The IBC-2018 is based on the design requirements of every structures, and portion including nonstructural components attached to structures and their supports in accordance with ASCE 7-16 Chaps. 11, 12, 13, 15, 17 and 18. In 2000, the UBC is replaced by the IBC published by the international Code Council (ICC). Current IBC-2018 adopts Risk Category instead of Seismic Use Group. In addition, the latest IBC-2018 classifies every building in a Seismic Design Category which determines the analysis procedure to be used, the maximum allowed height and drift limitations.

24.1 Response Spectral Acceleration: S_S, S_1

The reader may recall that the response spectral acceleration is defined as the maximum acceleration of a structural system, modeled as a linear single-degree-of-freedom system of mass m and stiffness k subjected to a specific time- history excitation at its base. For such a system, the maximum response (maximum displacement or maximum acceleration) is only a function of its natural period $\left(T = 2\pi\sqrt{m/k}\right)$ and of damping c expressed as a fraction of the critical damping $\left(\xi = c/c_{cr} \text{ with } c_{cr} = 2\sqrt{km}\right)$. In the IBC-2000 and current IBC-2018, the earthquake time-history excitation assumed at a given geographic location is designated as "Maximum Considered Earthquake" (MCE). The response spectral acceleration of a structural system with a natural period, $T_s = 0.2$ sec (short period) and with a natural period $T_1 = 1$ sec is obtained from response acceleration of two sets of maps prepared for various the regions of the United States. These maps are available from the Federal Emergency Management Agency (FEMA). They provide contour lines for the values of the response spectral acceleration S_S for the short period ($T_s = 0.2$ sec) and for the response spectral acceleration S_1 for period $T_1 = 1$ sec. Interpolation or the value of the next higher contour line may be used for sites located between contour lines. Because these two values, S_S and S_1 are obtained from maps, they are usually referred to as mapped response spectral accelerations. These maps provide the response spectral acceleration for an assumed damping in the structure equal to 5% of the critical damping and for a type of soil classified as Site Class B (rock). For a different type of soil other than rock, the mapped spectral response accelerations must be modified by factors that depend on the Site Class as described in the Sect. 24.2.

The Spectral Acceleration Maps are provided in two sets of eight maps each; a set of maps for the short period (T = 0.2 sec) a set for the long period (T = 1.0 sec).

Eectronic values of mapped acceleration parameters, and other seismic design parameters, are provided at the USGS Web site at http://earthquake.usgs.gov/designmaps, or through the SEI Web site at http://content.seinstitute.org.

24.2 Soil Modified Response Spectral Acceleration: S_{MS}, S_{M1}

To obtain the soil modified response spectral acceleration S_{MS} for the short period and S_{M1} for the period $T_1 = 1$ sec the values of the mapped response spectral accelerations S_S and S_1, for the short period ($T_s = 0.2$ sec) and for the period $T_1 = 1$ sec must be modified by Site Class Coefficients designated, respectively, as F_a and F_v, namely,

$$S_{MS} = F_a S_S \tag{24.1}$$

and

$$S_{M1} = F_v S_1 \tag{24.2}$$

where F_a is the Site Class Coefficient for the short period and F_v is the Site Class Coefficient for period $T_1 = 1$ sec. Numerical value for the coefficients F_a and F_v are given, respectively, in Tables 24.1 and 24.2 as functions of the Site Class and the values for S_S and S_1. In Tables 24.1 and 24.2, straight-light interpolation for intermediate values of mapped spectral response acceleration can be used for both short and long periods. Site Class classification and definition are described in Sect. 24.5.

24.3 Design Response Spectral Acceleration: S_{DS}, S_{D1}

The Design Response Spectral Accelerations (for 5% damping), S_{DS} for the short period and S_{D1} for the period $T = 1$ sec are calculated by

$$S_{DS} = \frac{2}{3} S_{MS} \tag{24.3}$$

and

$$S_{D1} = \frac{2}{3} S_{M1} \tag{24.4}$$

where S_{MS} is the Soil Modified Response Spectral Acceleration for the short period given by Eq. (24.1) and S_{M1} is the Soil Modified Earthquake Response Spectral Acceleration for the period $T = 1$ sec given by Eq. (24.2).

Table 24.1   Site coefficient (F_a) [IBC-2018: Table 1613.2.3 (1)]

Site class	Mapped risk targeted maximum considered earthquake (MCE$_R$) Spectral response acceleration at short periods					
	$S_S \leq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S = 1.25$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.9	0.9	0.9	0.9	0.9	0.9
C	1.3	1.3	1.2	1.2	1.2	1.2
D	1.6	1.4	1.2	1.1	1.0	1.0
E	2.4	1.7	1.3	[a]	[a]	[a]
F	[a]	[a]	[a]	[a]	[a]	[a]

[a]Values shall be determined in accordance with Section 11.4.8 of ASCE 7

Table 24.2   Site coefficient (F_v) [IBC-2018: Table 1613.2.3(2)]

Site class	Mapped risk targeted maximum considered earthquake (MCE$_R$) Spectral response acceleration at 1-Second period					
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 = 0.5$	$S_1 \geq 0.6$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.8	0.8	0.8	0.8	0.8	0.8
C	1.5	1.5	1.5	1.5	1.5	1.4
D	2.4	2.2[a]	2.0[a]	1.9[a]	1.8[a]	1.7[a]
E	4.2	3.3[a]	2.8[a]	2.4[a]	2.2[a]	2.0[a]
F	[b]	[b]	[b]	[b]	[b]	[b]

[a]See requirements for site-specific ground motions in Section 11.4.8 of ASCE 7
[b]Values shall be determined in accordance with Section 11.4.8 of ASCE 7

24.4   Site Class Definition: A, B . . .F

The classification of the Site Class (A, B, C, D, E or F) where the structure is located is based on the average properties in the top 100 ft of the soil profile according to the description given in Table 24.3. The Site Class is to be estimated or measured at the building site by a geotechnical engineer or by a geologist/seismologist.

