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DYNAMIC RESPONSE OF STEEL INDUSTRIAL STORAGE RACKS

By C. K. Chen[1] and S. A. Freeman[2]

INTRODUCTION

Industrial steel storage racks have traditionally been designed mainly for vertical loads, and little attention has been given to earthquake loadings. The need for considering seismic effects in the design of steel industrial storage racks was recognized by the Rack Manufacturer's Institute (RMI) in its 1972 publication Interim Specification for the Design, Testing, and Utilization of Industrial Steel Storage Racks(2). Several minor revisions were incorporated into this specification in June 1973(3). These criteria specify the total lateral seismic force, V, to be equal to ZKCW, where Z is a numerical coefficient that depends on the appropriate zone of earthquake risk, K is a factor that depends on the lateral force-resisting frame scheme of the rack, C is a factor that is a funtion of the location of the rack in the building, and W is the weight of the rack and load. Under these criteria, the maximum seismic force for a rack on grade located in seismic Zone 3 is $V = (1.0)(1.0)(0.10)W = 0.10W$ and the minimum force is $V = (0.67)(1.0)(0.10)W = 0.067W$.

The International Conference of Building Officials (ICBO) also recognized the need for seismic-resistant design of storage racks and adopted new seismic design requirements for storage racks in the 1973 Uniform Building Code (UBC)(6). The provisions require racks over 6 feet in height to be designed for a lateral force $F_p = ZC_pW$, where C_p is a factor that

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depends on the height of the rack and its location in the building. Under these provisions, for a two-level rack on grade located in seismic Zone 3, the lateral force would be $F_p = 0.2W$. For three or more levels, $F_p = 0.20W$ for the upper two levels and 0.16W for the remainder. The 1973 UBC criteria do not permit reduction of the coefficient C_p as a function of the period of the rack as is permitted in the design of lateral force-resisting framing of buildings.

The greater seismic load requirements (by a factor of 2 or more) in the 1973 UBC may require large increases in the size and thickness of rack framing, hence increasing the cost greatly. For this reason, a study was initiated to determine how typical steel industrial storage racks would respond to earthquake motions and what seismic design criteria would be compatible with UBC safety considerations. This study involved in-situ measurements of the dynamic characteristics of representative rack installations, dynamic analyses of the racks and correlation of the measured and analytical data, and determination of seismic design standards consistent with the UBC philosophy.

This paper summarizes the study (7) conducted by URS/John A. Blume & Associates, Engineers, for the Rack Manufacturer's Institute.

DESCRIPTION OF INDUSTRIAL STORAGE RACK TYPES

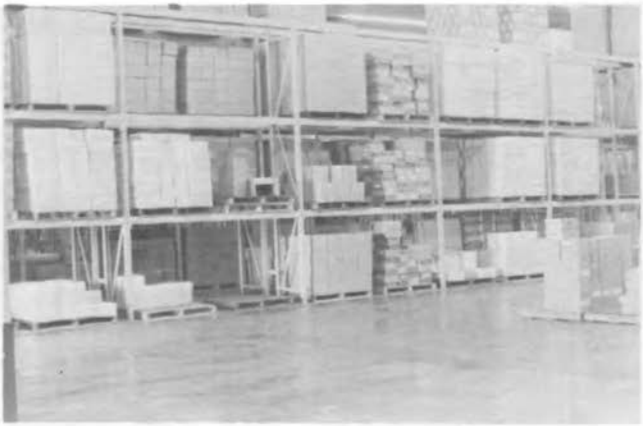
The study concentrated on industrial storage racks constructed of either cold-formed or hot-rolled structural steel members, supported at ground level, and effectively independent of other building structural systems.

Representative examples of industrial storage racks in common use were reviewed. These included standard pallet, drive-in or drive-through, cantilever, and stacker racks. A study objective was to determine the range of response characteristics for variations in geometry, manufacturer's details, and loading conditions that might be encountered. The four types of racks are described next.

Standard Pallet Racks - The standard pallet rack is probably the most common type of rack used for industrial storage. Figure 1 shows photographs of typical standard pallet rack installations. The standard pallet rack modular assembly consists of prefabricated uprights in the rack transverse direction and horizontal beams spanning in the longitudinal direction between successive uprights.

The uprights typically have two posts about 2 feet-9 inches apart (pallet depth minus bearing length) connected by horizontal members spaced from 4 to 6 feet vertically. The uprights are braced in their plane with either single-diagonal or X-bracing between the vertical post and horizontal member panel points. Upright posts have bearing plates at the bottom that usually have a single hole for installation of an anchor to the building floor. Connections of upright frame members can be welded, bolted, or made by special connector attachments.

