Chapter 4

CURRENT STORAGE RACK SEISMIC DESIGN PRACTICES

4.1 OVERVIEW

Single selective steel pallet storage racks are typically designed for seismic forces using the equivalent lateral force procedures found in model building codes and in the RMI standard (ANSI 16.1-04). Storage rack structural systems generally are moment frames in the down-aisle (longitudinal direction) and braced frames in the cross-aisle direction (transverse direction). The figures in Chapter 1 illustrate typical structural configuration. Storage racks placed in the middle of a floor area usually are attached back to back (Figures 1-1 and 1-2) whereas single rack configurations are used near building walls. Storage racks in store areas accessible to the public typically are loaded with pallets; however, in some merchandising situations, merchandise is stored directly on the shelves. Intermediate shelf heights vary depending on merchandising needs. Storage racks typically are subjected to the greatest loads when pallets are fully loaded and all racks in a given rack configuration contain fully loaded pallets. Pallets are designed to carry the maximum pallet design load. Criteria for determining effective seismic weights of pallets used in rack seismic design procedures vary between the model building codes and the RMI standard.

Because storage racks normally do not have horizontal bracing at the shelf levels, they typically are treated as structures with flexible diaphragms and are evaluated analytically as two-dimensional structural systems. For seismic loads, equivalent lateral forces are applied to the structural model, and the member forces are determined. These forces then are added to other loads using a series of load combinations to obtain design member and connection forces. The design member loads then are checked against member capacities and/or allowable stresses. The capacities and allowable stresses take into account that the members generally are cold form steel members and that the columns are likely perforated. Moment connections typically are checked for the computed moments by comparing against tested capacities (usually based on monotonic tested values with a factor of safety). These capacities typically are provided by the rack manufacturer. In the cross-aisle direction, base plates and anchor bolts are checked for the computed uplift forces. Other connections are part of a manufacturer's standardized components and are rarely included as part of the permit application process. Current storage rack design practice does not include increasing any of the connection forces or moments by the Ω_o factor although that is inherent in current building code procedures for building structural systems. Also, there currently are no ductility type prescriptive requirements for connection designs. Currently, P-delta effects are typically considered by the moment magnifier for member design.

Since current storage rack seismic design practice revolves primarily around the level of design seismic loads, rack designers are interested primarily in the determination of those loads. The procedures currently used to compute rack seismic loads vary depending upon whether the prevailing requirements are from the model building codes, the *NEHRP Recommended Provisions* or ASCE 7, or the RMI standard. In some cases, there is more than one acceptable method of calculating seismic loads.

This chapter describes the factors used for determining seismic loads, each of the currently used procedures and design factors, and how members and connections are designed.

4.2 PALLET LOADS AND EFFECTIVE SEISMIC WEIGHTS

The pallet is the supporting structure for the basic unit that is stored on the typical single selective steel storage rack. There are many pallet sizes, shapes, materials, and types of construction; however, the vast majority of pallets used in the United States are what is termed the "GMA pallet." The GMA pallet may be a two-way pallet or a four-way pallet, depending upon whether the handling equipment can lift the pallet from two or four sides (Figure 4-1).

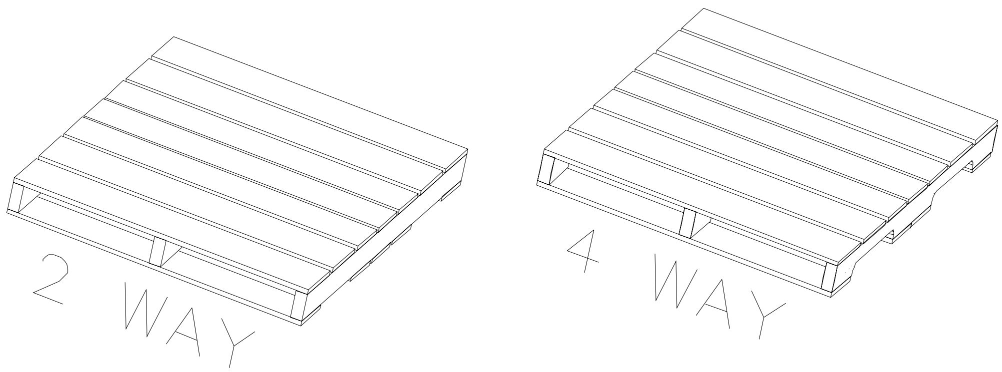

Figure 4.1 Typical pallets used in retail operations.

The GMA pallet is 40 inches wide by 48 inches long and is constructed of hard wood with three stringers running front-to-back and many regularly spaced deck boards oriented side to side on both the top and the bottom of the pallet.

The unit of the load to be stored on the rack includes both the pallet and the product on the pallet and is the unit that is individually handled by the fork-lifts or other handling equipment. The weight, size, and pallet type is specified by the operator of the rack system.

The unit load weight (PL) that the rack components are designed for is determined by the specifier of the rack system, who usually the end user.

The primary design weight is usually the maximum weight unit load ($PL_{Maximum}$) that will be present in the warehouse. If there is more than one weight unit load and the weights differ by a significant amount, then the second weight will also be specified and the locations of the storage of each weight load will be designated.

$PL_{Maximum}$ is used for the design of the load beams bending and deflection, the upright column axial capacity, and the cross-aisle frame bracing requirements (for vertical loads). The maximum pallet weight also is used to resist uplift when combined with cross-aisle seismic forces.

The average weight of the unit load ($PL_{Average}$) is the maximum total load expected in any individual rack row divided by the total number of storage positions in that row. This maximum total weight includes less-than-full-weight pallets and accounts for the number of storage positions normally expected to be empty. This is used for determining the down-aisle seismic force.