Table 24.3   Site class definitions [ASCE 7-16: Table 20.3-1]

Site class	Shear wave velocity, $\bar{v}_s$	Standard penetration blow/ft, $\bar{N}$ or $\bar{N}_{ch}$	Undrained shear strength, $\bar{s}_u$
A. Hard rock	>5000 ft/s	NA	NA
B. Rock	2500 – 5000 ft/s	NA	NA
C.Very dense soil and soft rock	1200 – 2500 ft/s	>50	>2000 psf
D. Stiff soil	600 – 1200 ft/s	15 to 50	1000 – 2000 psf
E. Soft clay soil	<600 ft/s	<15	<1000 psf
	Any profile with more than 10 ft of soil having the following characteristics: Plasticity index $PI > 20$ Moisture content $w \geq 40\%$ Undrained shear strength, $\bar{s}_u < 500 \ psf$		
F. Soil requiring site response analysis in accordance with ASCE 7-16 Section 21.1	ASCE 7-16 Section 20.3.1		

24.5   Risk Category and Seismic Importance Factor (I$_e$)

Each Structure is assigned a Seismic Risk Category based on the use of the building. An Importance Factor (I_e) is then assigned to each Risk Category. Four category designations (I, II, III and IV [defined in IBC-2018 Table 1604.5 and ASCE-16 Table 1.5-1]) and corresponding values of the Importance Factor (I_e) are defined and assigned as described in Table 24.4.

Table 24.4 Importance factor (I$_e$) by risk category of buildings and other structures for earthquake loads [IBC-2018: Table 1604.5 and ASCE 7-16: Table 1.5-2]

Brief description of occupancy or functions of structure (More detail in IBC 2018: Table 1604.5)	Risk category	Seismic importance factor, I$_e$
Miscellaneous structures	I	1.0
Standard occupancy	II	1.0
Hazardous structure	III	1.25
Essential structures	IV	1.50

24.6   Seismic Design Category (A, B, C, D, E and F)

The IBC-2018 stipulates that every structure must be designed and constructed to resist the effects of earthquake ground motions as required for the assigned Seismic Design Category. This assignment is based on the Risk Category described in Sect. 24.5 and the design response spectral acceleration coefficients S_{DS} and S_{D1}, determined in accordance with Sect. 24.3. Each building and structure should be assigned to the most severe seismic design category obtained from Table 24.5 or from Table 24.6, irrespective of the actual fundamental period, T, of the structure.

Where $S1$ is less than or equal to 0.04 and S_S is less than or equal to 0.15, the structure is permitted to be assigned to Seismic Design Category A.

Table 24.5 Seismic design category for short period response acceleration [IBC-2018: 1613.2.5(1)]

	Risk category		
VALUE OF S$_{DS}$	I or II	III	IV
$S_{DS} < 0.167$ g	A	A	A
0.167 g $\leq S_{DS} < 0.33$ g	B	B	C
0.33 g $\leq S_{DS} < 0.50$ g	C	C	D
0.50 g $\leq S_{DS}$	D	D	D

Table 24.6 Seismic design category for T = 1 sec period response acceleration [IBC-2018: 1613.2.5(2)]

	Risk category		
VALUE OF S$_{D1}$	I or II	III	IV
$S_{D1} < 0.067$ g	A	A	A
0.067 g $\leq S_{D1} < 0.133$ g	B	B	C
0.133 g $\leq S_{D1} < 0.20$ g	C	C	D
0.20 g $\leq S_{D1}$	D	D	D

Note: Seismic Risk Category I, II, and III structures located on sites with mapped maximum considered earthquake spectral response acceleration at 1-sec period, S_1, equal to or greater than 0.75 g, shall be assigned to Seismic Design Category E, and Risk Category IV structures located on such sites shall be assigned to Seismic Design Category F

The ASCE 7-16 provides for an exception in the determination of the Response Spectral Acceleration, which in turn affects the value for the Design Response Spectral Acceleration and the final Seismic Design Category for the structure.

> *Exception:* For regular structures having five or fewer number of stories and having a fundamental period $T \leq 0.5$ sec (see Section 24.8 for estimation of T), the value for the mapped short period needs not exceed $S_S = 1.5$g (ASCE 7-16 Section 12.8.1.3).

The MCE$_R$ response can be determined by multiplying the design response spectrum by 1.5 in accordance with ASCE 7-16 (Section 11.4.6).

24.7   Design Response Spectral Curve: S$_a$ Vs. T

The general procedure to plot the Design Response Spectrum Curve for a given geographical location results in a plot as the one shown in Fig. 24.1. This plot provides the Response Spectral Acceleration S_a as a function of the fundamental period T of the structure. The construction of the Design Response Spectral Curve requires the calculation of the following parameters:

$$T_0 = 0.2 \frac{S_{D1}}{S_{DS}} \quad \text{and} \quad T_s = \frac{S_{D1}}{S_{DS}} \tag{24.5}$$

where S_{DS} and S_{D1} are, respectively, the Design Response Spectral Acceleration for the short period [Eq. (24.3)] and the Design Response Spectral Acceleration for the period T = 1 sec [Eq. (24.4)]. T_L is the long-period transition period(s).
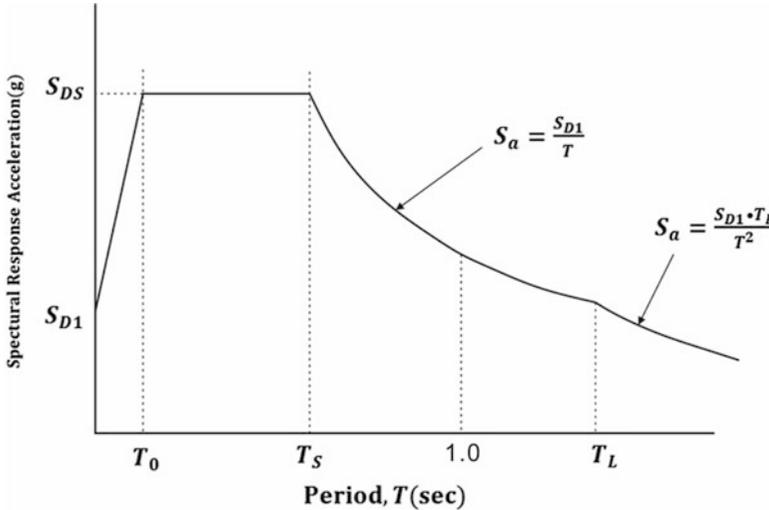