The horizontal beams supporting the pallets have spans that are usually from one to three pallet widths (about 9 feet average). The beam end connections (shelf connectors) are typically of clip-in type, and the upright posts are slotted along their full height to allow variations in beam vertical spacings. The beam shelf connectors generally have two shear transfer devices spaced vertically about the beam horizontal axis, and thus are capable of transmitting moments. The degree of fixity provided (equivalent linear spring constant) varies with the manufacturer's shear connector and upright post slot details. Submembers, called front-to-back members, are sometimes used to span transversely between the beams.



Front View

End View

FIG. 1 - Standard Pallet Racks

Bracing is not usually provided in the longitudinal direction of standard pallet racks. The horizontal load-carrying structural system of standard pallet racks is typically frame action in the longitudinal direction and bracing in the transverse direction.

The geometry and loading conditions of standard pallet rack assemblies can vary widely depending on the storage requirements of the user. Many installations are two-row rack assemblies in which two single-pallet-depth racks are connected back to back with ties at two or more upright frame locations. Ties may be spacers (about 12 inches) separating the racks, or they may be capable of transmitting moments and/or shears. Probably the most common standard pallet rack assembly is the two-row, back-to-back arrangement with two storage shelves above the base, giving an upright frame height of about 15 feet, and 8 to 10 three-pallet-width bays, resulting in a total assembly length of about 80 feet.

Drive-In and Drive-Through Racks - In the drive-in and drive-through storage racks, rail members spanning between short beams that cantilever from the upright frame posts are used to support storage pallets in lieu of beams spanning the bay width as in the standard pallet rack. Because the pallet-supporting beams are discontinuous from post to post, materials-handling equipment has access to pallets for the full depth of the rack. The major difference between drive-in and drive-through racks is that the drive-through type has no obstruction to the passage of a fork lift from one side of the rack to the other. The drive-in rack can have access from one or both sides, but does not permit clear fork lift passage through the rack. Photographs of representative drive-in storage racks are shown in Figure 2.

Upright frame assemblies are similar in construction to those described for the standard pallet racks. The upright frames are connected by a

Side View

Front View

FIG. 2 - Drive-In Racks

continuous rail that supports the pallets and is attached to the ends of the cantilever arms. The cantilever arms project from the upright frame posts, usually about every 10 inches, and use various manufacturers' connectors and configurations to develop the cantilever moment.

In the longitudinal direction, the upright frames are connected at the top with continuous tie members for drive-through racks. For drive-in racks, additional ties are located at intermediate levels at the back of the frames.

Horizontal load-carrying systems for drive-in and drive-through racks typically consist of bracing in the transverse direction and frame action in the longitudinal direction of the racks. Though variations in loading conditions and geometry are considerable, typical drive-in and drive-through rack assemblies are 12 feet in depth, 12 to 16 feet in height, and 50 to 100 feet in length.

Cantilever Racks - Cantilever racks, as shown in Figure 3, are used in installations where continuous unobstructed storage shelves are needed. Typical primary cantilever rack framing consists of transverse, free-standing, inverted-T assemblies spaced about 8 feet on center. These are diagonally or X-braced in the longitudinal direction between columns. Generally, the base-to-column connection is fully developed, and the base member is anchored to the building floor. Cantilever arms, usually about 4 feet in length, are attached to the columns at the desired vertical shelf spacing (4 to 5 feet). Shelf beams span between adjacent cantilever arms at each shelf level. Transverse front-to-back members between the shelf beams are normally used to support decking (plywood, etc.) upon which the storage loads are placed.

The geometry of cantilever racks can vary widely depending on the intended storage use. For storage of very heavy items (pipe, metal shapes,

End View

Side View

FIG. 3 - Cantilever Racks

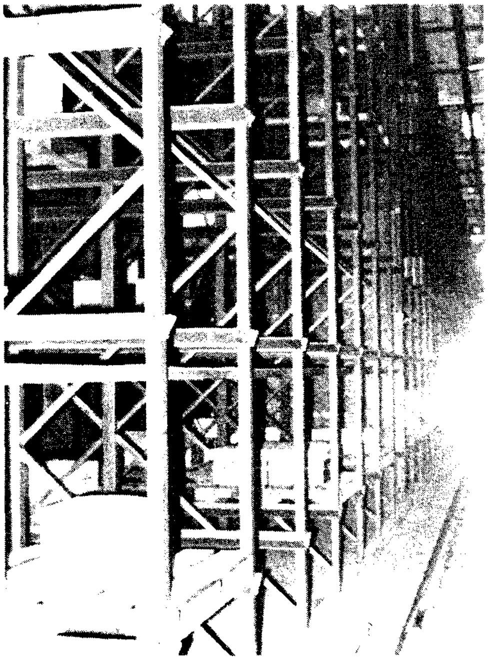
etc.), spacings of the inverted T-assemblies, lengths of cantilever arms, and so forth, are reduced accordingly. The general characteristics of the structural systems of cantilever racks, however, remain the same. In the transverse direction, horizontal loads are resisted primarily by free-standing column cantilever action. Longitudinally, horizontal loads are resisted by bracing between the columns.