In addition to the product load (PL), the rack structure is designed for the effects of the structure dead load (DL) and any live load (LL) that might be present. The dead load includes the frame weight, the shelf beam weight, and the weight of any accessory items on the rack such as pallet supports or wire mesh decks. The dead load is typically much less than 5 percent of the weight of the product stored on the rack structure. The live load is typically 60 psf or less.

The product load includes the pallet weight and the weight of the product on the pallet. The storage rack system is designed based on the full, maximum indicated product load. For a warehouse store, it is assumed that all rack system positions will be filled with full weight pallets.

For most storage racks, the effective seismic weight (W_s) is a function of the ratio of the average pallet weight to the maximum pallet weight and is determined in accordance with Sec. 2.7.2 of ANSI MH 16.1-04, the RMI standard, as:

$$W_s = \left(0.67 \times PL_{RF} \times PL\right) + DL + 0.25 \times LL$$

where PL_{RF} = product load reduction factor.

Seismic Force Direction	PL_{RF}
Cross-Aisle	1.0
Down-Aisle	$PL_{Average} / PL_{Maximum}$

$PL_{Average}$ is the maximum total weight of product expected on the shelves in any row divided by the number of shelves in that row.

$PL_{Maximum}$ is the maximum weight of product that will be placed on any one shelf in that row.

The 0.67 modification of the pallet weight comes not from the average load but from a determination of the amount of load that participates in developing the dynamic seismic force. Experience has shown that the full mass of the merchandise stored on the storage rack system does not participate in the inertia generated from the ground motion. There is some friction inducing energy dissipating relative movement between the storage rack, the pallets stored on the rack, and the product on the pallets during the seismic motions. This 0.67 factor represents the fraction of the load on the fully loaded system contributing to the effective horizontal seismic weight. This effective seismic weight factor does not apply to vertical gravity loads.

It should be noted that the effective seismic weight ratios provided in the *UBC* are different from those above (see Sec. 4.4).

4.3 RACK CONFIGURATION

The number of pallet loads wide on each shelf between uprights generally is specified by the operator of the warehouse. In a typical storage rack system, there usually two pallet loads wide between uprights. If there are cross-aisle tunnels in the system to allow movement between aisles, the bay will have three or four pallets wide but not have storage in the bottom two or three levels. At the tunnel bay, the column will have shelves attached on one side in the bottom region and on both sides above the tunnel. Infrequently, the tunnel may be located at the end of a rack row and the last frame in the row will not have shelf beam support in the bottom region, in which case a special design for that frame is required.

The shelf elevations are determined by the operator of the warehouse based on the height of the loads and the shelf beam size and clearances required for storing and removing the load. The shelves may be spaced regularly for the full height of the rack system if all the loads are the same height or the spacing may be varied to accommodate different height loads with a minimal amount of lost space.

The overall storage height is based on the lifting height limitation of the handling equipment and the clear building height. Handling equipment characteristics also may necessitate a low bottom shelf beam at or near the floor. This shelf beam is typically 6 inches from the floor to the bottom of the beam and, considering a 4-inch beam, 8 inches to the centerline of the beam. When distributing the seismic forces vertically, this bottom beam does not participate in the determination of seismic forces to levels above as would be indicated by the traditional vertical distribution. The seismic force including this beam will only govern the design on the horizontal force on the anchors. This situation is addressed in Sec. 2.7.4 of ANSI MH 16.1-04, the RMI standard.

4.4 SEISMIC LOADS

The seismic loading requirements are determined by the local building authority having jurisdiction at the location of the facility where the racks are to be installed. The *International Building Code* (*IBC*) currently is used by most building authorities.[1] There is, however, one notable exception, the State of California. The *California Building Code* (*CBC*) is still based on the 1997 edition of the *Uniform Building Code* and, although it appears that the state ultimately will adopt the *IBC*, this will be several years away. While no longer supported by any code development organization, the *UBC* will continue to serve as the basis for the *CBC* until the state adopts a new model building code; therefore, it will be discussed in this document.

A description of the various procedures for determining seismic loads is presented below. Also provided for purposes of comparison are tabulations adjusted for allowable stress design (ASD) of the seismic force coefficients in the down-aisle direction for each of the applicable codes and standards (see Sec. 4.4.7).

[1] Although a 2003 edition of the *IBC* is available, most jurisdictions are still using the 2000 edition of the *IBC*.

4.4.1 The 2000 Edition of the *International Building Code*. The primary reference for storage racks in the 2000 *IBC* is Sec. 1622.3.4 which presents two procedures for determining the seismic forces. The first procedure requires design in accordance with Sec. 1622.3.4.1 through 1622.3.4.4. The second procedure involves use of methods from Sec. 2.7 of ANSI MH 16.1-04, the RMI standard, with two added requirements. If the RMI standard is used, the seismic response coefficient (C_s) is determined using C_a equal to $S_{DS}/2.5$ and C_v equal to S_{D1}, but C_s shall not be less than $0.14S_{DS}$.

The determination of the seismic coefficients using the first procedure (i.e., *IBC* Sec. 1622.3.4.1 through 1622.3.4.4) is presented in Figure 4-2 for the down-aisle direction and for five different representative sites and periods ranging between 0.10 and 3.0 seconds. Near-field sites are not included in the represented sites.

The determination of the seismic coefficients using the second procedure (i.e., basically using the RMI standard with added requirements) is presented in Figure 4-3 for the down-aisle direction and for five different representative sites and periods ranging between 0.10 and 3.0 seconds. Near-field sites are not included in the represented sites.