Fig. 24.1 Design response spectrum plot

The construction of the Design Response Spectrum Plot for a given geographical location such as the plot shown in Fig. 24.1, can be obtained by entering the values of T$_0$, T$_s$, as defined in Eq. (24.5) and 1.0 in the abscissa and the values of the Design Spectral Acceleration, S$_{D1}$ and S$_{Ds}$, in the ordinate axis Then, on the left, two straight lines are drawn through established points, (0, S$_{D1}$), (T$_0$, S$_{DS}$) and (T$_s$, S$_{Ds}$). For the period of $0 < T < T_0$, the straight line can be expressed as, $S_a = S_{DS}\left(0.4 + 0.6\frac{T}{T_0}\right)$.

Finally, a hyperbolic curve defined by the function $S_a = S_{D1}/T$ is drawn on the right portion of the plot from $T_S < T < T_L$ as shown in Fig. 24.1. Where $T > T_L, S_a = \frac{S_{D1}T_L}{T^2}$ (Fig. 24.2).

Fig. 24.2 Screen caption for the inputs for Illustrative Example 24.1. (Source: USGS Web site)

Illustrative Example 24.1
Use the USGS Seismic Design tool to determine Seismic Design Category at a location with Zip Code 10001 corresponding to Central Latitude = 40.750 and Central Longitude = −73.997. Assume Risk Category = I or II and Soil Class = D (Stiff Soil). Using the Tables 24.5 and 24.6, $F_a = 1.576$ and $F_v = 2.40$.

Results: The following results are as follows:

For $T_s = 0.2$ sec: $S_S = 0.280$ g, $S_{MS} = F_aSs = 0.441$ g,
$S_{DS} = \frac{2}{3} S_{MS} = 0.294$ g, Seismic Design Category = B
For $T_1 = 1.0$ sec: $S_1 = 0.072$ g, $S_{M1} = F_VS_1 = 0.172$ g,
$S_{D1} = \frac{2}{3} S_{M1} = 0.115$ g, Seismic Design Category = B
If two categories are different, the most severe category must be used. Therefore, the Seismic Design
    Category is B.

24.8   Determination of the Fundamental Period

The ASCE 7-16 allows the determination of the fundamental period of the building using: (1) approximate empirical formulas, or (2) calculations by rational analysis using structural properties of the resisting elements in a properly substantiated analysis. In this relation, the Code provides the following information:

1. Natural Period determined using approximate formulas
   The fundamental period of the building may be taken as the approximate value T_a calculated by the following formula:

$$T_a = C_t h_n^x \tag{24.6}$$

where

h_n = total height of the building in feet, C_t and x are determined from Table 12.8-2 (ASCE 7-16). These values are depending on structural types (Table 24.7).

Table 24.7 Values of approximate period parameters C_t and x[ASCE 7-16: Table 12.8-2]

Structure type	C_t	x
Moment-resisting frame system in which the frames resist 100% of the required seismic force and are not enclosed or adjoined by components that are more rigid and will prevent the frames from deflecting where subjected to seismic forces:		
Steel moment-resisting frames	0.028	0.8
Concrete moment-resisting frames	0.016	0.9
Steel eccentrically braced frames in accordance with Table 12.2-1 lines B1 or D1 (ASCE 7-16)	0.03	0.75
Steel buckling-restrained braced frames	0.03	0.75
All other structural systems	0.02	0.75

Alternatively, the fundamental natural period of moment-resisting frames (steel or concrete) not exceeding 12 stories in height and having a minimum story height of 10 ft may be approximately determined as

$$T_a = 0.1N \tag{24.7}$$

where N is the number of stories.

2. Natural Period calculated by rational analysis.
   The fundamental period of the building, T, in the direction under consideration may be calculated using the structural properties of resisting elements in a properly substantiated analysis. However, the ASCE 7-16 requires that the calculated fundamental period T be less or equal to the coefficient C_u times the value of the period obtained by an approximate formula, that is

$$T \leq C_u T_a \tag{24.8}$$

where the upper limit coefficient C_u is given in Table 24.8 as a function of the design response spectral acceleration S_{D1} corresponding to the period $T = 1$ sec.

Table 24.8 Upper limit coefficient C_u [ASCE 7-16: Table 12.8-1]

| Design response spectral acceleration S_{D1}	Upper limit coefficient C_u
<0.4	1.4
0.3	1.4
0.2	1.5
0.15	1.6
>0.1	1.7

Note: Upper limit calculated for T does not apply for interstory drift determination

24.9   Minimum Lateral Force Procedure [ASCE 7-16: Section 1.4.3]

The Minimum Lateral Force Procedure is applicable to regular and irregular structures assigned to Seismic Design Category A in accordance with ASCE 7-16 Section 11.7. This procedure requires a complete lateral-force-resistant system designed to resist minimum forces, F_x, simultaneously applied at the various levels of the building as shown in Fig. 24.3. These minimum forces are calculated by

$$F_x = 0.01 \ w_x \tag{24.9}$$

in which w_x is the seismic weight allocated to level x of the building.

$$V = 0.01(W_t + W_3 + W_2 + W_1)$$
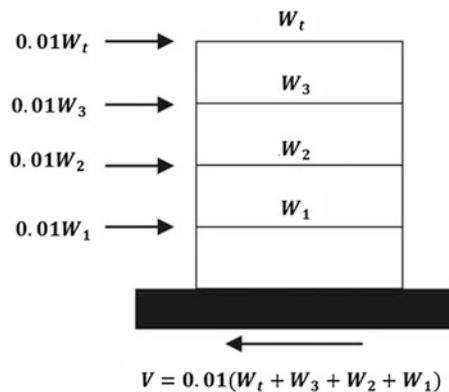
Fig. 24.3 Force distribution for Minimum Lateral Force Procedure

In the Minimum Lateral Force Procedure, the design seismic forces may be applied independently in two orthogonal directions (orthogonal combined effects are permitted to be neglected).

