Vibration Isolation and Seismic Control
Manufacturer's Association
994 Old Eagle School Road -- Suite 1019
Wayne, PA 19087-1866
www.viscma.com

ANALYTICAL STANDARD FOR EVALUATING RESTRAINT LOADS ON MECHANICAL EQUIPMENT

Purpose:

The only current standard offering guidance on how to distribute the code specified static forces among Seismic/Wind restraint components is the ASHRAE Application Handbook. Besides combination of equipment and restraint devices being specified for an application. This is time consuming and costly to all concerned. There is credence for these dynamic tests when working with complicated pieces of equipment used in critical applications however the simple Pass/Fail ratings that result are virtually useless for establishing any guidance for the use of the restraint components in less critical applications.

Both VISCMA and ASHRAE offering guidance on only an extremely limited number of cases, it is not only unbinding, but also the procedures defined by it are routinely not used by many of the individuals who are engineering these kinds of applications. In addition, where the building code documents offer any guidance on this issue, they opt for simplicity over accuracy. There are significant holes in the logic and although the goal is that the overly simplified methods of analyzing applications will produce conservative results that would yield higher safety factors, this is not always the case.

The net result is that it has been found in practice that failures can and do occur, even if the ratings and the analysis performed indicate otherwise. As a result, responsible agencies have backed away from accepting much of the inconsistent analytical data that is provided today and instead have mandated the need to physically test each have discussed and are in the preliminary stages of developing a component rating standard. When using the ratings in conjunction to size a component based on an analytical review of an application, it is mandatory that both the rating system and the analytical method by which the required loads are derived conform to some reasonable, accurate and agreed upon standard. Without that, there is no consistency in component selection and you have created nothing useful.

The purpose of this document is to discuss in generalities all of the factors that must be considered when performing an analysis. The exact method of performing the analysis can be varied based on current procedures and practices that may be in place with the organizations doing this work. No matter the method used however, it is critical that all load cases be considered and that the computed loads that are projected for the restraints are consistent with the intent of this standard.

General Load Factors to be considered:

First, when rating components, we will need to make a decision as to how to rate restraint components when developing a component rating standard with either ICC or ASHRAE. There are two analytical methods for sizing components (ASD and LRFD) which can produce significantly different rated capacities and these need to be consistent with the analytical method chosen to determine the loads. While it would be possible to offer both ratings, we recommend that we stick to one of the other to avoid confusion. Also, even though we know that the structural world is going to LRFD, it appears that ASD types of ratings are more appropriate for what we are doing. For purposes of this document, we will assume that we are working with an ASD methodology with the recognition that many of the basic load factors will change if the LRFD methodology is used instead.

Load Combinations:

Once the methodology is determined, the appropriate load combinations must be considered. These vary with the code and version used and as indicated before with the type of analysis being performed (ASD/LRFD). If we consider the newest IBC code version which references ASCE 7-10, the load combination section is Chapter 2 in ASCE. When analyzing using an LRFD type analysis, the appropriate load combinations are listed in section 2.3.2. For an ASD type analysis, the appropriate section would be 2.4.1. We will stick with the ASD numbers here.

The primary load combinations in section 2.4.1 are (5) *D + (.6W or .7E)*, (6a) *D + .75L + (.75(.6W) + .75(Lr, S or R)*, (6b) *D + .75L + (.75(.7E) + .75S*, (7) *.6D + .6W* , and (7) *.6D + .7E*. Some local codes (like the Florida building code with respect to wind) can be more severe and these should be taken into account when dealing with projects in these areas.

Seismic load determination:

These are dictated by the code parameters and are directly linked to the force equations in section 13.3.1 of ASCE. Note that there is a basic equation as well as a maximum and minimum screen value. The loads should be based on the full weight of the supported equipment including any auxiliary framework, fluids, etc. that will be a normal part of the system. The weight used in this case should not be de-rated as indicated in the load combination equations. There is also a requirement for a vertical load that is based on the weight, the full weight of the unit should be used when deriving this as well.