IBC 2000 Seismic Lateral Force
Down-aisle

S_S = 1.50	1.00	0.75	0.50	0.25
S_1 = 0.75	0.63	0.50	0.30	0.15
Site Class D				
Fa = 1.00	1.10	1.20	1.40	1.60
Fv = 1.50	1.50	1.50	1.80	2.20
S_{DS} = 1.00	0.73	0.60	0.47	0.27
S_{D1} = 0.75	0.63	0.50	0.36	0.22
R = 4.0	4.0	4.0	4.0	4.0
I_E = 1.5	1.5	1.5	1.5	1.5

T	0.7 V/PL				
0.10	0.189	0.139	0.113	0.088	0.050
0.20	0.189	0.139	0.113	0.088	0.050
0.30	0.189	0.139	0.113	0.088	0.050
0.40	0.189	0.139	0.113	0.088	0.050
0.50	0.189	0.139	0.113	0.088	0.050
0.60	0.189	0.139	0.113	0.088	0.050
0.70	0.189	0.139	0.113	0.088	0.050
0.80	0.177	0.139	0.113	0.085	0.050
0.90	0.158	0.131	0.105	0.076	0.046
1.00	0.142	0.118	0.095	0.068	0.042
1.10	0.129	0.107	0.086	0.062	0.038
1.20	0.118	0.098	0.079	0.057	0.035
1.30	0.109	0.091	0.073	0.052	0.032
1.40	0.101	0.084	0.068	0.049	0.030
1.50	0.095	0.079	0.063	0.045	0.028
1.60	0.089	0.074	0.059	0.043	0.026
1.70	0.083	0.069	0.056	0.040	0.024
1.80	0.079	0.066	0.053	0.038	0.023
1.90	0.075	0.062	0.050	0.036	0.022
2.00	0.071	0.059	0.047	0.034	0.021
2.10	0.071	0.059	0.045	0.032	0.020
2.20	0.071	0.059	0.043	0.031	0.019
2.30	0.071	0.059	0.041	0.030	0.018
2.40	0.071	0.059	0.039	0.028	0.017
2.50	0.071	0.059	0.038	0.027	0.017
2.60	0.071	0.059	0.036	0.026	0.016
2.70	0.071	0.059	0.035	0.025	0.015
2.80	0.071	0.059	0.034	0.024	0.015
2.90	0.071	0.059	0.033	0.023	0.014
3.00	0.071	0.059	0.032	0.023	0.014

$$V = C_S W$$

$$C_S = \frac{S_{DS}}{R/I_E}$$

C_S need not exceed:

$$C_S = \frac{S_{D1}}{\left(R/I_E\right)T}$$

But not less than:

$$C_S = 0.044 S_{DS} I_E$$

And for Design Category E and $S_1 \geq 0.6$ not less than:

$$C_S = \frac{0.5 S_1}{R/I_E}$$

if theDead Load is assumed to be 5% of the Pallet Load

W = (0.05 PL) + (0.67 PL)

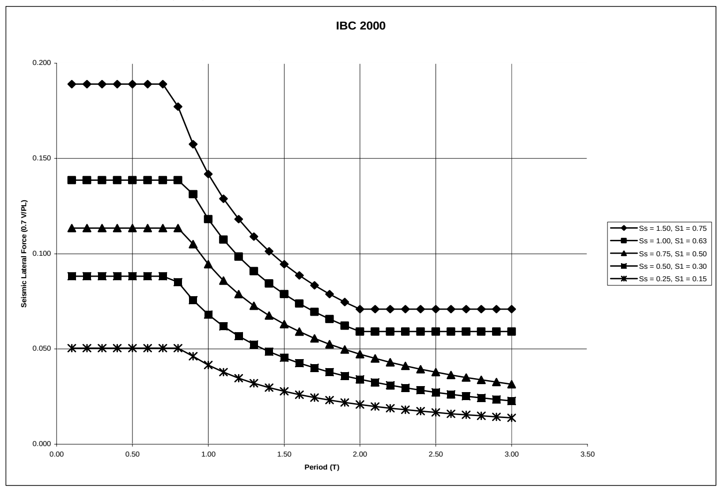

Figure 4-2 Determining seismic coefficients using IBC 2000 Sec. 1622.3.4.1 through 1622.3.4.4.

IBC 2000 & RMI 2002 Seismic Lateral Force
Down-aisle

S_S = 1.50	1.00	0.75	0.50	0.25
S_1 = 0.75	0.63	0.50	0.30	0.15
Site Class D				
Fa = 1.00	1.10	1.20	1.40	1.60
Fv = 1.50	1.50	1.50	1.80	2.20
S_{DS} = 1.00	0.73	0.60	0.47	0.27
S_{D1} = 0.75	0.63	0.50	0.36	0.22
R = 6.0	6.0	6.0	6.0	6.0
I_P = 1.5	1.5	1.5	1.5	1.5

$$V = C_S I_P W_S$$

$$C_S = \frac{1.2 C_V}{R T^{2/3}}$$ Where $C_V = S_{D1}$

But need not be greater than:

$$C_S = \frac{2.5 C_a}{R}$$ Where $C_a = S_{DS}/2.5$

and not less than:

$$C_S = 0.14 S_{DS}$$

if theDead Load is assumed to be 5% of the Pallet Load

W = (0.05 PL) + (0.67 PL)

T	0.67 V/PL				
0.10	0.121	0.088	0.072	0.056	0.032
0.20	0.121	0.088	0.072	0.056	0.032
0.30	0.121	0.088	0.072	0.056	0.032
0.40	0.121	0.088	0.072	0.056	0.032
0.50	0.121	0.088	0.072	0.056	0.032
0.60	0.121	0.088	0.072	0.056	0.032
0.70	0.121	0.088	0.072	0.056	0.032
0.80	0.121	0.088	0.072	0.056	0.032
0.90	0.116	0.088	0.072	0.056	0.032
1.00	0.109	0.088	0.072	0.052	0.032
1.10	0.102	0.085	0.068	0.049	0.030
1.20	0.101	0.080	0.064	0.047	0.028
1.30	0.101	0.076	0.061	0.047	0.027
1.40	0.101	0.074	0.061	0.047	0.027
1.50	0.101	0.074	0.061	0.047	0.027
1.60	0.101	0.074	0.061	0.047	0.027
1.70	0.101	0.074	0.061	0.047	0.027
1.80	0.101	0.074	0.061	0.047	0.027
1.90	0.101	0.074	0.061	0.047	0.027
2.00	0.101	0.074	0.061	0.047	0.027
2.10	0.101	0.074	0.061	0.047	0.027
2.20	0.101	0.074	0.061	0.047	0.027
2.30	0.101	0.074	0.061	0.047	0.027
2.40	0.101	0.074	0.061	0.047	0.027
2.50	0.101	0.074	0.061	0.047	0.027
2.60	0.101	0.074	0.061	0.047	0.027
2.70	0.101	0.074	0.061	0.047	0.027
2.80	0.101	0.074	0.061	0.047	0.027
2.90	0.101	0.074	0.061	0.047	0.027
3.00	0.101	0.074	0.061	0.047	0.027

