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SEISMIC EQUIPMENT QUALIFICATION BY SIMILARITY AND COMBINED ANALYSIS AND TESTING: TWO CASE STUDIES

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ABSTRACT

Industry standards do not recommend qualification of complex equipment by analysis only because of the great difficulty in developing an accurate equipment model and in obtaining numbers to describe the model physical parameters. For example, qualification by analysis cannot assess performance requirements, such as leaks that may form as a result of a seismic event, and pressure boundaries that may be compromised. Analysis without testing may be acceptable only if structural integrity alone can ensure the design-intended function. Additionally, operability during a seismic event can only be effectively demonstrated by testing.

Consistent with industry standards, the correlation between test and analysis results enables extension of the qualification by combined analysis and testing to other equipment, using similarity, dynamic characteristics, and analytically predicted response quantities. Therefore, qualification by testing and analysis can be applied to the entire population of equipment on the basis of similarity. Likewise, in cases in which developing accurate computer modeling is difficult, test results can be used to modify analytical models such that new analytical models can be developed from the calibrated generic model.

This paper presents two case studies related to the qualification of fans and battery racks using combined testing and analysis and similarity. Analysis and test results are presented for the representative reference samples. Excitation levels, physical system property and characteristics, and safety functions are provided for the entire population of equipment qualified to demonstrate how reference sample results are extrapolated.

INTRODUCTION

Institute of Electrical and Electronics Engineers (IEEE) -344 1987 (IEEE, 1987) lists four primary approaches for seismic qualification of equipment. These are qualification by analysis, qualification by testing, qualification by combined testing and analysis, and qualification using experience data. While the equipment manufacturer is free to select the qualification method, the selection should be based on the practicality of the method for the type, size, shape, and complexity of the equipment configuration, whether the safety function can be evaluated in terms of operability or structural integrity alone, and the appropriateness of the conclusions.

In a nuclear power plant (NPP), there are many instances in which the same type of equipment is used multiple times, with minor modifications. In such instances, it is not practical or essential to qualify each piece of equipment individually. Instead, the qualification performed for one piece of equipment can be extended to the broader population by similarity analysis. In accordance with the guidelines in IEEE-344 (IEEE, 1987), the similarity analysis considers physical parameters; materials of construction; method of fabrication; type of construction, i.e, bolted and/or welded; dynamic characteristics; and analytically predicted response quantities. Components qualified by similarity analysis must exhibit the same or proportional response to dynamic excitation or static loading. These dynamic characteristics depend upon parameters such as the following:

- Equipment physical dimensions
- Equipment weight, weight distribution, and center of gravity
- Equipment structural load transfer characteristics and stiffness to resist seismic excitation
- Equipment base anchorage strength and stiffness to ensure structural integrity and adequate boundary conditions
- Equipment interfaces with adjacent items or connecting accessories, such as cables and conduits

Sometimes equipment cannot be practically qualified by analysis or testing alone. This may be due to equipment size, complexity, or large number of similar configurations. In certain cases where similarity cannot be directly employed, the same type of equipment may have to be qualified via different qualification methods. For example, if the equipment is too complex such that it cannot be evaluated analytically, but at the same time, it is too large to fit on a shake test table, the results of an existing test of smaller equipment can be used to calibrate an analysis model, which can then be modified for the larger equipment. Various analytical options exist for using the test data obtained. The resulting measurement of dynamic response parameters, such as fundamental frequencies and mode shapes, can be used to verify the calculated values of previously formulated analytical models of the equipment.

QUALIFICATION BY SIMILARITY OF PRESSURE BLOWER FANS

Table 1 presents a typical quantity supply of pressure blower (PB) fans that serve various NPP heating, ventilation, and air-conditioning HVAC systems. The table also identifies by tag ID “Shake 1” the specific fan in the supply selected to be qualified by testing. This fan is selected on the basis that it is representative of other fans in terms of type, motor frame, construction, and support configuration. The study reported here illustrates how the seismic qualification of the tested item is utilized to qualify other items by similarity.

