DESIGN OF EARTHQUAKE ENGINEERING

RESPONSE OF RCC BUILDINGS TO SEISMIC LOADS

Introduction

Apart from gravity loads, the structure will experience dominant lateral forces of considerable magnitude during earthquake shaking. It is essential to estimate and specify these lateral forces on the structure in order to design the structure to resist an earthquake. It is impossible to exactly determine the earthquake induced lateral forces that are expected to act on the structure during its lifetime. However, considering the consequential effects of earthquake due to eventual failure of the structure, it is important to estimate these forces in a rational and realistic manner.
The earthquake forces in a structure depend on a number of factors such as,

- Characteristics of the earthquake (Magnitude, intensity, duration, frequency, etc.)
- Distance from the fault
- Site geology
- Type of structure and its lateral load resisting system.

Earthquake Resistant Design Philosophy

Apart from the factors mentioned above, the consequences of failure of the structure may also be of concern in the reliable estimation of design lateral forces. Hence, it is important to include these factors in the lateral force estimation procedures.
Code of practice for earthquake resistant design of structures primarily aims at accomplishing two primary objectives; total safety against loss of life and minimization of economic loss. These objectives are fulfilled by design philosophy with following criteria,

- Resist minor earthquake shaking without damage

- Resist moderate earthquake shaking without structural damage but possibly with some damage to nonstructural members
- Resist major levels of earthquake shaking with both structural and nonstructural damage, but the building should not collapse thus endangerment of the lives of occupants is avoided.

Conceptual representation of the earthquake resistant design philosophy is depicted in Figure 1.

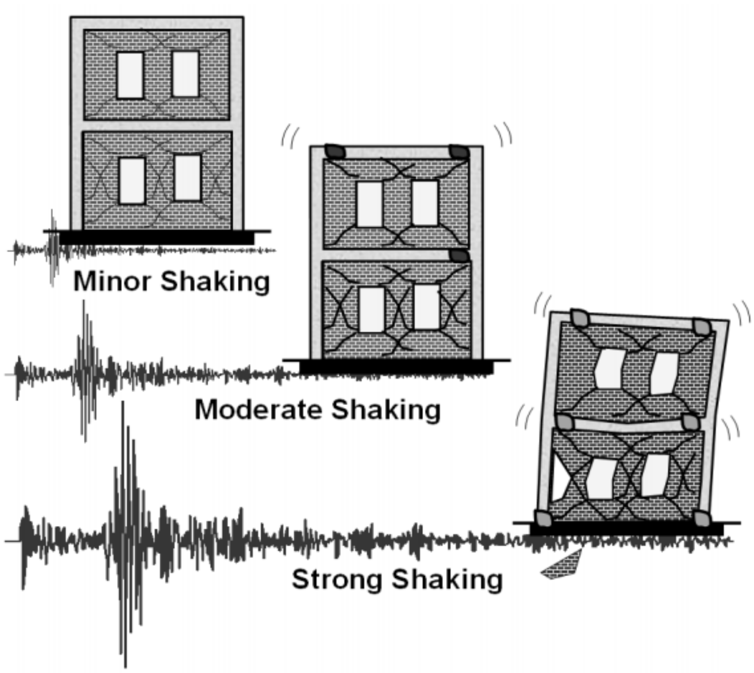


Figure 1: Schematic diagram depicting earthquake resistant design philosophy for different levels shaking

The purpose of an earthquake-resistant design is to provide a structure with features, which will enable it to respond satisfactorily to seismic effects. These features are related to five major objectives, which are listed in order of importance:

- The likelihood of collapse after a very severe earthquake should be as low as possible.
- Damage to non-structural elements caused by moderate earthquakes should be kept within reasonable limits. Although substantial damage due to severe earthquakes, which have a low probability of occurrence is acceptable, such damage is unacceptable in the case of moderate tremors which are more likely to occur.

