WORKSAFE TECHNOLOGIES
VALENCIA, CALIFORNIA

ISO-Base Technical Manual

Revision 1

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Degenkolb Job Number B6439012.00

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Table of Contents

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I. SEISMIC ISOLATION: WORKSAFE ISO-BASE PLATFORMS

1. Introduction

The WorkSafe ISO-Base platform takes a new approach to contents bracing in seismic areas by implementing isolation technology. Seismic isolation has been in use since the 1970s to protect buildings and other large structures from earthquake shaking in seismically active areas around the world. Seismic isolation technology works by decoupling the isolated component from the ground, essentially allowing the ground around to move underneath the component without transmitting the damaging accelerations above the plane of isolation.

Seismic isolation technology typically reduces damaging earthquake accelerations within the structure by a factor of 5 to 10, depending on the particular application. In building and bridge structures, as shown in Figure 1, isolators consist of large laminated rubber pads, or sliding Teflon and steel assemblies, capable of accommodating large relative displacements -- as much as 20” to 30” in many cases.

Figure 1 Seismic Isolators in a Building

2. ISO-Base

The WorkSafe ISO-Base platforms are unique in applying isolation technology to individual server cabinets, or rows of cabinets. The system uses the patented Ball ’N Cone isolators that are well suited to the lighter vertical loads for this application compared to those present in larger building and bridge structures.

Figure 2 WorkSafe ISO-Base Platform

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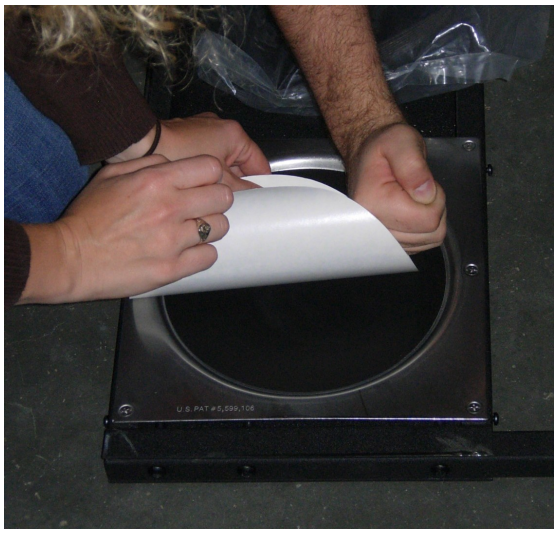
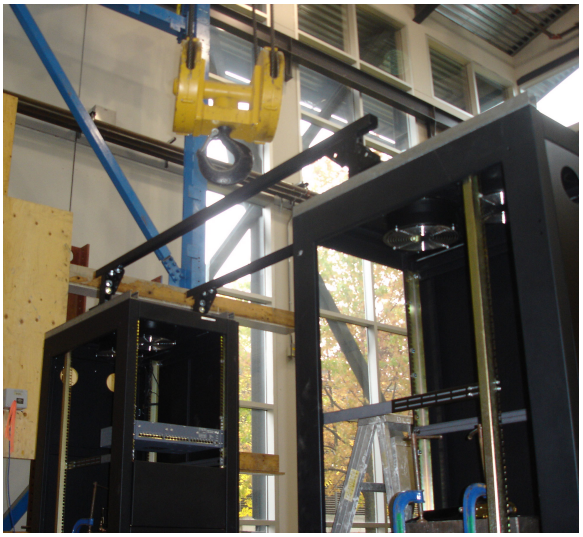
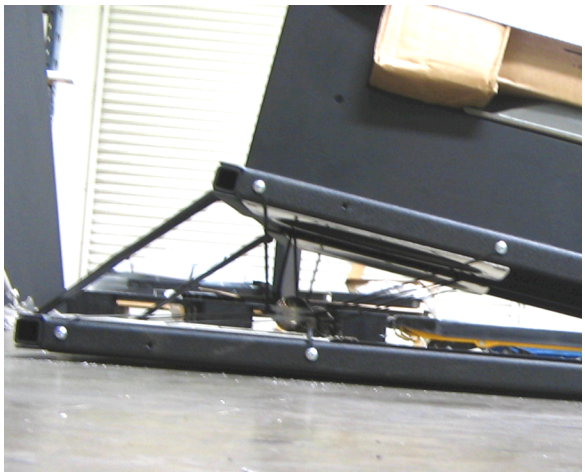


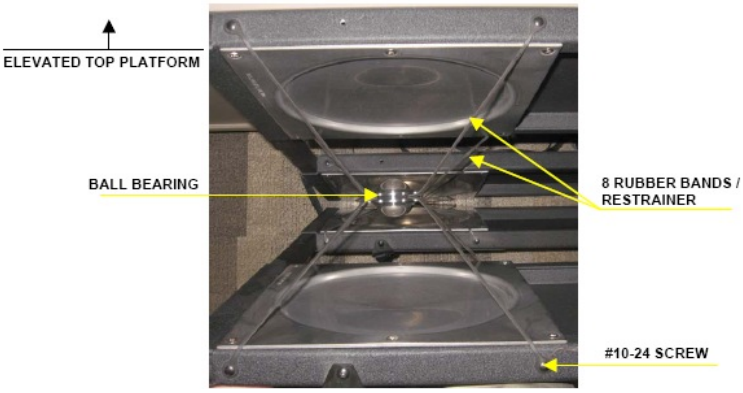
(a) Liners may be added to isolator dish



(c) Overhead braces interconnect aisles



(b) Restraint straps between top and bottom planks



(d) Restraint devices secure ball-bearing

Figure 3 WorkSafe ISO-Base Platform

II. PERFORMANCE CRITERIA

1. ISO-Base Performance Objectives

The benefits of using ISO-Base as opposed to conventional bracing are two-fold – critical server equipment is protected against damaging earthquake accelerations and facility managers do not have to deal with installing traditional bracing, with the associated concrete drilling and relatively heavy construction in the sensitive data center environment.

Currently, though, building codes do not address seismically isolated equipment specifically. There are provisions for seismically isolated buildings and for bracing "fixed-base" equipment – but not for seismically isolated equipment. The code requirements for isolated buildings include provisions that are not well suited to equipment, making it difficult to apply these in this case.

The building code does provide for an alternate method of compliance, whereby the submitter demonstrates that the proposed installation provides the equivalent level of safety intended by the building code, the "life-safety" performance level. Seismic isolation technology, including the ISO-Base platforms, is an inherently higher-performing system than those implied by the minimum life-safety standard adopted in the building code. Provided the isolator displacement capacity is not exceeded, the supported building or component will generally experience little or no damage, and will require no repair following the design earthquake.

Figure 4 Isolator Rim Contact

Should the earthquake displacement demand exceed the capacity of the isolators, then the isolator will experience a brief contact between the ball bearing and the rim of the dish and uplift (rocking) will occur and the benefit of isolation is lost. To reduce the probability that the isolator displacement capacity is exceeded, the code provisions for seismically isolated buildings require the isolation system to be capable of withstanding displacements larger than would be expected to occur in the representative design earthquake. These provisions dictate isolated building and bridges to have maximum total displacement capacities (D_{TM}) usually in excess 12-inches, frequently in the 24-inch to 30-inch range. The actual value depends on the site seismicity and soil conditions.

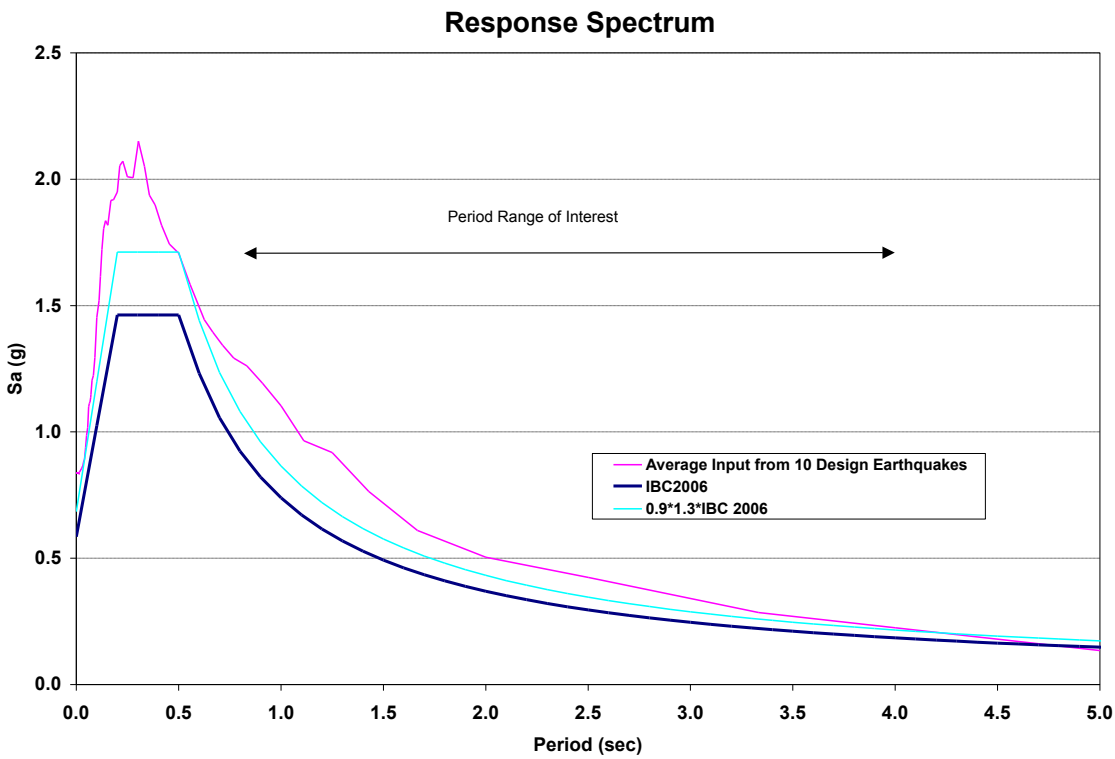


Figure 5 Typical Design Earthquake Response Spectra

The required displacement capacity does not scale down with size -- it is the same for large buildings and bridges as for much smaller isolated platforms such as ISO-Base. However, it is not practical to size the isolators for a 16-to-24-inch displacement capacity to accommodate all potential earthquakes as the required isolator size would exceed the ISO-Base platform size. Therefore, the ISO-Base platforms were designed to have a displacement capacity of approximately eight inches.