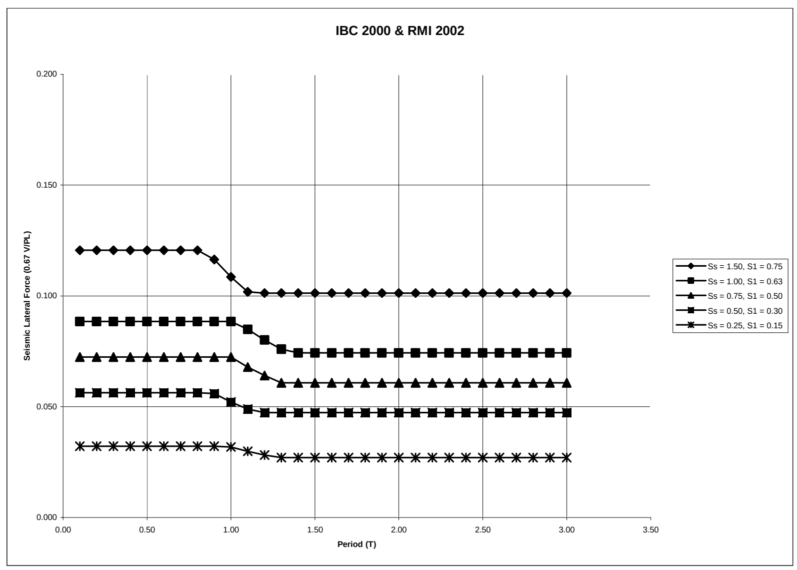

Figure 4-3 Determining seismic coefficients using IBC 2000 Sec. 1622.3.4
(the RMI standard with additional requirements).

4.4.2 The 2003 Edition of the *International Building Code*. The reference for storage racks in the 2003 *IBC* is Sec. 2208:

> SECTION 2208
> STEEL STORAGE RACKS
> 2208.1 Storage racks. The design, testing and utilization of industrial steel storage racks shall be in accordance with the *RMI Specification* for the Design, Testing and Utilization of Industrial Steel Storage Racks. Racks in the scope of this specification include industrial pallet racks, movable shelf racks and stacker racks, and does not apply to other types of racks, such as drive-in and drive-through racks, cantilever racks, portable racks or rack buildings. Where required, the seismic design of storage racks shall be in accordance with the provisions of Section 9.6.2.9 of ASCE 7.

This section requires that all listed types of steel storage racks be design in accordance with the 1997 edition of the RMI standard but further states that the seismic design of storage racks shall be in accordance with Sec. 9.6.2.9 of ASCE 7-02, which is discussed below.

4.4.3 American Society of Civil Engineers, *Minimum Design Loads for Buildings and Other Structures*, SEI/ASCE 7-02. ASCE 7 Sec. 9.6.2.9 requires that storage racks be designed to meet the force requirements of ASCE 7 Sec. 9.14, which pertains to nonbuilding structures. Sec. 9.14.6.3 directly addresses storage racks and presents two procedures.

The first procedure requires that the design satisfy Sec. 9.14.6.3.1, which, in turn, requires the design to be in accordance with the general provisions of Sec. 9.5 and Sec. 9.14.5 and the specific storage rack provisions of Sec. 9.14.6.3.1 through 9.14.6.4.3. These requirements for seismic force mandate the use of the requirements of Sec. 9.5 and an R of 4. The importance factor (I_p) is to be determined in accordance with Sec. 9.6.1.5 and, for warehouse retail stores open to the public, is 1.5. The minimum base shear coefficient is $0.14S_{DS}I$. In addition, where S_1 is equal to or greater than $0.75g$, the minimum base shear shall not be less than $0.8S_1I/R$. The storage racks must be designed considering two loading conditions: (a) 67 percent of all positions fully loaded and (b) the top storage position loaded to 100 percent only. The vertical distribution of the base shear force as specified in Sec. 9.5.5.4 with the factor k taken as 1.0.

4.4.4 Rack Manufactures Institute, *Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks*, 2002 Edition, with ASCE 7-02 Required Changes. The second design procedure for storage racks is to use the RMI standard with the following additional changes:

- C_a equal to $S_{DS}/2.5$ and C_v equal to S_{D1} but C_s shall not be less than $0.14S_{DS}$.
- I_p from Section 9.6.1.5 where for warehouse retail stores open to the public I_p is 1.5.

The seismic design requirements are in presented in Sec. 2.7 of the RMI standard along with the required changes of SEI/ASCE 7-02. The required seismic force coefficient is determined using the equivalent static force method:

$$V = C_s I_p W_s$$

where:

I_p = the system importance factor as defined below
1.5 for essential facilities or hazardous material storage
1.5 for storage racks in areas open to the public
1.0 for all other structures

W_s = the effective seismic weight (see Sec. 4.2.7 of this document)

C_s = the seismic response coefficient from Sec. 2.7.3 of the RMI standard:

$$C_s = \frac{1.2C_v}{RT^{2/3}}$$

where

C_V = S_{D1} from ASCE 7 Sec. 9.14.6.3
R = 4.0 for the braced direction and 6.0 for the unbraced direction and
T = the fundamental period of the rack in the direction under consideration

C_s need not be greater than:

$$C_s = \frac{2.5C_a}{R}$$

where C_a is $S_{DS}/2.5$ from ASCE 7 Sec. 9.14.6.

