pass examination on *Seismic Principles* which, e.g. in the State of California, include:

- Seismic Data and Seismic Design Criteria
- Seismic Characteristics of Engineered Systems
- Seismic Forces
- Seismic Analysis Procedures
- Seismic Detailing and Construction Quality Control

San Francisco after the 1906 earthquake and fire

To build up complex structural systems, seismic design utilizes, mostly, the same relatively small number of basic structural elements (to say nothing of vibration control devices) as any non-seismic design project.

Normally, according to building codes, structures are designed to "withstand" the largest earthquake of a certain probability that is likely to occur at their location. This means the loss of life should be minimized by preventing collapse of the buildings.

Seismic design is carried out by understanding the possible failure modes of a structure and providing the structure with appropriate strength, stiffness, ductility, and configuration to ensure those modes cannot occur.

Seismic design requirements

Seismic design requirements depend on the type of the structure, locality of the project and its authorities which stipulate applicable seismic design codes and criteria. For instance, California Department of Transportation's requirements called *The Seismic Design Criteria* (SDC) and aimed at the design of new bridges in California incorporate an innovative seismic performance based approach.

Metsamor, Armenia nuclear power plant was closed after the 1988 destructive earthquake

The most significant feature in the SDC design philosophy is a shift from a *force-based assessment* of seismic demand to a *displacement-based assessment* of demand and capacity. Thus, the newly adopted displacement approach is based on comparing the *elastic displacement* demand to the *inelastic displacement* capacity of the primary structural components while ensuring a minimum level of inelastic capacity at all potential plastic hinge locations.

In addition to the designed structure itself, seismic design requirements may include a *ground stabilization* underneath the structure: sometimes, heavily shaken ground breaks up which leads to collapse of the structure sitting upon it. The following topics should be of primary concerns: liquefaction; dynamic lateral earth pressures on retaining walls; seismic slope stability; earthquake-induced settlement.

Nuclear facilities should not jeopardise their safety in case of earthquakes or other hostile external events. Therefore, their seismic design is based on criteria far more stringent than those applying to non-nuclear facilities.

Failure modes

Failure mode is the manner by which an earthquake induced failure is observed. It, generally, describes the way the failure occurs. Though costly and time consuming, learning from each real earthquake failure remains a routine recipe for advancement in *seismic design* methods. Below, some typical modes of earthquake-generated failures are presented.

Typical damage to unreinforced masonry buildings at earthquakes

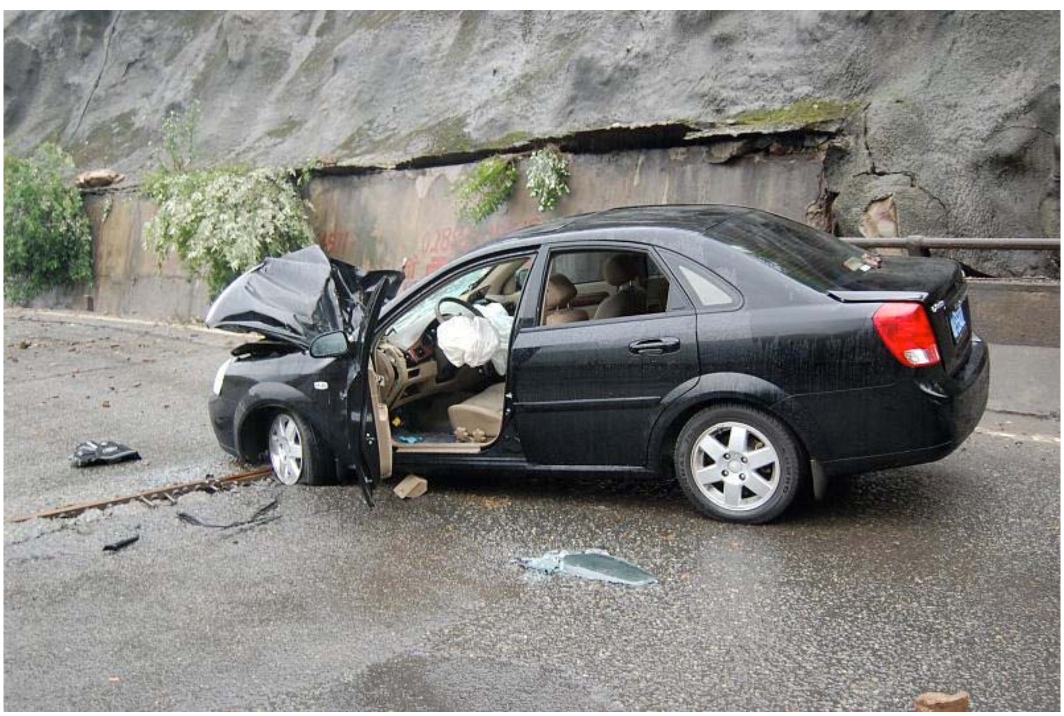
The lack of reinforcement coupled with poor mortar and inadequate roof-to-wall ties can result in substantial damage to a **unreinforced masonry building**. Severely cracked or leaning walls are some of the most common earthquake damage. Also hazardous is the damage that may occur between the walls and roof or floor diaphragms. Separation between the framing and the walls can jeopardize the vertical support of roof and floor systems.

Soft story collapse due to inadequate shear strength at ground level, Loma Prieta earthquake

Soft story effect. Absence of adequate shear walls on the ground level caused damage to this structure. A close examination of the image reveals that the rough board siding, once covered by a brick veneer, has been completely dismantled from the studwall. Only the rigidity of the floor above combined with the support on the two hidden sides by continuous walls, not penetrated with large doors as on the street sides, is preventing full collapse of the structure.

Effects of soil liquefaction during the 1964 Niigata earthquake

Soil liquefaction. In the cases where the soil consists of loose granular deposited materials with the tendency to develop excessive hydrostatic pore water pressure of sufficient magnitude and compact, liquefaction of those loose saturated deposits may result in non-uniform settlements and tilting of structures. This caused major damage to thousands of buildings in Niigata, Japan during the 1964 earthquake.



Car smashed by landslide rock, 2008 Sichuan earthquake

Landslide rock fall. A landslide is a geological phenomenon which includes a wide range of ground movement, including **rock falls**. Typically, the action of gravity is the primary driving force for a landslide to occur though in this case there was another contributing factor which affected the original slope stability: the landslide required an *earthquake trigger* before being released.

Effects of pounding against adjacent building, Loma Prieta

Pounding against adjacent building. This is a photograph of the collapsed five-story tower, St. Joseph's Seminary, Los Altos, California which resulted in one fatality. During Loma Prieta earthquake, the tower pounded against the independently vibrating adjacent building behind. A possibility of pounding depends on both buildings' lateral displacements which should be accurately estimated and accounted for.

Effects of completely shattered joints of concrete frame, Northridge

At Northridge earthquake, the Kaiser Permanente concrete frame office building had joints completely shattered, revealing **inadequate confinement steel**, which resulted in the second story collapse. In the transverse direction, composite end shear walls, consisting of two wythes of brick and a layer of shotcrete that carried the lateral load, peeled apart because of **inadequate through-ties** and failed.

7-story reinforced concrete **buildings on steep slope collapse** due to the following:

- Improper construction site on a foothill.
- Poor detailing of the reinforcement (lack of concrete confinement in the columns and at the beam-column joints, inadequate splice length).
- Seismically weak soft story at the first floor.
- Long cantilevers with heavy dead load.

Shifting from foundation, Whittier

Sliding off foundations effect of a relatively rigid residential building structure during 1987 Whittier Narrows earthquake. The magnitude 5.9 earthquake pounded the Garvey West Apartment building in Monterey Park, California and shifted its superstructure about 10 inches to the east on its foundation.

Earthquake damage in Pichilemu.

If a superstructure is not mounted on a base isolation system, its shifting on the basement should be prevented.

Insufficient shear reinforcement let main rebars to buckle, Northridge

Reinforced concrete column burst at Northridge earthquake due to **insufficient shear reinforcement mode** which allows main reinforcement to buckle outwards. The deck unseated at the hinge and failed in shear. As a result, the La Cienega-Venice underpass section of the 10 Freeway collapsed.

Support-columns and upper deck failure, Loma Prieta earthquake

Loma Prieta earthquake: side view of reinforced concrete **support-columns failure** which trigged **the upper deck collapse onto the lower deck** of the two-level Cypress viaduct of Interstate Highway 880, Oakland, CA.

Failure of retaining wall due to ground movement, Loma Prieta

Retaining wall failure at Loma Prieta earthquake in Santa Cruz Mountains area: prominent northwest-trending extensional cracks up to 12 cm (4.7 in) wide in the concrete spillway to Austrian Dam, the north abutment.

Lateral spreading mode of ground failure, Loma Prieta

Ground shaking triggered soil liquefaction in a subsurface layer of sand, producing differential lateral and vertical movement in an overlying carapace of unliquified sand and silt. This **mode of ground failure**, termed **lateral spreading**, is a principal cause of liquefaction-related earthquake damage.

Beams and pier columns diagonal cracking, 2008 Sichuan earthquake

Severely damaged building of Agriculture Development Bank of China after 2008 Sichuan earthquake: most of the **beams and pier columns are sheared**. Large diagonal cracks in masonry and veneer are due to in-plane loads while abrupt settlement of the right end of the building should be attributed to a landfill which may be hazardous even without any earthquake.

Tsunami strikes Ao Nang,

Twofold tsunami impact: sea waves hydraulic pressure and inundation. Thus, 2004 Indian Ocean earthquake of December 26, 2004, with the epicenter off the west coast of Sumatra, Indonesia, triggered a series of devastating tsunamis, killing more than 225,000 people in eleven countries by **inundating surrounding coastal communities with huge waves** up to 30 meters (100 feet) high.

Earthquake construction

Earthquake construction means implementation of **seismic design** to enable building and non-building structures to live through the anticipated earthquake exposure up to the expectations and in compliance with the applicable building codes.

Construction of Pearl River Tower X-bracing to resist lateral forces of earthquakes and winds

Design and construction are intimately related. To achieve a good workmanship, detailing of the members and their connections should be, possibly, simple. As any construction in general, earthquake construction is a process that consists of the building, retrofitting or assembling of infrastructure given the construction materials available.

The destabilizing action of an earthquake on constructions may be *direct* (seismic motion of the ground) or *indirect* (earthquake-induced landslides, soil liquefaction and waves of tsunami).

A structure might have all the appearances of stability, yet offer nothing but danger when an earthquake occurs. The crucial fact is that, for safety, earthquake-resistant construction techniques are as important as quality control and using correct materials. *Earthquake contractor* should be registered in the state of the project location, bonded and insured.

To minimize possible losses, construction process should be organized with keeping in mind that earthquake may strike any time prior to the end of construction.

Each construction project requires a qualified team of professionals who understand the basic features of seismic performance of different structures as well as construction management.

Adobe structures

Partially collapsed adobe building in Westmorland, California

Around thirty percent of the world's population lives or works in earth-made construction. Adobe type of mud bricks is one of the oldest and most widely used building materials. The use of adobe is very common in some of the world's most hazard-prone regions, traditionally across Latin America, Africa, Indian subcontinent and other parts of Asia, Middle East and Southern Europe.

Adobe buildings are considered very vulnerable at strong quakes. However, multiple ways of seismic strengthening of new and existing adobe buildings are available, see, e.g.

Key factors for the improved seismic performance of adobe construction are:

- Quality of construction.
- Compact, box-type layout.
- Seismic reinforcement.

Limestone and sandstone structures

Base-isolated City and County Building, Salt Lake City, Utah

Limestone is very common in architecture, especially in North America and Europe. Many landmarks across the world, including the pyramids in Egypt, are made of limestone. Many medieval churches and castles in Europe are made of limestone and sandstone masonry. They are the long-lasting materials but their rather heavy weight is not beneficial for adequate seismic performance.

Application of modern technology to seismic retrofitting can enhance the survivability of unreinforced masonry structures. As an example, from 1973 to 1989, the Salt Lake City and County Building in Utah was exhaustively renovated and repaired with an emphasis on preserving historical accuracy in appearance. This was done in concert with a seismic upgrade that placed the weak sandstone structure on base isolation foundation to better protect it from earthquake damage.

Timber frame structures

Half-timbered museum buildings, Denmark, date from 1560

Timber framing dates back thousands of years, and has been used in many parts of the world during various periods such as ancient Japan, Europe and medieval England in localities where timber was in good supply and building stone and the skills to work it were not.

The use of timber framing in buildings provides their complete skeletal framing which offers some structural benefits as the timber frame, if properly engineered, lends itself to better *seismic survivability*.

Light-frame structures

A two-story wooden-frame for a residential building structure

Light-frame structures usually gain seismic resistance from rigid plywood shear walls and wood structural panel diaphragms. Special provisions for seismic load-resisting systems for all engineered wood structures requires consideration of diaphragm ratios, horizontal and vertical diaphragm shears, and connector/fastener values. In addition, collectors, or drag struts, to distribute shear along a diaphragm length are required.

Reinforced masonry structures

Reinforced hollow masonry wall

A construction system where steel reinforcement is embedded in the mortar joints of masonry or placed in holes and after filled with concrete or grout is called **reinforced masonry**.

Devastating 1933 Long Beach earthquake revealed that masonry construction should be improved immediately. Then, the California State Code made the reinforced masonry mandatory.

There are various practices and techniques to achieve reinforced masonry. The most common type is the reinforced hollow unit masonry. The effectiveness of both vertical and horizontal reinforcement strongly depends on the type and quality of the masonry, i.e. masonry units and mortar.

To achieve a ductile behavior of masonry, it is necessary that the shear strength of the wall is greater than the tensile strength of reinforcement to ensure a kind of bending failure.

Reinforced concrete structures

Stressed Ribbon pedestrian bridge over the Rogue River, Grants Pass, Oregon

Reinforced concrete is concrete in which steel reinforcement bars (rebars) or fibers have been incorporated to strengthen a material that would otherwise be brittle. It can be used to produce beams, columns, floors or bridges.

Prestressed concrete is a kind of reinforced concrete used for overcoming concrete's natural weakness in tension. It can be applied to beams, floors or bridges with a longer span than is practical with ordinary reinforced concrete. Prestressing tendons (generally of high tensile steel cable or rods) are used to provide a clamping load which produces a compressive stress that offsets the tensile stress that the concrete compression member would, otherwise, experience due to a bending load.

To prevent catastrophic collapse in response earth shaking (in the interest of life safety), a traditional reinforced concrete frame should have ductile joints. Depending upon the methods used and the imposed seismic forces, such buildings may be immediately usable, require extensive repair, or may have to be demolished.