This means that the ISO-Base platforms may exceed their displacement capacity during the code-specified design earthquake. When this happens, the ball-n-cone isolators will experience an instantaneous contact between the ball bearing and the rim of cone shaped dish and the resulting accelerations will be transmitted to the isolated component. The contact accelerations, however, are similar in magnitude, but shorter in duration, to the accelerations that would occur if the equipment was rigidly anchored (bolted), or left unanchored and subject to potential toppling. These accelerations have been measured in shake-table testing for various levels of shaking intensity.

Ball bearing contact is acceptable from a life-safety performance perspective, provided that toppling of the equipment (or other potentially hazardous damage) does not occur. The important difference between a building or bridge structure and an ISO-Base platform is that the consequences of isolator contact can be much more easily managed in a small piece of equipment weighing 2,500 lbs. than in a building weighing perhaps 25,000,000 lbs.

When the ISO-Base platforms are capable of accommodating displacements associated with the code earthquake, their performance would exceed that of the building in most cases – i.e. the server equipment would be undamaged and operational, but the building would be damaged and potentially evacuated. In cases where the building has been specifically designed to a higher performance level, this should be considered when evaluating the expected performance of the installation.

The degree of protection provided by ISO-Base – i.e. the earthquake size for which the isolator displacement is not exceeded – varies according to local seismicity, fault distance, soil type, and where the installation occurs in the building (height above ground). For relatively lightly-loaded platforms, rubber liners can be provided to decrease earthquake displacements and increase the level of protection afforded by the system.

The earthquake size that can be accommodated by a given ISO-Base installation is expressed either as a percentage of the code design earthquake, or as an average return period for the earthquake. For example, ISO-Base installations can typically accommodate close to 80% to 100% of the code design earthquake in earthquake zones of moderate seismicity – e.g. parts of Oregon, Central California, Sacramento, etc. In addition, if the building is located on a stiff soil or rock site (Site Class Sc or better), then many California moderate-to-high-seismicity locations can also be accommodated, with the exception of those close to active faults. For a typical soil site (Site Class Sd) located in non-near-field California or Western US sites, the ISO-Base platforms can accommodate 40% to 60% of the design earthquake. This percentage drops closer to active faults and for progressively softer soil sites.

Because earthquake size decreases with frequency of occurrence, this can also be expressed in terms of a recurrence interval: the average number years between events measured over a very long time period. The building code design earthquake has a recurrence interval that varies between about 300 to 500 years, depending on location. The average recurrence interval for an earthquake that exceeds the eight-inch ISO-Base displacement capacity can range between 30 and 500 years, depending on the site seismicity and location.

In summary, the approach adopted by WorkSafe is to provide an Operational level of performance for frequently-occurring earthquakes, and to assure that the system meets the Life-Safety performance level for larger earthquakes and for the code-specified design earthquake in areas of high seismicity.

Table 1 Summary of ISO-Base Performance

Earthquake Type	Recurrence Interval	Performance Level
Small to Moderate Earthquakes	Typically less than 300 years	No contact. Life safety is assured and equipment accelerations are low
Large Earthquakes	Typically greater than 300 years	Life safety is assured but equipment accelerations may be high

2. ISO-Base Performance Evaluation

The natural frequency of the ISO-Base platform varies with displacement but is typically in the two-to-four second range. This means that the seismic demands on ISO-Base system are best characterized by the parameter S_1, the spectral acceleration (g) at one second for the design earthquake, including soil adjustment factors (S_{D1}). The procedure can also be used with other values if performance is being evaluated for, say, the MCE (S_{M1}), or for floor levels above grade.

Based on shake table testing and analysis results (Appendices A & B), two alternate methods of assessing ISO-Base performance were developed. These are summarized in Appendix E and the resulting simplified evaluation process is summarized below. The limitations of this simplified procedure are also described.

The results from shake table testing were adjusted to account for bi-directional loading using a numerical model calibrated to the test data. This introduces an element of analysis into this process. However, the adjustment made to the results is relatively modest and, therefore, the evaluation procedure is still primarily "by physical test".

3. Simplified ISO-Base Performance Evaluation

Based on the shake table test and SAP2000 analysis considering two-directional load effects (see Appendices), a simplified method for evaluating ISO–Base performance was developed using the Contact Acceleration Approach.

The key design tool is provided in Figure 6. Separate curves were developed to evaluate performance of the ISO-Base with and without liners. To use Figure 6, simply enter the horizontal axis of the plot with the appropriate value of S1, and then move upward to intersect the appropriate curve (liners versus no-liners). Move horizontally to the left or right to determine the base shear reaction or rack accelerations, respectively.

The left vertical axis of the plot represents the base shear and the right vertical axes represent the acceleration at the top, middle and bottom height of a rack. The base shear value can be used to design the floor and the acceleration information can be used to estimate the level of acceleration in equipment in the rack during an earthquake. The rack height used in this plot is approximately 7.5 ft. Therefore, if the height of rack differs by more than 1 ft. from 7.5 ft., this plot is not applicable and additional evaluation must be performed.

At large S_1 values, when contact occurs, the isolator may uplift due to rocking of the rack and the potential for loss of the isolator ball-bearing exists. Once this occurs the top-plank may separate from the bottom plank and the risk of toppling increases. Significant uplift was observed to occur for base shear reactions above 1.5g, which should be considered the maximum limit of applicability for this procedure without the bearing-restraint devices. When the bearing-restraint devices are provided the limit of applicability for the procedure is 5.5g.

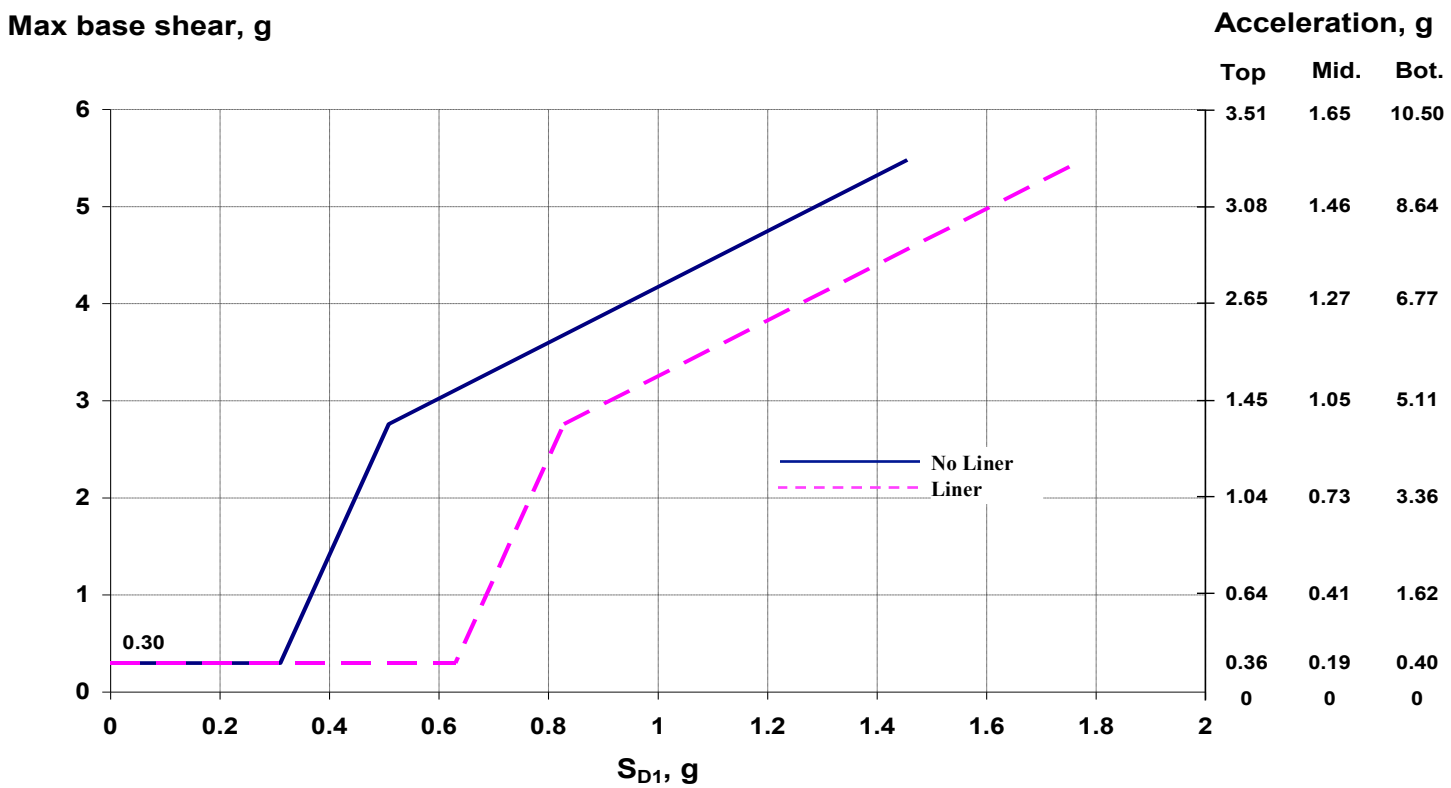


Figure 6 Curves for Simplified Performance Evaluation

The performance of ISO-Base without liners is relatively independent of weight, which means that this data can be used up to the load rating of the ISO-Base units. Provided the liners are well-adhered to the dish the liners can be used for supported weights up to approximately 750 lbs per isolator. Values greater than this require additional evaluation. For heavy rack units it is possible to provide an additional (third) isolator per plank to reduce the average isolator load.