Wind load determination:

Wind face pressure loads are defined by ASCE and are a function of the local site conditions, the wind map, the elevation above grade and the location of the equipment on the roof. Note also that local codes such as the Florida building code, may trump ASCE. In ASCE, the appropriate design section would be chapter 29. The horizontal load component is per equation 29.5-1 or 29.5-2 depending on the elevation and the vertical load component (for buildings up to 60 ft tall) is per equation 29.5-3. Per 29.1.4, no reductions should be made for shields or barriers.

Per section 29.5, the area to be used in conjunction with the wind force above is to be the "projected area normal to the wind". In most cases, this would be the diagonal dimension of the equipment in the plan view. The area used for the vertical force is the plan view area. When working with equipment exposed to wind loads, the appropriate weight to use is the minimum weight as specified by the load combination equation.

Load Reactions:

Once the load is determined for wind or seismic conditions as per the above, the remainder of the analysis is basically common and we will not make reference to the load type in the remainder of this document. Instead we will refer to these as "input forces".

There are a number of load distribution methods that can identify static loads at the various reaction points with relative accuracy and the detailed method used is not important to this document. What is critical is that the method does take into account all of the various factors and that the computed loads are equal to or greater than those that might be expected when actually testing a piece of equipment by statically loading it as directed by the input force equations.

The code indicates that equipment can be assumed to be a rigid "black box". While this is not a bad assumption for equipment that is either small in size or is isolated (to the point that the flex in the equipment is less than the permitted movement in the restraint system), it leaves a bit to be desired for large, highly flexible hard mounted equipment with multiple anchorage points (typically made of gauge material). On the good side however, is that the flexible nature of this equipment tends to reduce the loads at the most heavily loaded restraints rather than increase them. As a result, staying with the rigid analysis is conservative and valid for the purpose of this document.

Primary Load Analysis:

These loads have to do with those that act on the equipment CG (seismic) or Center of Area (wind) and generate forces at the restraint element location in the restraint device itself. Unless the restraint device is an anchor, these loads are **not** the loads that should be considered for the anchor, but instead only a step in the process of getting there. The next several segments are related to the Primary load analysis only and we will address the secondary load analysis (getting the loads from the restraint element to the anchors) later on. Note that often the ratings on the isolators include considerations of this secondary analysis, but varying anchor and baseplate modification issues may require this secondary portion to be reviewed independently.

Horizontal Loads (primary analysis):

The horizontal restraint loads for restrained equipment can be derived in a number of different ways. For any piece of equipment with more than 2 attachment points, the systems become redundant and as such, there are many combinations of horizontal loads at the various restraint points that can all be acceptable. It should be noted that (assuming the equipment is indeed rigid), any distribution of the horizontal loads that takes into account offsets in the CG (seismic) or Center of Area (wind) and remain within the limits of the restraint devices would be a valid analysis.

Having said that, there are 2 methods in common use that minimize the stress in the equipment and are typically the preferred way to go. The first is to average the weight of the unit over the array of restraints and then use the dimension between the CG or Area Center and the center of the restraint array to determine a "rotational" moment arm that results from the offset load. The resulting moment is then used to compute an additional horizontal load component that can be spread between the restraints that are located the furthest from the pattern center.

The alternate method is to use a load distribution routine to establish a weight or wind area for all the of the different restraint locations that takes into consideration the offset CG or Area Center. The general input force equation can then be applied to each segment and a horizontal load associated with the restraint point computed.

For both of the above methods, the horizontal loads computed are to be calculated based on the "true" un-factored weight of the equipment.

Uplift Loads (primary analysis):

In many ways, the computation of uplifting loads (those created by the input forces and not those due to gravity) are computed in a very similar fashion to that used for the horizontal forces.