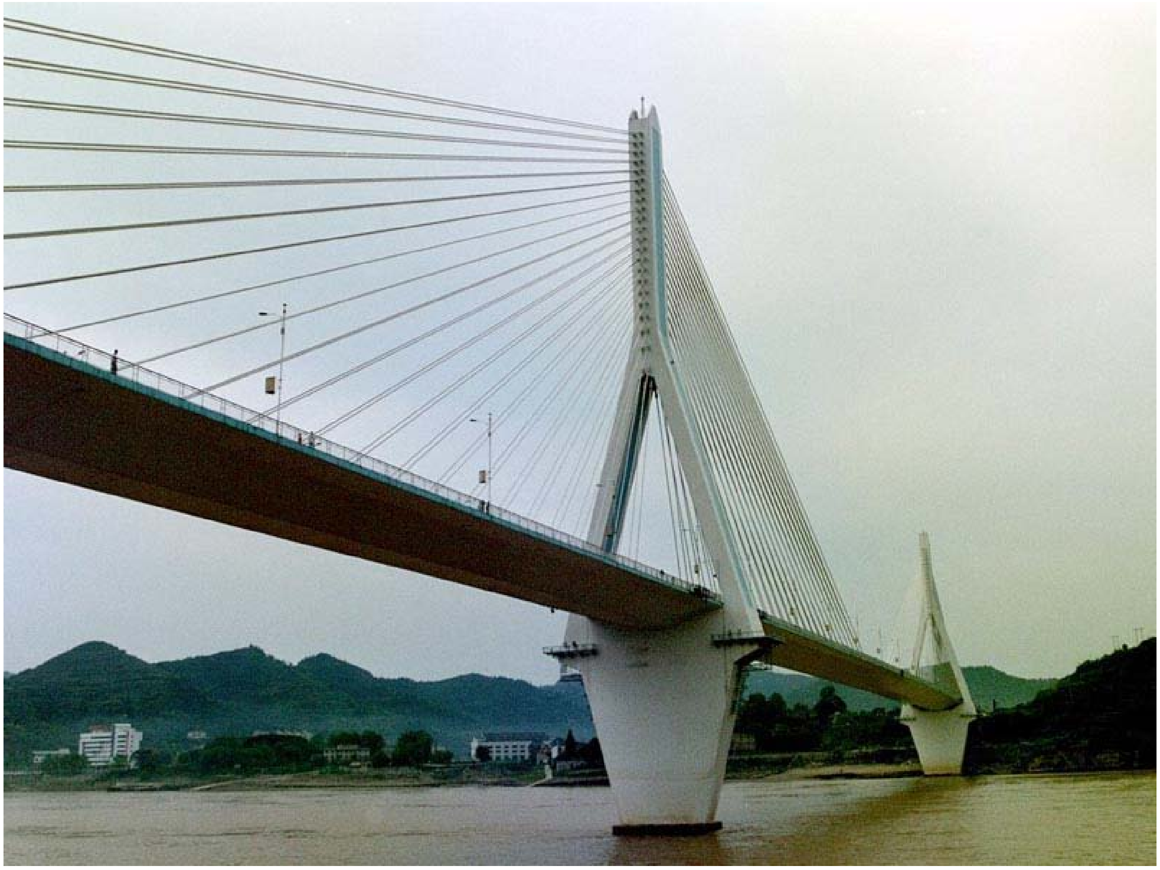
Prestressed structures

Prestressed structure is the one whose overall integrity, stability and security depend, primarily, on a *prestressing*. *Prestressing* means the intentional creation of permanent stresses in a structure for the purpose of improving its performance under various service conditions.

Naturally pre-compressed exterior wall of Colosseum, Rome

There are the following basic types of prestressing:

- Pre-compression (mostly, with the own weight of a structure)
- Pretensioning with high-strength embedded tendons
- Post-tensioning with high-strength bonded or unbonded tendons



Prestressed concrete cable-stayed bridge over Yangtze river

Today, the concept of prestressed structure is widely engaged in design of buildings, underground structures, TV towers, power stations, floating storage and offshore facilities, nuclear reactor vessels, and numerous kinds of bridge systems.

A beneficial idea of *prestressing* was, apparently, familiar to the ancient Rome architects; look, e.g., at the tall attic wall of Colosseum working as a press for the wall piers beneath.

Steel structures

Collapsed section of the San Francisco – Oakland Bay Bridge in response to Loma Prieta earthquake

Steel structures are considered mostly earthquake resistant but their resistance should never be taken for granted. A great number of welded steel moment frame buildings, which looked earthquake-proof, surprisingly experienced brittle behavior and were hazardously damaged in the 1994 Northridge earthquake. After that, the Federal Emergency Management Agency (FEMA) initiated development of repair techniques and new design approaches to minimize damage to steel moment frame buildings in future earthquakes.

For structural steel seismic design based on Load and Resistance Factor Design (LRFD) approach, it is very important to assess ability of a structure to develop and maintain its bearing resistance in the inelastic range. A measure of this ability is ductility, which may be observed in a *material itself*, in a *structural element*, or to a *whole structure*.

As a consequence of Northridge earthquake experience, all pre-qualified connection details and design methods contained in the building codes of that time have been rescinded. The new provisions stipulated that new designs be substantiated by testing or by use of test-verified calculations.

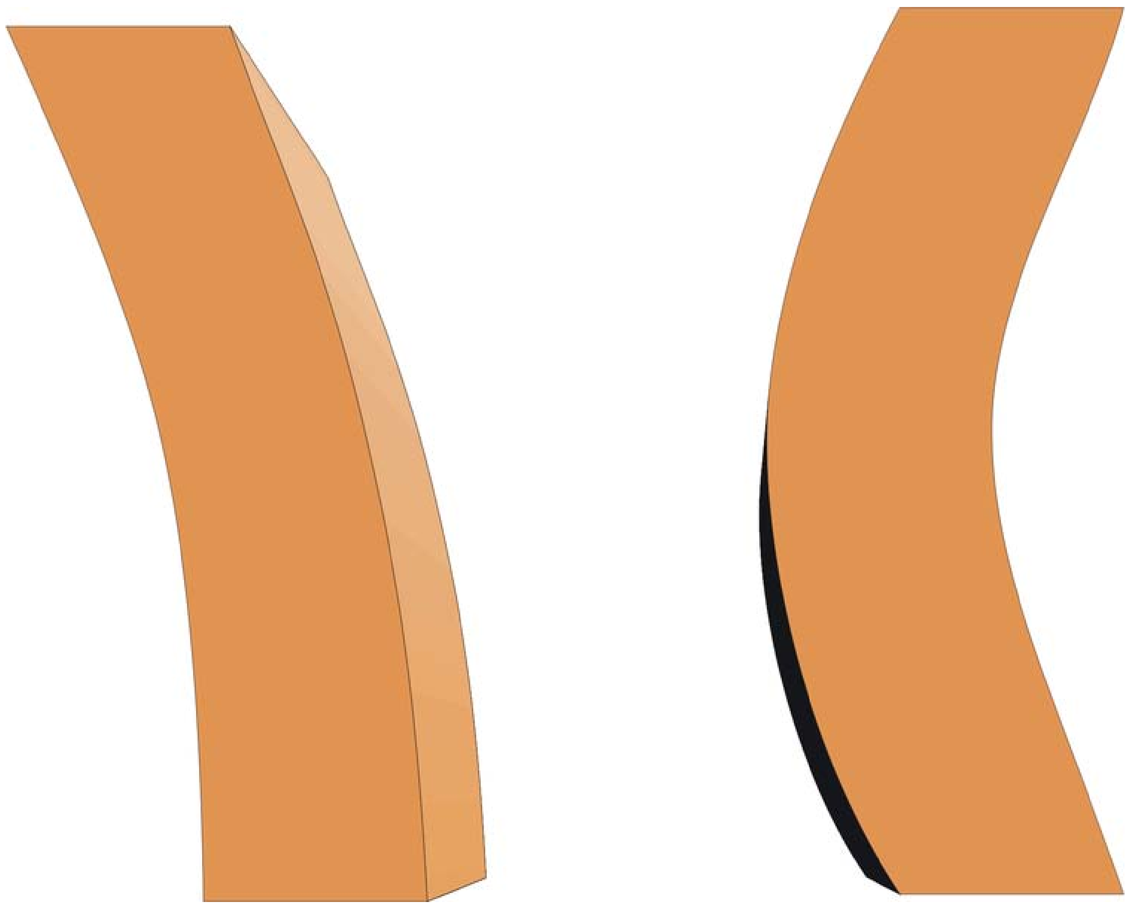
Prediction of earthquake losses

Earthquake loss estimation is usually defined as a *Damage Ratio* (**DR**) which is a ratio of the earthquake damage repair cost to the total value of a building. *Probable Maximum Loss* (**PML**) is a common term used for earthquake loss estimation, but it lacks a precise definition. In 1999, ASTM E2026 'Standard Guide for the Estimation of Building Damageability in Earthquakes' was produced in order to standardize the nomenclature for seismic loss estimation, as well as establish guidelines as to the review process and qualifications of the reviewer.

Earthquake loss estimations are also referred to as *Seismic Risk Assessments*. The risk assessment process generally involves determining the probability of various ground motions coupled with the vulnerability or damage of the building under those ground motions. The results are defined as a percent of building replacement value.

Chapter 2

Seismic Analysis



First and second modes of building seismic response

Seismic Analysis is a subset of structural analysis and is the calculation of the response of a building (or nonbuilding) structure to earthquakes. It is part of the process of structural design, earthquake engineering or structural assessment and retrofit in regions where earthquakes are prevalent.

As seen in the figure, a building has the potential to 'wave' back and forth during an earthquake (or even a severe wind storm). This is called the 'fundamental mode', and is the lowest frequency of building response. Most buildings, however, have higher modes of response, which are uniquely activated during earthquakes. The figure just shows the second mode, but there are higher 'shimmy' (abnormal vibration) modes. Nevertheless, the first and second modes tend to cause the most damage in most cases.

The earliest provisions for seismic resistance were the requirement to design for a lateral force equal to a proportion of the building weight (applied at each floor level). This approach was adopted in the appendix of the 1927 Uniform Building Code (UBC), which was used on the west coast of the USA. It later became clear that the dynamic properties of the structure affected the loads generated during an earthquake. In the Los Angeles County Building Code of 1943 a provision to vary the load based on the number of floor levels was adopted (based on research carried out at Caltech in collaboration with Stanford University and the U.S. Coast and Geodetic Survey, which started in 1937). The concept of "response spectra" was developed in the 1930s, but it wasn't until 1952 that a joint committee of the San Francisco Section of the ASCE and the Structural Engineers Association of Northern California (SEAONC) proposed using the building period (the inverse of the frequency) to determine lateral forces.

The University of California, Berkeley was an early base for computer-based seismic analysis of structures, led by Professor Ray Clough (who coined the term finite element). Students included Ed Wilson, who went on to write the program SAP in 1970, an early "Finite Element Analysis" program.

Earthquake engineering has developed a lot since the early days, and some of the more complex designs now use special earthquake protective elements either just in the foundation (base isolation) or distributed throughout the structure. Analyzing these types of structures requires specialized explicit finite element computer code, which divides time into very small slices and models the actual physics, much like common video games often have "physics engines". Very large and complex buildings can be modeled in this way (such as the Osaka Internation Convention Center).

Structural analysis methods can be divided into the following five categories.

Equivalent Static Analysis

This approach defines a series of forces acting on a building to represent the effect of earthquake ground motion, typically defined by a seismic design response spectrum. It assumes that the building responds in its fundamental mode. For this to be true, the building must be low-rise and must not twist significantly when the ground moves. The response is read from a design response spectrum, given the natural frequency of the building (either calculated or defined by the building code). The applicability of this method is extended in many building codes by applying factors to account for higher buildings with some higher modes, and for low levels of twisting. To account for effects due to "yielding" of the structure, many codes apply modification factors that reduce the design forces (e.g. force reduction factors).

Response Spectrum Analysis

This approach permits the multiple modes of response of a building to be taken into account (in the frequency domain). This is required in many building codes for all except for very simple or very complex structures. The response of a structure can be defined as a combination of many special shapes (modes) that in a vibrating string correspond to the "harmonics". Computer analysis can be used to determine these modes for a structure. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass, and they are then combined to provide an estimate of the total response of the structure. Combination methods include the following:

- absolute - peak values are added together
- square root of the sum of the squares (SRSS)
- complete quadratic combination (CQC) - a method that is an improvement on SRSS for closely spaced modes

The result of a response spectrum analysis using the response spectrum from a ground motion is typically different from that which would be calculated directly from a linear dynamic analysis using that ground motion directly, since phase information is lost in the process of generating the response spectrum.

In cases where structures are either too irregular, too tall or of significance to a community in disaster response, the response spectrum approach is no longer appropriate, and more complex analysis is often required, such as non-linear static or dynamic analysis.

A sample response spectrum analysis.

Linear Dynamic Analysis

Static procedures are appropriate when higher mode effects are not significant. This is generally true for short, regular buildings. Therefore, for tall buildings, buildings with torsional irregularities, or non-orthogonal systems, a dynamic procedure is required. In the linear dynamic procedure, the building is modelled as a multi-degree-of-freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix.

The seismic input is modelled using either modal spectral analysis or time history analysis but in both cases, the corresponding internal forces and displacements are determined using linear elastic analysis. The advantage of these linear dynamic procedures with respect to linear static procedures is that higher modes can be considered. However, they are based on linear elastic response and hence the applicability decreases with increasing nonlinear behaviour, which is approximated by global force reduction factors.

In linear dynamic analysis, the response of the structure to ground motion is calculated in the time domain, and all phase information is therefore maintained. Only linear properties are assumed. The analytical method can use modal decomposition as a means of reducing the degrees of freedom in the analysis.

Non-linear Static Analysis

In general, linear procedures are applicable when the structure is expected to remain nearly elastic for the level of ground motion or when the design results in nearly uniform distribution of nonlinear response throughout the structure. As the performance objective of the structure implies greater inelastic demands, the uncertainty with linear procedures increases to a point that requires a high level of conservatism in demand assumptions and acceptability criteria to avoid unintended performance. Therefore, procedures incorporating inelastic analysis can reduce the uncertainty and conservatism.

This approach is also known as "pushover" analysis. A pattern of forces is applied to a structural model that includes non-linear properties (such as steel yield), and the total force is plotted against a reference displacement to define a capacity curve. This can then be combined with a demand curve (typically in the form of an acceleration-displacement response spectrum (ADRS)). This essentially reduces the problem to a single degree of freedom system.

Nonlinear static procedures use equivalent SDOF structural models and represent seismic ground motion with response spectra. Story drifts and component actions are related subsequently to the global demand parameter by the pushover or capacity curves that are the basis of the non-linear static procedures.

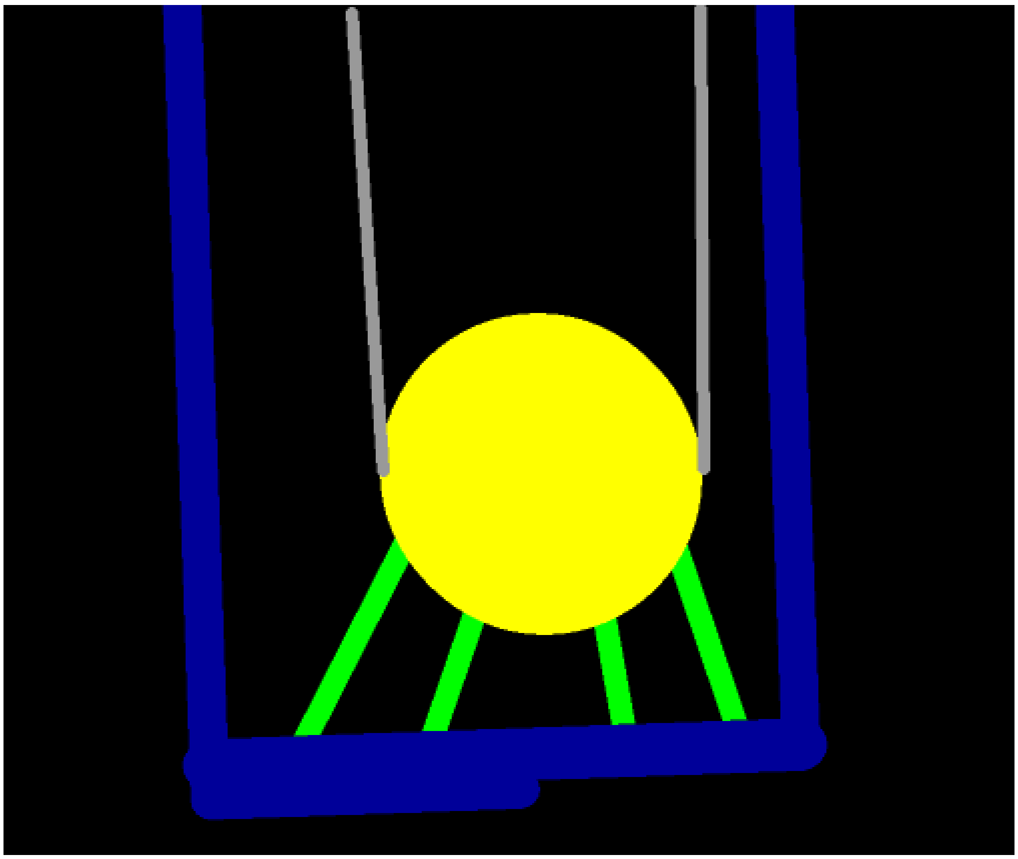
Non-linear Dynamic Analysis

Nonlinear dynamic analysis utilizes the combination of ground motion records with a detailed structural model, therefore is capable of producing results with relatively low uncertainty. In nonlinear dynamic analyses, the detailed structural model subjected to a ground-motion record produces estimates of component deformations for each degree of freedom in the model and the modal responses are combined using schemes such as the square-root-sum-of-squares.