The ISO-Base testing with liners amounted to 225lbs per isolator. Insufficient test data exists to determine the relationship between weight and rolling friction for liners. A conservative approach is to assume that it remains constant irrespective of weight. The simplified procedure can be used with this assumption by appropriately interpolating between the liner and no-liner curves according to the actual weight per dish for the installation.

Recently, WorkSafe Technologies has developed a new coating, QuakeCoat, which is superior in strength and toughness to the previous urethane liners. QuakeCoat is a spray-applied coating that provides many improvements over the urethane liners. Based on recent testing performed at the University of Oklahoma, the new coating provides 25% equivalent viscous damping, which meets or exceeds the damping provided by the urethane liners tested at the University of British Columbia. Therefore, until more detailed testing can be performed on QuakeCoat, the use of the urethane liners and QuakeCoat is considered equivalent with respect to earthquake performance and the same evaluation procedure applies.

The ISO-Base units are commonly ganged together in rows. This configuration is preferred as single units are more prone to toppling in the short direction and due to biaxial rocking affects. When the performance of a row is being evaluated, average isolator properties (weight per dish) should be used to assess displacements. If the weight distribution varies along the row there may be some tendency for the row to twist slightly, this may result in early contact at one end of the row. This behavior is not considered in this simplified procedure and a more detailed evaluation would be required if the effect is to be investigated.

The neoprene liners provided underneath the bottom plank are sufficient to prevent slip up to contact base shear values of 3.0g. At contact base shear values of 5.5g up to 2.5 inches of slip was observed between the bottom plank and the shake table floor. The effect of slip is to reduce the contact accelerations as is observed by the reduced slope of the line from 3.0g to 5.5g. The slip of the bottom platform is therefore beneficial in reducing the level of base shear and accelerations and therefore we recommend that the ISO-Base units not be anchored to the floor provided this is acceptable to the local jurisdiction.

If connection is provided between the bottom plank and the supporting floor then the SEOR may wish to detail it to accommodate the required slip displacement. If for some reason the bottom plank is to be rigidly bolted to the structural or access floor, and the expected contact accelerations are above 3.0g, then this simplified procedure is not applicable and an additional evaluation must be performed to determine the base reactions.

The shake table testing was conducted with a rack weight of 1,100 pounds and the maximum base shear reaction was 5.5g, for a total base reaction of 6,000 pounds. The tested rack was connected to the top plank with the standard straps provided by WorkSafe. This is therefore the limit of applicability for this procedure and use of the strap method of attachment.

When the computed base reaction (rack weight times base shear in units of g) exceeds 6,000 pounds alternate means of connection between the rack and the top plank may be required. In addition, supplemental straps may need to be provided between the top and bottom planks to ensure these items do not separate. The need and detailing of these items requires a more detailed engineering evaluation than provided here.

The location of center of gravity of the tested rack was slightly below the rack mid-height (0.4H) and the cabinet was tested in the long direction (42-inch depth). If the installed rack has a significantly higher center of gravity compared to cabinet depth, then appropriate adjustment of the results should be performed by the SEOR, and the maximum acceptable S_1 value should be adjusted downward accordingly.

4. Limitations on Use

This methodology presented herein is intended for use by the SEOR in the assessment of the installation, and is therefore subject to review, concurrence, and stamp. There are limits to its applicability, and it is recommended that the SEOR extend or modify these procedures, or perform a more detailed evaluation according to the following requirements:

- The procedure is intended to apply primarily to Occupancy Category II buildings (i.e. those meeting a life-safety performance level). If the installation is located in an Occupancy Category III or IV building, (i.e. those meeting a higher performance level such as Immediate Occupancy) a more detailed evaluation must be performed by the SEOR.
- The supported racks or equipment are assumed to be similar in size, aspect ratio, and weight distribution to the tested configuration (See Appendix A). Suggested measures for accommodating variation are provided for consideration.
- If the maximum computed base reaction exceeds 1.5g then the risk of toppling increases and bearing restraint devices must be provided. Above 5.5g a more detailed evaluation must be performed.
- If the maximum computed base reaction exceeds 6,000 pounds, alternate measures may be required to connect the rack to the top plank, and prevent separation of the top and bottom planks. This requires that a more detailed evaluation be performed to design this connection.
- The tested rack was of average weight (1,100 lbs). The methodology includes provision for heavier racks, up to the specified base shear limit of 6,000 pounds. In addition, the maximum load per isolator should be limited to 750 lbs when rubber liners are used. The maximum load per isolator without liners is approximately 1,000 pounds (subject to confirmation by WorkSafe).

- The S_{D1} value used in the evaluation must account for the effect of ground motion amplification above grade, where this occurs. It is suggested that this affect may be ignored for two-or-three story buildings of relatively recent design and construction, however this judgment must be must made by the SEOR. If this effect must be accounted for, then the assessment complexity may grow significantly, as the entire building must be evaluated and modeled to capture the interaction between the building and the ISO-base system. Installations are not recommended in high-rise or base-isolated buildings without careful engineering review.
- A more detailed evaluation is also required if any of the following conditions exist:
    - The building is located on a soft soil site, e.g., Site Class F.
    - The one second spectral acceleration (typically given by S_{D1}) exceeds 1.4g without liners or 1.6g with liners.
    - The bottom plank is rigidly bolted to the structural or access floor (no slip permitted) and the computed base reaction exceeds 3.0g.

This methodology is intended for use by appropriately qualified design professionals to estimate the expected accelerations and displacements for a given ISO-Base performance. The procedure and data is provided "for information only", and must be verified by the SEOR.

The procedure does not address the following items that may impact the overall seismic performance of the installation:

- Structural integrity of the rack structure or any supported equipment, equipment operation – during or following the event.
- The vertical or lateral capacity of the access floor or structural floor to accommodate the imposed loads.
- The seismic performance of the building, contents or systems - including those that may be required for the successful operation of ISO-Base and the supported equipment.

5. Evaluation and Permit Process

To obtain a building permit for an ISO-Base installation, a set of engineering drawings and calculations must be submitted to the local Department of Building Inspection for review and approval.

To perform the evaluation, the following information is required:

1. Building location, address, or latitude and longitude.
2. Summary of proposed rack and ISO-Base layout.
3. Equipment weights, dimensions, and approximate weight distribution.
4. Site geotechnical report including soil type.
5. Site seismicity information. This is typically available from hazard maps provided by the USGS, but in the case of very near fault locations, a site specific hazard evaluation may be required assuming one has not already been performed.

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Using this information the Structural Engineer of Record for the installation will perform the following scope of work:

1. Generate plans and details showing the ISO-Base installation. Depending on the size of the installation, this can usually be shown on one full-size drawing sheet.
2. Generate a set of corresponding structural calculations for review, which may include this supporting documentation if used in the assessment.
3. Submit the required number of stamped, signed copies to the local building department as part of the permit review process. Frequently, the ISO-Base installation will be part of a larger construction project for which a permit is already being obtained and can be referenced. If not, a permit will have to be obtained.
4. Respond to plan review comments. The local building official will generate comments that usually require written response, with revised drawings or calculations. The ISO-Base system is different from typical bracing systems and the compliance approach (alternative means via shake table testing) is different from that adopted for typical seismic bracing. This means that the review process may become more detailed in some cases.
5. Respond to questions from WorkSafe and/or the General Contractor issued during construction.
6. Visit the site during or following installation to perform construction observation, which may be required by the local jurisdiction.

The assessment process can take several weeks, depending on the time required to gather the necessary information. The review process is subject to the schedule and requirements of the reviewing agency. In the case of one recent project, the time between submittal and permit issue was approximately one month.

III. APPENDICES

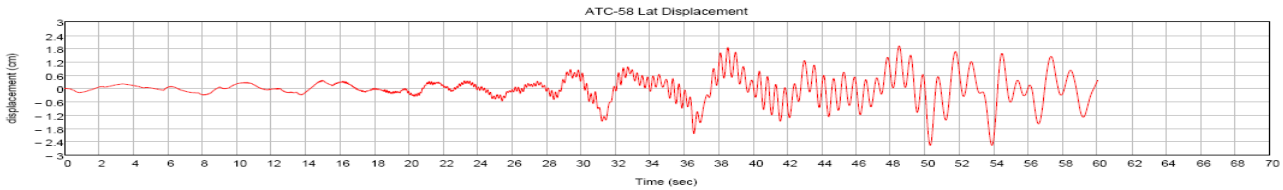
1. Appendix A. Validation of ISO-Base Performance: Shake Table Tests

A. Input Motion and Test Procedure

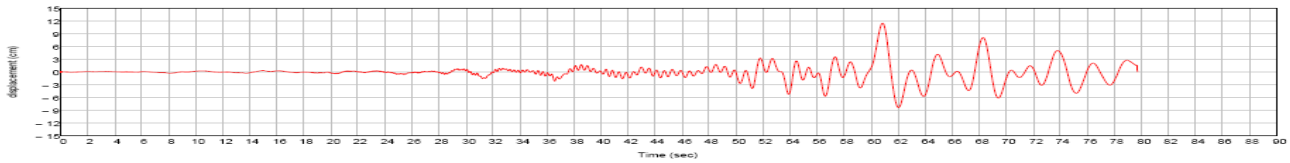
Traditional shake table testing of components such as server racks is performed using standard testing protocols, such as AC-156, *Acceptance Criteria For Seismic Qualification By Shake-Table Testing Of Non Structural Component And Systems*. These protocols were written around fixed or bolted equipment and are not well-suited for evaluating the expected behavior of isolated equipment. The primary issue is that the shake table machines used to simulate the earthquake is usually not capable of replicating the large displacements and velocities associated with the code design earthquake. They can replicate the high frequency accelerations, i.e. the forces, but not the lower frequency displacements and velocities.