24.10 Simplified Lateral Force Analysis Procedure [ASCE 7-16: Section 12.14.8 and IBC 2018 Section 1613.2.5.2]

The use of the Simplified Analysis Procedure is permitted for one- or two- story bearing wall structures with limited irregularity (e.g, light-frame wood structural bearing wall). The simplified lateral-force procedure is only applicable to structures a permitted by Table ASCE 7-16:

Table 12.6-1. Generally, this is not intended to use for routine practice. Also, the estimated base shear is generally conservative compared to other IBC/ASCE lateral load procedure.

24.10.1 Seismic Base Shear

The seismic base shear, V, in a given direction shall be determined with the following equation:

$$V = \frac{1.2 S_{DS}}{R} W \qquad (24.10)$$

where

S_{DS} = The Design Response Spectral Acceleration for the Short Period. (Eq. 24.3).
R = The Response Modification Factor from Table 24.9.
W = Seismic weight of the structure that includes the dead weight and any permanent weight on the building. It also includes (1) a minimum of 25% of the live load, (2) partition load or a minimum of 10 pounds per square foot where partition load is included in the floor load design, (3) total operating weight of permanent equipment, and (4) twenty percent of flat roof snow load where the design flat roof snow load exceeds 30 pounds per square foot.
Note: The design story drift (Δ) may be taken as 1% of story height.

24.10.2 Response Modification Factor R

The Response Modification Factor R used in the calculation of base shear force V and of the lateral forces F_x, respectively, given by Eqs. (24.10) and (24.11) serve to reduce the design loads to account for the ductility in the structural system as well as for increase damping as the structure is subjected to large deformations beyond the elastic range. Table 24.9 contains an abbreviated set of values for R obtained from a much more detailed table provided by ASCE 7-16.

Table 24.9 Response modification factors R and deflection amplification factor C_d [ASCE 7-16: Abbreviated Table 12.2-11]

Basis seismic force resisting system	Response modifications coefficient, R	Deflection amplification factor, C_d
Bearing Wall Systems		
Special reinforced concrete shear walls	5 1/2	5
Ordinary reinforced concrete shear walls	4 1/2	4
Special reinforced masonry shear walls	5	3 1/2
Ordinary reinforced masonry shear walls	2 1/2	1 3/4
Building Frame Systems		
Special steel concentrically braced frames	6	5
Special reinforced concrete shear walls	6	5
Moment Resisting Frame Systems		
Special steel moment frames	8	5 1/2

Table 24.9 (continued)

Basis seismic force resisting system	Response modifications coefficient, R	Deflection amplification factor, C_d
Intermediate steel moment frames	6	−5
Special steel truss moment frames	7	5 1/2
Ordinary steel moment frames	4	3 1/2
Special reinforced concrete moment frames	8	5 1/2
Dual Systems with Intermediate Moment Frames		
Special steel concentrically braced frames[a]	6	5
Ordinary steel concentrically braced frames[a]	5	4 1/2
Special reinforced concrete shear walls	6	5
Ordinary reinforced concrete shear walls	5 1/2	4 1/2
Inverted Pendulum Systems and Cantilevered Column Systems		
Special steel moment frames	2 1/2	2 1/2
Ordinary steel moment frames	1 1/4	2 1/2

[a]Ordinary moment frame is permitted to be used in lieu of intermediate moment frame in Seismic Design Categories B and C

24.10.3 Vertical Distribution of Lateral Forces

Lateral equivalent forces, F_x, applied at each level of the building shall be calculated by the following equation:

$$F_x = \frac{F\,S_{DS}}{R} w_x \qquad (24.11)$$

where

w_x is the portion of the Seismic Weight, W allocated at level x of the building, and F is 1.0 for one-story building, 1.1 for two-story building, and 1.2 for three-story building.

24.11 Equivalent Lateral Force Procedure [ASCE 7-16: Section 12.8]

The earthquake resistant design provisions in the International Building Code (IBC-2018) refers to mainly on the ASCE 7-16. Originally, 1997 NEHRP publication (National Earthquake Hazard Reduction Program) that is distributed by FEMA (Federal Emergency Management Agency) are used to develop IBC-2000. The key provisions of the ASCE 7-16 for the Equivalent Seismic Lateral Force Method are presented and in this section.

The ASCE 7-16 stipulates that the structure should be designed for a total base shear force calculated by the formula:

$$V = C_S W \qquad (24.12)$$

in which W is seismic weight of the structure that includes the dead weight and any permanent weight

on the building. It also includes (1) a minimum of 25% of the reduced live load, (2) partition load or a minimum of 10 pounds per square foot where partition load is included in the floor load design, (3) total operating weight of permanent equipment, and (4) twenty percent of flat roof snow load where the design flat roof snow load exceeds 30 pounds per square foot.

The coefficient C_S is the Seismic Response Coefficient given by

$$C_S = \frac{S_{DS}}{R/I_e} \tag{24.13}$$

in which

S_{DS} is the Design Spectral Acceleration for short period defined by Eq. (24.3).
R is the response modification factor from Table 24.9.
I_e is the Occupancy Importance Factor described in Sect. 24.8.

The value of the seismic response coefficient, C_S, calculated by Eq. (24.13) cannot be less than 0.01, nor can it exceed the following:

When $T \leq T_L$,

$$C_S \leq \frac{S_{D1}}{(R/I_e)T} \tag{24.14a}$$

When $T > T_L$,

$$C_S \leq \frac{S_{DS}T_L}{T^2(R/I_e)} \tag{24.14a}$$

but shall not be less than

$$C_S \geq 0.044 S_{DS}I_e \geq 0.01 \tag{24.15}$$

and for buildings in categories E and F and buildings for which $S_1 \geq 0.6$ g, the value of CS shall not be less than

$$C_S \geq \frac{0.5 S_1}{R/I_e} \tag{24.16}$$

where

R is the Response Modification Factor from Table 24.9.
I_e is the Importance Factor given in Table 24.4.
S_{DI} is the Design Response Spectral Acceleration defined by Eq. (24.4).
S_1 is the mapped earthquake response spectral; acceleration at T = 1-sec period determined in accordance with Sect. 24.1.
T_L is the long-period transition period in ASCE 7-16 Section 11.4.5.