- Buildings in which many people are usually present should have deformability features which will enable occupants to remain calm even in the event of strong shocks.
- Personal injury should be avoided.
- Damage to neighboring buildings should be avoided

Guidelines for Earthquake Resistant Design

As mentioned above, the philosophy of earthquake design is to prevent non-structural damage in frequent minor ground shaking, is to prevent structural damage and minimize non-structural damage in occasional moderate ground shaking and to avoid collapse or serious damage in rare major ground shaking. In order to meet these requirements the code of practice for earthquake resistant design of structures generally prescribes guidelines with respect to following aspects,

- Intensity of shaking is prescribed based on zone factor depending upon seismic activity in the region of geographical location of the site
- Characteristics of the structures that affect its dynamic behaviour is accounted by prescribing appropriate natural period depending on distribution of mass and stiffness properties also, by considering type of soil beneath its foundation.
- Importance factor is assigned depending on occupancy type, functionality etc. of the structure
- Capability of a particular structure to resist lateral forces is incorporated by identifying its redundancy and ductility features through response modification factor.

When inertia of the structure offers resistance to ground motions, structure will experience earthquake forces. The relative movement between the ground and the structure induces a force dependent on the ground acceleration, mass and stiffness properties of the structure. The ground acceleration depends on the magnitude and intensity of the seismic event at a location. Based on seismic records, experience, and research, some areas of the country are determined to have a greater probability of earthquakes than others, and some areas have more severe earthquakes. This is taken into account by dividing the country into different zones that represent estimates of future earthquake occurrence and strength.

The magnitude of the seismic force also depends on the type of foundation soil under the building. Some soils tend to amplify seismic waves and can even tend to liquefy during an earthquake. Hence, it is important to suitably incorporate the effect of prevailing soil conditions in the procedures of evaluation of seismic forces on the structure.

Introduction of an occupancy importance factor to provide for more conservative design of important facilities is necessary such that the structure importance factor indirectly accounts for less risk, or better expected performance specified for important structures. Important structures are those

- Emergency facilities that are expected to remain functional after a severe earthquake such as hospitals, fire stations, etc.
- Buildings, whose failure may lead to other disasters, affecting people or environment, such as nuclear power plants, dams, petrochemical facilities, etc.
- Life-line facilities e.g. communication lines, pipelines, bridges, power stations, etc.
- Facilities for large number of people such as community centers, schools, etc.

Accordingly these structures are designed for higher lateral strength, and hence they are expected to sustain less damage under the design earthquake.

Finally, it is imperative to rationally incorporate means of reducing the required lateral strength in case of structures that are capable of withstanding extensive inelastic behaviour by virtue of their structural configuration and detailing. In this regard, generally provision is made in the code of practice by introducing the response modification factor. The response reduction factor essentially reduces the design lateral strength of the structure from required strength to resist the linear response to the strength that would be required to limit inelastic behaviour to acceptable levels. Response reduction factor magnitude mainly depends on the ductility characteristics of the structure under consideration. Structural systems deemed capable of withstanding extensive inelastic behavior are assigned relatively high response reduction factor values, permitting minimum design strength that is required for elastic response to the design ground motion. Systems deemed to be incapable of providing reliable inelastic behavior are assigned with low response reduction factor value that results in strength sufficient to resist design motion in a nearly elastic manner.

General Earthquake Resistant Design Principles of IS-1893 (2002)

Clause 6.1 of IS-1893 (2002) provides the following design principles,

- The random earthquake ground motions, which cause the structure to vibrate, can be resolved in any three mutually perpendicular directions. The predominant direction of ground vibration is usually horizontal.
- Earthquake-generated vertical inertia forces are to be considered in design unless checked and proven in specimen calculations to be not significant. Vertical acceleration should be considered in structures with large spans and those in which stability is a criterion for design. Reduction in gravity force due to vertical component of ground motions can be particularly detrimental in cases of prestressed horizontal members and of cantilevered members. Hence, special attention should be paid to the effect of vertical component of the ground motion on prestressed or cantilevered beams, girders and slabs.
- The response of a structure to ground vibration is a function of the nature of foundation soil: materials, form, size and mode of construction of structures and the duration and characteristics of ground motion. IS-1893 specifies design forces for structures standing on rocks or soils which do not settle or liquefy or slide due to loss of strength during ground vibrations.
- The design approach adopted in IS 1893 ensures that structures possess at least a minimum strength to withstand minor earthquakes of intensity less than DBE (Design Basis Earthquake) without damage; resist moderate earthquakes equal to DBE without significant structural damage though some non-structural damage may occur; and aims that structures withstand a major earthquake (Maximum Considered Earthquake - MCE) without collapse.
- Actual forces that appear on structures during earthquakes are much greater than the design forces specified in the code. However, ductility, arising from inelastic material behaviour and detailing, and over strength, arising from the additional reserve strength in structures over and above the design strength, are relied upon to account for this difference in actual and design lateral loads.
- The design lateral force specified in this standard shall be considered in each of the two orthogonal horizontal directions of the structure. For structures which have lateral force resisting elements in the two orthogonal directions only, the design lateral force shall be