This limitation means that shake table test protocols such as AC-156 are written to permit the shake table input to drop significantly below the building code design earthquake for frequencies below 1Hz. Seismic isolated systems have natural frequencies typically below 0.5Hz and so are not subjected to the appropriate level of shaking. Fixed or bolted equipment usually has a natural frequency of 5Hz or greater as so is not affected by this limitation.

The ATC-58 Interim Protocol 2, *Shake Table Testing of Structural and Nonstructural Components*, was used to validate the performance of the ISO-Base system. The ATC-58 lateral component motion was modified to include response for frequencies below 0.5 HZ. A series of shake-table tests for both large and small earthquakes were performed at the University of British Columbia since this table has a relatively large displacement capacity of +\-16 inches and can, therefore, capture the earthquake input over the required frequency range. This excitation input was applied in the direction of short side of the rack which produced higher possibility to topple over the rack than if applied in any other directions.

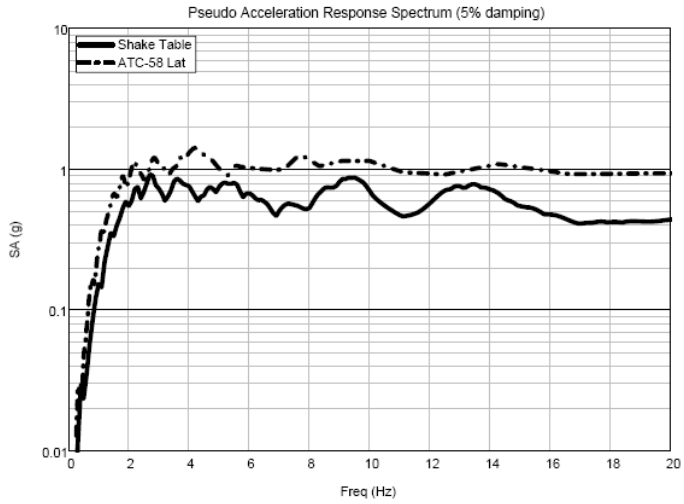


(a) ATC-58 Lateral Component Motion

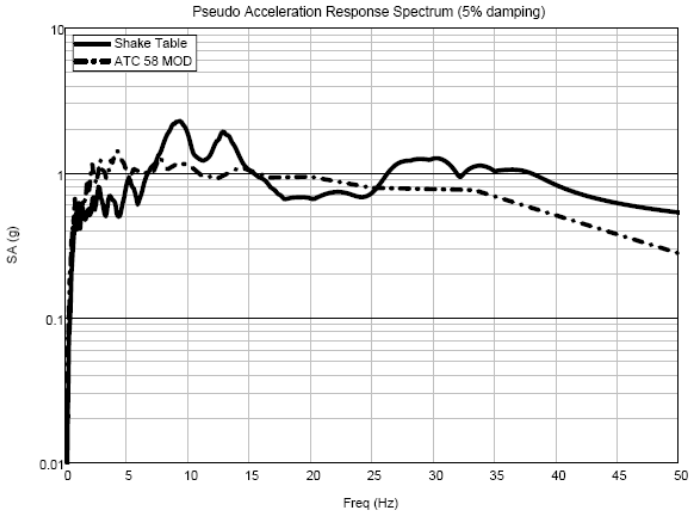


(b) Modified ATC-58 Lateral Component Motion

Figure 7 Comparison of Displacement-Time Histories Obtained From The Shake Table Tests



(a) ATC-58 Lateral Component Motion



(b) Modified ATC-58 Lateral Component Motion

Figure 8 Comparison of Response Spectrum

Setup and instrumentation of a shake table test were described in Figure 9 and Figure 10. Seismic performance of the ISO-Base system under various conditions was evaluated using different levels of shaking from the modified ATC-58 motion. The test variables for the shake-table tests to validate performance of ISO-Base were as follows:

1. ***Scale of input record***: Modified ATC-58 motion was scaled by a factor from 0.25 to 2.75 to produce spectra with S1 ranging from 0.13g to 1.39g.
2. ***Use of ISO-Base***: Sever rack was either bolted or unbolted into the table if ISO-Base was not used.
3. ***Use of rubber dish liner:*** Dishes with no liner, standard liner or heavy-duty liner were used in the platform.
4. ***Configuration of server racks and surcharge weights.***

Figure 9 Shake Table Testing

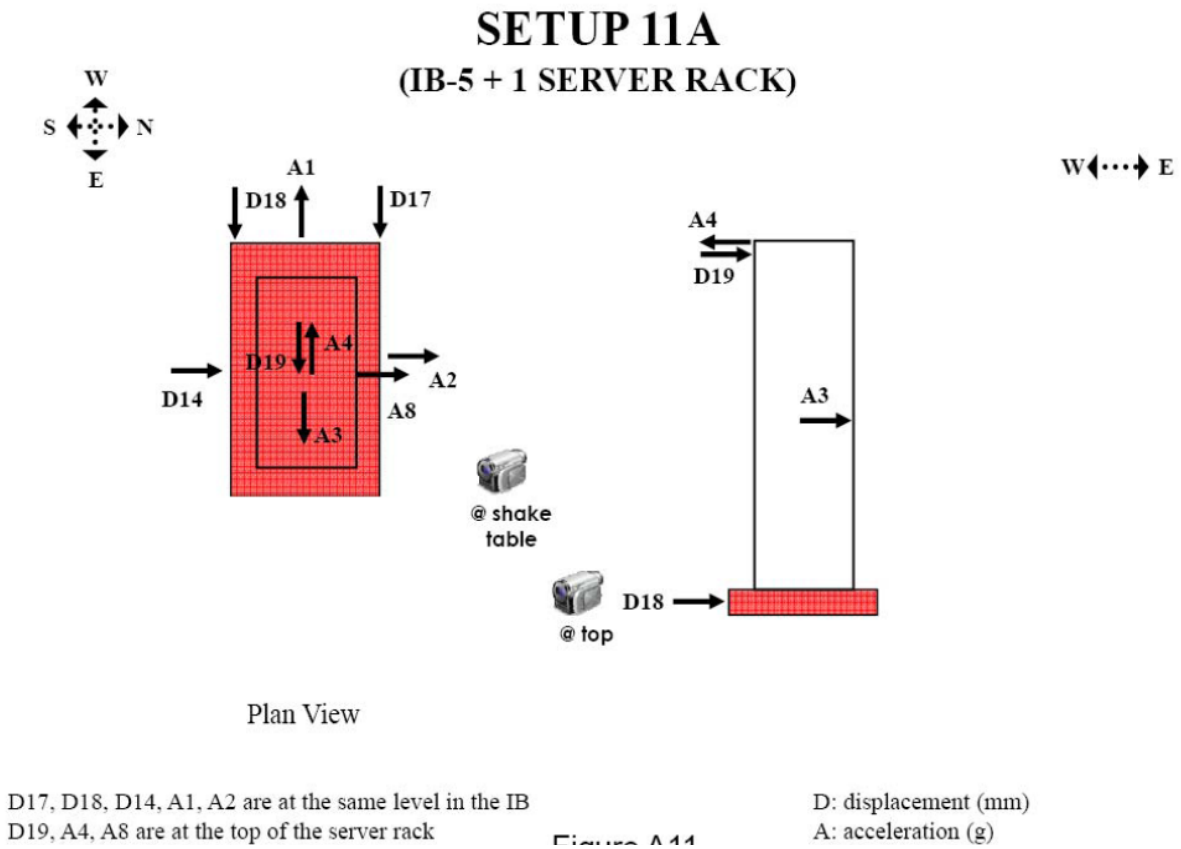


Figure 10 Instrumentation of Shake Table Test, Setup 11A

B. Test Results

The measured acceleration and displacement from the tests were plotted according to the seismic demand, S1 as the reference parameter for the ground motion input. These plots represent the performance of the ISO-Base system in various conditions under various level of seismic demand. The measured acceleration and displacement from the Test Setup 11A are shown in Figure 11 and Figure 12.

In case of Test Setup 11A, ISO-Base without liners, the isolator did not contact with the dish rim for the test with S1 equal to or less than 0.25g. Isolator contact with dish rim did occur on the test with S1 greater than 0.25g. The ISO-Base top plank separated from the bottom plank for the test with S1=1.39g. These different performance levels, depending on S1, provide design criteria for the ISO-Base.

Rubber dish liners can be used to reduce the displacement and avoid contact of the isolator to the dish rim. However, the contact may occur in a larger earthquake event such as the code-specified earthquake.