Stacker Racks - Stacker racks are an industrial storage system that generally uses floor-running stacker crane equipment for storage and retrieval of goods in large distribution centers. Stacker cranes are usually remote-controlled and can operate in a small aisle width so that material storage density can be maximized. With computerized controls, stacker racks can provide an efficient, inventory-controlled materials-handling system. Figure 4 is a photograph of a representative stacker rack assembly.

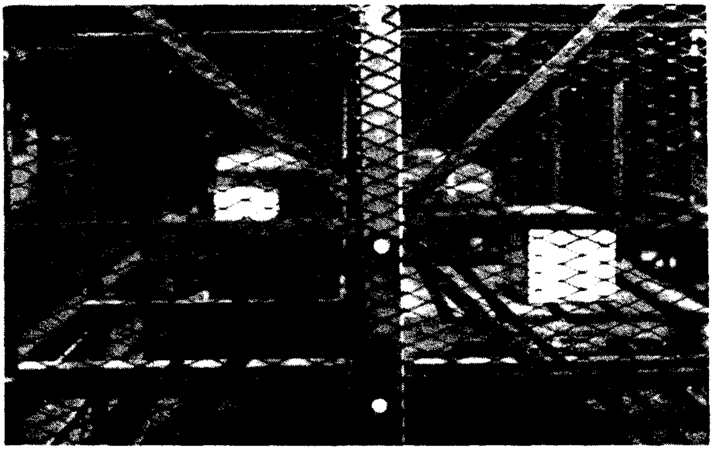
Components of most stacker rack frame assemblies resemble the drive-in rack configuration previously described, but are usually more complex structures due to their size. Horizontal load-carrying systems generally consist of bracing in the transverse direction and frame action (often combined with supplemental bracing) in the longitudinal direction.

FIELD MEASUREMENTS

General - Measurements were made on representative steel industrial storage racks of the standard pallet, drive-in and drive-through, cantilever, and stacker crane types for the purpose of obtaining data describing the natural response periods and damping ratios that characterize the various storage rack structural systems. The racks used for measurements were selected from various distribution centers in the San Francisco Bay area and represent typical steel storage racks in daily use. Articles stored on the various racks tested included a wide variety of such items



End View



Transverse Bracing

FIG. 4 - Stacker Racks

as pharmaceutical products, wood products, foods, dry goods, furniture and appliances, industrial equipment, and bulk raw materials. Where possible, storage racks of a particular type having heavy, average, and light loading conditions were tested in order to evaluate the extreme as well as the mean values of response characteristics.

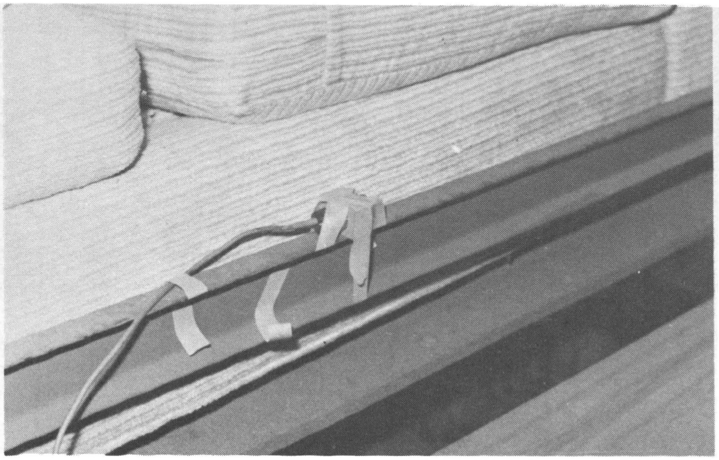
Test Equipment and Procedures - Records of fundamental response frequencies (reciprocals of periods) for the selected storage racks were obtained at two levels of excitation: ambient and man-induced. These represent average fundamental response accelerations on the order of 0.005g and 0.015g, respectively. Damping ratios were obtained from the man-induced vibration records. These low levels of motion were obtained without disrupting normal warehouse functions, thereby permitting adequate records for a larger number of storage rack installations than would have been practicable with use of electro-mechanical motion-generating equipment.

Field measurement of the racks was done in conjunction with the Stanford University Civil Engineering Department, which supplied the test equipment and operating technicians. The measurements were performed under the direction of Professor Haresh C. Shah of Stanford. The test method used was to evaluate the predominant response frequencies and damping ratios for the racks from the power spectral density function (PSD) of a set of response acceleration time-histories recorded for each particular rack structure axis of interest. The PSD represents the mean squared amplitude density of the filtered response acceleration signal and furnishes a convenient means of identifying the frequencies at which the mean response of a signal power is concentrated. The band width of the PSD at a predominant frequency provides a measure of the damping associated with the mode represented by that frequency.