considered along one direction at a time, and not in both directions simultaneously. Structures, having lateral force resisting elements (for example frames, shear walls) in directions other than the two orthogonal directions, shall be analysed considering the load combinations specified in Clause: 6.3.2 [IS-1893 (2002)]. Where both horizontal and vertical seismic forces are taken into account, load combinations specified in Clause: 6.3.3 [IS-1893 (2002)] shall be considered. (Refer to equation (3) & (4) for load combinations specified in IS-1893)

Assumptions Made Earthquake Resistant Design of Structures

The following assumptions are made in IS-1893 (2002) for earthquake resistant design of structures

- Earthquake causes impulsive ground motions, which are complex and irregular in character, changing in period and amplitude each lasting for a small duration. Therefore, resonance of the type as visualised under steady-state sinusoidal excitations, will not occur as it would need time to build up such amplitudes
- Earthquake is not likely to occur simultaneously with wind or maximum flood or maximum sea waves.
- The value of elastic modulus of materials, wherever required, may be taken as for static analysis unless a more definite value is available for use in such condition

Load combinations

Clause: 6.3 of IS-1893 (2002) specifies

- In the plastic design of steel structures, the following load combinations shall be accounted for:

$$\begin{aligned} &1)\ 1.7(DL+IL)\\ &2)\ 1.7(DL\pm IL) \qquad (1)\\ &3)\ 1.3(DL+IL\pm EL) \end{aligned}$$

- In the limit state design of reinforced and prestressed concrete structures, the following load combinations shall be accounted for:

$$
\begin{aligned}
&1)\ 1.5(DL+IL)\\
&2)\ 1.2(DL+IL\pm EL)\\
&3)\ 1.5(DL\pm IL)\\
&4)\ 0.9DL\pm 1.5EL
\end{aligned}
\qquad (2)
$$

Where DL, IL and EL denote dead load, imposed load and earthquake load respectively.

- Design Horizontal Earthquake Load:
  - When the lateral load resisting elements are oriented along orthogonal horizontal direction, the structure shall be designed for the effects due to full design earthquake load in one horizontal direction at time.
  - When the lateral load resisting elements are not oriented along the orthogonal horizontal directions, the structure shall be designed for the effects due to full design earthquake load in one horizontal direction plus 30 percent of the design earthquake load in the other direction
- Design Vertical Earthquake Load: When effects due to vertical earthquake loads are to be considered, the design vertical force shall be calculated in accordance with Clause: 6.4.5 of IS-1893 (2002). (i.e., the design acceleration spectrum for vertical motions may be taken as two-thirds of the design horizontal acceleration spectrum)
- Combination for Two or Three Component Motion: When responses from the three earthquake components are to be considered, the responses due to each component may be combined using the assumption that when the maximum response from one component occurs, the responses from the other two components are 30 percent of their maximum. All possible combinations of the three components (EL_x, EL_y and EL_z where x and y are two orthogonal directions and z is vertical direction) including variations in sign (plus or minus) shall be considered. Thus, the response due earthquake force (EL) is the maximum of the following three cases

$$
\begin{aligned}
&1)\ \pm EL_x \pm 0.3EL_y \pm 0.3EL_z\\
&2)\ \pm 0.3EL_x \pm EL_y \pm 0.3EL_z\\
&3)\ \pm 0.3EL_x \pm 0.3EL_y \pm EL_z
\end{aligned}
\qquad (3)
$$

Or as an alternative to the procedure mentioned above, the response (*EL)* due to the combined effect of the three components can be obtained (Clause: 6.3.4.2, IS 1893-2002) on the basis SRSS that is,

$$EL = \sqrt{(EL_x)^2 + (EL_y)^2 + (EL_z)^2} \tag{4}$$

Design Spectrum

- For the purpose of determining seismic forces, the country is classified into four seismic zones as shown in Figure 2.