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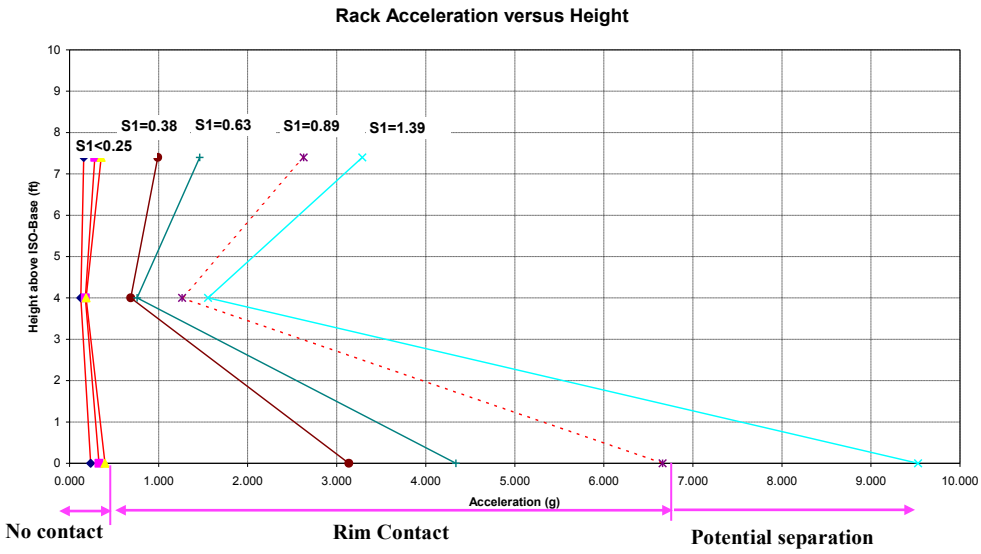


Figure 11 Acceleration versus Rack Height, S1 from 0.13g to 1.39g, Setup 11A

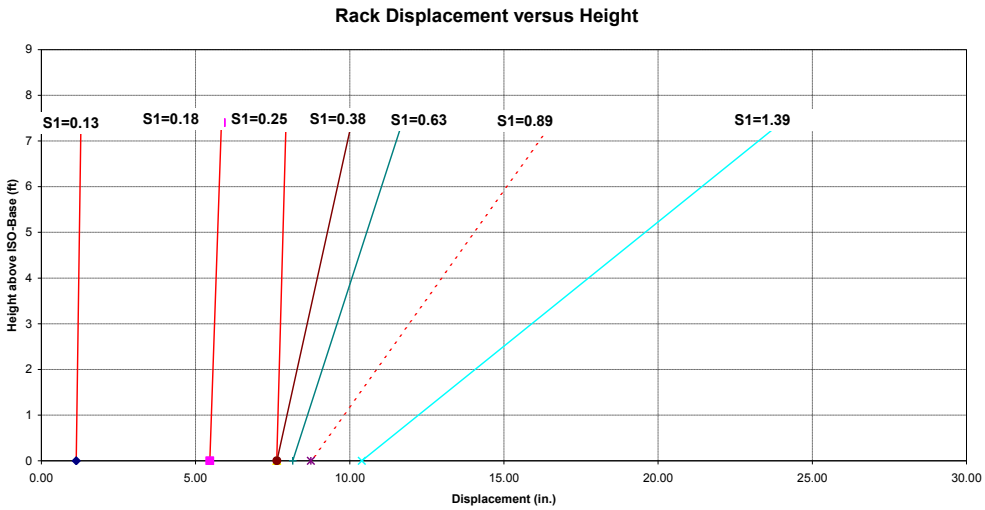


Figure 12 Displacement versus Rack Height, S1 from 0.13g to 1.39g, Setup 11A

(a) No Contact, S1 < 0.25g

(b) Rim Contact, 0.38g < S1 < 0.89g

Figure 13 Performance of ISO-Base Depending on S1, Setup 11A

2. Appendix B. Computer Analysis: SAP2000 Model

A. Computer Model Correlation with Shake Table Tests

The server rack and ISO-Base platform models were developed in SAP2000. A calibration study was performed for the ISO-Base and rack model, which matched the behavior of the SAP model to recorded behavior from a shake table test. Comparisons between the test results and the analysis results are shown in Figure 15 and Figure 16.

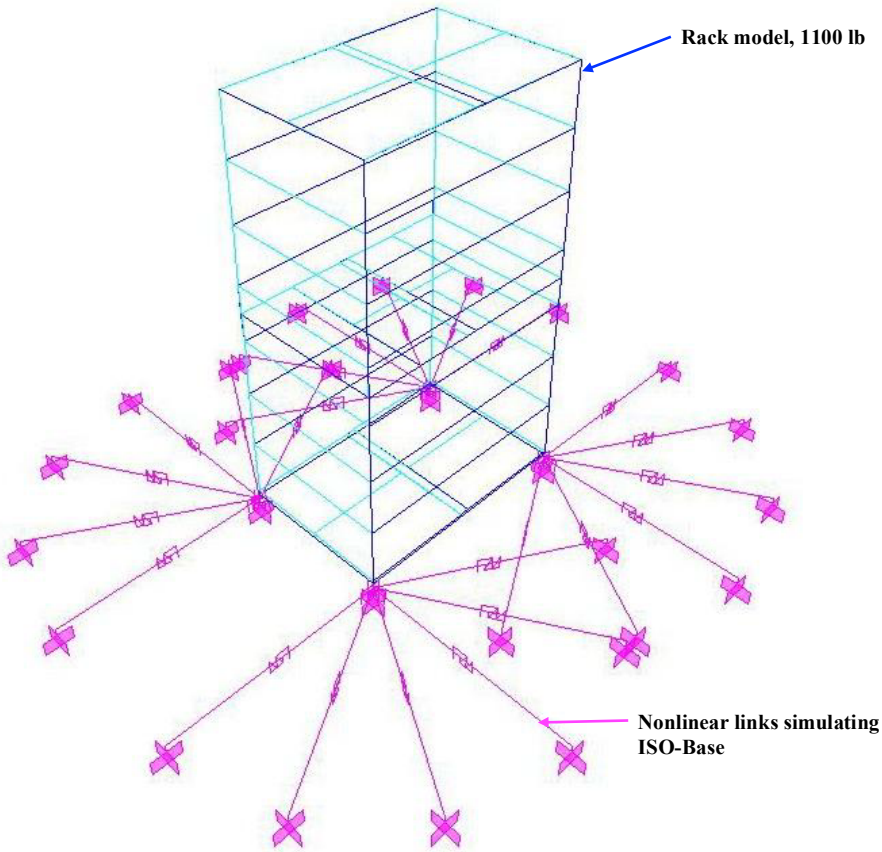


Figure 14 SAP2000 Model of Rack and ISO-Base

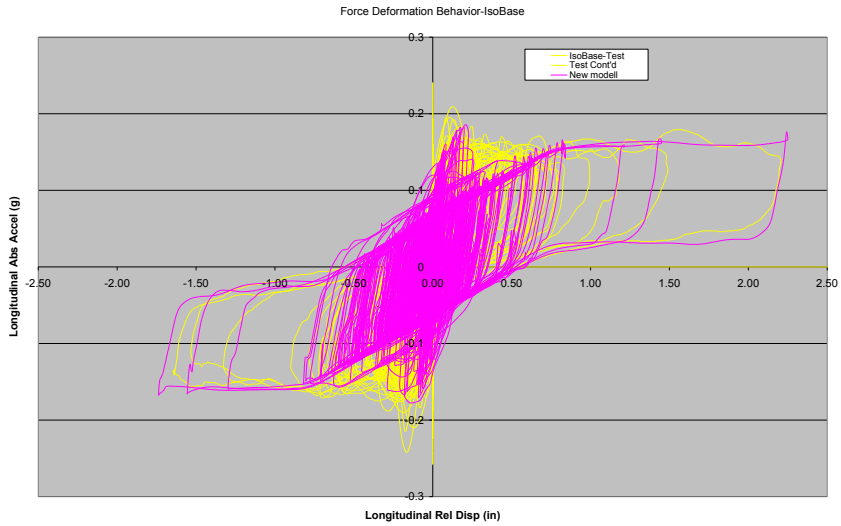


Figure 15 Comparison of Test Results with Computer Analysis, Setup 5, Test 4

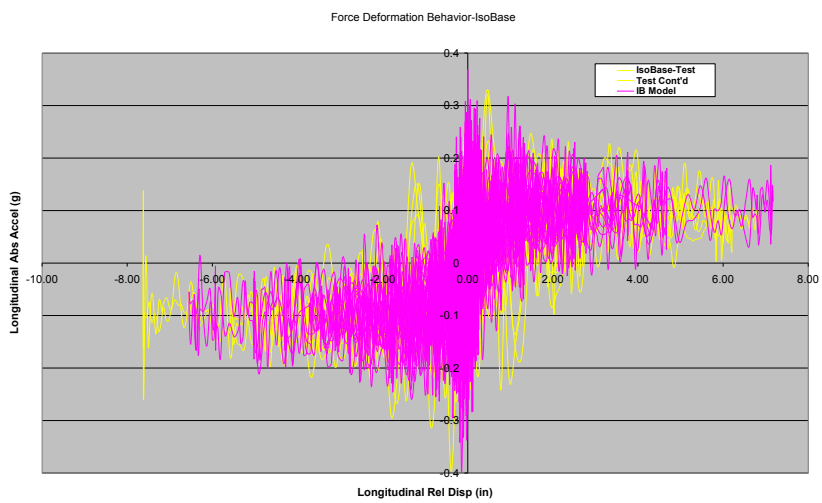


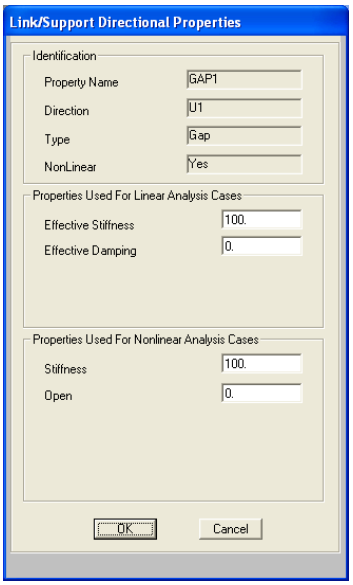
Figure 16 Comparison of Test Results with Computer Analysis, Setup 11A, Test3