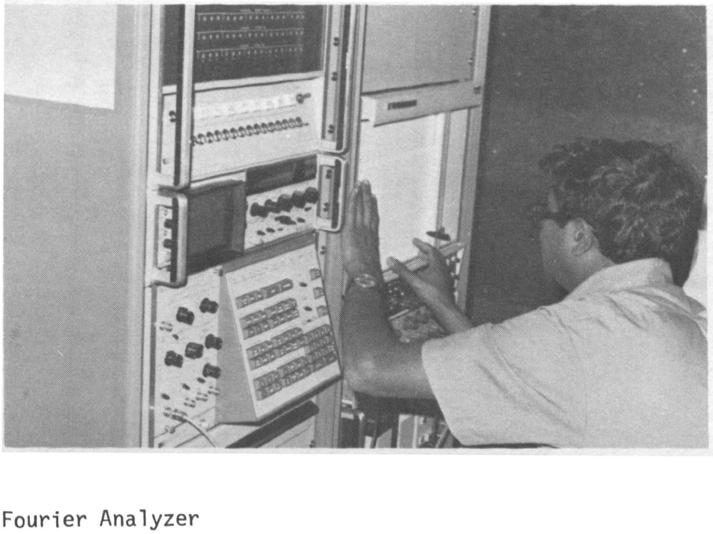
The test equipment consisted basically of a highly sensitive accelerometer and amplifier unit coupled to a Fourier analyzer. The Fourier analyzer contained signal conditioning equipment, a digital computer, and display units. Figure 5 shows a photograph of the accelerometer pickup taped to a storage rack member for a test sequence in the orientation of the member axis and a photograph of the Fourier analyzer.

A test sequence for a particular storage rack axis consisted of generating PSD plots for both ambient and man-induced vibration levels. The accelerometer pickup was generally placed near the top of the storage racks (for fundamental mode data), close to the rack center, and then at one end of the rack (to identify torsional effects). Ambient vibrations were scanned from a seismic response standpoint in the frequency range covering the regions of interest, and the ambient vibration PSD plot was reviewed to identify predominant response frequencies within this band. The racks were then man-excited near these frequencies (usually in the range of 1 to 5 Hz) to distinquish between torsional, translational fundamental, and higher mode response. Damping ratios were determined from the man-induced PSDs.

Results - Table 1 summarizes field-measured data for representative steel industrial storage racks of various types, geometry, and loading conditions. These data represent measurements of the fundamental period, damping ratio, and root-mean-square response acceleration for twelve standard pallet racks, two drive-in racks, three cantilever racks, and two stacker racks. From the Table 1 data, the representative dynamic characteristics of the primary horizontal load-resisting systems of typical racks, for low amplitudes of motion, are as follows:



Accelerometer Mounted
on Rack Framing



Fourier Analyzer

FIG. 5 - Test Equipment

TABLE 1. - SUMMARY OF FIELD-MEASURED DATA FOR SELECTED STEEL INDUSTRIAL STORAGE RACKS

Rack designation[a]	Rack configuration			Rack dimensions, in feet-inches			Rack storage condition[b]	Fundamental period, in seconds		Damping ratio, in % of critical		Response acceleration, in RMS % gravity	
	Rows	Bays	Levels	Row width	Bay width	Total height		Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
SP-1	1	8	2	2-9	9-1	14-6	P	0.64	0.36	1.5	NR	2.0	NR
SP-2	1	8	2	2-9	9-1	14-6	P	0.64	0.36	2.0	NR	3.0	NR
SP-3	1	3	4	2-9	9-0	19-0	F	0.53	0.24	3.2	1.7	0.5	0.6
SP-4	1	3	4	2-9	9-0	19-0	F	0.83	0.32	NR	1.0	NR	NR
SP-5	1	3	4	2-9	9-0	19-0	F	0.78	0.32	NR	1.0	NR	NR
SP-6	1	8	3	2-9	9-1	16-0	F	0.73	0.29	1.4	NR	1.8	NR
SP-7	2	10	3	2-3	10-2	18-9	F	0.63	0.22	1.6	2.2	3.0	0.8
SP-8	2	14	2	2-1	7-8	8-3	F	0.67	0.25	2.0	NR	0.5	NR
SP-9	1	5	3	3-0	7-3	15-0	F	0.76	0.20	7.9	2.7	0.6	0.3
SP-10	1	6	2	3-0	7-3	10-0	F	0.74	0.20	5.8	1.5	0.3	0.2
SP-11	1	2	2	3-6	9-0	13-2	U	0.41	NR[c]	0.8	NR	4.0	NR
SP-12	2	8	5	3-0	12-0	20-10	F	0.30	0.13	2.4	1.3	1.3	0.3
DI-1	5	6	2	5-3 max.	5-0	17-0 max.	P	1.00	0.06	5.5	3.0	2.3	0.3
DI-2	5	35	2	3-5 max.	6-0	22-0 max.	P	0.63	0.21	NR	NR	NR	NR
C-1	2	12	4	4-0	8-0	14-0	P	0.13	0.31	NR	NR	NR	NR
C-2	2	12	3	4-0	7-8	13-10	P	0.13	NR	NR	NR	NR	NR
C-3	1	11	4	5-0	10-1	17-4	F	0.15	0.42	NR	3.8	NR	1.7
S-1	1	56	6	3-6	4-8	43-7	P	0.24	0.27	NR	NR	NR	NR
S-2	2	56	6	3-6	4-8	43-7	P	0.24	0.19	NR	NR	NR	NR

[a] Standard pallet (SP), Drive-in (DI), Cantilever (C), Stacker (S).