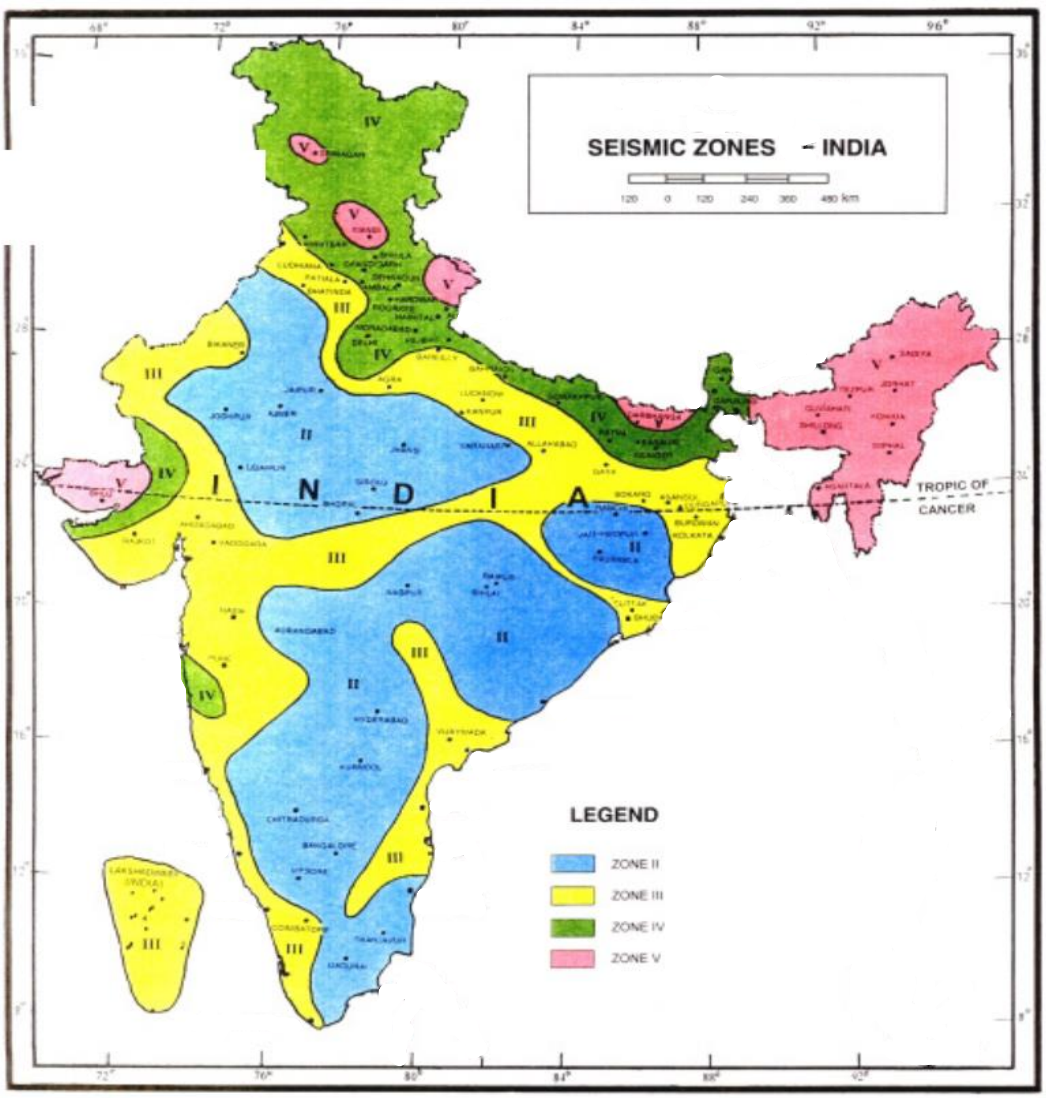


Figure 2

- The design horizontal seismic coefficient for a structure shall be determined by the following expression

$$A_h = \frac{Z}{2}\frac{S_a}{g}\frac{I}{R} \qquad (5)$$

Provided that for any structure with T ≤ 0.1 s, the value of A_h will not be taken less than *Z/2* whatever be the value of *I/R*. Where,

Z = Zone factor given in Table 1, is for the Maximum Considered Earthquake (MCE) and service life of structure in a zone. The factor 2 in the denominator of Z is used so as to reduce the Maximum Considered Earthquake (MCE) zone factor to the factor for Design Basis Earthquake (DBE).