B. Computer Model of Rack

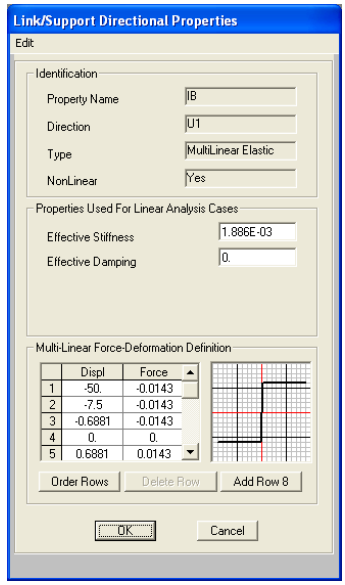
The prototype rack for this study is a 24-inch wide by 42-inch deep by 89-inch tall server rack, which weighs 1,100 pounds, including the ISO-Base platform. The weight is assumed evenly distributed over the height of the server rack. The mass in the model is distributed according to tributary area and lumped at the nodes of the model. The period of the rack is approximately 0.1 seconds in the transverse direction and 0.05 seconds in the longitudinal direction.

C. Computer Model of ISO-Base

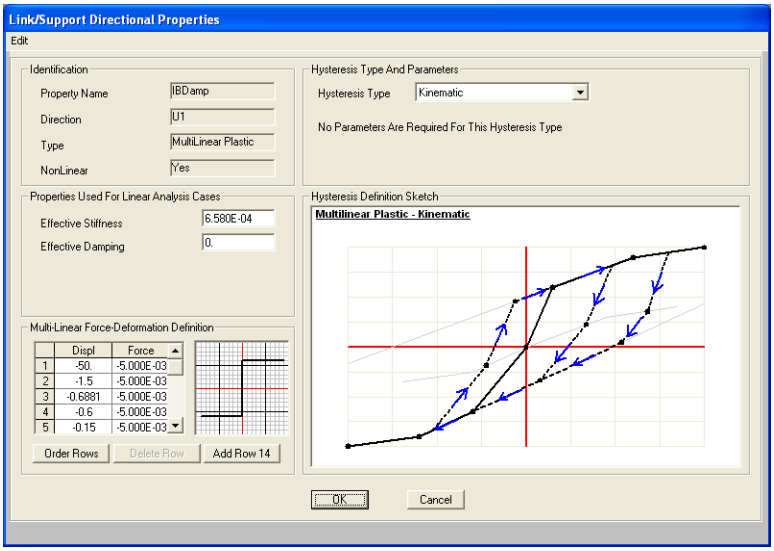
The isolation layer was represented in the model by assemblies of multi-linear link elements placed under the cabinet. Uplift at the isolation layer was accounted for using the Gap links, which have only compression stiffness in vertical direction. The multi-linear link elements links, with the exception of the Gap links, are assembled radially around the center of the dish and have properties so that, when combined, effectively produce the ISO-Base properties in any horizontal direction. The effect of the slope of approximately 10% for the dish was modeled using the ISO-Base links. Energy dissipation due to rolling friction or friction between liners and ball bearings was simulated using the IB Damp links. Initial static friction and effect of geometry of the apex were simulated using the Apex links. Due to modeling limitations, the model captures only accelerations that occur at frequencies equal to and less than 20Hz.



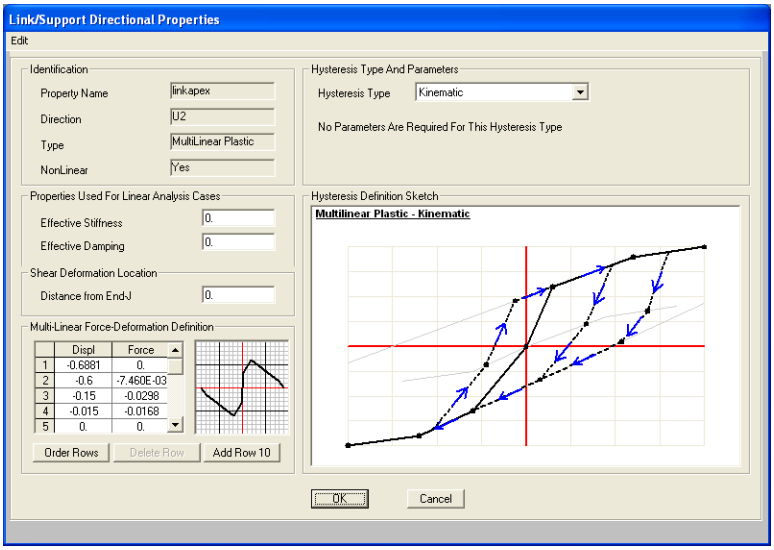
(a) Gap Link Element



(b) ISO-Base Link Element



(c) IB Damp Link Element



(d) Apex Link Element

Figure 17 Multi-linear Link Elements

3. Appendix C. Effect of Direction of Earthquake Force

In the test program, one directional excitation using a modified ATC-58 ground motion was applied to the ISO-Base system. The excitation was applied to the short-side direction of the rack that produced the highest possibility of toppling the rack over. In addition, the performance criteria discussed in this report were developed using this one-directional test. However, since earthquake force is not always subjected to a building in one specific direction, effect of earthquake force in an arbitrary direction needs to be considered. This effect is accounted in the building code by two-directional excitation. Therefore, performance of ISO-Base was evaluated under two-directional loading to calibrate the performance criteria based on the shake table testing.

ASCE7-05 criteria were used to develop the range of site-specific design spectra. The response spectra for 6 sites with different levels of SD1 are shown in Figure 18. These response spectra represent the seismicity of the sites. The seismicity of 6 sites is summarized in Table 2.

Ten ground motion pairs were selected and scaled to simulate two-directional excitation at different sites by ASCE7-05 procedure. These ten ground motion pairs, previously developed by SAC Steel Project, have been used extensively in various research projects. A plot of the average of the scaled SRSS motion response spectra and design spectra at San Francisco is shown in Figure 19. The ten ground-motion pairs were scaled such that the average SRSS spectrum did not fall below 130% of the design spectrum by more than 10%, as required by ASCE7-05. This process was conducted for all 6 sites and plots of the average SRSS spectra for the sites are shown in Figure 20. The performance of ISO-Base in two-directional excitation was evaluated by applying these scaled ground motion pairs to the SAP2000 model using response history procedure.

The rack was modeled without dish rim to find S1 corresponding to the impact displacement. In addition, this SAP2000 analysis was conducted both for the model without liners and with standard liners. The average displacement response to site specific two-directional excitations was plotted in Figure 21. As shown in Figure 21, the S1 values corresponding to contact do not match between one directional loading and two directional loading. S1 values corresponding to contact are 0.25g and 0.74g (Figure 24) for one-directional loading and 0.31 g and 0.63g for two-directional loading. Therefore, the curves from the test results were calibrated considering effect of two-directional loading.

Table 2 Summary of Seismicity

Location		Ss	S1	Sds	Sd1	S1, average of SRSS of 10 pairs
				(site class D)		
San Francisco, CA	37.62, -122.38	1.92	1.00	1.28	1.00	1.46
Los Angeles, CA	zip 90071	2.19	0.74	1.46	0.74	1.10
Regence, UT	40.63, -111.81	1.58	0.64	1.05	0.55	0.79
Barstow, CA	34.8, -117.3	1.20	0.47	0.82	0.48	0.70
Memphis, TN	35.05, -90.00	1.13	0.32	0.79	0.37	0.55
Amador, CA	38.5, 120.5	0.72	0.40	0.48	0.27	0.39