Again there are 2 methods in common use. The first is still to average the weight of the unit over the array of restraints and then use a ratioing approach to determine the heaviest of lightest corner based on the CG or Area Center offset. These values are then summed together. The resulting weight is then multiplied by the input force coefficient to determine a vertical load at the various restraint points.

The alternate method is to use the same load distribution routine as was used in the horizontal load analysis as a baseline for the vertical load computation. The general vertical input force equation can then be applied to each segment and a load associated with each restraint point computed.

For both of the above methods, the loads computed are to be calculated based on the "true" un-factored weight of the equipment.

Overturning Loads (primary analysis):

Overturning moments are computed by multiplying the sum of the horizontal loads previously computed by the vertical dimension from the equipment CG (seismic) or Area Center (wind) to the elevation of the restraint element in the restraint device itself.

The most unstable axis for the application of this load is then determined and the moment is applied in this direction. The resulting maximum uplift and downward loads at the restraints are computed based on this orientation. Again there are 2 primary methods used to identify this orientation and to quantify the resulting loads. Both are addressed in the ASHRAE handbook. *Note: these "most unstable" conditions rarely occur on either of the principal axes of the equipment being reviewed.*

The first method is to use the geometry of the anchorage arrangement to compute a "worst case load angle", then apply to moment at that angle and compute the resultant loads. The second is to compute the overturning load reactions at all the restraint points, indexing the applied load in 1 degree increments, tracking and holding the max and min load for each restraint.

For equipment with 4 or less restraints, there is no significant difference in determining the above loads for isolated versus solid mounted applications. When the number of restraints increases beyond that, there is a significant difference between Isolated and solid mounted applications.

When looking at solid mounted equipment with more than 4 restraints, it is not an unrealistic expectation for all of the vertical restraints to be able to absorb some of the uplift and/or overturning loads. For an arrangement with 6 restraints arranged in 2 rows of 3 each for example, all will be loaded by the pure uplift load. In the case of the rocking load, one edge of the equipment will be in compression against the structure and the opposite edge will try to lift. Where 2 restraints are aligned, the one closest to the compression side will see no tensile force but the ones on the opposite side will see a tensile force that when multiplied by the span between the restraint and the compression edge will balance the overturning moment previously computed. On the axis where 3 restraints are aligned, relative to the overturning load there will be a triangular load distribution. If the 3 restraints are equally spaced, the one on the compression side will have no tensile load, the one on the opposite side will have a maximum tensile load and the one in the center will have half the maximum tensile load. The total input force generated tensile load will be the sum of the overturning and the uplift loads at each point.

If the equipment is isolated however, there will be clearance in the restraints. In this case, the equipment on one end will drop and bear against the downward stops on the compression end. On the opposite end the equipment will lift and bear against the uplift stops. The restraint in the center, will neither lift nor drop and will operate in its normal operating clearance range. Thus it cannot contribute to the vertical restraint of either the overturning load or the pure uplift load and instead, these vertical loads will need to be countered by forces purely in the end restraints.

Since the worst case load direction is rarely (if ever) aligned with one of the principle axes of the equipment, the above condition will occur on both axes. In that case, there is no load sharing of the vertical loads and it realistically must be assumed that these loads are countered by tensile and compression loads on the diagonal opposite corners of a piece of equipment.

Failing to take this into account will significantly understate the tensile loads to which corner restraints will be subjected. The direct result of this is that it is likely that the components selected will fail if subjected to any dynamic or even static testing where a load is applied diagonally.

Additional Restraint Considerations for Isolated Equipment:

Under some conditions it is possible for the compression load in equipment support coils to act against the restraints and/or the restraint anchorage. Where this can happen, it must be taken into account to produce a valid analysis. Similar to the issues on isolated equipment with a large number of vertical restraints, failure to do so will lead to a significant under estimation of the loads to which the restraint will be subjected in service.