I = Importance factor, depending upon the functional use of the structures, characterised by hazardous consequences of its failure, post earthquake functional needs, historical value, or economic importance (Table 2).

(S_a / *g*) = Average response acceleration coefficient for rock or soil sites as given by Figure 3 (or from table adjacent to the Figure 3) based on appropriate natural periods and damping of the structure. These curves represent free field ground motion. Figure 3 shows the proposed 5% spectra for rocky and soils sites and Table 3 gives the multiplying factors for obtaining spectral values for various other damping.

R = Response reduction factor, depending on the perceived seismic damage performance of the structure, characterised by ductile or brittle deformations. However, the ratio *(I/R)* shall not be greater than 1.0. The values of *R* for buildings are given in Table 4.

- Where a number of modes are to be considered for dynamic analysis, the value of A_h as defined in equation (5), for each mode shall be determined using the natural period of vibration of that mode.
- For underground structures and foundations at depths of 30 m or below, the design horizontal acceleration spectrum value shall be taken as half the value obtained from equation (5). For structures and foundations placed between the ground level and 30 m depth, the design horizontal acceleration spectrum value shall be linearly interpolated between A_h and $0.5A_h$ where A_h is as specified in equation (5)

Table 1: Zone factor (*Z*) [Table 2, IS-1893 (2002)]

Seismic Zone	II	III	IV	V
Seismic Intensity	Low	Moderate	Severe	Very Severe
Z	0.10	0.16	0.24	0.36

Table 2: Importance factor (*I*) [Table 6, IS-1893 (2002)]

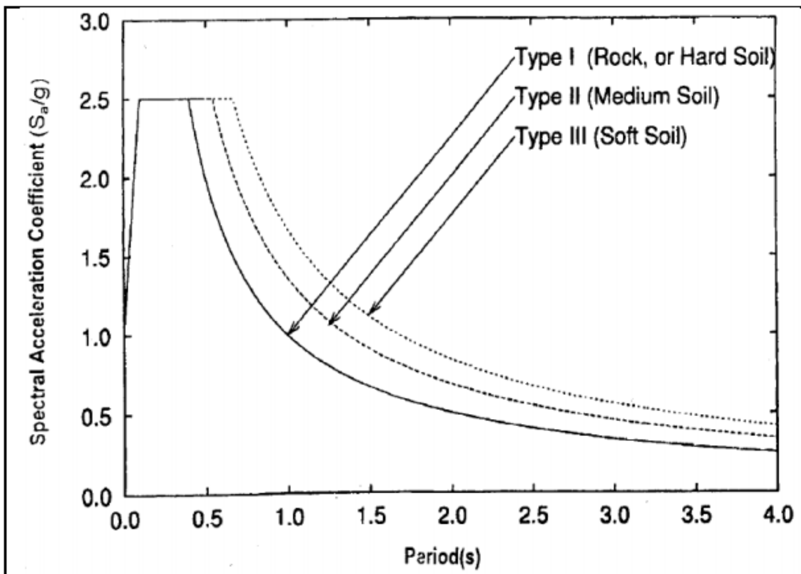
SI. No. (1)	Structure (2)	Importance Factor (3)
i)	Important service and community buildings, such as hospitals; schools; monumental structures; emergency buildings like telephone exchange, television stations, radio stations, railway stations, tire station buildings; large community halls like cinemas, assembly halls and subway stations, power stations	1.5
ii)	All other buildings	1.0

NOTES

1. The design engineer may choose values of importance factor *I* greater than those mentioned above.

2. Buildings not covered in SI. No. (i) and (ii) above may be designed for higher value of *I*. depending on economy, strategy considerations like multi-storey buildings having several residential units

3. This docs not apply to temporary structures like excavations, scaffolding etc of short duration.



For rocky, or hard soil sites

$$\frac{S_a}{g} = \begin{cases} 1+15T & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.40 \\ 1.00/T & 0.40 \le T \le 4.00 \end{cases}$$

For medium soil sites

$$\frac{S_a}{g} = \begin{cases} 1+15T & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.55 \\ 1.36/T & 0.55 \le T \le 4.00 \end{cases}$$