C_s shall not be taken less 0.14 S_{DS} (per ASCE 7 Sec. 9.14.6.3).

In determining the C_s factor, it is important that the period include all the characteristics of all the structural members that make up the load path for the forces. For example, in the down-aisle direction, the period should include the deformation of the beam-to-column connection; in the cross-aisle direction the eccentricities of the frame bracing connections should be included. The period should be the elastic period consistent with code applied forces. Current practice is to use rotational spring stiffness (F) based on the test procedures of Sec. 9.4.1 of the RMI standard when determining the down-aisle fundamental period. Because of the nonlinear stiffness of the beam-to-column connection, the down-aisle period changes significantly with applied load. Shake-table testing for high levels of ground motions has shown that, for some racks, the measured period may be greater than 1.5 seconds. However, the building code limits the C_s factor to $0.14S_{DS}$, effectively putting an upper bound on the period of slightly less than 1.0 sec.

For the seismic loads, the S_{DS} and S_{D1} factors may be determined by looking up the values of S_S and S_1 for the site location on the ASCE 7 seismic maps -- Figure 9.4.1.1(a) through (j) -- and adjusting for the site class effects with factors found in ASCE 7 Tables 9.4.1.2.4a and b. The resulting values of S_{MS} and S_{M1} are scaled by two-thirds to obtain S_{DS} and S_{D1}. However, today it is easier to obtain the seismic factors using the Seismic Design Parameters CD that accompanies the *NEHRP Recommended Provisions* and other codes and standards. The latitude and longitude of the site are needed to use the CD and can be obtained from a variety of other software or internet resources. Because it has not yet been widely recognized that the site classification is as important a seismic design factor as "seismic zone," it usually is not included as a part of the information that is transmitted to the rack designer. Consequently, Site Class D is usually used and required if the site class is unknown.

The RMI standard then distributes the base shear to each storage level based on the height and load but modifies the standard distribution for a low first shelf. Sec. 2.7.4 requires that:

If the centerline of the first shelf level is 12 inches (30.5 cm) above the floor or less:

$F_1 = C_s I_p w_1$ for the first shelf level

and

$$F_x = \frac{(V - F_1)\, w_x h_x^k}{\sum_{i=2}^{n} w_i h_i^k} \text{ for levels above the first level}$$

If the centerline of the first shelf level is greater than 12 inches (30.5 cm):

$$F_x = \frac{V w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} \text{ for all levels}$$

where

V = total design lateral force or shear at the base of the rack

w_i or w_x = the portion of the total gravity load (including live load, dead load and product load times the product load reduction factor, see Sec. 2.7.2) of the rack, located or assigned to the bottom shelf level, level i or x

h_i or h_x = the height from the base to level i or x

k = an exponent related to the structure's period

period ≤ 0.5	$k = 1$
period ≥ 2.5	$k = 2$

For racks having a period between 0.5 and 2.5 seconds, k shall be 2 or shall be determined by linear interpolation between 1 and 2. If the base shear is based on the default C_s then the k shall be taken as 1.

An example of the RMI/ASCE7-02 seismic force calculation for a given site is presented below. Near-field sites have not been included.

Find the latitude and longitude of the warehouse location. Use the Seismic Design Parameters CD (see Sec. 4.5.4.2) to determine the parameters S_s and S_1 for the site. The factors F_a and F_v

also can be determined using the CD for a specific site class and most often rack design is based on the default Site Class D.