[b] Partially loaded (P), Unloaded, (U), Fully loaded (F).

[c] No record (NR)

	Fundamental Translational Period T (sec)	Average Damping Ratio (% of critical)
Moment-Resisting Frame Action	0.6 - 0.8	3
Bracing Action	0.2 - 0.4	2

Torsional modes of vibration present in many of the rack configurations were represented at periods averaging 0.4 second.

The root-mean-square response acceleration levels corresponding to the above values average from 1% to 2% of gravity. At motion levels associated with a major earthquake, the tabulated periods would be expected to increase 20% or more, and structure damping would be expected to increase by a factor of 2 or greater (4). Energy absorption due to the rocking and interaction of storage goods with each other would in most cases be expected to contribute additional nonstructural damping to the system. (In many cases, even at low amplitudes of motion, appreciable energy in frequency bands that do not appear to be representative of rack structural modes or background noise can be seen in the PSD plots. These energy densities are suspected to be caused by the motions of materials stored on the racks). For storage racks under severe seismic conditions, a damping ratio of 5% of critical is therefore considered to be a reasonable value.

Comparisons were made to determine if the fundamental translational periods of typical steel storage racks could be estimated from the geometric relationships used to characterize building periods. Measured rack periods were compared with periods derived from the <u>UBC</u> (section 2314) expressions $T = 0.05\, h_n/\sqrt{D}$ and $T = 0.10N$. Results are presented in Figures 6 and 7.

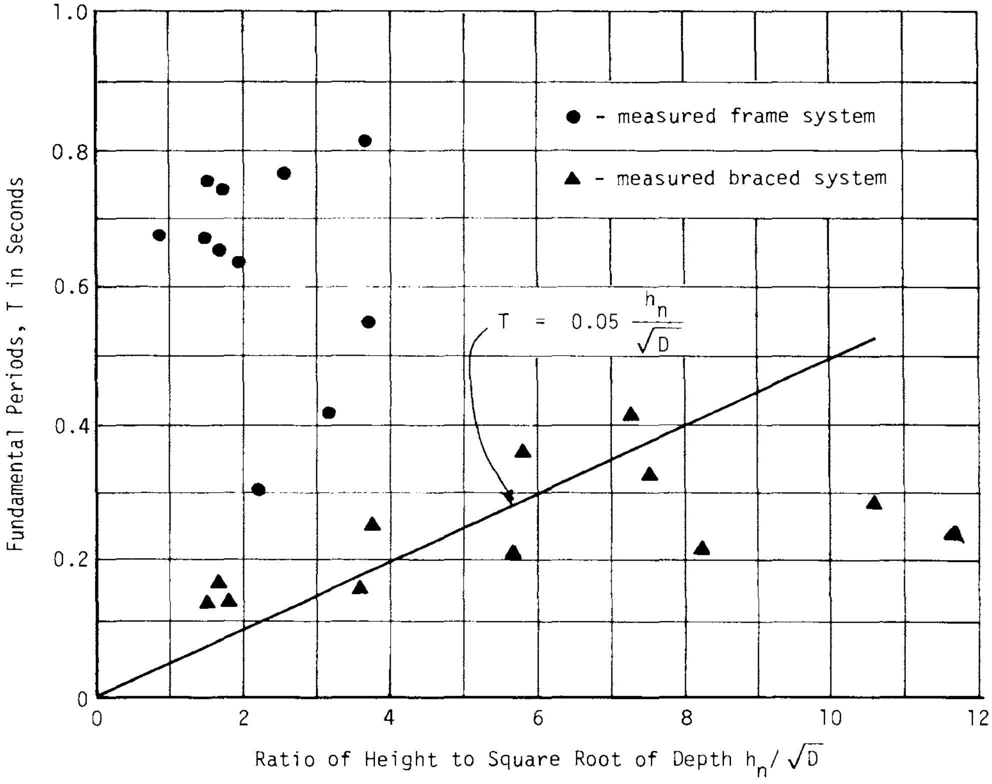


FIG. 6 - Fundamental Translational Periods of Steel Storage Racks Verses Ratio of Height to Square Root of Depth