In non-linear dynamic analysis, the non-linear properties of the structure are considered as part of a time domain analysis. This approach is the most rigorous, and is required by some building codes for buildings of unusual configuration or of special importance. However, the calculated response can be very sensitive to the characteristics of the individual ground motion used as seismic input; therefore, several analyses are required using different ground motion records.

Chapter 3

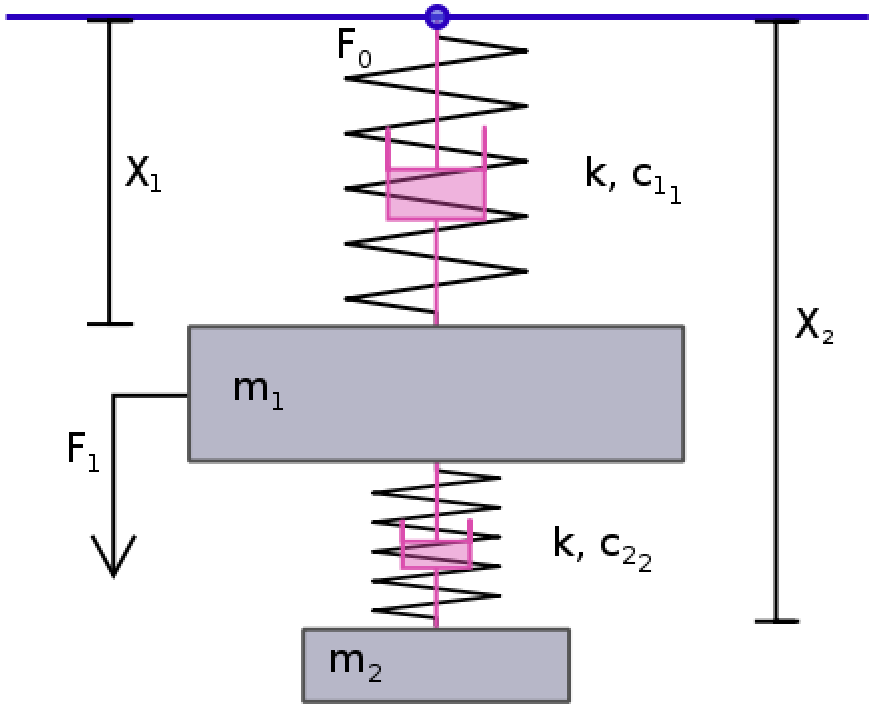
Tuned Mass Damper



An image showing the movement of a skyscraper versus the mass damper. The green indicates the hydraulic cylinders used to damp the motion of the skyscraper.

A **tuned mass damper**, also known as an **active mass damper** (**AMD**) or **harmonic absorber**, is a device mounted in structures to reduce the amplitude of mechanical vibrations. Their application can prevent discomfort, damage, or outright structural failure. They are frequently used in power transmission, automobiles, and buildings.

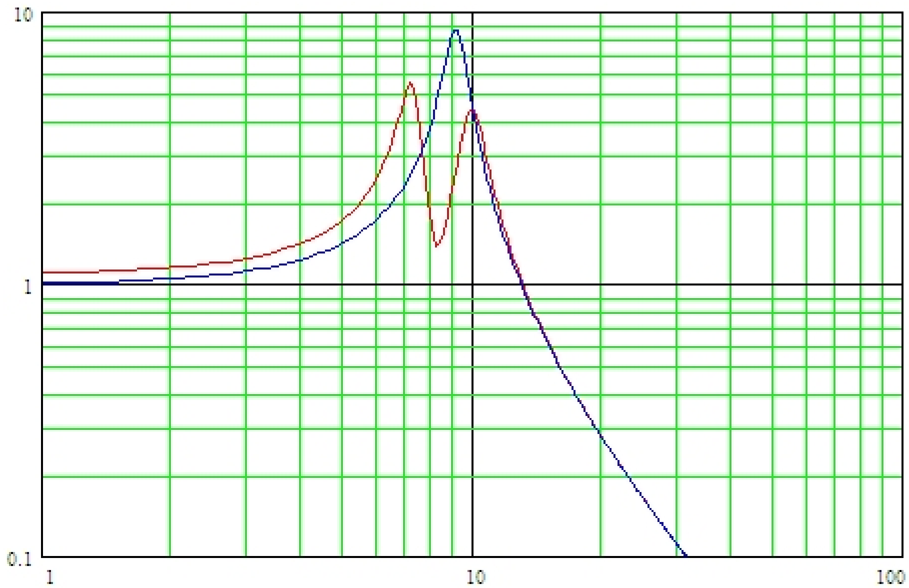
Principle



A schematic of a simple spring–mass–damper system used to demonstrate the tuned mass damper system.

Tuned mass dampers stabilize against violent motion caused by harmonic vibration. A tuned damper reduces the vibration of a system with a comparatively lightweight component so that the worst-case vibrations are less intense. Roughly speaking practical systems are tuned to either move the main mode away from a troubling excitation frequency, or to add damping to a resonance that is difficult or expensive to damp directly. An example of the latter is a crankshaft torsional damper. Mass dampers are frequently implemented with a frictional or hydraulic component that turns mechanical kinetic energy into heat, like an automotive shock absorber. An electrical analogue is a LCR circuit.

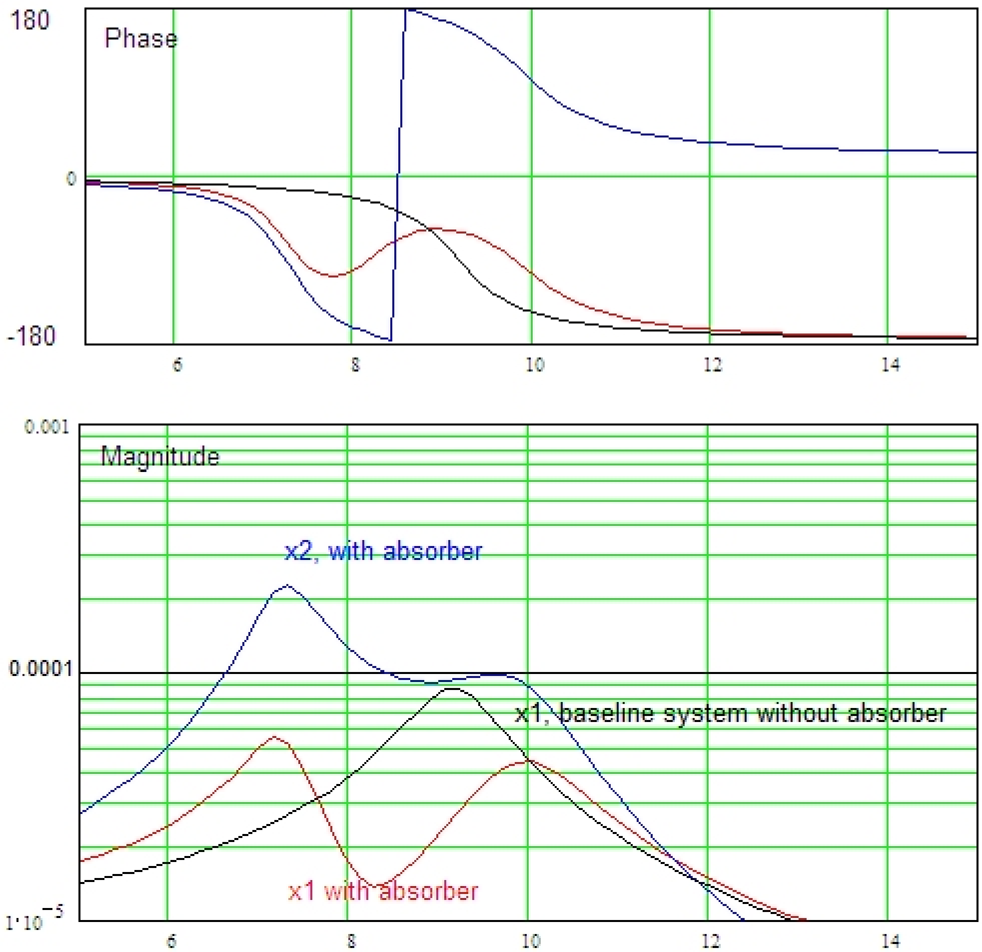
Given a motor with mass m_1 attached via motor mounts to the ground, the motor vibrates as it operates and the soft motor mounts act as a parallel spring and damper, k_1 and c_1. The force on the motor mounts is F_0. In order to reduce the maximum force on the motor mounts as the motor operates over a range of speeds, a smaller mass, m_2, is connected to m_1 by a spring and a damper, k_2 and c_2. F_1 is the effective force on the motor due to its operation.



Response of the system excited by one unit of force, with (red) and without (blue) the 10% tuned mass. The peak response is reduced from 9 units down to 5.5 units. While the maximum response force is reduced, there are some operating frequencies for which the response force is increased.

The graph shows the effect of a tuned mass damper on a simple spring–mass–damper system, excited by vibrations with an amplitude of one unit of force applied to the main mass, m_1. An important measure of performance is the ratio of the force on the motor mounts to the force vibrating the motor, F_0 / F_1. This assumes that the system is linear, so if the force on the motor were to double, so would the force on the motor mounts. The blue line represents the baseline system, with a maximum response of 9 units of force at around 9 units of frequency. The red line shows the effect of adding a tuned mass of 10% of the baseline mass. It has a maximum response of 5.5, at a frequency of 7. As a side effect, it also has a second normal mode and will vibrate somewhat more than the baseline system at frequencies below about 6 and above about 10.

The heights of the two peaks can be adjusted by changing the stiffness of the spring in the tuned mass damper. Changing the damping also changes the height of the peaks, in a complex fashion. The split between the two peaks can be changed by altering the mass of the damper (m_2).



A Bode plot of displacements in the system with (red) and without (blue) the 10% tuned mass.

The Bode plot is more complex, showing the phase and magnitude of the motion of each mass, for the two cases, relative to F1.

In the plots at right, the black line shows the baseline response ($m_2 = 0$). Now considering $m_2 = m_1 / 10$, the blue line shows the motion of the damping mass and the red line shows the motion of the primary mass. The amplitude plot shows that at low frequencies, the damping mass resonates much more than the primary mass. The phase plot shows that at low frequencies, the two masses are in phase. As the frequency increases m_2 moves out of phase with m_1 until at around 9.5 Hz it is 180° out of phase with m_1, maximizing the damping effect by maximizing the amplitude of $x_2 - x_1$, this maximizes the energy dissipated into c_2 and simultaneously pulls on the primary mass in the same direction as the motor mounts.

Mass dampers in automobiles

Motorsport

The tuned mass damper was introduced as part of the suspension system by Renault, on its 2005 F1 car (the R25), at the 2005 Brazilian Grand Prix. It was deemed to be legal at first, and it was in use up to the 2006 German Grand Prix.

At Hockenheim, the mass damper was deemed illegal by the FIA, since the mass wasn't rigidly attached to the chassis and, due to the influence it had on the pitch attitude of the car, which in turn significantly affected the gap under the car and hence the ground effects of the car, to be a movable aerodynamic device and hence as a consequence, to be illegally influencing the performance of the aerodynamics.

The Stewards of the meeting deemed it legal, but the FIA appealed against that decision. Two weeks later, the FIA International Court of Appeal deemed the mass damper illegal.

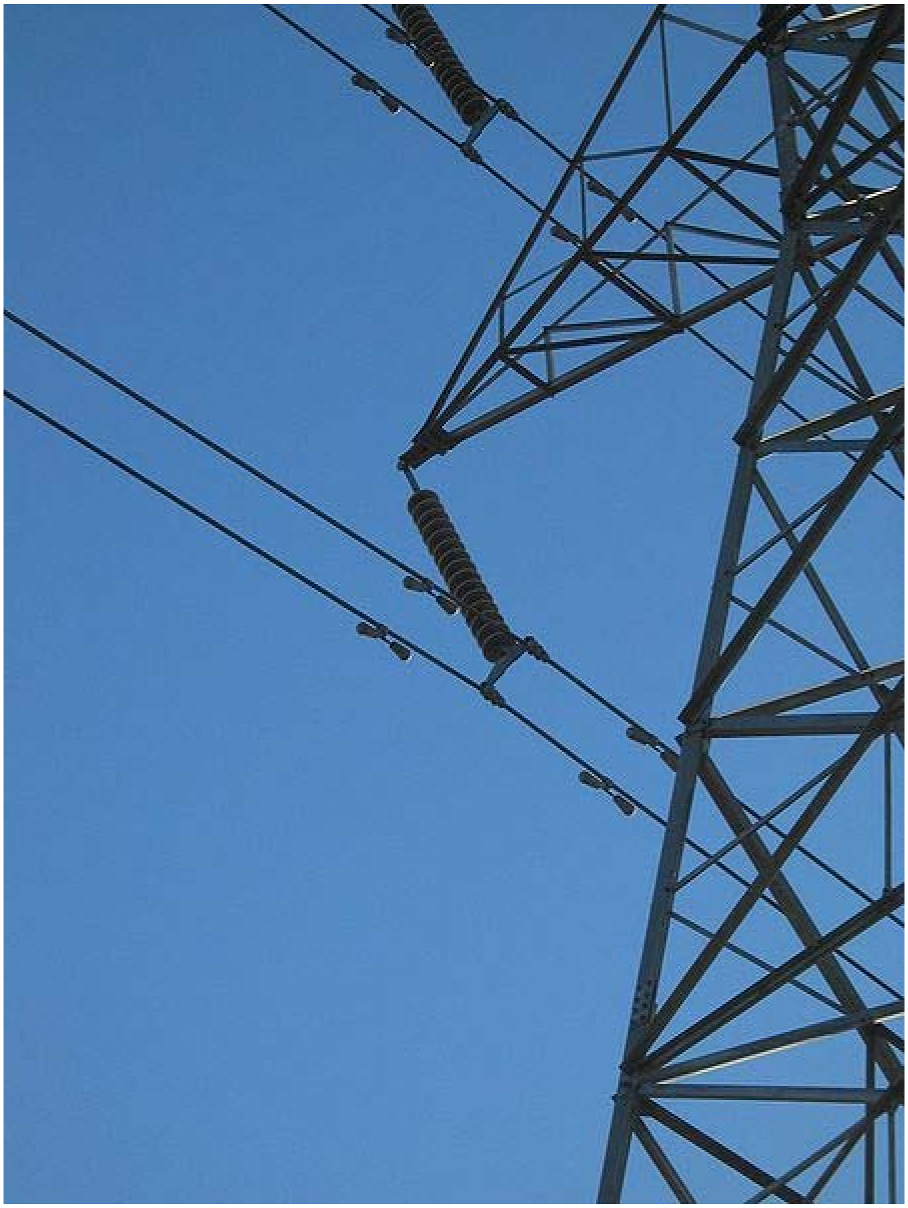
Production cars

Tuned mass dampers are widely used in production cars, typically on the crankshaft pulley to control torsional vibration and bending modes of the crankshaft, on the driveline for gearwhine, and other noises. They are also used on the exhaust, on the body and on the suspension. Almost all cars will have one mass damper, some may have 10 or more.

Mass dampers in spacecraft

One proposal to reduce vibration on NASA's Ares solid fuel booster is to use 16 tuned mass dampers as part of a design strategy to reduce peak loads from 6g to 0.25 g, the TMDs being responsible for the reduction from 1 g to 0.25 g, the rest being done by conventional vibration isolators between the upper stages and the booster.