24.11.1 Distribution of Lateral Forces [ASCE 7-16: Section 12.8.3]

The total base shear force V calculated from Eq. (24.12) is distributed over the height of the structure as a lateral force, F_x at each level calculated by

$$F_x = \frac{w_x h_x^k}{\sum\limits_{i=1}^{N} w_i h_i^k} V \tag{24.17}$$

where

V = total base shear
N = total number of stories above the base of the building
h_x = height of level x
w_x = seismic weight assigned to 5 the x level of the building
k = 1.0 for buildings having a period $T \leq 0.5$ sec
k = 2.0 for buildings having a period $T \geq 2.5$ sec
k is determined by linear interpolation for buildings having a period $0.5 < T < 2.5$ sec

The distribution of the lateral forces F_x is shown in Fig. 24.4 for a multistory building. The ASCE 7-16 stipulate that the force F_x at level x, be applied over the area of the building according to the mass distribution at that level.

The story shear, V_x, is the sum of the force F_x above that story. The seismic design story shear in any story shall be determined from the following equation:

$$V_x = \sum_{i=x}^{n} F_i \tag{24.18}$$

where F_i = the protion of the seismic base shear (V) induced at level, i.
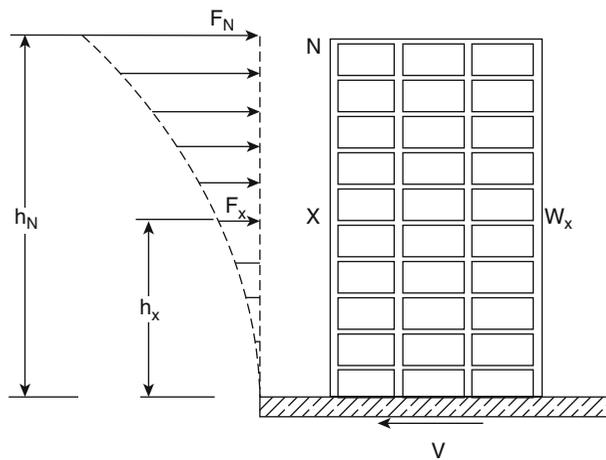

Fig. 24.4 Vertical distribution of the base shear force

24.11.2 Overturning Moments [ASCE 7-16: Section 12.8.5]

The ASCE 7-16 requires that overturning moments be determined at each level of the building. The overturning moment is calculated by static from the equivalent lateral forces F_x [Eq. (24.17)] applied at the levels of the building above the level under consideration. However, the code allows for a reduction in the design overturning moment. Hence, the overturning moment M_x at level x of the building is given by

$$M_x = \sum_{i=x+i}^{N} F_i(h_i - h_x) \tag{24.19}$$

In accordance with ASCE 7-16 Section 2.13.4, overturning effects at the soil–foundation interface are permitted to be taken as at least 75% for foundations of structures that satisfy both of the following conditions. This 25% reduction is permitted when higher mode are unlikely to occur simultaneously with mode 1.

24.11.3 Horizontal Torsional Moment

The ASCE 7-16 states that consideration should be given for the increased shear force resulting from horizontal torsion where diaphragms are not flexible. Diaphragms are considered flexible when the maximum lateral deformation of the diaphragm is more than twice the average story drift of the associated stories. The torsional moment at a given story results from the difference in location of the center of the mass between the applied seismic lateral forces at the levels above that story and the center of stiffness of the resisting elements of the story. The code also requires that when diaphragms are not flexible an accidental eccentricity be added by displacing the center of mass in five percent of the building dimension at that level perpendicular to the direction of the applied forces.

Further provisions in the code account for torsional irregularities in buildings in Seismic Design Categories C through F by increasing the accidental torsion by an amplification factor A, determined as

$$A = \left(\frac{\delta_{\max}}{1.2\delta_{avg}}\right)^2 \leq 3.0 \tag{24.20}$$

Where

$\delta_{\max}$ = The maximum displacement at level x
δ_{avg} = The average displacement at the extreme points of the structure at level x

24.11.4 *P*-Delta Effect (P–Δ) [ASCE 7-16: Section 12.8.7]

The $P - \Delta$ effect was presented and discussed in Sect. 24.10 of Chap. 24. The ASCE 7-16 treats the $P - \Delta$ effects in exactly the same manner as in the UBC-97, except that the calculation of the ratio θ_x, at level x, between the secondary overturning moment, M_x', and the primary moment M_x includes the Deflection Amplification Factor C_d. That is, in the ASCE 7-16 the ratio θ_x is calculated by

$$\theta_x = \frac{M'_x}{M_x} = \frac{P_x \Delta_x I_e}{V_x h_{sx} C_d} \qquad (24.20)$$

where:

P_x = total weight at level x and above, no individual load factor need exceed 1.0.
Δ_x = Drift of story x
V_x = shear force of story x
h_{sx} = height of story x
C_d = Deflection Amplitude Factor (Table 24.9)
I_e = Importance Factor determined in accordance to Sect. 24.5

24.11.5 Story Drift [ASCE 7-16: Sect. 12.8.6]

The ASCE 7-16 (Sect. 12.8.6) specifies that the design deflection δ_x, at level x, be determined in accordance with the following equation:

$$\delta_x = \frac{C_d \delta_{xe}}{I_e} \qquad (24.21)$$

where

C_d = Deflection Amplification Factor (Table 24.9)
δ_{xe} = Deflection determined by an elastic analysis of the seismic-force-resisting system
I_e = Importance Factor determined in accordance to Sect. 24.5

The design story drift, Δ, is computed as the difference of the lateral deflections of the center of mass at the top and bottom levels of the story under consideration. However, for structures assigned to Seismic Design Categories C, D, E or F (see Sect. 24.6) with plan irregularities, the design story drift Δ shall be computed as the largest difference of the deflection along any of the edges of the structure at the top and bottom levels of the story under consideration.