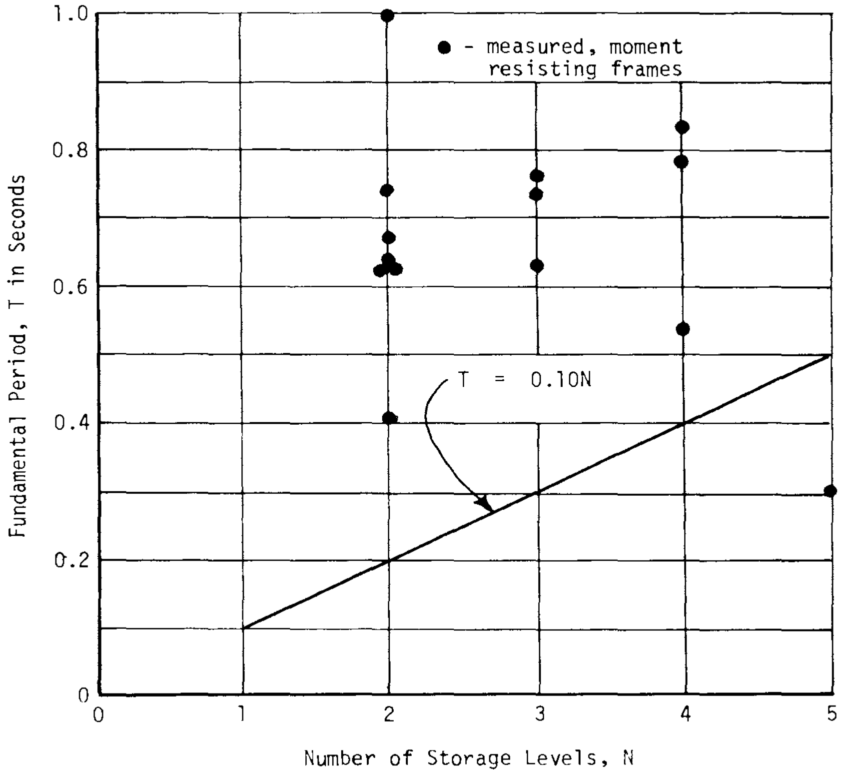


FIG.7 - Fundamental Translational Period of Steel Storage Racks Verses Number of Storage Levels

Figure 6 shows that for $h_n/\sqrt{D}$ ratios up to a value of about 6, there is some consistency between the measured periods for braced directions of storage racks and the UBC relationship 0.05 $h_n/\sqrt{D}$. Beyond a value of 6, however, there is practically no correlation. As illustrated in both Figure 6 and Figure 7, measured periods for racks in directions corresponding to moment-resistant frame action show essentially no correlation with either of the UBC expressions. Moment-resisting frames in storage racks represented by the data are considerably more flexible than would be expected of building framing of similar configuration.

The presence of scatter in the data, due primarily to the wide range of loading conditions for racks of similar proportions, illustrates that rack fundamental periods should not be estimated on the basis of geometric relationships. When a sufficient body of data on measured storage rack periods becomes available, it may be possible to express rack fundamental periods in terms of simplified relationships for various categories of storage racks. At present, fundamental response periods of storage racks for use in seismic design should be determined from appropriate analytical models that represent the rack structure characteristics or from properly substantiated test data. In lieu of these alternatives, storage rack periods could be conservatively assumed to have values corresponding to the maximum lateral force coefficient of the criteria response spectrum (i.e., C = 0.10).

ANALYTICAL STUDIES

Mathematical Models - The selected storage racks were analyzed with the help of a computer program in order to compare natural periods of vibration computed from the models to field-measured values and then to predict mode shapes of the storage racks. Input data consisted of the dimentions of the structure, the moment of inertia, the areas of the structural members, and the masses at each storage level.

Pinned column bases were assumed for all of the rack configurations except the transverse direction of cantilever racks. For storage rack axes in which moment-resisting frame action is the lateral load-resisting system, beam elements of frames were assumed to have fully fixed end conditions. In the braced direction of storage racks, pinned end conditions were assumed for connections of post-horizontal bar and post-diagonal bracing.

In most cases of double-row standard pallet racks, back-to-back ties used were small-diameter rods that were not capable of transmitting significant amounts of shear or moment. In these instances, it was assumed that each rack row acted essentially independently for purposes of computing fundamental periods.

<u>Results</u> - Table 2 compares measured and computed periods. Table 3 illustrates computed modal participation factors and computed effects of higher mode response with respect to fundamental mode response for various representative steel storage racks.

Table 2 shows reasonable agreement between measured and computed storage rack fundamental periods for most of the racks. Where the agreement is not so good, the differences may be due to connection details and mass distribution. As previously stated, the periods would normally be expected to increase about 20% under ranges of strain associated with response to a major earthquake. If mechanically nonlinear joint conditions occur in the rack framing, periods would be expected to increase considerably more than 20%, and measured damping ratios mentioned earlier would also be expected to increase by more than a factor of 2.