Dampers in power transmission lines



Stockbridge dampers on power lines.

High-tension lines often have small barbell-shaped Stockbridge dampers hanging from the wires to reduce the high-frequency, low-amplitude oscillation termed flutter.

Dampers in buildings and related structures

Tuned mass damper atop Taipei 101.

Typically, the dampers are huge concrete blocks or steel bodies mounted in skyscrapers or other structures, and moved in opposition to the resonance frequency oscillations of the structure by means of springs, fluid or pendulums.

Sources of vibration and resonance

Unwanted vibration may be caused by environmental forces acting on a structure, such as wind or earthquake, or by a seemingly innocuous vibration source causing resonance that may be destructive, unpleasant or simply inconvenient.

Earthquakes

The seismic waves caused by an earthquake will make buildings sway and oscillate in various ways depending on the frequency and direction of ground motion, and the height and construction of the building. Seismic activity can cause excessive oscillations of the building which may lead to structural failure. To enhance the building's seismic performance, a proper building design is performed engaging various seismic vibration control technologies.

Mechanical human sources

Dampers on the Millennium Bridge in London. The white disk is not part of the damper.

Masses of people walking up and down stairs at once, or great numbers of people stomping in unison, can cause serious problems in large structures like stadiums if those structures lack damping measures. Vibration caused by heavy industrial machinery, generators and diesel engines can also pose problems to structural integrity, especially if mounted on a steel structure or floor. Large ocean going vessels may employ tuned mass dampers to isolate the vessel from its engine vibration.

Wind

The force of wind against tall buildings can cause the top of skyscrapers to move more than a metre. This motion can be in the form of swaying or twisting, and can cause the upper floors of such buildings to move. Certain angles of wind and aerodynamic properties of a building can accentuate the movement and cause motion sickness in people.

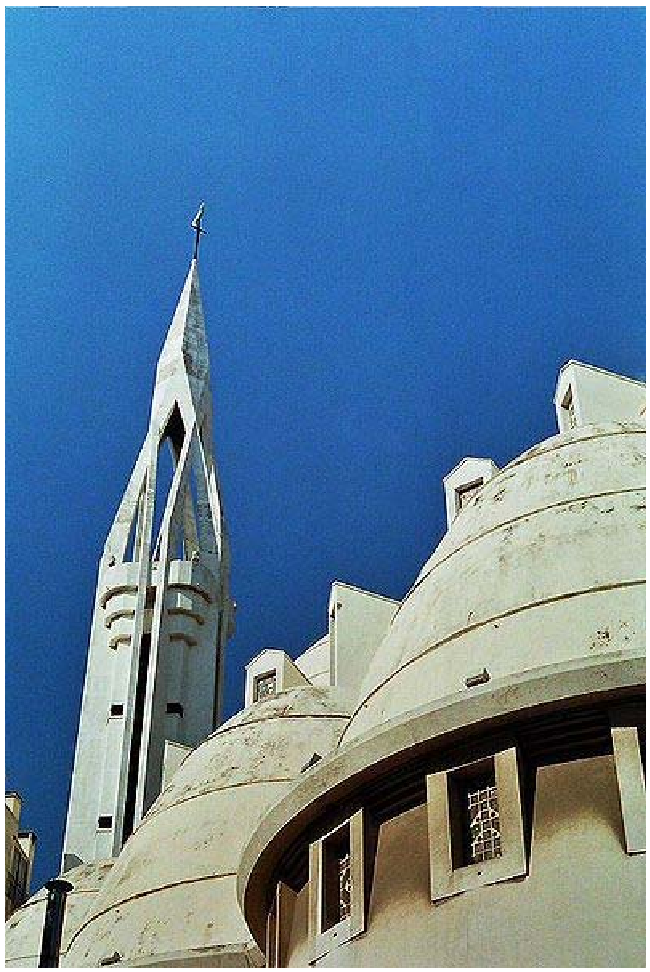
Examples of buildings and structures with tuned mass dampers

- Bally’s to Bellagio, Bally’s to Caesars Palace, and Treasure Island to The Venetian Pedestrian Bridges in Las Vegas
- Berlin Television Tower (Fernsehturm) — tuned mass damper located in the spire.

- Bloomberg Tower/731 Lexington in New York
- Burj al-Arab in Dubai — 11 tuned mass dampers.
- Citigroup Center in New York City — Designed by William LeMessurier and completed in 1977, it was one of the first skyscrapers to use a tuned mass damper to reduce sway. Uses a concrete version.
- Comcast Center in Philadelphia, PA — Contains the largest Tuned Liquid Column Damper (TLCD) in the world at 1,300 tons.
- Dublin Spire in Dublin, Ireland — This narrow slender structure was designed with a tuned mass damper to ensure aerodynamic stability during a wind storm.
- Grand Canyon Skywalk
- John Hancock Tower in Boston — A tuned mass damper was added to it after it was built.
- London Millennium Bridge — 'The Wobbly Bridge'
- One Rincon Hill South Tower — First building in California to have a liquid tuned mass damper
- One Wall Centre in Vancouver — It employs tuned liquid column dampers, at the time of its installation, a unique form of tuned mass damper.
- Park Tower in Chicago — The first building in the United States to be designed with a tuned mass damper from the outset.
- Random House Tower Uses two liquid filled dampers in New York City
- Sakhalin-I — An offshore drilling platform
- Shanghai World Financial Center in Shanghai, China
- Taipei 101 skyscraper — Contains one of the world's largest tuned mass dampers, at 730 tons.
- Theme Building at Los Angeles International Airport
- Trump World Tower in New York
- Yokohama Landmark Tower

Chapter 4

Reinforced Concrete



Reinforced concrete at Sainte Jeanne d'Arc Church (Nice, France): architect Jacques Dror, 1926–1933

Reinforced concrete is concrete in which reinforcement bars ("rebars"), reinforcement grids, plates or fibers have been incorporated to strengthen the concrete in tension. The term Ferro Concrete refers only to concrete that is reinforced with iron or steel. Other materials used to reinforce concrete can be organic and inorganic fibres as well as composites in different forms. Concrete is strong in compression, but weak in tension, thus adding reinforcement increases the strength in tension. In addition, the failure strain of concrete in tension is so low that the reinforcement has to hold the cracked sections together. For a strong, ductile and durable construction the reinforcement shall have the following properties:

- High strength
- High tensile strain
- Good bond to the concrete
- Thermal compatibility
- Durability in the concrete environment

In most cases reinforced concrete uses steel rebars that have been inserted to add strength.

Use in construction

Rebars of Sagrada Familia's roof in construction (2009)

Concrete is reinforced to give it extra tensile strength; without reinforcement, many concrete buildings would not have been possible.

Reinforced concrete can encompass many types of structures and components, including slabs, walls, beams, columns, foundations, frames and more.

Reinforced concrete can be classified as precast or cast in-situ concrete.

Much of the focus on reinforcing concrete is placed on floor systems. Designing and implementing the most efficient floor system is key to creating optimal building structures. Small changes in the design of a floor system can have significant impact on material costs, construction schedule, ultimate strength, operating costs, occupancy levels and end use of a building.

Behavior of reinforced concrete

Materials

Concrete is a mixture of cement (usually Portland cement) and stone aggregate. When mixed with a small amount of water, the cement hydrates form microscopic opaque crystal lattices encapsulating and locking the aggregate into a rigid structure. Typical concrete mixes have high resistance to compressive stresses (about 4,000 psi (28 MPa)); however, any appreciable tension (*e.g.,* due to bending) will break the microscopic rigid lattice, resulting in cracking and separation of the concrete. For this reason, typical non-reinforced concrete must be well supported to prevent the development of tension.

If a material with high strength in tension, such as steel, is placed in concrete, then the composite material, **reinforced concrete**, resists not only compression but also bending and other direct tensile actions. A reinforced concrete section where the concrete resists the compression and steel resists the tension can be made into almost any shape and size for the construction industry.

Key characteristics

Three physical characteristics give reinforced concrete its special properties.

First, the coefficient of thermal expansion of concrete is similar to that of steel, eliminating large internal stresses due to differences in thermal expansion or contraction.

Second, when the cement paste within the concrete hardens this conforms to the surface details of the steel, permitting any stress to be transmitted efficiently between the different materials. Usually steel bars are roughened or corrugated to further improve the bond or cohesion between the concrete and steel.

Third, the alkaline chemical environment provided by the alkali reserve (KOH, NaOH) and the portlandite (calcium hydroxide) contained in the hardened cement paste causes a passivating film to form on the surface of the steel, making it much more resistant to corrosion than it would be in neutral or acidic conditions. When the cement paste exposed to the air and meteoric water reacts with the atmospheric CO_2, portlandite and the Calcium Silicate Hydrate (CSH) of the hardened cement paste become progressively carbonated and the high pH gradually decreases from 13.5 – 12.5 to 8.5, the pH of water in equilibrium with calcite (calcium carbonate) and the steel is no longer passivated.

As a rule of thumb, only to give an idea on orders of magnitude, steel is protected at pH above ~11 but starts to corrode below ~10 depending on steel characteristics and local physico-chemical conditions when concrete becomes carbonated. Carbonation of concrete along with chloride ingress are amongst the chief reasons for the failure of reinforcement bars in concrete.

The relative cross-sectional area of steel required for typical reinforced concrete is usually quite small and varies from 1% for most beams and slabs to 6% for some columns. Reinforcing bars are normally round in cross-section and vary in diameter. Reinforced concrete structures sometimes have provisions such as ventilated hollow cores to control their moisture & humidity.

Distribution of concrete (in spite of reinforcement) strength characteristics along the cross-section of vertical reinforced concrete elements is inhomogeneous article "Concrete Inhomogeneity of Vertical Cast-In-Situ Elements In Frame-Type Buildings".

Anti-corrosion measures

In wet and cold climates, reinforced concrete for roads, bridges, parking structures and other structures that may be exposed to deicing salt may benefit from use of epoxy-coated, hot dip galvanised or stainless steel rebar, although good design and a well-chosen cement mix may provide sufficient protection for many applications. Epoxy coated rebar can easily be identified by the light green colour of its epoxy coating. Hot dip galvanized rebar may be bright or dull grey depending on length of exposure, and stainless rebar exhibits a typical white metallic sheen that is readily distinguishable from carbon steel reinforcing bar. Reference ASTM standard specifications **A767** Standard Specification for Hot Dip Galvanised Reinforcing Bars, **A775** Standard Specification for Epoxy Coated Steel Reinforcing Bars and **A955** Standard Specification for Deformed and Plain Stainless Bars for Concrete Reinforcement.

Another, cheaper way or protecting rebars is coating them with zinc phosphate. Zinc phosphate slowly reacts with calcium cations and the hydroxyl anions present in the cement pore water and forms a stable hydroxyapatite layer.

Penetrating sealants typically must be applied some time after curing. Sealants include paint, plastic foams, films and aluminum foil, felts or fabric mats sealed with tar, and layers of bentonite clay, sometimes used to seal roadbeds.

Corrosion inhibitors, such as calcium nitrite [$Ca(NO_2)_2$], can also be added to the water mix before pouring concrete. Generally, 1–2 wt. % of [$Ca(NO_2)_2$] with respect to cement weight is needed to prevent corrosion of the rebars. The nitrite anion is a mild oxidizer that oxidizes the soluble and mobile ferrous ions (Fe^{2+}) present at the surface of the corroding steel and causes it to precipitate as an insoluble ferric hydroxide ($Fe(OH)_3$). This causes the passivation of steel at the anodic oxidation sites. Nitrite is a much more active corrosion inhibitor than nitrate, a less powerful oxidizer of the divalent iron.

Reinforcement and terminology of Beams

A beam bends under bending moment, resulting in a small curvature. At the outer face (**tensile face**) of the curvature the concrete experiences tensile stress, while at the inner face (**compressive face**) it experiences compressive stress.

A **singly-reinforced** beam is one in which the concrete element is only reinforced near the tensile face and the reinforcement, called tension steel, is designed to resist the tension.

A **doubly-reinforced** beam is one in which besides the tensile reinforcement the concrete element is also reinforced near the compressive face to help the concrete resist compression. The latter reinforcement is called compression steel. When the compression zone of a concrete is inadequate to resist the compressive Moment(positive moment), extra reinforcement has to be provided if the architect limits the dimensions of the section.

An **under-reinforced** beam is one in which the tension capacity of the tensile reinforcement is **smaller** than the combined compression capacity of the concrete and the compression steel (under-reinforced at tensile face). When the reinforced concrete element is subject to increasing bending moment, the tension steel yields while the concrete does not reach its ultimate failure condition. As the tension steel yields and stretches, an "under-reinforced" concrete also yields in a ductile manner, exhibiting a large deformation and warning before its ultimate failure. In this case the yield stress of the steel governs the design.

An **over-reinforced** beam is one in which the tension capacity of the tension steel is **greater** than the combined compression capacity of the concrete and the compression steel (over-reinforced at tensile face). So the "over-reinforced concrete" beam fails by crushing of the compressive-zone concrete and before the tension zone steel yields, which does not provide any warning before failure as the failure is instantaneous.

A **balanced-reinforced** beam is one in which both the compressive and tensile zones reach yielding at the same imposed load on the beam, and the concrete will crush and the tensile steel will yield at the same time. This design criterios is however as risky as over-reinforced concrete, because failure is sudden as the concrete crushes at the same time of the tensile steel yields, which gives a very little warning of distress in tension failure.

Steel-reinforced concrete moment-carrying elements should normally be designed to be under-reinforced so that users of the structure will receive warning of impending collapse.

The **characteristic strength** is the strength of a material where less than 5% of the specimen shows lower strength.

The **design strength** or **nominal strength** is the strength of a material, including a material-safety factor. The value of the safety factor generally ranges from 0.75 to 0.85 in Allowable Stress Design.

The **ultimate limit state** is the theoretical failure point with a certain probability. It is stated under factored loads and factored resistances.

Prestressed Concrete

Prestressed concrete is a technique that greatly increases loadbearing strengh of concrete beams. The reinforcing steel in the bottom part of the beam, which will be subjected to tensile forces when in service, is placed in tension prior to the concrete being poured around it. Once the concrete has hardened, the tension on the reinforcing steel is released, placing a built-in compressive force on the concrete. When loads are applied, the reinforcing steel takes on more stress and the compressive force in the concrete is reduced, but does not become a tensile force. Since the concrete is always under compression, it is less subject to cracking and failure.

Common failure modes of steel reinforced concrete

Reinforced concrete can fail due to inadequate strength, leading to mechanical failure, or due to a reduction in its durability. Corrosion and freeze/thaw cycles may damage poorly designed or constructed reinforced concrete. When rebar corrodes, the oxidation products (rust) expand and tends to flake, cracking the concrete and unbonding the rebar from the concrete. Typical mechanisms leading to durability problems are discussed below.

Mechanical failure

Cracking of the concrete section can not be prevented; however, the size of and location of the cracks can be limited and controlled by reinforcement, placement of control joints, the curing methodology and the mix design of the concrete. Cracking defects can allow moisture to penetrate and corrode the reinforcement. This is a serviceability failure in limit state design. Cracking is normally the result of an inadequate quantity of rebar, or rebar spaced at too great a distance. The concrete then cracks either under excess loading, or due to internal effects such as **early thermal shrinkage** when it cures.

Ultimate failure leading to collapse can be caused by crushing of the concrete, when compressive stresses exceed its strength; by yielding or failure of the rebar, when bending or shear stresses exceed the strength of the reinforcement; or by bond failure between the concrete and the rebar.

Carbonation

Rebar for foundations and walls of sewage pump station.