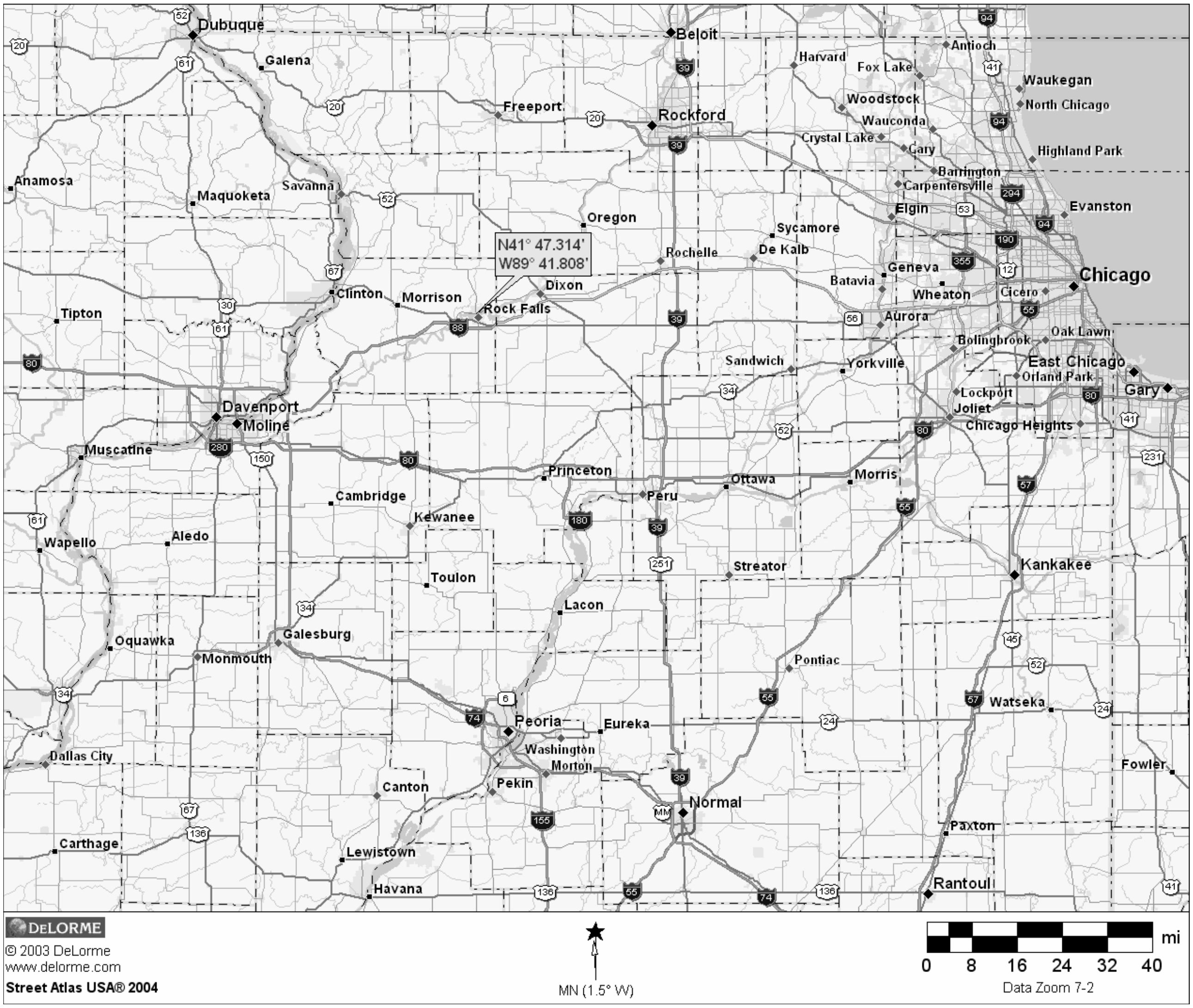

Figure 4-4 Map to determine latitude and longitude.

MCE Ground Motion – Conterminous 48 States

Latitude = 41.7891 Longitude = -89.6922

Period (sec)	MCE S_a (%g)	
0.2	016.6 MCE Value of S_a, Site Class B	
1	006.3 MCE Value of S_1, Site Class B	

Spectral Parameters for Site Class D

0.2	026.6 $S_{MS} = F_a S_s$	$F_a = 1.60$
1	015.1 $S_{M1} = F_v S_1$	$F_v = 2.40$

ASCE 7-02 and the 2002 RMI Standard

$S_{DS} = 2/3\ S_{MS}$ = 0.177
$S_{D1} = 2/3\ S_{M1}$ = 0.101

$C_a = S_{DS}/2.5$ = 0.071

$C_v = S_{D1}$ = 0.101

where

$T =$ 1.5 sec
$R =$ 4.0
$I =$ 1.50

$C_s = \frac{1.2C_v}{RT^{2/3}}$ = 0.023

or

$C_s = \frac{1.2C_v}{R}$ = 0.044

but not less than

$C_s = 0.14 S_{DS}$ = 0.025 ← USE THIS

$V = C_s I(0.67P)$ = $0.025PL$

4.4.5 The 2003 *NEHRP Recommend Provisions*. The 2003 *NEHRP Recommended Provisions* serves as the basis for the ASCE 7-05 seismic requirements. The next editions of the two model building codes (i.e., the 2006 edition of the *IBC* and the 2005 edition of *NFPA-5000*) will both reference ASCE 7-05 for their seismic requirements; therefore the seismic provisions found in these editions of the building codes will essentially be based on the 2003 *NEHRP Recommended Provisions*. The seismic provisions for storage racks found in *Provisions* Sec. 14.3.5 are essentially identical to those found in ASCE 7-02. The only difference is that for the first procedure, the minimum base shear coefficient of $0.14S_{DS}I$ is replaced by $0.01S_{DS}I$. For the second procedure which references the ANSI MH 16.1-04, the minimum value of C_s is still 0.14 $S_{DS}I$.

4.4.6 The 1997 *Uniform Building Code*. As noted above, the *UBC* was originally developed and promulgated by the International Conference of Building Code Officials (ICBO). It has been superseded by the *IBC* and is generally considered to be obsolete; however, it will serve as the basis for the *California Building Code* until the state adopts a new code, which should occur in the relatively near future. *UBC* Chapter 22, Division X, “Design Standard for Steel Storage Racks,” directly addresses the design of storage racks for all situations including seismic and is based on the 1990 edition of the RMI standard. For seismic design, Division X, Sec. 2228.5.2 specifies minimum earthquake forces. This section prescribes the lateral forces, at strength design levels, be determined by the static force procedure in Sec 1630.2.1 with the *R* factor and *W* as defined in Division X. Further, this section modifies the distribution of the seismic force to not include a distinct top force.

The required seismic force coefficient is determined using the equivalent static force method of *UBC* Sec. 1630.2.1:

$$V = \frac{C_v I}{RT} W \qquad \text{(}\textit{UBC}\text{ Eq. 30-4)}$$

but need not exceed:

$$V = \frac{2.5 C_a I}{R} W \qquad \text{(}\textit{UBC}\text{ Eq. 30-5)}$$

nor not be less than:

$$V = 0.11 C_a I W \qquad \text{(}\textit{UBC}\text{ Eq. 30-6)}$$

In addition, in Seismic Zone 4, *V* shall not be less than:

$$V = \frac{0.8 Z N_v I}{R} W \qquad \text{(}\textit{UBC}\text{ Eq. 30-7)}$$

The following terms are defined in Division X:

R = 4.4 for racks where lateral stability is dependent on diagonal or x-bracing. This is usually the factor used of the cross-aisle direction.

R = 5.6 for racks where lateral stability is wholly dependent on moment – resisting frame action.