TABLE 2. - COMPARISON OF MEASURED AND COMPUTED FUNDAMENTAL PERIODS OF STEEL STORAGE RACKS

Rack designation (1)	Period, in seconds			
	Longitudinal		Transverse	
	Measured (2)	Calculated (3)	Measured (4)	Calculated (5)
SP-1	0.64	0.67	0.36	0.15
SP-2	0.64	0.67	0.36	0.15
SP-3	0.53	0.54	0.24	0.22
SP-4	0.83	0.68	0.32	0.27
SP-5	0.78	0.68	0.32	0.27
SP-6	0.73	0.56	0.29	0.24
SP-7	0.63	0.55	0.22	0.17
SP-8	0.67	0.47	0.25	0.12
SP-9	0.76	0.39	0.20	0.13
SP-10	0.74	0.38	0.20	0.13
SP-11	0.41	0.23	NR[b]	0.06
SP-12	0.30	0.35	0.13	0.12
DI-1	1.00	1.09	0.06	0.06
DI-2	0.63	0.97	0.21	0.10
C-1	0.13	0.07	0.31	0.37
C-2	0.13	0.11	NR	0.40
C-3	0.15	0.12	0.42	0.50
S-1	0.24	NC[a]	0.27	NC
S-2	0.24	NC	0.19	NC

[a] Not computed (NC)

[b] Not recorded (NR)

TABLE 3. - COMPUTED SECOND MODE EFFECTS IN SAMPLE STEEL INDUSTRIAL STORAGE RACKS

Rack designation	Longitudinal Direction					Transverse Direction				
	Period, in seconds		Participation factor[a]		R[b]	Period, in seconds		Participation factor		R
(1)	First Mode (2)	Second Mode (3)	First Mode (4)	Second Mode (5)	(6)	First Mode (7)	Second Mode (8)	First Mode (9)	Second Mode (10)	(11)
SP-1	0.67	0.16	1.11	0.11	0.02	0.15	0.06	1.25	0.25	0.03
SP-2	0.67	0.16	1.11	0.11	0.02	0.15	0.06	1.25	0.25	0.03
SP-3	0.54	0.16	1.15	0.15	0.01	0.22	0.07	1.33	0.31	0.04
SP-4	0.68	0.18	1.16	0.18	0.03	0.27	0.07	1.24	0.35	0.06
SP-5	0.68	0.18	1.16	0.18	0.03	0.27	0.07	1.24	0.35	0.06
C-1	0.07	0.03	1.63	0.31	0.01	0.37	0.06	1.34	0.45	0.11

[a] Ratio of top story modal acceleration to spectral acceleration

[b] Ratio of increase of combined first and second mode top shelf acceleration (square root of the sum of the squares) to first mode acceleration

The data in Table 3, illustrating the contribution of second mode acceleration response to total response, were based on the use of an acceleration response spectrum having the same shape as is described by the UBC equation $C = 0.05/\sqrt[3]{T}$. The R value in Table 3 illustrates the effect of considering the second mode of vibration in determination of top level acceleration response of the racks. The average R value for the racks listed is about 4%, this indicating that higher mode effects are relatively insignificant.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions - Based on the measured and analytical data that represent the dynamic response characteristics of steel industrial storage racks, the following conclusions can be drawn:

1. Horizontal load-resisting systems for storage racks are comparable in concept to those commonly used in steel buildings. The predominant horizontal rack framing systems are: (a) diagonal bracing, which is usually employed in the transverse direction of the racks, and (b) moment-resisting frames normally used in the longitudinal direction of the racks. Because column elements in a typical rack assembly are relatively closely spaced and are part of the lateral load-resisting system in both directions, diaphragm requirements are less than in most buildings. Under earthquake loadings, inertia forces of the rack contents are usually resisted locally by the framing of each bay. Differences between steel storage rack and building framing systems are primarily in overall geometry and the configuration of structural elements.
2. Compared to buildings of similar proportions, loaded storage racks are considerably more flexible in directions where horizontal loads

are resisted by moment-resistant frame action, and about the same or, in some cases, slightly stiffer in braced directions. Thus, for a typical earthquake response spectrum, loaded storage racks would be subjected to seismic base shear forces either considerably less than or about equal to those for a building system of the same geometry.

3. The fundamental translational period of storage racks cannot generally be predicted from the geometric expressions 0.05 $h_n/\sqrt{D}$, or the relationship 0.10N, which characterize building periods. Actual rack fundamental periods measured in the study over a range of storage-loading conditions and rack geometry averaged around 0.6 to 0.8 second for moment-resistant frame action, and 0.2 to 0.4 second for bracing action. Torsional modes present in many of the rack configurations were represented at periods averaging 0.4 second. These values would probably increase 20% or more under ranges of strain associated with response to a major earthquake.
4. Measured structure damping ratios for storage racks averaged around 2% to 3% of critical at root-mean-square response acceleration levels averaging 1% to 2% of gravity. At high strain ranges that would result under critical seismic conditions, structure damping would be expected to increase by a factor of 2 or more. Nonstructural damping, resulting from rocking and interaction of storage goods, would in most cases add appreciable energy absorption to the system. Thus, a damping ratio of 5% of critical for storage racks under seismic conditions is considered reasonable.
5. Natural periods determined from linear elastic analytical models of the various rack types correlate reasonably well with field-measured periods. Higher mode effects in most storage racks were found to be generally insignificant.