Carbonation, or neutralisation, is a chemical reaction between carbon dioxide in the air with calcium hydroxide and hydrated calcium silicate in the concrete. The water in the pores of Portland cement concrete is normally alkaline with a pH in the range of 12.5 to 13.5. This highly alkaline environment is one in which the embedded steel is passivated and is protected from corrosion. According to the Pourbaix diagram for iron, the metal is passive when the pH is above 9.5. The carbon dioxide in the air reacts with the alkali in the cement and makes the pore water more acidic, thus lowering the pH. Carbon dioxide will start to carbonate the cement in the concrete from the moment the object is made. This **carbonation** process will start at the surface, then slowly move deeper and deeper into the concrete. The rate of carbonation is dependent on the relative humidity of the concrete - a 50% relative humidity being optimal. If the object is cracked, the carbon dioxide in the air will be better able to penetrate into the concrete. When designing a concrete structure, it is normal to state the concrete cover for the rebar (the depth within the object that the rebar will be). The minimum concrete cover is normally regulated by design or building codes. If the reinforcement is too close to the surface, early failure due to corrosion may occur. The concrete cover depth can be measured with a cover meter. However, carbonated concrete only becomes a durability problem when there is also sufficient moisture and oxygen to cause electro-potential corrosion of the reinforcing steel.

One method of testing a structure for carbonation is to drill a fresh hole in the surface and then treat the cut surface with phenolphthalein indicator solution. This solution will turn [pink] when in contact with alkaline concrete, making it possible to see the depth of carbonation. An existing hole is no good because the exposed surface will already be carbonated.

Chlorides

The Paulins Kill Viaduct, Hainesburg, New Jersey, is 115 feet (35 m) tall and 1,100 feet (335 m) long, and was heralded as the largest reinforced concrete structure in the world when it was completed in 1910 as part of the Lackawanna Cut-Off rail line project. The Lackawanna Railroad was a pioneer in the use of reinforced concrete.

Chlorides, including sodium chloride, can promote the corrosion of embedded steel rebar if present in sufficienty high concentration. Chloride anions induce both localized corrosion (pitting corrosion) and generalized corrosion of steel reinforcements. For this reason, one should only use fresh raw water or potable water for mixing concrete, insure that the coarse and fine aggregates do not contain chlorides, and not use admixtures that contain chlorides.

It was once common for calcium chloride to be used as an admixture to promote rapid set-up of the concrete. It was also mistakenly believed that it would prevent freezing. However, this practice has fallen into disfavor once the deleterious effects of chlorides became known. It should be avoided when ever possible.

The use of de-icing salts on roadways, used to reduce the freezing point of water, is probably one of the primary causes of premature failure of reinforced or prestressed concrete bridge decks, roadways, and parking garages. The use of epoxy-coated reinforcing bars and the application of cathodic protection has mitigated this problem to some extent. Also FRP rebars are known to be less susceptible to chlorides. Properly designed concrete mixtures that have been allowed to cure properly are effectively impervious to the effects of deicers. (One common problem today is that contractors allow concrete to "dry" (out) for two to three days by before it cures and thus ultimately develops less than 10% of its design strength).

Another important source of chloride ions is from sea water. Sea water contains by weight approximately 3.5 wt.% salts. These salts include sodium chloride, magnesium sulfate, calcium sulfate, and bicarbonates. In water these salts dissociate in free ions (Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) and migrate with the water into the capillaries of the concrete. Chloride ions are particularly aggressive for the corrosion of the carbon steel reinforcement bars and make up about 50% of these ions.

Alkali Silica Reaction

Characteristic crack pattern associated to the alkali-silica reaction affecting a concrete step barrier on an US motorway (photograph courtesy of the Federal Highway Administration, US Department of Transportation).

The **Alkali-Silica Reaction** (ASR) is a reaction which occurs over time in concrete between the highly alkaline cement paste and reactive non-crystalline (amorphous) silica, which is found in many common aggregates.

The ASR reaction is the same as the Pozzolanic reaction which is a simple acid-base reaction between calcium hydroxide, also known as Portlandite, or ($Ca(OH)_2$), and silicic acid (H_4SiO_4, or $Si(OH)_4$). For the sake of simplicity, this reaction can be schematically represented as following:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

This reaction causes the expansion of the altered aggregate by the formation of a swelling gel of Calcium Silicate Hydrate (CSH). This gel increases in volume with water and exerts an expansive pressure inside the material, causing spalling and loss of strength of the concrete, finally leading to its failure.

So, ASR can cause serious expansion and cracking in concrete, resulting in critical structural problems that can even force the demolition of a particular structure.

The mechanism of ASR causing the deterioration of concrete can be described in four steps as follows:

1. The alkaline solution attacks the siliceous aggregate to convert it to viscous alkali silicate gel.
2. Consumption of alkali by the reaction induces the dissolution of Ca^{2+} ions into the cement pore water. Calcium ions then react with the gel to convert it to hard calcium silicate hydrate.
3. The penetrated alkaline solution converts the remaining siliceous minerals into bulky alkali silicate gel. The resultant expansive pressure is stored in the aggregate.
4. The accumulated pressure cracks the aggregate and the surrounding cement paste when the pressure exceeds the tolerance of the aggregate.

Mitigation

ASR can be mitigated in concrete by three complementary approaches:

1. **Limit the alkali metal content of the cement**. Many standards impose limits on the "Equivalent Na_2O" content of cement.
2. **Limit the reactive silica content of the aggregate**. Certain volcanic rocks are particularly susceptible to ASR because they contain volcanic glass (obsidian) and should not be used as aggregate. The use of calcium carbonate aggregates is sometimes envisaged as an ultimate solution to avoid any problem. However, while it may be considered as a necessary condition, it is not a sufficient one. In principle, limestone ($CaCO_3$) is not expected to contain high level of silica, but it actually depends on its purity. Indeed, some siliceous limestones (a.o., Kieselkalk found in Switzerland) may be cemented by amorphous or poorly crystalline silica and can be very sensitive to the ASR reaction as observed with some siliceous limestones exploited in quarries in the area of Tournai in Belgium. So, the use of limestone as aggregate is not a guarantee against ASR in itself. The silica content of the limestone and its reactivity must remain below a threshold value that has to be carefully experimentally assessed by the aggregate producer.
3. **Add very fine siliceous materials** to neutralize the excessive alkalinity of cement with silicic acid by voluntary provoking a controlled pozzolanic reaction at the early stage of the cement setting. Convenient pozzolanic materials to add to the mix may be, *e.g.*, pozzolan, silica fume, fly ashs, or metakaolin. These react preferentially with the cement alkalis without formation of an expansive pressure, because siliceous minerals in fine particles convert to alkali silicate and then to calcium silicate without formation of semipermeable reaction rims.

In other words, as it is sometimes possible *to fight the fire by the fire*, it is also feasible to combat the ASR reaction by itself. A prompt reaction initiated at the early stage of concrete hardening on very fine silica particles will help to suppress a slow and delayed reaction with large siliceous aggregates on the long term. Following the same principle, the fabrication of low-pH cement also implies the addition of finely-divided pozzolanic materials rich in silicic acid to the concrete mix to decrease its alkalinity.

ASR test

The concrete microbar test was proposed by Grattan-Bellew *et al.* (2003) as a universal accelerated test for alkali-aggregate reaction.

Conversion of high alumina cement

Resistant to weak acids and especially sulfates, this cement cures quickly and reaches very high durability and strength. It was greatly used after World War II for making precast concrete objects. However, it can lose strength with heat or time (conversion), especially when not properly cured. With the collapse of three roofs made of prestressed concrete beams using high alumina cement, this cement was banned in the UK in 1976. Subsequent inquiries into the matter showed that the beams were improperly manufactured, but the ban remained.

Sulfates

Sulfates (SO_4) in the soil or in groundwater, in sufficient concentration, can react with the Portland cement in concrete causing the formation of expansive products, e.g. ettringite or thaumasite, which can lead to early failure of the structure. The most typical attack of this type is on concrete slabs and foundation walls at grade where the sulfate ion, via alternate wetting and drying, can increase in concentration. As the concentration increases, the attack on the Portland cement can begin. For buried structures such as pipe, this type of attack is much rarer especially in the Eastern half of the United States. The sulfate ion concentration increases much slower in the soil mass and is especially dependent upon the initial amount of sulfates in the native soil. The chemical analysis of soil borings should be done during the design phase of any project involving concrete in contact with the native soil to check for the presence of sulfates. If the concentrations are found to be aggressive, various protective coatings can be used. Also, in the US ASTM C150 Type 5 Portland cement can be used in the mix. This type of cement is designed to be particularly resistant to a sulfate attack.

Steel plate construction

In steel plate construction, stringers join parallel steel plates. The plate assemblies are fabricated off site, and welded together on-site to form steel walls connected by stringers. The walls become the form into which concrete is poured. Steel plate construction speeds reinforced concrete construction by cutting out the time consuming on-site manual steps of tying rebar and building forms. The method has excellent strength because the steel is on the outside, where tensile forces are often greatest.

Fiber reinforced concrete

Fibre reinforced concrete (FRC) is concrete containing fibrous material which increases its structural integrity. It contains short discrete fibres that are uniformly distributed and randomly oriented. Fibres include steel fibres, glass fibres, synthetic fibres and natural fibres. Within these different fibres that character of fibre reinforced concrete changes with varying concretes, fibre materials, geometries, distribution, orientation and densities.

Historical perspective

The concept of using fibres as reinforcement is not new. Fibres have been used as reinforcement since ancient times. Historically, horsehair was used in mortar and straw in mud bricks. In the early 1900s, asbestos fibres were used in concrete, and in the 1950s the concept of composite materials came into being and fibre reinforced concrete was one of the topics of interest. There was a need to find a replacement for the asbestos used in concrete and other building materials once the health risks associated with the substance were discovered. By the 1960s, steel, glass (GFRC), and synthetic fibres such as polypropylene fibres were used in concrete, and research into new fibre reinforced concretes continues today.

Effect of fibres in concrete

Fibers are usually used in concrete to control cracking due to both plastic shrinkage and drying shrinkage. They also reduce the permeability of concrete and thus reduce bleeding of water. Some types of fibres produce greater impact, abrasion and shatter resistance in concrete. Generally fibres do not increase the flexural strength of concrete, and so cannot replace moment resisting or structural steel reinforcement. Indeed, some fibres actually reduce the strength of concrete. The amount of fibres added to a concrete mix is expressed as a percentage of the total volume of the composite (concrete and fibres), termed volume fraction (V_f). V_f typically ranges from 0.1 to 3%. Aspect ratio (l/d) is calculated by dividing fibre length (l) by its diameter (d). Fibres with a non-circular cross section use an equivalent diameter for the calculation of aspect ratio. If the modulus of elasticity of the fibre is higher than the matrix (concrete or mortar binder), they help to carry the load by increasing the tensile strength of the material. Increase in the aspect ratio of the fibre usually segments the flexural strength and toughness of the matrix. However, fibres which are too long tend to "ball" in the mix and create workability problems.

Some recent research indicated that using fibres in concrete has limited effect on the impact resistance of the materials[1 & 2]. This finding is very important since traditionally, people think that ductility increases when concrete is reinforced with fibres. The results also indicated out that the use of micro fibres offers better impact resistance compared with the longer fibres.

The High Speed 1 tunnel linings incorporated concrete containing 1 kg/m³ of polypropylene fibres, of diameter 18 & 32 μm, giving the benefits noted below.

Benefits

Polypropylene fibres can:

- Improve mix cohesion, improving pumpability over long distances
- Improve freeze-thaw resistance
- Improve resistance to explosive spalling in case of a severe fire
- Improve impact resistance
- Increase resistance to plastic shrinkage during curing

Steel fibres can:

- Improve structural strength
- Reduce steel reinforcement requirements
- Improve ductility
- Reduce crack widths
- Improve impact & abrasion resistance
- Improve freeze-thaw resistance

Blends of both steel and polymeric fibres are often used in construction projects in order to combine the benefits of both products; structural improvements provided by steel fibres and the resistance to explosive spalling and plastic shrinkage improvements provided by polymeric fibres.

In certain specific circumstances, steel fibre can entirely replace traditional steel reinforcement bar in reinforced concrete. This is most common in industrial flooring but also in some other precasting applications. Typically, these are corroborated with laboratory testing to confirm performance requirements are met. Care should be taken to ensure that local design code requirements are also met which may impose minimum quantities of steel reinforcement within the concrete. There are increasing numbers of tunnelling projects using precast lining segments reinforced only with steel fibres.

Useful standards:

- EN 14889-1:2006 Fibres for Concrete. Steel Fibres. Definitions, specifications & conformity
- EN 14889-2:2006 Fibres for Concrete. Polymer Fibres. Definitions, specifications & conformity
- EN 14845-1:2007 Test methods for fibres in concrete
- ASTM A820-06 Standard Specification for fibres in Fibre Reinforced Concrete
- ASTM C1018-07 Standard test methods for flexural toughness & first crack strength

Some developments in fibre reinforced concrete

The newly developed FRC named Engineered Cementitious Composite (ECC) is 500 times more resistant to cracking and 40 percent lighter than traditional concrete. ECC can sustain strain-hardening up to several percent strain, resulting in a material ductility of at least two orders of magnitude higher when compared to normal concrete or standard fibre reinforced concrete. ECC also has unique cracking behaviour. When loaded to beyond the elastic range, ECC maintains crack width to below 100 μm, even when deformed to several percent tensile strains.

Recent studies performed on a high-performance fibre-reinforced concrete in a bridge deck found that adding fibres provided residual strength and controlled cracking. There were fewer and narrower cracks in the FRC even though the FRC had more shrinkage than the control. Residual strength is directly proportional to the fiber content.

A new kind of natural fibre reinforced concrete (NFRC) made of cellulose fibres processed from genetically modified slash pine trees is giving good results. The cellulose fibres are longer and greater in diameter than other timber sources. Some studies were performed using waste carpet fibers in concrete as an environmentally friendly use of recycled carpet waste. A carpet typically consists of two layers of backing (usually fabric from polypropylene tape yarns), joined by $CaCO_3$ filled styrene-butadiene latex rubber (SBR), and face fibres (majority being nylon 6 and nylon 66 textured yarns). Such nylon and polypropylene fibres can be used for concrete reinforcement.

Non-steel reinforcement

Some construction cannot tolerate the use of steel. For example, MRI machines have huge magnets, and require nonmagnetic buildings. Another example are toll-booths that read radio tags, and need reinforced concrete that is transparent to radio.

In some instances, the lifetime of the concrete structure is more important than its initial costs. Since corrosion is the main cause of failure of reinforced concrete, a corrosion-proof reinforcement can extend a structure's life substantially.

For these purposes some structures have been constructed using fiber-reinforced plastic (FRP) rebar, grids or fibers. The "plastic" reinforcement can be as strong as steel. Because it resists corrosion, it does not need a protective concrete cover of 30 to 50 mm or more as steel reinforcement does. This means that FRP-reinforced structures can be lighter, have longer lifetime and for some applications be price-competitive to steel-reinforced concrete.

Although FRP and concrete are brittle materials, in general structures with internal FRP reinforcement show a great elastic deformability which is comparable to the plastic deformability (ductility) of steel reinforced structures.

Existing structures can be reinforced with external reinforcement as carbon fibre. In this case especially the strength can be increased.

One drawback to use of FRP reinforcement is the limited fire resistance. Structures employing FRP have to ensure the strength and the anchoring of the forces at elevated temperatures. This can be achieved by defining a suitable concrete cover or protective cladding.

Another problem is the effectiveness of shear reinforcement. Stirrups made by (before hardening) bended FRP show generally reduced strength through waved fibres. Exposed to strain and slip the transition between the straight and bent part is loaded by the superposition of a strong bending stress, shear and the longitudinal stress. Alternative shear reinforcement elements can solve this problem.

However, the addition of short monofilament polypropylene fibers to the concrete during mixing may have the beneficial effect of reducing spalling during a fire. In a severe fire, such as the Channel Tunnel fire of 1996, conventionally reinforced concrete can suffer severe spalling leading to failure. This is in part due to the pore water remaining within the concrete boiling explosively; the steam pressure then causes the spalling. The action of fibers within the concrete is due to their ability to melt, forming pathways out through the concrete, allowing the steam pressure to dissipate.