The ASCE 7-16 specified a maximum allowable story drift Δ_a which depends on the type of building and on the Risk Category. Table 24.10 provides values for Δ_a, the allowable story drift. Therefore, the limitation on the story drift, Δ_x may be expressed as:

$$\Delta_x = (\delta_x - \delta_{x-1}) \leq \Delta_a \qquad (24.22)$$

where

δ_x is the lateral displacement at level x calculated by Eq. (24.21).
Δ_a is the allowable story drift from Table 24.10.

Table 24.10   Allowable story drift (Δ_a) [ASCE 7-16: Table 12.12-1][a, b]

	Risk category		
Building	I or II	III	IV
Buildings 4 stories in height (other than masonry)	$0.025 \, h_{sx}$[c]	$0.020 \, h_{sx}$	$0.015 \, h_{sx}$
Masonry cantilever shear wall bldgs.	$0.010 \, h_{sx}$	$0.010 \, h_{sx}$	$0.010 \, h_{sx}$
Other masonry shear wall buildings[d]	$0.007 \, h_{sx}$	$0.007 \, h_{sx}$	$0.007 \, h_{sx}$
All other buildings	$0.020 \, h_{sx}$	$0.015 \, h_{sx}$	$0.010 \, h_{sx}$

[a]h_{sx} = story height below level x
[b]For seismic force-resisting systems comprised solely of moment frames in Seismic Design Categories D, E, and F, the allowable story drift shall comply with the requirements of Section 12.12.1.1
[c]There shall be no drift limit for single-story structures with interior walls, partitions, ceilings, and exterior wall systems that have been designed to accommodate the story drifts. The structure separation requirement of ASCE 7-16 Section 12.12.3 is not waived
[d]Structures in which the basic structural system consists of masonry shear walls designed as vertical elements cantilevered from their base or foundation support which are so constructed that moment transfer between shear walls (coupling) is negligible

24.12   Redundancy [ASCE 7-16: Section 12.3.4]

Redundancy is an important characteristic of a structure to provide multiple paths of resistance. Higher redundancy indicates better reliability. When the redundancy is low, inelastic behavior during major seismic event can cause the collapse of the structure. When the structures are potentially exposed to severe inelastic demand, the structure should be designed with high redundancy to increase the numbers of load paths. Loads can be redirected to be distributed to other lateral-force-resisting elements. The redundancy factor is applied to increase the horizontal forces (ASCE 7-16: Section 12.3.4). The redundancy factor value varies between 1.0 and 1.3.

The value of ρ is 1.0 for the following type of calculation:

- Structures assigned to Seismic Design Category B or C.
- Drift calculation and P-delta effects.
- Design of nonstructural components.
- Design of nonbuilding structures that are not similar to buildings.
- Design of systems and members such as collector elements, splices, and their connections where overstrength factor are used.
- Diaphragm loads and structures with damping systems
- Design of structural walls for out-of-plane forces, including their anchorage.

For structures assigned to Seismic Design Category D, E, or F, ρ is 1.3 unless one of the following two conditions is met, whereby ρ is permitted to be taken as 1.0:

1. Each story resisting more than 35% of the base shear in the direction of interest shall comply with Table 24.11 (ASCE 7-16 Section Table 12.3-3).
2. Structures are regular in plan at all levels, provided that the seismic force-resisting systems consist of at least two bays of seismic force-resisting perimeter framing on each side of the structure in each orthogonal direction at each story resisting more than 35% of the base shear.

Table 24.11 Requirements for each story resisting more than 35% of the base shear [ASCE 7-16: Table 12.3-3]

Lateral force-resisting element	Requirement
Braced frames	Removal of an individual brace, or connection thereto, would not result in more than a 33% reduction in story strength, nor does the resulting system have an extreme torsional irregularity (horizontal structural irregularity type 1b)
Moment frames	Loss of moment resistance at the beam-to-column connections at both ends of a single beam would not result in more than a 33% reduction in story strength, nor does the resulting system have an extreme torsional irregularity (horizontal structural irregularity type 1b).
Shear walls or wall pier with a height-to-length ratio of greater than 1.0	Removal of a shear wall or wall pier with a height-to-length ratio greater than 1.0 within any story, or collector connections thereto, would not result in more than a 33% reduction in story strength, nor does the resulting system have an extreme torsional irregularity (horizontal structural irregularity type 1b).
Cantilever columns	Loss of moment resistance at the base connections of any single cantilever column would not result in more than a 33% reduction in story strength, nor does the resulting system have an extreme torsional irregularity (horizontal structural irregularity type 1b).
Other	No requirements

24.13 Earthquake Load Effect [ASCE 7-16 Section 12.4.2]

The ASCE 7-16 specifies that the Earthquake Load, E, on a structural element be calculated as the sum of the effects due to the lateral seismic forces amplified by the redundancy factor ρ plus the effect of the vertical component of the earthquake ground motion. Namely,

$$E = \rho Q_E + 0.2 S_{DS} D \tag{24.24}$$

where

Q_E = the effect of horizontal seismic forces
ρ = Redundancy Factor to be taken as the largest of the values for ρ_i obtained in accordance to Sect. 24.1
S_{DS} = Design Spectral Response Acceleration for short periods calculated by Eq. (24.4)
D = vertical seismic load on an element