There are 2 primary cases where this can be an issue. The first is when the restraints are completely independent of the isolators. The second is when the isolator includes a restraint component, but the spring bears against the supporting structure and is not contained by the isolator housing.

To offer a more visual example, say you have a piece of equipment that weighs 1000 lbs. and it is sitting on base with 2" deflection coils that are properly adjusted and are restrained using independent restraint devices. If you remove the equipment and don't readjust the spring coils, they will be pushing up on the restraint devices with a force of just under 1000 lbs. This will add to the tensile force that is seen by the anchors.

Compare this to a piece of equipment that is sitting on isolators that include restraint elements. Now if you remove the equipment, the spring forces are trapped within the isolator housing itself and the anchors see no load.

The net result of the above is that when working with this type of arrangement and summing all of the appropriate loads using the load summation equations, the gravity term should not be included as the gravity force is offset by the spring load and there is no net change in the anchor load due to this term.

Secondary Load Analysis:

These loads have to do with those that act on the restraint device itself. Where the Restraint Device is more than just a simple anchor, it will have a point at which the primary vertical and horizontal loads will be applied (The centerline of the Snubber element). This will create loads at its attachment points to the structure that need to be addressed in a similar fashion as were those when the primary loads were distributed out to the restraints. Sometimes these are included in the Restraint rating, but rated values are meaningless if special anchorage conditions exist (like reduce edge distance, lightweight concrete, oversized baseplates, etc.)

We are not addressing this analysis in detail here as it basically the same as the primary analysis procedure. Instead we are just highlighting the need for it to be performed when required.

Simplified Load Summations: Seismic Horizontal Loads

Input Seismic Horizontal Force = Seismic Horizontal Factor * Equipment Weight

Nominal Seismic Horizontal loads = Input Horizontal Force / Number of Restraints

Seismic Load Variation Factor = CG offset * Input Horizontal force /(Number of Restraints at Max Radius * Max Radius) Wind Horizontal Loads

Input Wind Horizontal force = Wind Face Pressure * Diagonal Surface Area * (Windward + Leeward Factors)

Nominal Wind Horizontal loads = Input Horizontal force / Number of Restraints

Wind Load Variation Factor = Wind Area offset * Input Horizontal force /(Number of Restraints at Max Radius * Max Radius)

Seismic Vertical Loads

Nominal (Seismic) Weight load = Code Weight De-ration factor * Equipment Weight / Number of Restraints

Imbalance Factor = +/- CG offset / Restraint Pattern Diagonal * Nominal Weight (Seismic) load

Vertical Seismic Uplift loads = +/- Equipment Weight (at each location) * Input Seismic Vertical Factor

Wind Vertical Loads

Nominal (Wind) Weight load = Code Weight De-ration factor * Equipment Weight / Number of Restraints

Imbalance Factor = +/- CG offset / Restraint Pattern Diagonal * Nominal (Wind) Weight load

Vertical Wind Uplift loads = Equipment Plan View Area * Input Wind Vertical Pressure Coefficient

Wind Imbalance Factor = +/- Area Center Offset / Restraint Pattern Diagonal * Vertical Wind Uplift loads

Seismic Rocking Loads

Solid Mounted Equipment

Peak EW axis Rocking Load = +/- Input Seismic Horizontal Force * CG elevation / Y * ($S_{0-(x-1)}$ $1-(n/X)^2$ * EW Span)

Peak NS axis Rocking Load = +/- Input Seismic Horizontal Force * CG elevation / X * / ($S_{0-(y-1)}$ $1-(n/Y)^2$ * NS Span)

(where X = restraints on EW axis and Y = restraints on NS axis)

+/- Total Solid Mounted Seismic Rocking Load = Peak EW Load + Peak NS Load (Occurs at corners)

Isolated Equipment

Peak EW axis Rocking Load = +/- Input Seismic Horizontal Force * CG elevation / (2 * EW Span)

Peak NS axis Rocking Load = +/- Input Seismic Horizontal Force * CG elevation / (2 * NS Span)