Chapter 5

Earthquake Engineering Structures

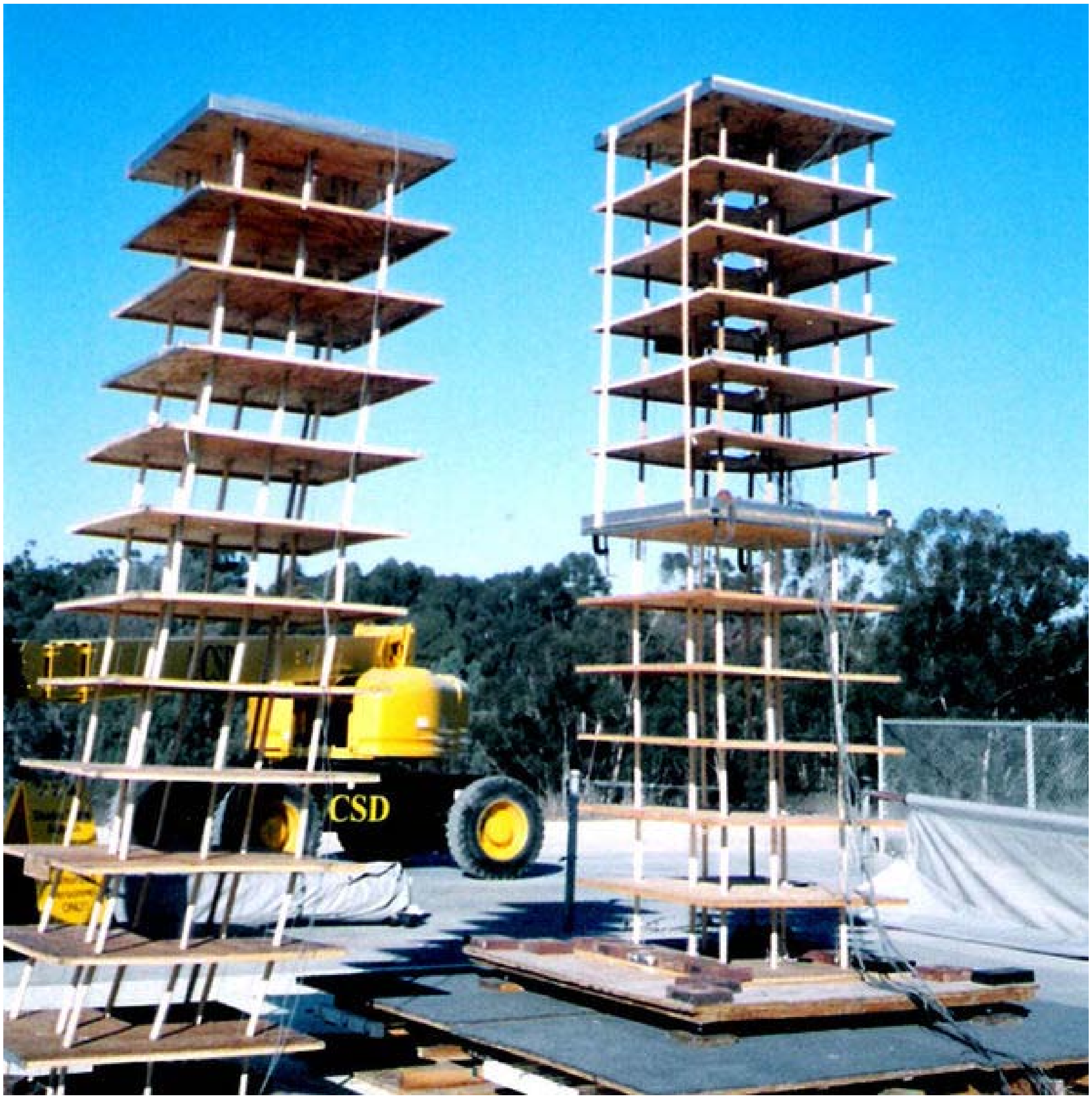
Earthquake-proof and massive pyramid El Castillo, Chichen Itza.

Earthquake engineering structures are designed and constructed to withstand various types of hazardous earthquake exposures at the sites of their particular location.

Earthquake engineering is treating its subject structures like defensive fortifications in military engineering but for the warfare on earthquakes. Both earthquake and military general design principles are similar: be ready to slow down or mitigate the advance of a possible attacker.

According to building codes, earthquake engineering structures are meant to "withstand" the largest earthquake of a certain probability that is likely to occur at their location. This means the loss of life should be minimized by preventing collapse of the buildings.

Ancient architects believed that devastating earthquakes were a result of wrath of gods and therefore, could not be resisted by humans. Nowadays, the people's attitude has changed dramatically though the term "earthquake engineering structure" does not necessarily mean it is an extremely strong or expensive one like the El Castillo pyramid at Chichen Itza.



Shake-table of testing base-isolated (right) and regular (left) building model

Currently, the most powerful and cost-effective tool of earthquake engineering is base isolation which makes use of passive structural vibration control technologies, used for example in the Cathedral of Our Lady of the Angels.

Trends and projects

Some of the new state-of-the-art trends and/or projects in the field of earthquake engineering structures are presented below.

Proofed low cost earthquake building material

A leading German composite construction company developed an proofed earthquake-safe supported core material RexWall - based on internal beam/frame constructions. The same principle allows construction of hurricane-safe houses.

Earthquake shelter

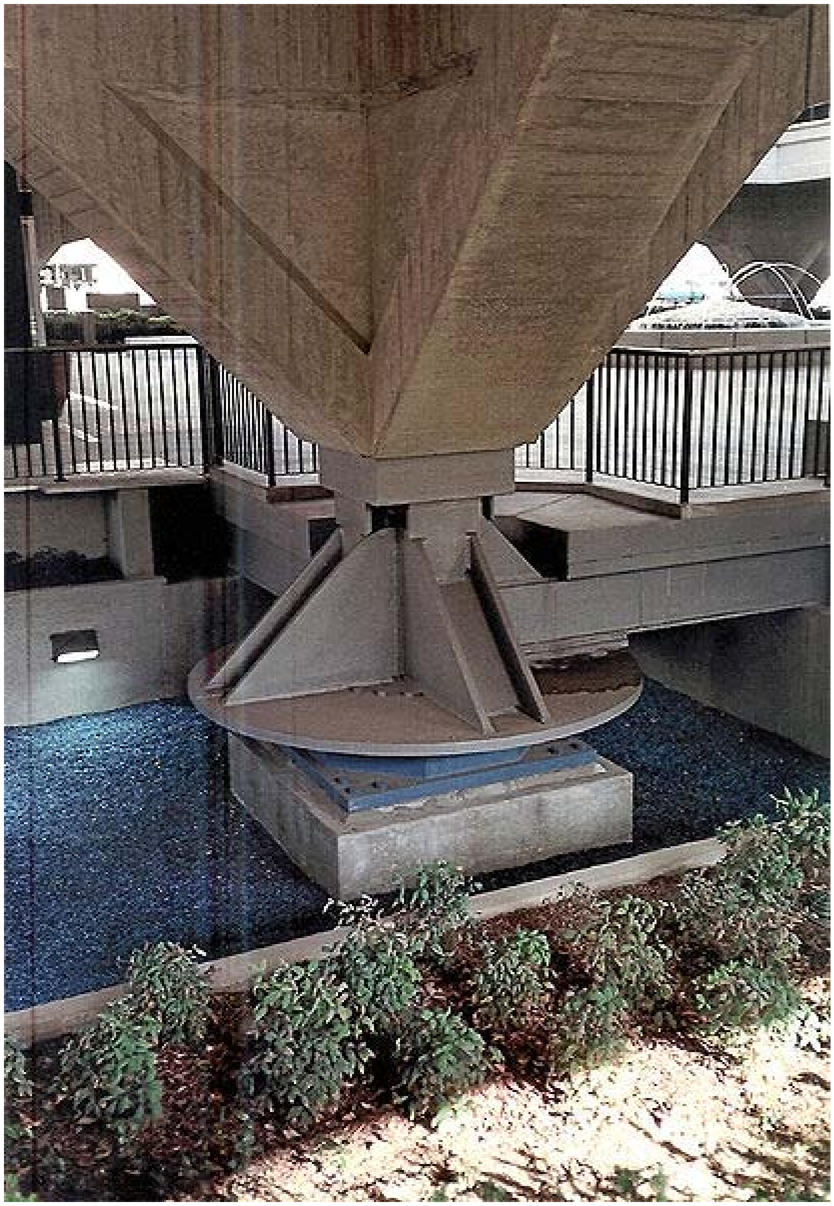
One Japanese construction company has developed a six-foot cubical shelter, presented as an alternative to earthquake-proofing an entire building.

Concurrent shake-table testing

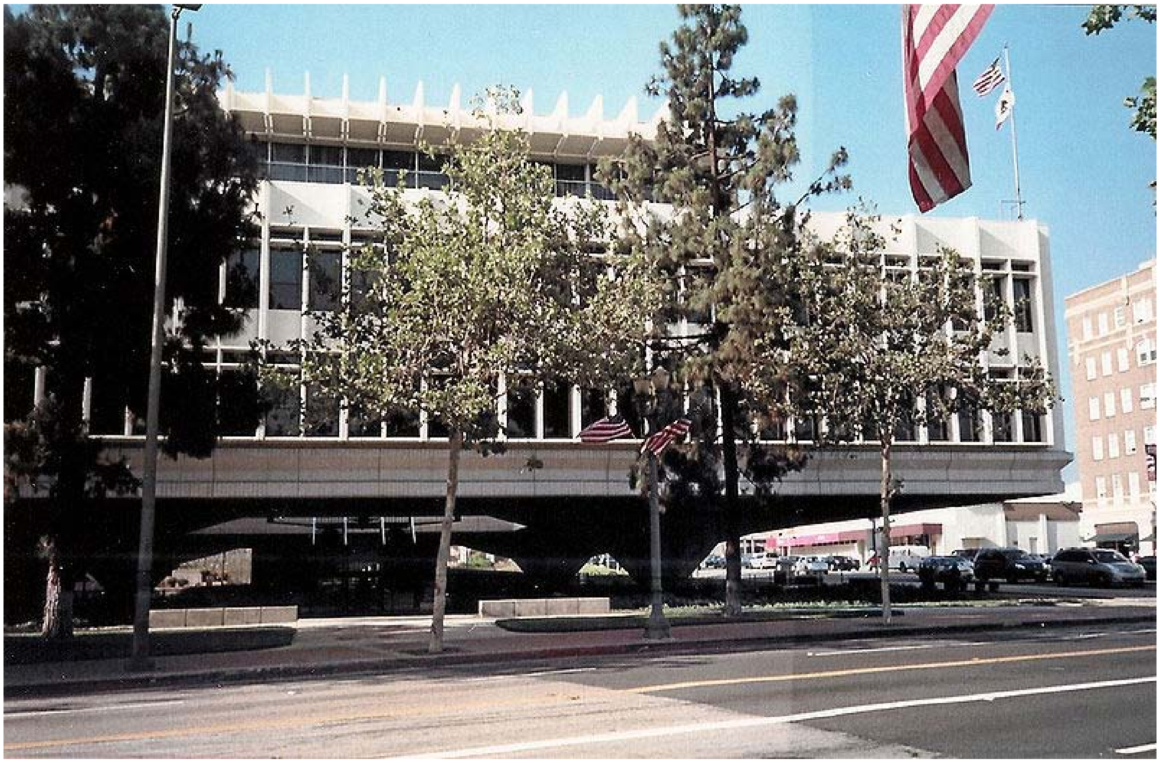
Concurrent shake-table testing of two or more building models is a vivid, persuasive and effective way to validate earthquake engineering solutions experimentally.

Thus, two wooden houses built before adoption of the 1981 Japanese Building Code were moved to E-Defense for testing. The left house was reinforced to enhance its seismic resistance, while the other one was not. These two models were set on E-Defense platform and tested simultaneously.

Combined vibration control solution



Close-up of abutment of seismically retrofitted Municipal Services Building in Glendale, CA



Seismically retrofitted Municipal Services Building in Glendale, CA

Designed by architect Merrill W. Baird of Glendale, working in collaboration with A. C. Martin Architects of Los Angeles, the Municipal Services Building at 633 East Broadway, Glendale was completed in 1966. Prominently sited at the corner of East Broadway and Glendale Avenue, this civic building serves as a heraldic element of Glendale's civic center.

In October 2004 Architectural Resources Group (ARG) was contracted by Nabih Youssef & Associates, Structural Engineers, to provide services regarding a historic resource assessment of the building due to a proposed seismic retrofit.

In 2008, the Municipal Services Building of the City of Glendale, California was seismically retrofitted using an innovative combined vibration control solution: the existing elevated building foundation of the building was put on high damping rubber bearings.

Steel plate shear walls system

Coupled steel plate shear walls, Seattle, Copyright Mehdi Kharrazi

The Ritz-Carlton/JW Marriott hotel building engaging the advanced steel plate shear walls system, LA

A steel plate shear wall (SPSW) consists of steel infill plates bounded by a column-beam system. When such infill plates occupy each level within a framed bay of a structure, they constitute a SPSW system.

SPSW behavior is analogous to a vertical plate girder cantilevered from its base. Similar to plate girders, the SPSW system optimizes component performance by taking advantage of the post-buckling behavior of the steel infill panels.

The Ritz-Carlton/JW Marriott hotel building, a part of the LA Live development in Los Angeles, California, is the first building in Los Angeles that uses an advanced steel plate shear wall system to resist the lateral loads of strong earthquakes and winds.

Kashiwazaki-Kariwa Nuclear Power Plant is partially upgraded

Kashiwazaki-Kariwa Nuclear Power Plant: aerial view, Japan

The Kashiwazaki-Kariwa Nuclear Power Plant, the largest nuclear generating station in the world by net electrical power rating, happened to be near the epicenter of the strongest M_w 6.6 July 2007 Chūetsu offshore earthquake. This initiated an extended shutdown for structural inspection which indicated that a greater earthquake-proofing was needed before operation could be resumed.

On May 9, 2009, one unit (Unit 7) was restarted, after the seismic upgrades. The test run had to continue for 50 days. The plant had been completely shut down for almost 22 months following the earthquake.

Seismic Test of Seven-Story Building

Seven-story wooden structure prior to shake-table testing, Japan

A destructive earthquake struck a lone, wooden condominium in Japan. The experiment was webcast live on July 14, 2009 to yield insight on how to make wooden structures stronger and better able to withstand major earthquakes.

The Miki shake at the Hyogo Earthquake Engineering Research Center is the capstone experiment of the four-year NEESWood project, which receives its primary support from the U.S. National Science Foundation Network for Earthquake Engineering Simulation (NEES) Program.

“NEESWood aims to develop a new seismic design philosophy that will provide the necessary mechanisms to safely increase the height of wood-frame structures in active seismic zones of the United States, as well as mitigate earthquake damage to low-rise wood-frame structures,” said Rosowsky, Department of Civil Engineering at Texas A&M University. This philosophy is based on the application of seismic damping systems for wooden buildings. The systems, which can be installed inside the walls of most wooden buildings, include strong metal frame, bracing and dampers filled with viscous fluid.

Chapter 6

Framing (Construction)

A two-story wooden-frame house under construction—the location of the upper floor platform is readily discerned by the wide joists between the floors, and the upper structure rests on this platform.

Framing, in construction known as **light-frame construction**, is a building technique based around structural members, usually called studs, which provide a stable frame to which interior and exterior wall coverings are attached, and covered by a roof comprising horizontal ceiling joists and sloping rafters (together forming a truss structure) or manufactured pre-fabricated roof trusses—all of which are covered by various sheathing materials to give weather resistance.

Modern light-frame structures usually gain strength from rigid panels (plywood and other plywood-like composites such as oriented strand board (OSB) used to form all or part of wall sections, but until recently carpenters employed various forms of diagonal bracing (called *wind braces*) to stabilize walls. Diagonal bracing remains a vital interior part of many roof systems, and in-wall wind braces are required by building codes in many municipalities or by individual state laws in the United States.