W = weight of racks plus contents

If four or more columns are connected together in both the cross-aisle and the down-aisle direction, 50 percent of the rack content load may be used. Further, in Seismic Zones 3 and 4 in wholesale and retail sales areas, the 50 percent may be used only when C_v/RT is 0.7 C_a in Eq. 30-4 and with 2.5/R is 0.7 in Eq. 30-5.

The other terms are the standard UBC definition of the terms:

C_a from *UBC* Table 16-Q
C_v from *UBC* Table 16-R
I is the seismic importance factor from *UBC* Table 16-K
Z is the seismic zone factor from *UBC* Table 16-I
N_v from *UBC* Table 16-T
T is the fundamental period of vibration of the rack.

It should be noted that *UBC* Sec. 1630.2.2 Method A is only applicable to building structures and is not applicable to rack structures. The building approximation, accounting for the damping of nonstructural elements and contents is not valid for rack structures. Method B, without its limitation to Method A, is what is recommended by RMI.

The total base shear is distributed over the height of the rack triangularly proportioned based on the loading, without a special concentrated force at the top:

$$F_i = \frac{VW_i h_i}{\sum_{i=1}^{n} W_i h_i}$$

An example of the 1997 *UBC* seismic force calculation for five representative sites (Seismic Zones 1, 2A, 2B, 3 and 4) is presented in Figure 4-5. Near-field sites have not been included.

UBC 1997 Division X & Section 1630.2.1
Down-aisle

9/16/2004

Zone	4	3	2B	2A	1
Z=	0.40	0.30	0.20	0.15	0.075

Site Class D

Ca =	0.44	0.36	0.28	0.22	0.12
Cv =	0.64	0.54	0.40	0.32	0.18
N_V = 1.00					
R =	5.6	5.6	5.6	5.6	5.6
I =	1	1	1	1	1

T	(V/PL) / 1.4				
0.10	0.121	0.099	0.049	0.039	0.021
0.20	0.121	0.099	0.049	0.039	0.021
0.30	0.121	0.099	0.049	0.039	0.021
0.40	0.121	0.099	0.049	0.039	0.021
0.50	0.121	0.099	0.049	0.039	0.021
0.60	0.121	0.099	0.047	0.037	0.021
0.70	0.121	0.099	0.040	0.032	0.018
0.80	0.107	0.090	0.035	0.028	0.016
0.90	0.095	0.080	0.031	0.025	0.014
1.00	0.086	0.072	0.028	0.022	0.013
1.10	0.078	0.066	0.026	0.020	0.011
1.20	0.071	0.060	0.023	0.019	0.011
1.30	0.066	0.056	0.022	0.017	0.010
1.40	0.061	0.052	0.020	0.016	0.009
1.50	0.057	0.048	0.019	0.015	0.008
1.60	0.054	0.045	0.018	0.014	0.008
1.70	0.050	0.043	0.017	0.013	0.007
1.80	0.048	0.040	0.016	0.012	0.007
1.90	0.045	0.038	0.015	0.012	0.007
2.00	0.043	0.036	0.014	0.011	0.006
2.10	0.043	0.034	0.013	0.011	0.006
2.20	0.043	0.033	0.013	0.010	0.006
2.30	0.043	0.032	0.012	0.010	0.005
2.40	0.043	0.032	0.012	0.010	0.005
2.50	0.043	0.032	0.012	0.010	0.005
2.60	0.043	0.032	0.012	0.010	0.005
2.70	0.043	0.032	0.012	0.010	0.005
2.80	0.043	0.032	0.012	0.010	0.005
2.90	0.043	0.032	0.012	0.010	0.005
3.00	0.043	0.032	0.012	0.010	0.005

W = DL + 0.5PL
not in Zones 3 & 4

W = DL + 0.5PL
in Zone 3 & 4 if
$C_V / RT = 0.70\ C_a$ in (30-4)
2.5 / R = 0.70 in (30-5)

$$V = \frac{C_V I}{RT} W \quad \text{(30-4)} \quad \text{or} \quad V = 0.70 C_a I W$$

But need not exceed:

$$V = \frac{2.5 C_a I}{R} W \quad \text{(30-5)} \quad \text{or} \quad V = 0.70 C_a I W$$

And not less than:

$$V = 0.11 C_a I W$$

In Seismic Zones 3 & 4, wholesale and retail areas, the 50% may only be used when

In addition, in Zone 4, not less than:

$$V = \frac{0.8 Z N_V I}{R} W$$

if the Dead Load is assumed to be 5% of the Pallet Load
W = (0.05 PL) + (0.50 PL) W = (0.05 PL) + (0.50 PL)

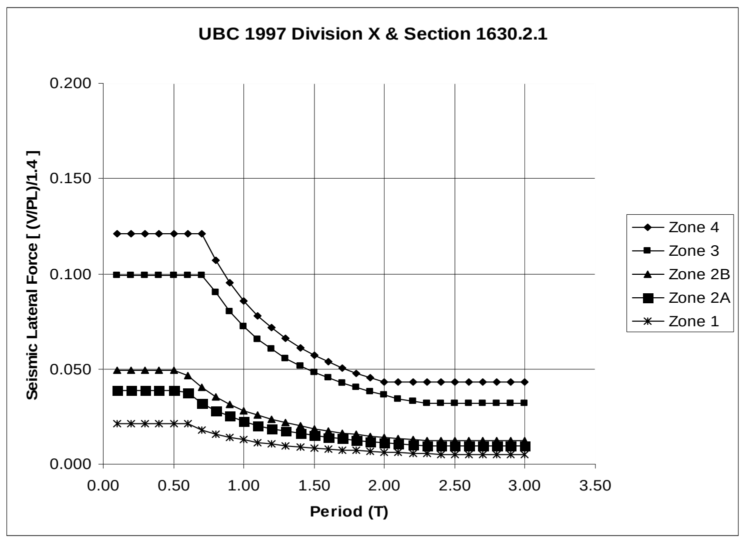

Figure 4-5 Determining seismic coefficients using UBC 1997, Division X.