24.14 Building Irregularities [ASCE 7-16 Section 12.3.2.1]

The Equivalent Lateral Force Procedure is based on the assumptions and characteristics of regular structures. Building irregularities are the cause of stress concentrations leading to structural damage and poor performance. If the structure has irregularities, it must comply with additional code requirements and assignment of seismic design categories listed in Table 12.3-1. Figures 24.5 and 24.8 show, respectively, examples of plan irregularities and of vertical irregularities (Fig. 24.6).
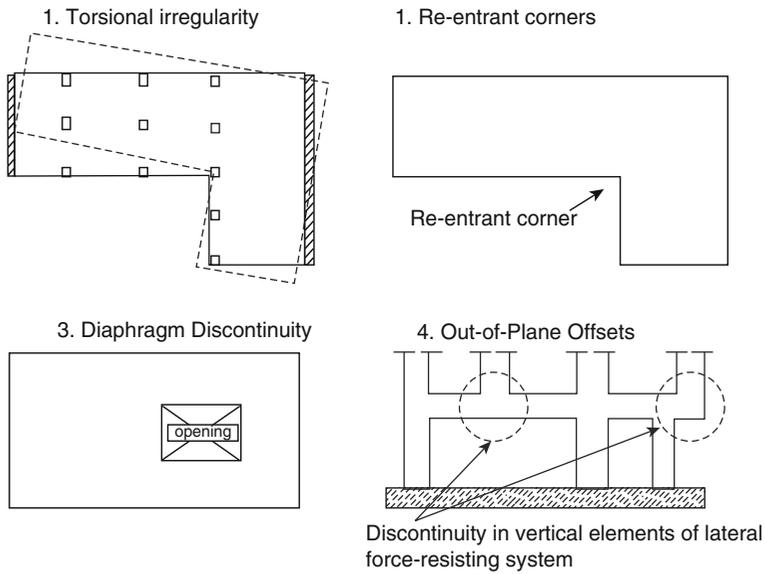
1. Torsional irregularity

1. Re-entrant corners

Re-entrant corner

3. Diaphragm Discontinuity

opening

4. Out-of-Plane Offsets

Discontinuity in vertical elements of lateral
force-resisting system

Fig. 24.5 Examples of structural plan irregularities

1. Stiffness – Soft Story

Stiff
resisting
elements

2. Weight (Mass)

Heavy Mass

3. Vertical Geometric

4. In-Plane Discontinuity in Vertical
Lateral Force-resisting Elements

5. Discontinuity in Strength – Weak Story
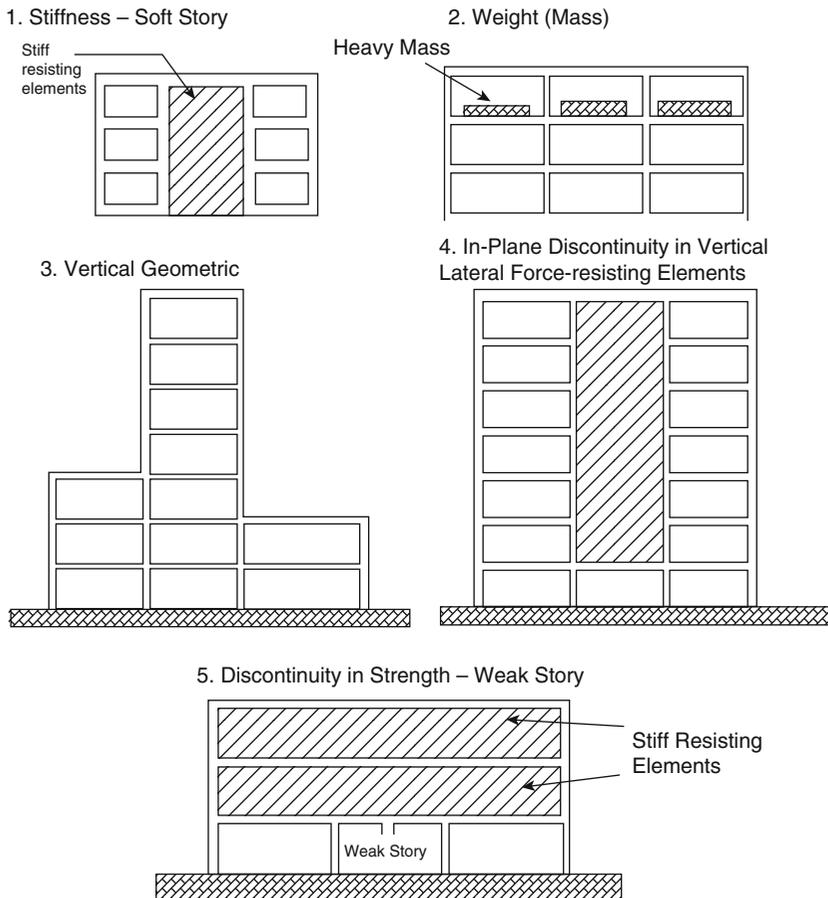
Stiff Resisting
Elements

Weak Story

Fig. 24.6 Examples of vertical structural irregularities

Illustrative Example 24.2 Using the Equivalent Lateral Force Method of the IBC-2018 and ASCE 7-16, perform the seismic analysis of four-story concrete building of Illustrative Example 23.1 presented in Chap. 23. The building site is in Seattle, Washington with Zip Code 94704.

Solution:

The following values are obtained from Illustrative Example 24.1:

Seismic weights:

$$w_1 = w_2 = w_3 = 781.1 \text{ kip}$$
$$w_4 = 645.1 \text{ kip}$$

Total weight of the building:

$$W = 781.1 \times 3 \times 645.1 = 3012.4 \text{ kip}$$

Fundamental period:

$T_a = C_t \ h_N^x$	Eq. (24.6) repeated

where

$C_t = 0.016$ (for reinforced concrete moment-resisting frame)
$x = 0.9$
$h_N = 48$ ft (total height of the building)

Then

$T = 0.016 \times 48^{0.9} = 0.52 \text{ sec}$

Importance Factor (Warehouse)

$I = 1.0$	(Table 24.4)

Mapped Response Spectral Acceleration:

(Use USGS Web site at http://earthquake.usgs.gov/designmaps)

Results:

Short Period: ($T = 0.2$ sec):	$S_S = 1.360$ g
Long Period ($T = 1.0$ sec)::	$S_1 = 0.527$ g

The response spectra are obtained for Illustrative Example 24.2.