Light frame construction using standardized dimensional lumber has become the dominant construction method in North America and Australia because of its economy. Use of minimal structural materials allows builders to enclose a large area with minimal cost, while achieving a wide variety of architectural styles. The ubiquitous platform framing and the older balloon framing are the two different light frame construction systems used in North America.

Walls

Wall framing in house construction includes the vertical and horizontal members of exterior walls and interior partitions, both of bearing walls and non-bearing walls. These *stick* members, referred to as studs, wall plates and lintels (*headers*), serve as a nailing base for all covering material and support the upper floor platforms, which provide the lateral strength along a wall. The platforms may be the boxed structure of a ceiling and roof, or the ceiling and floor joists of the story above. The technique is variously referred to colloquially in the building trades as *stick and frame*, *stick and platform*, or *stick and box* as the sticks (studs) give the structure its vertical support, and the box shaped floor sections with joists contained within length-long post and lintels (more commonly called *headers*), supports the weight of whatever is above, including the next wall up and the roof above the top story. The platform, also provides the lateral support against wind and holds the stick walls true and square. Any lower platform supports the weight of the platforms and walls above the level of its component headers and joists.

Framing lumber should be grade-stamped, and have a moisture content not exceeding 19%.

There are three historically common methods of framing a house.

- Post and Beam, which is now used predominately in barn construction.
- Balloon framing using a technique suspending floors from the walls was common until the late 1940s, but since that time, platform framing has become the predominant form of house construction.
- Platform framing often forms wall sections horizontally on the sub-floor prior to erection, easing positioning of studs and increasing accuracy while cutting the necessary manpower. The top and bottom plates are end-nailed to each stud with two nails at least 3.25 in (83 mm) in length (*16d* or *16 penny* nails). Studs are at least doubled (creating posts) at openings, the jack stud being cut to receive the lintels(headers) that are placed and end-nailed through the outer studs.

Wall sheathing, usually a plywood or other laminate, is usually applied to the framing prior to erection, thus eliminating the need to scaffold, and again increasing speed and cutting manpower needs and expenses. Some types of exterior sheathing, such as asphalt-impregnated fibreboard, plywood, oriented strand board and waferboard, will provide adequate bracing to resist lateral loads and keep the wall square, but construction codes in most jurisdictions will require a stiff plywood sheathing. Others, such as rigid glass-fibre, asphalt-coated fibreboard, polystyrene or polyurethane board, will not. In this latter case, the wall should be reinforced with a diagonal wood or metal bracing inset into the studs. In jurisdictions subject to strong wind storms (hurricane countries, tornado alleys) local codes or state law will generally require both the diagonal wind braces and the stiff exterior sheathing regardless of the type and kind of outer weather resistant coverings.

Corners

A multiple-stud post made up of at least three studs, or the equivalent, is generally used at exterior corners and intersections to secure a good tie between adjoining walls and to provide nailing support for the interior finish and exterior sheathing. Corners and intersections, however, must be framed with at least two studs.

Nailing support for the edges of the ceiling is required at the junction of the wall and ceiling where partitions run parallel to the ceiling joists. This material is commonly referred to as 'dead wood' or backing.

Exterior wall studs

Wall framing in house construction includes the vertical and horizontal members of exterior walls and interior partitions. These members, referred to as studs, wall plates and lintels, serve as a nailing base for all covering material and support the upper floors, ceiling and roof.

Exterior wall studs are the vertical members to which the wall sheathing and cladding are attached. They are supported on a bottom plate or foundation sill and in turn support the top plate. Studs usually consist of 2 × 4 in (51 × 100 mm) or 2 × 6 in (51 × 150 mm) lumber and are commonly spaced at 16 in (410 mm) on centre. This spacing may be changed to 12 in (300 mm) or 24 in (610 mm) on centre depending on the load and the limitations imposed by the type and thickness of the wall covering used. Wider 2 × 6 in (51 × 150 mm) studs may be used to provide space for more insulation. Insulation beyond that which can be accommodated within a 3.5 in (89 mm) stud space can also be provided by other means, such as rigid or semi-rigid insulation or batts between 2 × 2 in (51 × 51 mm) horizontal furring strips, or rigid or semi-rigid insulation sheathing to the outside of the studs. The studs are attached to horizontal top and bottom wall plates of 2 in (nominal) (38 mm) lumber that are the same width as the studs.

Interior partitions

Interior partitions supporting floor, ceiling or roof loads are called loadbearing walls; others are called non-loadbearing or simply partitions. Interior loadbearing walls are framed in the same way as exterior walls. Studs are usually 2 × 4 in (51 × 100 mm) lumber spaced at 16 in (410 mm) on centre. This spacing may be changed to 12 in (300 mm) or 24 in (610 mm) depending on the loads supported and the type and thickness of the wall finish used.

Partitions can be built with 2 × 3 in (51 × 76 mm) or 2 × 4 in (51 × 100 mm) studs spaced at 16 or 24 in (400 or 600 mm) on center depending on the type and thickness of the wall finish used. Where a partition does not contain a swinging door, 2 × 4 in (51 × 100 mm) studs at 16 in (410 mm) on centre are sometimes used with the wide face of the stud parallel to the wall. This is usually done only for partitions enclosing clothes closets or cupboards to save space. Since there is no vertical load to be supported by partitions, single studs may be used at door openings. The top of the opening may be bridged with a single piece of 2 in (nominal) (38 mm) lumber the same width as the studs. These members provide a nailing support for wall finish, door frames and trim.

Lintels (headers)

Lintels (or, headers) are the horizontal members placed over window, door and other openings to carry loads to the adjoining studs. Lintels are usually constructed of two pieces of 2 in (nominal) (38 mm) lumber separated with spacers to the width of the studs and nailed together to form a single unit. The preferable spacer material is rigid insulation. The depth of a lintel is determined by the width of the opening and vertical loads supported.

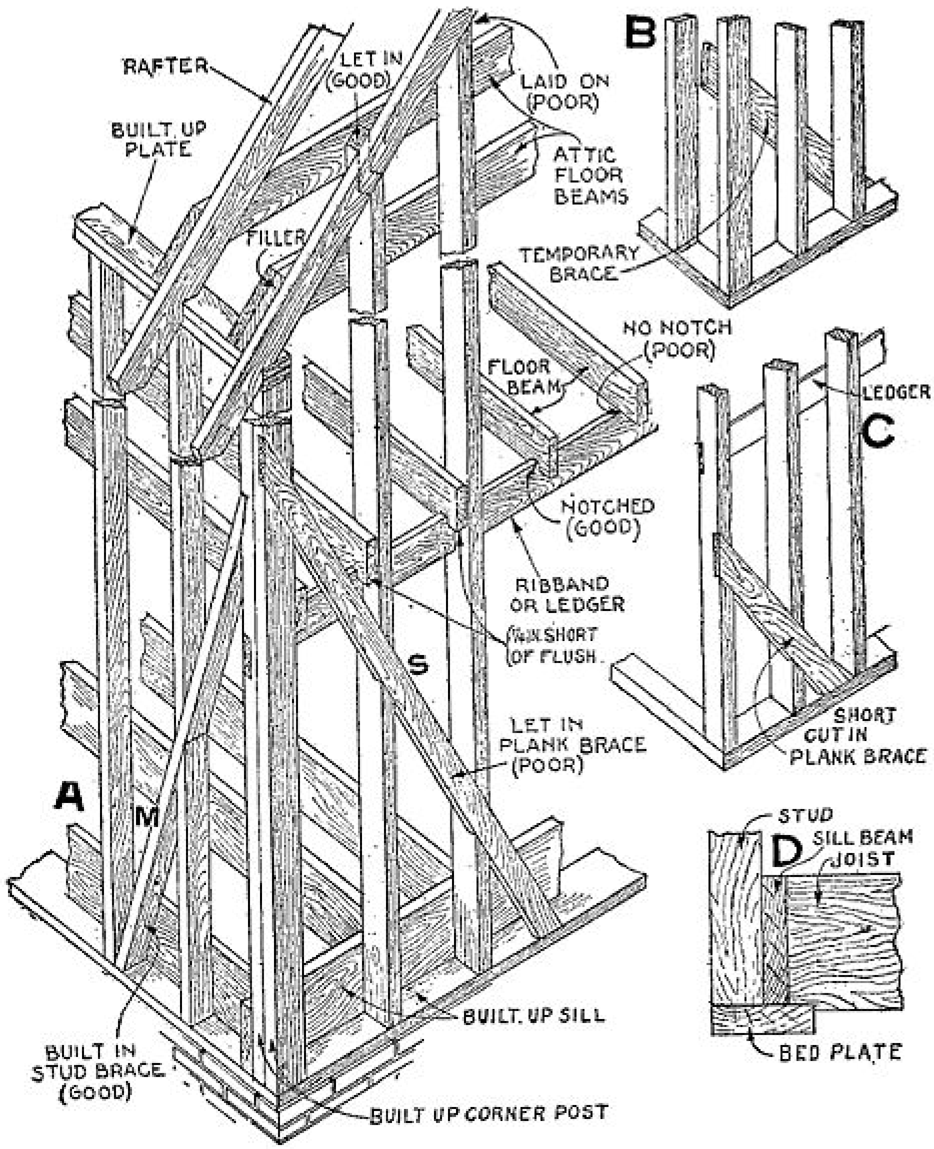
Wall Sections

The complete wall sections are then raised and put in place, temporary braces added and the bottom plates nailed through the subfloor to the floor framing members. The braces should have their larger dimension on the vertical and should permit adjustment of the vertical position of the wall.

Once the assembled sections are plumbed, they are nailed together at the corners and intersections. A strip of polyethylene is often placed between the interior walls and the exterior wall, and above the first top plate of interior walls before the second top plate is applied to attain continuity of the air barrier when polyethylene is serving this function.

A second top plate, with joints offset at least one stud space away from the joints in the plate beneath, is then added. This second top plate usually laps the first plate at the corners and partition intersections and, when nailed in place, provides an additional tie to the framed walls. Where the second top plate does not lap the plate immediately underneath at corner and partition intersections, these may be tied with 0.036 in (0.91 mm) galvanized steel plates at least 3 in (76 mm) wide and 6 in (150 mm) long, nailed with at least three 2.5 in (64 mm) nails to each wall.

Balloon framing



Balloon framing is a method of wood construction used primarily in Scandinavia, Canada and the United States (up until the mid-1950s). It utilizes long continuous framing members (studs) that run from sill plate to eave line with intermediate floor structures nailed to them, with the heights of window sills, headers and next floor height marked out on the studs with a storey pole. Once popular when long lumber was plentiful, balloon framing has been largely replaced by *platform framing*.

While no one is sure who introduced balloon framing in the U.S., the first building using balloon framing was probably a warehouse constructed in 1832 in Chicago by George Washington Snow. The following year, Augustine Taylor (1796–1891) constructed St.

Mary's Catholic Church in Chicago using the balloon framing method. Alternately, the balloon frame has been shown to have been introduced in Missouri as much as fifty years earlier.

The name comes from a French Missouri type of construction, *maison en boulin*. The curious name of this framing technique is conventionally thought to be a derisive one. Historians have fabricated the following story: As Taylor was constructing his first such building, St. Mary's Church, in 1833, skilled carpenters looked on at the comparatively thin framing members, all held together with nails, and declared this method of construction to be no more substantial than a balloon. It would surely blow over in the next wind! Though the criticism proved baseless, the name stuck.

Although lumber was plentiful in 19th century America, skilled labor was not. The advent of cheap machine-made nails, along with water-powered sawmills in the early 19th century made balloon framing highly attractive, because it did not require highly-skilled carpenters, as did the dovetail joints, mortises and tenons required by post-and-beam construction. For the first time, any farmer could build his own buildings without a time-consuming learning curve.

It has been said that balloon framing populated the western United States and the western provinces of Canada. Without it, western boomtowns certainly could not have blossomed overnight. It is also a fair certainty that, by radically reducing construction costs, balloon framing improved the shelter options of poorer North Americans. For example, many 19th century New England working neighborhoods consist of balloon-constructed three-story apartment buildings referred to as triple deckers.

The main difference between platform and balloon framing is at the floor lines. The balloon wall studs extend from the sill of the first story all the way to the top plate or end rafter of the second story. The platform-framed wall, on the other hand, is independent for each floor.

Balloon framing has several disadvantages as a construction method:

1. The creation of a path for fire to readily travel from floor to floor. This is mitigated with the use of firestops at each floor level.
2. The lack of a working platform for work on upper floors. Whereas workers can readily reach the top of the walls being erected with platform framing, balloon construction requires scaffolding to reach the tops of the walls (which are often two or three stories above the working platform).
3. The requirement for long framing members.
4. In certain larger buildings, a noticeable down-slope of floors towards central walls, caused by the differential shrinkage of the wood framing members at the perimeter versus central walls. Larger balloon-framed buildings will have central bearing walls which are actually platform framed and thus will have horizontal sill and top plates at each floor level, plus the intervening floor joists, at these central walls. Wood will shrink much more across its grain than along the grain.

Therefore, the cumulative shrinkage in the center of such a building is considerably more than the shrinkage at the perimeter where there are much fewer horizontal members. Of course, this problem, unlike the first three, takes time to develop and become noticeable.

5. Present day balloon framing buildings have considerably higher heating costs, due to the lack of insulation separating a room from its exterior walls.

Since steel is generally more fire-resistant than wood, and steel framing members can be made to arbitrary lengths, balloon framing is growing in popularity again in light gauge steel stud construction. Balloon framing provides a more direct load path down to the foundation. Additionally, balloon framing allows more flexibility for tradesmen in that it is significantly easier to pull wire, piping and ducting without having to bore through or work around framing members.

Platform framing

In Canada and the United States, the most common method of light-frame construction for houses and small apartment buildings as well as some small commercial buildings is *platform framing*.

The framed structure sits atop a concrete (most common) or treated wood foundation. A sill plate is anchored, usually with 'J' bolts to the foundation wall. Generally these plates must be pressure treated to keep from rotting. The bottom of the sill plate is raised a minimum 6 inches (150 mm) above the finished grade by the foundation. This again is to prevent the sill-plate from rotting as well as providing a termite barrier.

The floors, walls and roof of a framed structure are created by assembling (using nails) consistently sized framing elements of dimensional lumber (2×4, 2×6, etc.) at regular spacings (12 in, 16 in, and 24 in on center. Sometimes the lesser known -19.2" on center-method is used), forming stud-bays (wall) or joist-bays (floor). The floors, walls and roof are typically made torsionally stable with the installation of a plywood or composite wood skin referred to as sheathing. Sheathing has very specific nailing requirements (such as size and spacing); these measures allow a known amount of shear force to be resisted by the element. Spacing the framing members properly allows them to align with the edges of standard sheathing. In the past, tongue and groove planks installed diagonally were used as sheathing. Occasionally, wooden or galvanized steel braces are used instead of sheathing. There are also engineered wood panels made for shear and bracing.

The floor, or the platform of the name, is made up of joists (usually 2x6, 2×8, 2×10 or 2×12, depending on the span) that sit on supporting walls, beams or girders. The floor joists are spaced at (12 in, 16 in, and 24 in on center) and covered with a plywood subfloor. In the past, 1x planks set at 45-degrees to the joists were used for the subfloor.

Where the design calls for a framed floor, the resulting platform is where the framer will construct and stand that floor's walls (interior and exterior load bearing walls and space-dividing, non-load bearing partitions). Additional framed floors and their walls may then be erected to a general maximum of four in wood framed construction. There will be no framed floor in the case of a single-level structure with a concrete floor known as a *slab on grade*.

Stairs between floors are framed by installing stepped *stringers* and then placing the horizontal *treads* and vertical *risers*.

A framed roof is an assembly of rafters and wall-ties supported by the top story's walls. Prefabricated and site-built trussed rafters are also used along with the more common stick framing method. *Trusses* are engineered to redistribute tension away from wall-tie members and the ceiling members. The roof members are covered with sheathing or strapping to form the roof deck for the finish roofing material.