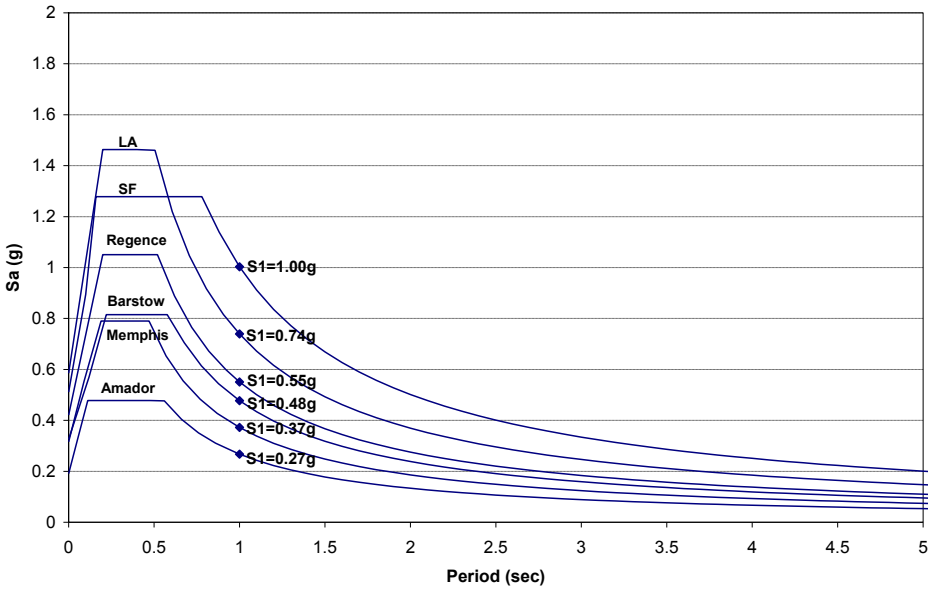


Figure 18 ASCE7-05 Design Spectra, 6 sites

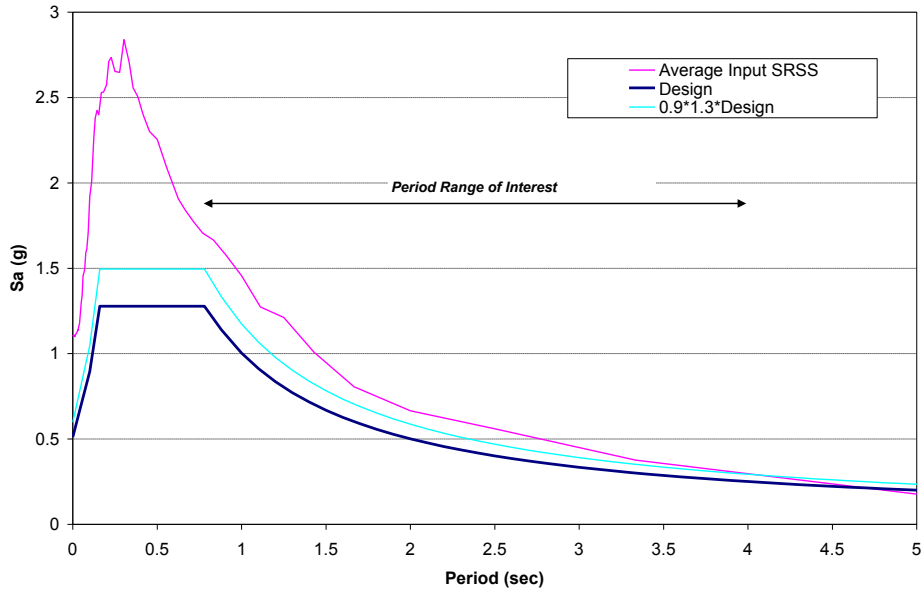


Figure 19 Average of the scaled SRSS response spectra and design spectra, San Francisco

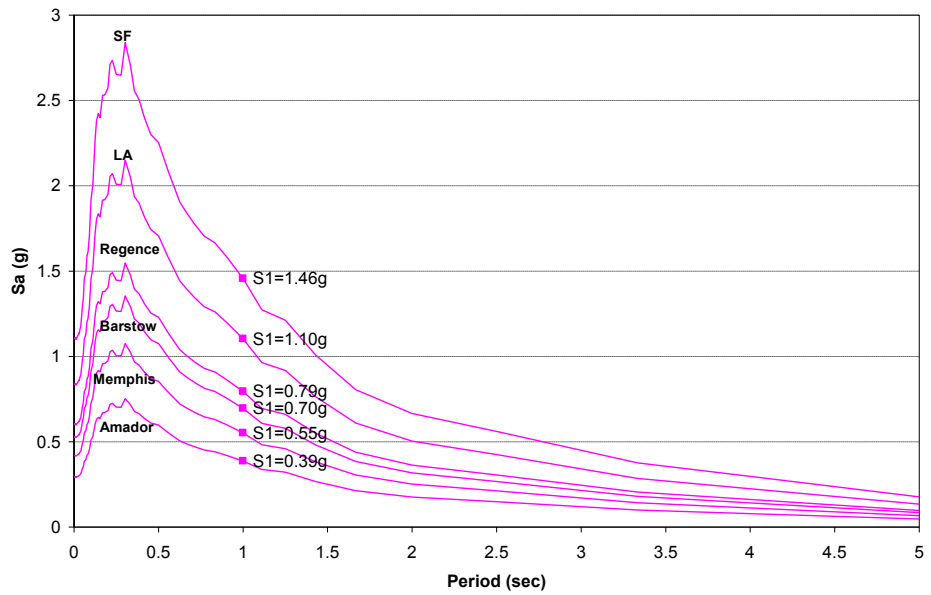


Figure 20 Average SRSS Response Spectra of 10 Pairs

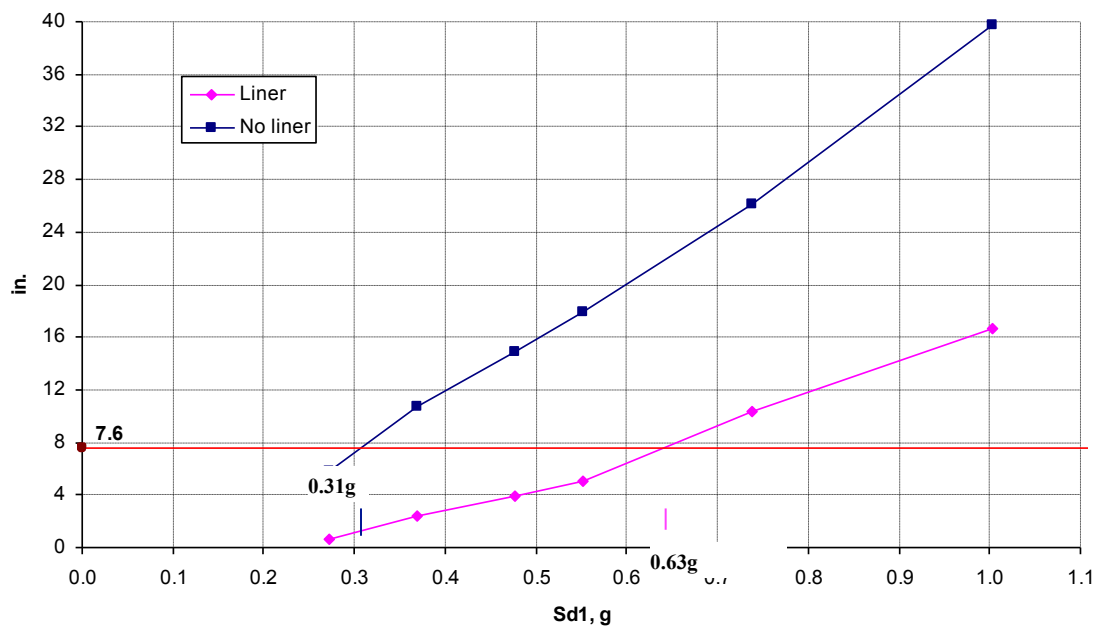


Figure 21 Comparison Between Response For Two And One Directional Loading – Displacement vs. Sd1

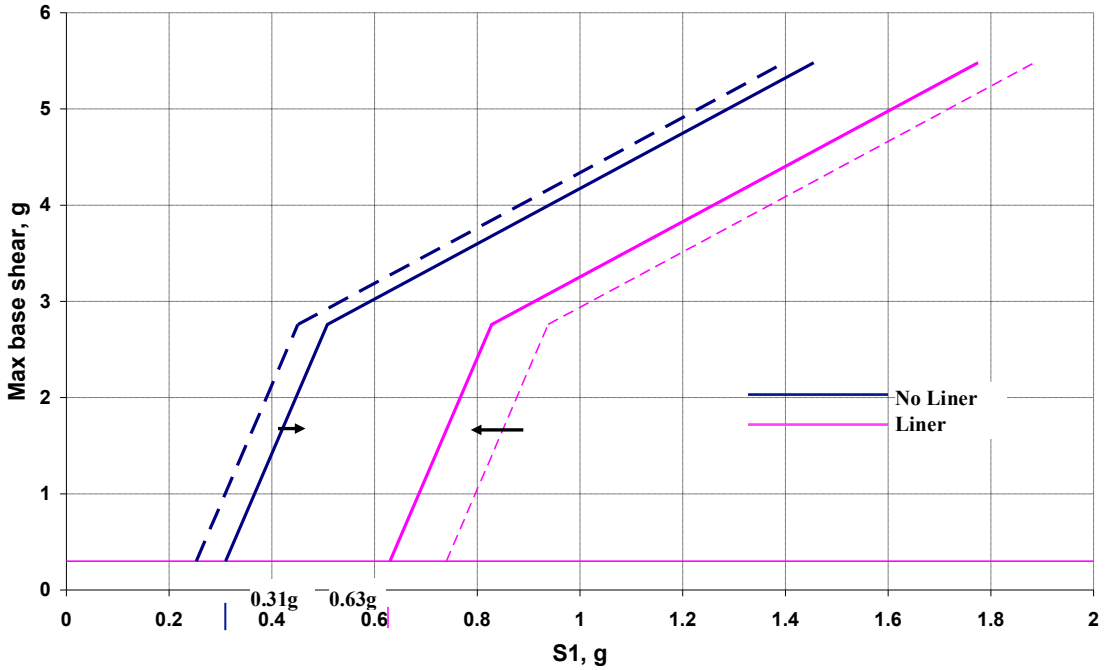


Figure 22 Calibration of Base Shear- S1 Curves Considering Two-Directional Loading

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4. Appendix D. Effect of Rack Weight

Resistance of ISO-Base against lateral loading is provided by slope of the dish so the lateral force resistance is linearly proportional to the weight of the system. The damping of ISO-Base is provided by rolling friction between the ball bearing and dishes. Rabinowicz (1995) have reported *"the (rolling) friction force varies as some power of the load, ranging from the 1.2 to 2.4th."*

In our analysis, we assumed that for steel dishes with no liners the rolling friction is linearly proportional to the supported weight. This is therefore proportional to the 1st power of the load, which is a conservative assumption. The shake table test results provided the initial value of the rolling friction force, which was also assumed to be proportional to weight. This means that the reported base shear and acceleration results (in units of g) are independent of weight.