4.5 MEMBER DESIGN

4.5.1 Shelf Design

Each rack manufacturer uses a unique and proprietary beam-to-column connector to join the horizontal and vertical members in the down-aisle direction. The connector usually is welded to each end of a shelf beam and engages slots or holes in the face and/or the side of the column (see Figure 1-3). Some connectors are bolted to the column, some have protruding rivets that slip into perforations in the column, and some have tabs formed from the connector that are inserted into slots in the column.

It is because of this multiplicity of connection types, the RMI standard requires the determination of the strength and stiffness of the connections by testing. Once the testing is completed for one product line, the results may be used for all projects using that type of connection. The connection stiffness test produces a connection rotational spring constant, *F*. This rotational spring is then introduced between the end of the beam and the column and the structure analyzed.

When the load on the shelf is distributed by a pallet, the shelf beam bending is generally computed based on a uniformly distributed load for the entire length of the shelf beam. The beam may be designed as a simply supported beam, which AISC calls Type 2 construction, or may include the effects of the semi-rigid end connections, which AISC calls Type 3 construction. The span of the beam is generally considered to be the clear distance between the upright columns. Commentary Sec. 5.2 of the RMI standard provides guidance on including the effects of the connection stiffness in calculating the strength and deflection of the shelf for Type 3 construction. The strength for Type 3 construction is calculated with:

$$M_{Max} = \frac{WL}{8} r_m$$

where

$$r_m = 1\frac{2FL}{6EI_b + 3FL}$$

E = the modulus of elasticity

F = the joint rotational spring constant determined either by the cantilever test described in Sec. 9.4 of the RMI standard or by pallet beam in upright frames assembly test described in Sec. 9.3.2 of the RMI standard.

I_b = the beam moment of inertia about the bending axis

L = the span of the beam

W = the total load on each beam (including vertical impact loads)

and where

$M_e = \frac{wL}{8}(1 - r_m)$ and M_e = the beam end moment.

The deflection of a shelf beam under full design load is limited to 1/180 of the beam span. When considering semi-rigid joints, the following expression for maximum deflection δ_{max} can be derived:

$$\delta_{Max} = \delta_{ss} r_d$$

where

$$\delta_{ss} = \frac{5WL^3}{384EI_b}$$

$$r_d = 1 - \frac{4FL}{5FL + 10EI_b}$$

4.5.2 Member Design in Down-Aisle Direction

Columns are designed in accordance with the rules of the AISC specification for hot-rolled members or the AISI specification for cold-formed members. There have been some modifications to those two specifications in areas that are unique to storage rack members. In particular, rack columns usually have a series of perforations regularly spaced for the entire column height that allow the mechanical attachment of shelf beams at many elevations. However, the elevation of the shelf beam from the floor and between beams is a critical limitation of the specific design applicable to an installation.

As discussed elsewhere, although the shelves can be located at any elevation, it is a function of the engineering of that system that determines whether the beam may be located at that spacing and still satisfy the design criteria.

The RMI standard requires testing to determine the effects of perforations punched in the column. Design limitations based on that testing then are prescribed.

Static stability, as well as seismic stability, in the down-aisle direction is dependant on the stiffness of the beam-to-column connections. For static stability, one suggested design method computes a column *k* factor based on the initial connector stiffness from testing. To determine the *k* factor, the nomographs from the commentary to the AISC specification are used with a beam stiffness modified by the connector stiffness. There are many simplifying assumptions that must be made in order for the nomographs to be applicable. Because of this, work is under way to permit use of a notional load and second order type approach for static stability.

Story drift limitations are not applicable to storage rack structures with the exception of making sure that the rack structure will not impact surrounding structures such as the warehouse building. In the absence of any other calculations, the model building codes require a separation of 5 percent of the overall height. The actual drift may be substantially less than this 5 percent value and the actual calculated drift at the design earthquake level may be used for the separation distance.

4.5.3 Member Design in the Cross-Aisle Direction

Two design aspects are unique to cross-aisle storage rack frame bracing. First, the bracing can seldom be attached such that the lines of action of the structural components meet at a point. The commentary to the RMI standard defines what is an acceptable deviation from the ideal. Second, in many frame designs, the connections of the diagonals and horizontals to the column are designed on the basis of the compression in the members. It is not unusual for a bracing member to be designed first to fit into the available location (e.g., between the flange returns). Further, the bracing often is located such that it may take either tension or compression depending on the direction of the force. The diagonal just above a bracing panel often is oriented in the opposite direction.

Because the frame brace may have more capacity than required, it is frequently checked for adequacy by comparing the requirement to known, tested capacities.

When the two diagonals are in opposite directions, the force on the bracing system is limited to the compression capacity of one of the diagonals.

The RMI standard requires anchoring for all bases in every storage rack system. There may be no net base uplift calculated for the rack configuration but anchors are required regardless. Base plates frequently are sized to provide one or more locations for anchor bolts. There may be more than one hole even though there is only one anchor required. The size of the anchor required is based on the net uplift at the base under the worst of two conditions: (a) with the top load only in place and the appropriate seismic force resulting from that pallet applied at the top shelf level or (b) with a 350 pound lateral load applied horizontally at the top load level. The 350 pound force is applied in one location at a time and may be distributed over several uprights if they are adequately connected together. The uplift of the base plate under this 350 pound load is checked when there is no product load in any position of the uprights that are resisting this load.

A wide variety of post-installed anchors are used for storage rack systems. The selection of the appropriate anchor to resist the forces at the base is left up to the rack designer. However, no matter what anchor is used, it is important that the anchor be installed to meet the requirements of the anchor manufacturer and that the anchor loading not exceed the load capacity stated by the manufacturer. In some jurisdictions, the allowable anchor capacity may be required to be based on independent anchor evaluations such as those provided by the ICC Evaluation Service.