Floor joists can be engineered lumber (trussed, I-joist, etc.), conserving resources with increased rigidity and value. They allow access for runs of plumbing, HVAC, etc. and some forms are pre-manufactured.

Double framing is a style of framing used to reduce heat loss and air infiltration. Two walls are built around the perimeter of the building with a small gap in between. The inner wall carries the structural load of the building and is constructed as described above. The exterior wall is not load bearing and can be constructed using lighter materials. Insulation is installed in the entire space between the outside edge of the exterior wall and the inside edge of the interior wall. The size of the gap depends upon how much insulation is desired. The vapour barrier is installed on the outside of the inner wall, rather than between the studs and drywall of a standard framed structure. This increases its effectiveness as it is not perforated by electrical and plumbing connections.

Materials

Light-frame materials are most often wood or rectangular steel tubes or C-channels. Wood pieces are typically connected with nails or screws; steel pieces are connected by screws. Preferred species for linear structural members are softwoods such as spruce, pine and fir. Light frame material dimensions range from 38 mm by 89 mm (1.5 in by 3.5 in; i.e., a two-by-four) to 5 cm by 30 cm (two-by-twelve inches) at the cross-section, and lengths ranging from 2.5 m (8.2 ft) for walls to 7 m (23 ft) or more for joists and rafters. Recently, architects have begun experimenting with pre-cut modular aluminum framing to reduce on-site construction costs.

Wall panels built of studs are interrupted by sections that provide rough openings for doors and windows. Openings are typically spanned by a header or lintel that bears the weight of structure above the opening. Headers are usually built to rest on trimmers, also called jacks. Areas around windows are defined by a sill beneath the window, and cripples, which are shorter studs that span the area from the bottom plate to the sill and sometimes from the top of the window to a header, or from a header to a top plate.

Diagonal bracings made of wood or steel provide shear (horizontal strength) as do panels of sheeting nailed to studs, sills and headers.

Light-gauge metal stud framing

Wall sections usually include a bottom plate which is secured to the structure of a floor, and one, or more often two top plates that tie walls together and provide a bearing for structures above the wall. Wood or steel floor frames usually include a rim joist around the perimeter of a system of floor joists, and often include bridging material near the center of a span to prevent lateral buckling of the spanning members. In two-story construction, openings are left in the floor system for a stairwell, in which stair risers and treads are most often attached to squared faces cut into sloping stair stringers.

Interior wall coverings in light-frame construction typically include wallboard, lath and plaster or decorative wood paneling.

Exterior finishes for walls and ceilings often include plywood or composite sheathing, brick or stone veneers, and various stucco finishes. Cavities between studs, usually placed 40–60 cm (16–24 in) apart, are usually filled with insulation materials, such as fiberglass batting, or cellulose filling sometimes made of recycled newsprint treated with boron additives for fire prevention and vermin control.

In natural building, straw bales, cob and adobe may be used for both exterior and interior walls. The part of a structural building that goes diagonally across a wall is called a T-bar. It stops the walls from collapsing in gusty winds.

Roofs

Roofs are usually built to provide a sloping surface intended to shed rain or snow, with slopes ranging from 1 cm of rise per 15 cm (less than an inch per linear foot) of rafter length, to steep slopes of more than 2 cm per cm (two feet per foot) of rafter length. A light-frame structure built mostly inside sloping walls comprising a roof is called an A-frame.

Roofs are most often covered with shingles made of asphalt, fiberglass and small gravel coating, but a wide range of materials are used. Molten tar is often used to waterproof flatter roofs, but newer materials include rubber and synthetic materials. Steel panels are popular roof coverings in some areas, preferred for their durability. Slate or tile roofs offer more historic coverings for light-frame roofs.

Light-frame methods allow easy construction of unique roof designs. Hip roofs, which slope toward walls on all sides and are joined at hip rafters that span from corners to a ridge. Valleys are formed when two sloping roof sections drain toward each other. Dormers are small areas in which vertical walls interrupt a roof line, and which are topped off by slopes at usually right angles to a main roof section. Gables are formed when a length-wise section of sloping roof ends to form a triangular wall section. Clerestories are formed by an interruption along the slope of a roof where a short vertical wall connects it to another roof section. Flat roofs, which usually include at least a nominal slope to shed water, are often surrounded by parapet walls with openings (called scuppers) to allow water to drain out. Sloping crickets are built into roofs to direct water away from areas of poor drainage, such as behind a chimney at the bottom of a sloping section.

Structure

Light-frame buildings are often erected on monolithic concrete slab foundations that serve both as a floor and as a support for the structure. Other light-frame buildings are built over a crawlspace or a basement, with wood or steel joists used to span between foundation walls, usually constructed of poured concrete or concrete blocks.

Engineered components are commonly used to form floor, ceiling and roof structures in place of solid wood. I-joists (closed-web trusses) are often made from laminated woods, most often chipped poplar wood, in panels as thin as 1 cm (0.4 in), glued between horizontally laminated members of less than 4 cm by 4 cm (*two-by-twos*), to span distances of as much as 9 m (30 ft). Open web trussed joists and rafters are often formed of 4 cm by 9 cm (*two-by-four* [sic]) wood members to provide support for floors, roofing systems and ceiling finishes.

Chapter 7

Protection of Exposed Concrete

Protection of exposed concrete is necessary to prolong its service life. A 120 year design life for concrete infrastructure has become increasingly common. Without early preventive maintenance this design life target may be optimistic. The design service life of reinforced concrete structures often is not reached because of early deterioration and damage. The service life of some modern concrete structures is 20 to 30 years at most. Even good quality engineering concrete is made up of countless invisible interconnecting capillary pores. The concrete acts like a "hard sponge" which absorbs damaging liquids such as water and aggressive water-borne salts. The strength of any concrete lessens as a result of static and dynamic loading, chloride ion ingress (from sea water) and the application of deicing salts. This leaves the concrete vulnerable to corrosion of the embedded steel. Concrete can also be damaged by sulfate attack, alkali silica reaction, carbonation, temperature change, abrasion, biological attack, salt crystallization, efflorescence and freeze-thaw attack. Many of these processes are surface water driven and can be mitigated by early preventive maintenance with alkyl alkoxy silane impregnation.

Capillary suction

Water and salts are drawn into the capillaries of the concrete via capillary suction and wicking, i.e. water moving from the saturated zone to the dry zone. The "war zones" for marine concrete are those areas that are subjected to the constant wet-dry cycles of wave action and wind. This causes oxygen, water and chloride ions to become plentiful. The corners of concrete in these areas are particularly vulnerable as they are attacked from two directions.

Capillary action is caused by surface tension and by the relative value of the adhesion between the water and the concrete to the cohesion of the water. The action of surface tension is to cause the water to rise within a small capillary that is partially immersed in the water. The water can rise to its maximum height occurs when the contact angle is zero. The smaller the pore radius the higher the water can rise. This is the same mechanism that gets water from the root of a tree to the tip of its highest leaf.

Chloride ion

Sea water contains approximately 3.5 wt. % salts by weight including; sodium chloride, magnesium sulphate, calcium sulphate and bicarbonates. In water these salts dissociate and migrate with the water into the capillaries of the concrete. Chloride ions are particularly aggressive for the corrosion of steel reinforcement bars and make up about 50 % of these ions. Chloride ions are easily incorporated in the crystal lattice of hydrated cement Afm phases where they form Friedel's salt. These salts can only penetrate into the concrete when dissolved in water. If the water is stopped from penetrating the concrete so are the salts it contains.

Saline water from the sea or de-icing salts (e.g. calcium chloride) provides a strong electrolyte to help drive the electro-potential corrosion of reinforcing steel. Local micro-environmental differences along the length of the reinforcement are enough to set up a potential difference and initiate corrosion. Chloride ions act a catalyst pulling the iron ions into solution to form rust in the presence of water and oxygen, resulting in the pitting corrosion of the steel. Rust can cause iron to expand 3-7 times its original size and this causes high tensile stress in surrounding concrete. If the stress is great enough the concrete will crack, spall and may delaminate the concrete cover.

De-icing salts such as calcium chloride and sodium chloride are added to road surfaces in winter to lower the freezing point of any surface water (over 50 million tons of de-icing salts are used each year on US roads). When it does freeze, unlike most liquids, water expands by 9 %. The cyclic freeze thaw action causes great pressures e.g. 200 MPa to build up in the pores causing micro-cracking and scaling.

Sea water and some ground water contain many aggressive salts such as sodium chloride, calcium chloride, magnesium sulphate, sodium sulphate, calcium sulphate and bicarbonates. When these salts dry in the surface pores the resulting crystallization causes reduced cohesion of the cement paste, softens the concrete and reduces its strength.

Alkali silica reaction

When the alkalis in cement react with amorphous (i.e. non crystalline) silica aggregate in the presence of water then a disruptive swelling reaction occurs in the cement paste. When this happens to concrete railway sleepers the rails may end up out of alignment and cause a derailment.

Preventive treatment

Relative to the capillary pore size of concrete the alkyl alkoxy silane molecule is very small and can penetrate deeply. There are a number of silanes available and these vary with the alkyl part of the molecule to suit the application. For example some alkyl groups can only repel water but not oil and others can repel both water and oil. The preferred alkoxy group is ethoxy. The reason for this is because the ethoxy is a relatively slow reacting group allowing the silane to penetrate deeply, even displacing water that may be present, before reacting. Also, this group over time reacts with water in the pores or air to form ethanol which is a far safer and environmentally sound by-product than a methoxy group which would form methanol.

The result is a permanent connection with the capillary pore walls that repels liquids. The pores remain unblocked and allow the passage of water vapour, which being a gas has no surface tension. Allowing water vapour to escape has the effect of increasing the resistivity of the concrete and thus slowing down the rate of electro-potential corrosion of the reinforcing steel. Concrete can be silane-treated from the low tide level and above. It may take several treatments some weeks apart to obtain a good depth of impregnation between the low and high tide levels. Multiple applications over time allow the concrete to dry and allow for the silane to penetrate. Even though concrete with a pore diameter of say 2×10^{-6} m can temporarily resist over 4 m head of water pressure (P = -4x surface tension x Cos (contact angle)/pore diameter) i.e. only exposed surface should be treated. Below the low tide mark the available oxygen levels drops off steeply. At 15 °C at sea level there is only 7 mg of oxygen dissolved per litre of sea water. Air contains 250 mg of oxygen per litre, i.e. 36 time more oxygen available than in water.

When the capillaries are treated with silane the contact angle typically become 110 °. In the equation Cos (110 °) is a negative number and this describes the result of the treatment i.e. a repulsion of the water and salts. Only the pores are treated and there is no film or coating on the surface and so there is little or no change in its frictional properties or appearance.

Low Volatile Organic Carbon (VOCs) impregnating silane water-based creams are now available. VOCs include any volatile compound of carbon that participates in atmospheric photochemical reactions. In water repellents and related materials, a VOC is typically a formulation ingredient that will evaporate (volatilize) under normal use and is expressed as grams per liter. On July 1, 2006, the South Coast Air Quality Management District (SCAQMD) in California implemented the most stringent VOC requirements in the world. It is reasonable to expect that the rules we see in place in California today will influence a large portion of the world in the next few years. For SCAQMD, [waterproof|[waterproofing]] concrete sealers need to have VOC content below (excluding water and exempt compounds) 100 grams per Litre. The VOC content does not change regardless of how much water or exempt solvent is added to the sealer.

Silane cream can be applied in one coat using a foam roller or low pressure spray unit. The typical application rate is 1 litre per 3 to 4 sq.m. depending on the surface absorption and depth of penetration required. It needs to be protected from moisture for a minimum of 12 hours. The 21 day reduction in 15 % NaCl brine water uptake in accordance NCHRP Report 244 method is up to 70 % for liquid silane and 64 % for cream.

The cream combines the best aspects of both water-based and solvent-based technologies. The cream sits on the surface and once the water evaporates the solvents take over to penetrate deeply into the surface. Unlike a typical water-based coating the cream can even pass through a previously impregnated (i.e. water repelling surface). The cream is applied in one coat and allows the applicator better control particularly in windy conditions and on vertical and overhead surfaces.

If not used correctly, solvent-based silanes pose significant health and safety problems with potential risk of skin and eye irritation and damage to vegetation and aquatic environments. There is little risk in using cream-based products.

Impregnation undertaken in the UK is known to be effective for at least 15 years, provided it is applied correctly. Longer service life is anticipated.

Case study

The quay-wall of a new container terminal at Zeebrugge Harbor, Belgium, was protected against chloride ingress by means of a water-repellent agent immediately after construction in 1993. An alkyl triethoxy silane was used pre-evaluated in a preliminary research program. To judge the in site effectiveness of the hydrophobic agent as a water repellent treatment, three subsequent in site surveys were conducted in 1996, 1998 and recently in 2005. Based on the cores drilled, the chloride profiles are determined as a function of time, both in a non-treated and treated location. Because of the long-term data sequence, the long-term effectiveness of the treatment can be assessed in an objective way. Predicted service life represents the 50 % probability of chloride ions to reaching reinforcing bars at a depth of 120 mm with a sufficient concentration of 0.7 % chloride ion by weight of cement to start the corrosion process i.e. untreated 16.5 years, treated 107 years.

Depth of impregnation

Amongst the most decisive parameters determining the effectiveness of a water repellent treatment is the penetration depth. A good depth of penetration not only protects the treatment from weathering and traffic but also sets up a hydrophobic barrier. The depth of penetration is tested by breaking open the treated specimen and spraying the fractured surface with water. The depth of the dry zone is taken as the effective depth of impregnation. This barrier stops the passage of liquid water and salts into or out of the concrete. Depth of penetration is also a good quality control check. A 50 mm diameter 40 mm deep button core is recommended to be randomly taken for every 300 sq.m. of concrete treated. This can be compared with a known sample to ensure that the contractor is applying the correct quantity of silane. It should be greater than or equal to 5 mm. It should be noted that existing treated surfaces can easily absorb more applications and the new material will penetrate deeper levels in the concrete. This is enhanced by waiting for each application to fully dry.

Alberta Transportation and Utilities carried out a series of five day water immersion tests to measure the reduction in water uptake on concrete samples treated with common sealers i.e. epoxy, acrylic, siloxane and silane. The water uptake was also measured after sandblasting to abrade (total of 3 % removed by weight) the surface as a means of simulated accelerated weathering. Only the silanes kept on performing after significant surface abrasion. It is estimated that a highway concrete wearing surface will lose 1 mm of concrete every 7 years.

Theoretical break through pressure

The anti-capillary force caused by the silane treatment can be overcome by applying a sufficiently high force such as extreme wind driven rain pressure or by hydrostatic pressure on the liquid trying to enter the pore. The amount of force needed to push the water into the concrete is proportional to the imparted critical surface tension of the substrate and the pore's diameter.

$$Breakthrough\ pressure = \frac{-4\gamma \cos\theta}{d}$$

where:

γ: the liquid-air surface tension (energy/surface area)
θ: the contact angle (angle)
d: diameter of pore (length)

For a concrete, using SI units:

γ= 0.072 J/m^2 at 20 °C
θ = 107 ° (angle)
d = 2.1 x 10^{-6} m

Breakthrough pressure is 40,100 N/m^2 or 4.092 metres (i.e. 40100/101325 x 10.34 = 4.092 m) pressure head of water. By comparison 50 mm pressure head is the same pressure from 104 km per hour wind driven rain.

If the pore size increases, the head pressure resistance will decrease. Water vapour does not have a surface tension, it can pass freely through a substrate made water repellent with the silane treatment.

Conclusion

Many of the processes that deteriorate the strength of engineering concrete are surface-water driven and can be mitigated by early preventive maintenance with a alkyl alkoxy impregnating silane. The silane is used to line capillary pores and make them hydrophobic stopping capillary suction and wicking action These products are non-film forming; able to greatly reduce water uptake; an excellent chloride ion screen; highly water vapour permeable; deeply penetrating; very alkali resistant; do not change the appearance or frictional property of the surface and can seal hairline cracks.