For soft soil sites

$$\frac{S_a}{g} = \begin{cases} 1+15T & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.67 \\ 1.67/T & 0.67 \le T \le 4.00 \end{cases}$$

Figure 3: Response spectra for rock and soil sites for 5% damping [Fig. 2, IS-1893 (2002)]

Table 3 Multiplying factors for damping other than 5% [Table 3, IS-1893 (2002)]

Damping Percent	0	2	5	7	10	15	20	25	30
Factors	3.20	1.40	1.00	0.90	0.80	0.70	0.60	0.55	0.50

Table 4: Response reduction factor (*R*) for building systems [Table 7, IS-1893 (2002)]

SI. No.	**Lateral Load Resisting System**	***R***
(1)	(2)	(3)
	Building Frame Systems	
(i)	Ordinary RC moment-resisting frame (OMRF)[2)]	3.0
(ii)	Special RC moment-resisting frame (SMRF)[3)]	5.0
(iii)	Steel frame with	
	a) Concentric braces	4.0
	b) Eccentric braces	5.0
(iv)	Steel moment resisting frame designed as per SP 6 (6)	5.0
	Building with Shear Walls[4)]	
(v)	Load bearing masonry wall buildings[5)]	
	a) Unreinforced	1.5
	b) Reinforced with horizontal RC bands	2.5
	c) Reinforced with horizontal RC bands and vertical bars at comers of rooms and	3.0
(vi)	Ordinary reinforced concrete shear walls[6)]	3.0
(vii)	Ductile shear walls[7)]	4.0
	Buildings with Dual System[8)]	
(viii)	Ordinary shear wall with OMRF	3.0
(ix)	Ordinary shear wall with SMRF	4.0
(x)	Ductile shear wall with OMRF	4.5
(xi)	Ductile shear wall with SMRF	5.0

1) The values of response reduction factors are to be used for buildings with lateral load resisting elements, and not just for the lateral load resisting elements built in isolation.

2) OMRF are those designed and detailed as per IS 456 or IS 800 but not mooting ductile detailing requirement as per IS 13920 or SP 6 (6) respectively.

3) SMRF defined in 4.15.2.

4) Buildings with shear walls also include buildings having shear walls and frames, but where:

a) frames are not designed to carry lateral loads, or

b) frames are designed to carry lateral loads but do not fulfil the requirements of 'dual systems'.

5) Reinforcement should be as per IS 4326.

6) Prohibited in zones IV and V.

7) Ductile shear walls are those designed and detailed as per IS 13920.

8) Buildings with dual systems consist of shear walls (or braced frames) and moment resisting frames such that:

a) the two systems arc designed to resist the total design force in proportion to their lateral stiffness considering the interaction of the dual system at all floor levels; and

b) the moment resisting frames are designed to independently resist at least 25 percent of the design seismic base shear.

Design imposed loads for earthquake force calculation [Clause 7.3, IS 1893 (2002)]

- For various loading classes as specified in IS 875 (Part 2), the earthquake force shall be calculated for the full dead load plus the percentage of imposed load as given in Table 5.

Table 5: Percentage of imposed load to be considered in seismic weight calculation [Table 8, IS-1893 (2002)]

Imposed Uniformly Distributed Floor Loads (kN/m^2)	Percentage of Imposed Load
Up to and including 3.0	25
Above 3.0	50

- For calculating the design seismic forces of the structure, the imposed load on roof need not be considered.
- The percentage of imposed loads given above shall also be used for 'Whole frame loaded' condition in the load combinations specified in equation (2) and equation (3) where the gravity loads are combined with the earthquake loads. No further reduction in the imposed load will be used as envisaged in IS 875 (Part 2) for number of storeys above the one under consideration or for large spans of beams or floors.
- The proportions of imposed load indicated above for calculating the lateral design forces for earthquakes are applicable to average conditions. Where the probable loads at the time of earthquake are more accurately assessed, the designer may alter the proportions indicated or even replace the entire imposed load proportions by the actual assessed load. In such cases, where the imposed load is not assessed as mentioned above only that part of imposed load, which possesses mass, shall be considered. Lateral design force for earthquakes shall not be calculated on contribution of impact effects from imposed loads.
- Other loads apart from those given above (for example snow and permanent equipment) shall be considered as appropriate.