Recommendations - Based on the above findings, the following recommendations for seismic design of steel storage racks are judged to be consistent with the current UBC seismic design philosophy.

1. Industrial storage racks constructed of structural steel that are not connected to buildings or other structures should be designed to resist a minimum lateral seismic force

   $V = ZKCW$

   where: V = lateral seismic force

   Z = numerical coefficient dependent upon the appropriate zone from the latest UBC seismic risk map.

   K = (a) 1.33 for racks or portions thereof where lateral stability depends on diagonal or X-bracing; (b) 1.0 for racks where lateral stability depends wholly on moment-resistant frame action; (c) 0.67 or 0.80 where ductility can be demonstrated.

   C = $0.05/\sqrt[3]{T} \leq 0.1$ for racks installed on the ground level. T is the fundamental period of vibration of the rack in seconds in the direction under consideration. In the absence of such data, the value of C shall be taken as 0.10.

   W = total maximum live load and dead load in the rack structure. No reductions are permitted.

2. Storage racks located in buildings at levels above the ground level, and racks that depend on attachments to buildings or other structures at other than the floor level for their lateral stability should be designed for earthquake effects on the basis of a rational dynamic analysis.

These recommendations are under consideration for adoption by ICBO(1).

Recommended Further Study - While much initial work has already been accomplished under the sponsorship of the Rack Manufacturer's Institute, including preliminary laboratory studies, field work, and office studies to develop design recommendations, additional research is needed for verification and implementation of the initial findings. Consequently, a follow-up research proposal has been prepared by URS/John A. Blume & Associates, Engineers, and is being reviewed by the National Science Foundation.

The objective of the proposed research is to perform the necessary investigations to develop realistic criteria and procedures for the seismic design of industrial steel racks. Static cyclic load tests will be conducted on full-size frames and on sub-assemblies. Appropriate input seismic motion criteria will be developed, and detailed dynamic analysis will be performed using the postulated input motion, rack load-deformation data, and results of earlier studies. The results will then be correlated with the results of shaking table tests of full-scale loaded and unloaded racks.

Recent recommendations of the Structural Engineers Association of California (5) revises the base shear to $V = ZKCSIW$ where C equals $1/15\sqrt{T}$, S is soil factor, and I is an importance factor. The combined effect of C times S is to increase the value of the base shear $V = ZKCW$ and may require special investigation for its applicability to the seismic design of the industrial steel storage racks.

SUMMARY

The results of a study of the dynamic response characteristics of steel industrial storage racks have been used to establish seismic design criteria compatible with Uniform Building Code philosophy. The study included field measurements, structural analysis, and dynamic response calculations for representative racks of various types, geometry and loading conditions.

APPENDIX I - REFERENCES

1. Building Standards, Part IV, Reports of ICBO Subcommittees on Code Changes. International Conference of Building Officials, Whittier, California, January - February, 1975, pp. 41-44.

2. Interim Specification for the Design, Testing, and Utilization of Industrial Storage Racks, Rack Manufacturer's Institute, Pittsburgh, Pennsylvania, 1972.

3. Interim Specification for the Design, Testing, and Utilization of Industrial Storage Racks - Supplement No. 1, Rack Manufacturer's Institute, Pittsburgh, Pennsylvania, 1973.

4. Newmark, N. M., and Hall, W. J., "Building Practices for Disaster Mitigation," National Bureau of Standards, U.S. Department of Commerce, 1973, pp. 209-236.

5. Recommended Lateral Force Requirements and Commentary, Seismology Committee, Structural Engineers Association of California, San Francisco, California, 1974.

6. Uniform Building Code, International Conference of Building Officials, Whittier, California, 1973.

7. URS/John A. Blume & Associates, Engineers, "Seismic Investigation of Steel Industrial Storage Racks," San Francisco, California, 1973.

APPENDIX II - NOTATIONS

The following symbols are used in this paper:

C = numerical coefficient for lateral seismic force at the base;

C_p = numerical coefficient for lateral force on the part or portions of the structure;

D = width of storage rack in direction considered;

F_p = lateral force on the part or portions of the structure;

h_n = height of top storage level above the base;

K = numerical coefficient depending on the lateral force resisting frame scheme of the storage rack;

N = number of storage levels above the base;

T = fundamental period of vibration;

V = total lateral seismic force, $V = ZKCW$;

W = weight of rack plus contents;

Z = numerical coefficient depending on the appropriate zone of earthquake risk.