However, for the ISO-Base units with liners in the steel dishes, shake table testing was only performed for one rack weight. Separate in-house testing confirmed that the adhered liners can accommodate cyclic displacements with up to 750lbs per isolator with only moderate damage to the liner.

5. Appendix E. Design Procedure Development

The natural frequency of the ISO-Base platform varies with displacement but is typically in the two-to-four second range. This means that the seismic demands on ISO-Base system are best characterized by the parameter S_1, the spectral acceleration (g) at one-second for the design earthquake, including soil adjustment factors (S_{D1}). The procedure can be used with other values if performance is being evaluated for the MCE, or for levels above grade.

Based on the shake table testing and analysis results (Appendix A & B), two alternate methods of assessing ISO-Base performance were developed. These are summarized in this appendix.

A. Impact Acceleration Approach

The *Impact acceleration approach* is based on accelerations measured during the shake table test, where S_1 is the parameter used in characterizing the seismicity of a specific site. Accelerations measured at the bottom, middle and top of the rack were plotted with respect to S1 of the input motions. S1-acceleration relationship at the bottom of the rack is shown in Figure 23. This information can be used to estimate the level of acceleration that equipment in the rack will experience during an earthquake. For example, a computer server in the lower level of a rack located at the ground floor of a building with a site S_{D1}=0.4, may experience approximately 3.3g when the rack is installed on the ISO- Base without dish liners while it will experience only 0.3g when it is located on the ISO-Base with the standard dish liners.

The base shear force was calculated based on the measured accelerations and mass distribution in the rack and also plotted with respect to S1 (Figure 24). The plot was simplified using bi-linear curve that provides a conservative estimation of base shear force for an ISO-Base system with different liner conditions. The seismic-force demand in the gravity direction on the access floor in the server room can be calculated using the base shear and geometry of racks.

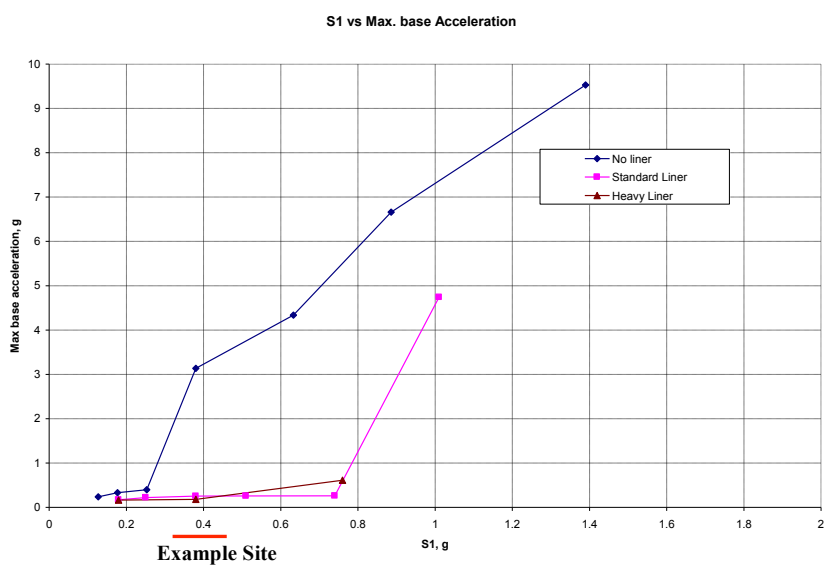


Figure 23 Acceleration at the Bottom of Server Rack vs. S1

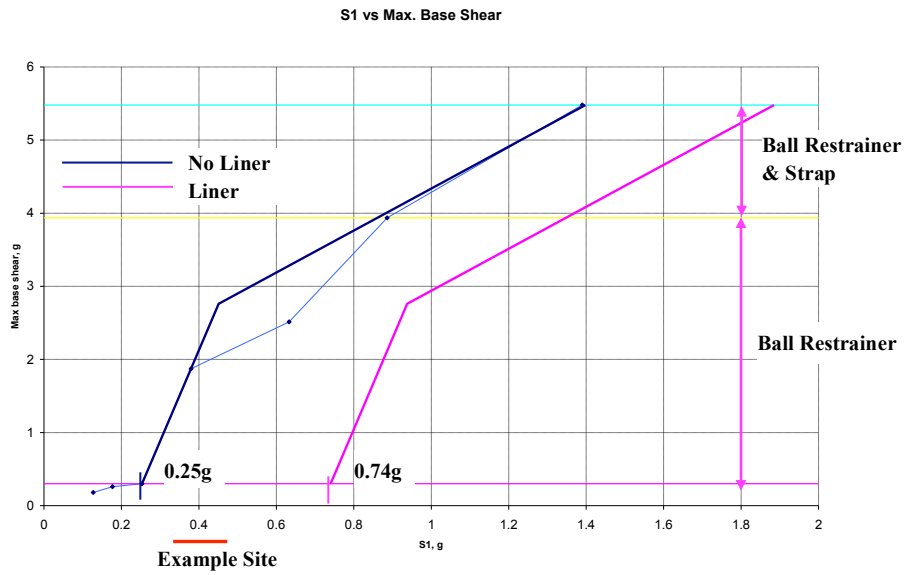


Figure 24 Base Shear Force vs. S1

B. Contact Velocity Approach

Another approach for evaluation of ISO-Base performance is the *contact velocity approach*. In the ideal condition, the contact velocity of the system is linearly proportional to contact acceleration (Appendix D). The velocity of the base when it passes the dish rim was found through analysis using the ground motions used in the shake table tests and SAP models without dish rims. This velocity was considered as contact velocity and the analysis results were plotted with respect to S1. As shown in Figure 25, the shape of velocity curve is similar to the acceleration curve shown in Figure 23.

Using the velocity corresponding to measured contact acceleration, the contact acceleration of the base can be estimated. Although the contact velocity approach is more complicated than contact acceleration approach, this approach is effective when a more-detailed evaluation of the base is required or ground motion of specific site is provided.

Generally, the contact acceleration approach provides more conservative results than the contact velocity approach. The contact velocity also can be used for ISO-Base system with new dish-liners by simple tests of liner material.

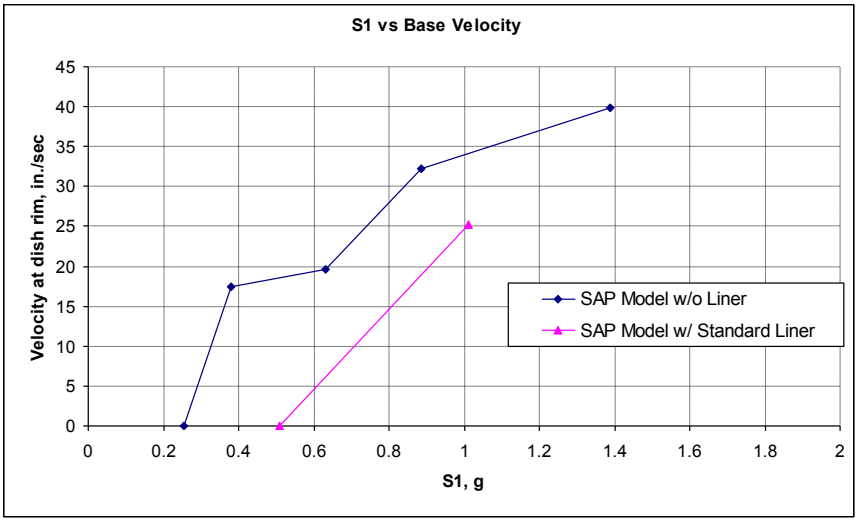


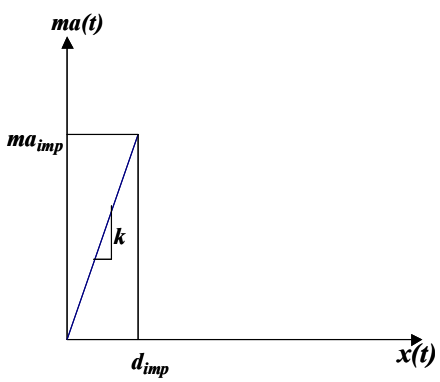
Figure 25 Contact Velocity, SAP Analysis, vs. S1

Assumptions:

- No energy loss during impact
- Acceleration is linear proportion to impact displacement of system

$$m : total\ mass\ of\ system$$
$$V_{imp} : impact\ velocity$$
$$a(x) : acceleration, linear\ fuction\ of\ displacement\ due\ to\ impact$$
$$x : ISO - Base\ displacement(slip)\ due\ to\ impact$$
$$d_{imp} : final\ impact\ displacement$$
$$a_{imp} : impact\ acceleration$$

$$\frac{1}{2} m V_{imp}{}^2 = \int_0^{d_{imp}} ma(x)dx$$



$$d_{imp} = \frac{ma_{imp}}{k}$$

$$\int_0^{d_{imp}} ma(x)dx = \int_0^{d_{imp}} kxdx = \frac{1}{2} kd_{imp}{}^2$$

$$\frac{1}{2} m V_{imp}{}^2 = \frac{1}{2} kd_{imp}{}^2 = \frac{1}{2} k \left(\frac{ma_{imp}}{k} \right)^2$$

$$V_{imp} = a_{imp} \sqrt{\frac{m}{k}}$$

$$\therefore V_{imp} \propto a_{imp}$$