Site Class = B for rock	(Table 24.3)
Site coefficient $F_a = 1.0$	(Table 24.1)
Site Coefficient $F_B = 1.0$	(Table 24.2)

Soil Modified Response Spectral Acceleration:

$S_{MS} = F_a S_S = 1.360$	by Eq. (24.1)
$S_{M1} = F_v S_1 = 0.527$	by Eq. (24.2)

Design Response Spectral Acceleration:

$S_{DS} = \frac{2}{3} S_{MS} = 0.907$	by Eq. (24.3)
$S_{D1} = \frac{2}{3} S_{M1} = 0.351$	by Eq. (24.4)

Response Modification Factor: (Table 24.9)

$R = 8$ (Special Reinforced Concrete Moment Frame).

Seismic Design Category $=$ D (Tables 24.5 and 24.6)
Seismic Coefficient

$C_S = \frac{S_{DS}}{R/I_e} = \frac{0.907}{8/1.0} = 0.113$	by Eq. (24.13)

Check maximum value for C_S:
Since $T \leq T_L = 6\text{sec}$

$C_S \leq \frac{S_{D1}}{(R/I_e)T} = \frac{0.351}{(8/1)0.52} = 0.084$	by Eq. (24.14a)

Check minimum value for C_S:

$C_S \geq 0.044 S_{D1} I_e$ $= 0.044 \times 0.351 \times 1.0 = 0.0154 \geq 0.01$	OK	by Eq. (24.15)

Then

$C_S = 0.084$

Base Shear Force:

$V = C_S W$	Eq. (24.12) repeated

$$V = 0.084 \times 3012.4 = 253.04 \text{ kips}$$

Vertical Force Distribution:

$F_x = \dfrac{w_x h_x^k}{\sum\limits_{i=1}^{N} w_i h_i^k} V$	Eq. (24.17) repeated

$$T = 0.52 \text{ sec} > 0.5 \text{ sec}$$

k = 1.01 (by interpolation)	(Sect. 24.13)

Table 24.12 contains the necessary calculations to determine F_x at the various levels of the building in Illustrative Example 24.2.

Overturning Moments:

$$M_x = \sum_{i=x+1}^{N} F_i(h_i - h_x) \qquad \text{Eq. (24.18) repeated}$$

Calculated values for the overturning moments at the various levels of the building are shown in the last column of Table 24.12.

Story Drift and Lateral Displacement:

For a structure modeled as a shear building the drifts, Δ_x, or relative displacement between consecutive levels is given by

$$\Delta_x = \frac{V_x}{K_x}$$

where

V_x is the story shear force calculated in Table 24.12.
K_x is the stiffness of the story calculated in the solution of Illustrative Example 24.1, now listed in Table 24.13.

Lateral Displacement and Story Drift:

The elastic lateral displacement δ_{ex} may be calculated at each level of the building by adding story drifts for the story at that level and those below as shown calculated in Table 24.13.
The design lateral displacement, δ_x, is then determined by

$$\delta_x = \frac{C_d \delta_{xe}}{I} \qquad \text{Eq. (24.21) repeated}$$

$C_d = 5.5$	(Deflection Amplification Factor)	(Table 24.9)
$I_e = 1.0$	(Importance Factor)	(Table 24.4)

Calculated values for the design lateral displacements, δ_x at the various levels of the building are shown in Table 24.13.

Table 24.12   Calculation of seismic lateral forces for Illustrative Example 24.2

Level	h_x (ft)	W_x (kip)	h_x^k (ft)	$w_x h_x^k$ (kip-ft)	F_x (kip)	V_x (kip)	M_x (kip-ft)
4	48	645.1	49.89	32,187	90.20	90.20	
3	36	781.1	37.31	29,146	81.68	171.88	1082
2	24	781.1	24.77	19,352	54.23	226.11	3145
1	12	781.1	12.30	9609	26.93	253.04	5858
				90,293			10,086

The inelastic story drift is then given by

$$\Delta_{Mx} = \delta_x - \delta_{x-1} \le \Delta_a \qquad \text{Eq. (24.22) repeated}$$

where the allowable story drift Δ_a is given by

$$\Delta_a = 0.025 h_x = 0.025 \times 144 = 3.6 \text{ in} \qquad \text{(Table 24.10)}$$

Values calculated for the inelastic story drift Δ_{Mx} shown in the last column of Table 24.13 are well below the allowable limit $\Delta_a = 3.6$ in.

Table 24.13 Lateral displacement and story drift for Illustrative Example 24.2

Level x	Story shear V_x (kip)	Story stiffness K_x (kip/in.)	Story drift (Elastic) Δ_x (in.)	Lateral displ. (Elastic) δ_{xe} (in.)	Lateral displ. (Inelastic) δ_x (in.)	Story drift (Inelastic) Δ_{Mx} (in.)	Allowable story drift (Inelastic) Δ_a (in.)
4	90.20	1757.7	0.0513	0.2972	1.63	0.28	3.6
3	171.88	1757.7	0.0978	0.2459	1.35	0.54	3.6
2	226.11	3236.0	0.0699	0.1481	0.81	0.38	3.6
1	253.04	3236.0	0.0782	0.0782	0.43	0.43	3.6

Redundancy Factor:

  The Seismic Design Category is assigned to be D, ρ is determined to be 1.3 without satisfying one of the two conditions presented in Sect. 24.12 is met.

$$\rho = 1.3$$

24.15 Summary

The International Building Code was prepared by the International Code Council (ICC), whose members are representatives of BOCA (Building Officials and Code Administrators), ICBO (International Conference of Building Officials) and SBCCI (Southern Building Code Congress International). The unified effort of all three agencies resulted in the International Building Code, which contains provisions for earthquake resistant design specified in the latest versions of several building codes. These codes are in current use in different regions of the country. This chapter shows the application of USGS Seismic Design tool to determine Seismic Design Category. This chapter is updated with current IBC-2018 and ASCE 7-16 using Equivalent Lateral Force Procedure. The modal response spectrum analysis is presented in Chap. 23.