+/- Total Isolated Seismic Rocking Load = Peak EW Load + Peak NS Load (Occurs at corners)

Wind Rocking Loads

Solid Mounted Equipment

Peak EW axis Rocking Load = +/- Input Wind Horizontal Force * Face Area Center Elevation / Y * ($S_{0-(x-1)}$ $1-(n/X)^2$ * EW Span)

Peak NS axis Rocking Load = +/- Input Wind Horizontal Force * Face Area Center Elevation / X * / ($S_{0-(y-1)}$ $1-(n/Y)^2$ * NS Span)

(where X = restraints on EW axis and Y = restraints on NS axis)

+/- Total Solid Wind Mounted Rocking Load = Peak EW Load + Peak NS Load (Occurs at corners)

Isolated Equipment

Peak EW axis Rocking Load = +/- Input Wind Horizontal Force * Face Area Center Elevation / (2 * EW Span)

Peak NS axis Rocking Load = +/- Input Seismic Horizontal Force * Face Area Center Elevation / (2 * NS Span)

+/- Total Isolated Wind Rocking Load = Peak EW Load + Peak NS Load (Occurs at corners)

Seismic Load Combinations:

Horizontal Loads for all Equipment

Horizontal Seismic Design Load = Nominal Seismic Horizontal load +/- Seismic Load Variation Factor

Vertical Loads for Solid Mounted Equipment

Vertical Seismic Design Load = Nominal (Seismic) Weight load +/- Imbalance Factor +/- Vertical Seismic Uplift loads +/- Total Solid Mounted Seismic Rocking Load - (Nominal (Seismic) Weight load +/- Imbalance Factor)

Vertical Loads for Isolated Equipment on Combination Isolator Restraint Components

Vertical Seismic Design Load = Nominal (Seismic) Weight load +/- Imbalance Factor +/- Vertical Seismic Uplift loads +/- Total Isolated Seismic Rocking Load - (Nominal (Seismic) Weight load +/- Imbalance Factor)

Vertical Loads for Isolated Equipment with Independent Isolator and Restraint Components

Vertical Seismic Design Load = Nominal (Seismic) Weight load +/- Imbalance Factor +/- Vertical Seismic Uplift loads +/- Total Isolated Seismic Rocking Load

Wind Load Combinations:

Horizontal Loads for all Equipment

Horizontal Wind Design Load = Nominal Wind Horizontal load +/- Wind Load Variation Factor

Vertical Loads for Solid Mounted Equipment

Vertical Wind Design Load = Nominal (Wind) Weight load +/- Wind Imbalance Factor +/- Vertical Wind Uplift loads +/- Total Solid Mounted Wind Rocking Load - (Nominal (Wind) Weight load +/- Imbalance Factor)

Vertical Loads for Isolated Equipment on Combination Isolator Restraint Components

Vertical Wind Design Load = Nominal (Wind) Weight load +/- Imbalance Factor +/- Vertical Wind Uplift loads +/- Total Isolated Wind Rocking Load - (Nominal (Wind) Weight load +/- Imbalance Factor)

Vertical Loads for Isolated Equipment with Independent Isolator and Restraint Components

Vertical Wind Design Load = Nominal (Wind) Weight load +/- Imbalance Factor +/- Vertical Wind

Uplift loads +/- Total Isolated Wind Rocking Load

VISCMA is a non-profit association representing the manufacturers of seismic restraint, vibration isolation and noise control equipment. The primary objectives of the organization are to educate the construction industry on the proper use and application of vibration isolation and seismic restraint and to develop standards to continually improve the industry.

In partnership with FEMA and ASCE, VISCMA also publishes three Seismic Installation and Inspection Manuals designed to assist field personnel.

The association office is located at 994 Old Eagle School Road, Suite 1019, Wayne, PA 19087-1866 and can be reached at 610-971-4850 or info@viscma.com.

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