As shown in Figure 1, the typical fan assembly includes the driving motor, shaft, fan housing unit containing the wheel (blades), and an inlet box. Figure 1 through Figure 3 show the fan assembly selected as the PB test sample, Shake-1. This PB assembly is a direct-drive pressure blower. It has a 26-inch-diameter wheel with a 12-inch-diameter exhaust. The assembly includes the PB wheel enclosed in the wheel housing, coupling guard, and shaft and bearing guard. The wheel housing is fabricated of all-welded heavy-gage metal, designed to prevent “flexing” at high pressures. The wheel housing, the shaft coupling guard, the bearing guard, and the motor are all supported by an integral mounting pedestal.

Fans classified as Quality Level (QL) -1 need to remain active during and after the design earthquakes to perform their intended safety function. Fans classified as QL-4 are required to prevent failure that may degrade the required safety function of QL-1 equipment by interaction.

All of the fans in the supply are mounted on isolators. The isolators are provided to mitigate transmissibility of operating vibrations in the vertical direction to the supporting structural floor and do not affect seismic isolation. The seismic response of isolator-mounted fans is controlled by the stiffness of the seismic restraints and the isolator frame. Typical fundamental frequencies of the fan assemblies accounting for isolator frame stiffness generally exceed 25 hertz (Hz). Therefore, the PB fans in Table 1 are in the rigid range of the required response spectra, and the hard-mounted test fan is taken to represent the support configuration of isolator-mounted fans.

The PB fan that is qualified by testing (Shake 1) is also evaluated by structural integrity analysis. It is analyzed under the same safe shutdown earthquake (SSE) and operating-basis earthquake (OBE) loads that the fan is subjected to during the shake table testing. In addition, other operating and accidental loads are considered, such as internal pressure and temperature differentials that envelop the entire population of PB fans.

Table 1: General fan information.

Fan Evaluated	Quality Level	Mounting	Fan Size	Drive Type	Total Gross Dimensions (in.)	Motor Weight (lbs)	Total Weight (lbs)
Shake 1	QL-1	Hard Mounted	2612S	D	50W x 60.5L x 50H	626	1614
1A	QL-1	Floor/Isolation	1908	D	37W x 45L x 49.5H	159.5	870
1B	QL-1	Floor/Isolation	2108	D	37W x 45L x 49.5H	159.5	870
2A	QL-1	Floor/Isolation	1908	D	37W x 45L x 49.5H	159.5	870
2B	QL-1	Floor/Isolation	2108	D	37W x 45L x 49.5H	159.5	880
3A	QL-1	Floor/Isolation	2410S	D	48W x 55L x 50H	645.7	1,600
3B	QL-1	Floor/Isolation	2410S	D	48W x 55L x 50H	645.7	1,600
4A	QL-1	Floor/Isolation	2504S	D	46W x 51L x 46H	288.2	1,250
4B	QL-1	Floor/Isolation	2504S	D	46W x 51L x 46H	288.2	1,250
5	QL-4	Floor/Isolation	2306	D	39W x 39.5L x 47H	144.1	778
6	QL-4	Floor/Isolation	1906	D	37W x 43L x 48.5H	159.5	840
7	QL-4	Floor/Isolation	2612	B	47W x 47L x 56.5H	283.8	1189
8	QL-4	Floor/Isolation	1608	B	35W x 32L x 37H	81.4	630
9	QL-4	Floor/Isolation	1608	B	35W x 32L x 37H	81.4	630
10	QL-4	Floor/Isolation	1608	B	35W x 32L x 37H	81.4	630
11	QL-4	Floor/Isolation	1608	B	35W x 32L x 37H	81.4	630
12	QL-4	Floor/Isolation	1608	B	35W x 32L x 37H	81.4	630
13A	QL-4	Floor/Isolation	1506	D	32W x 47.5L x 42.5H	198.0	795
13B	QL-4	Floor/Isolation	1606	D	32W x 47.5L x 42.5H	198.0	800

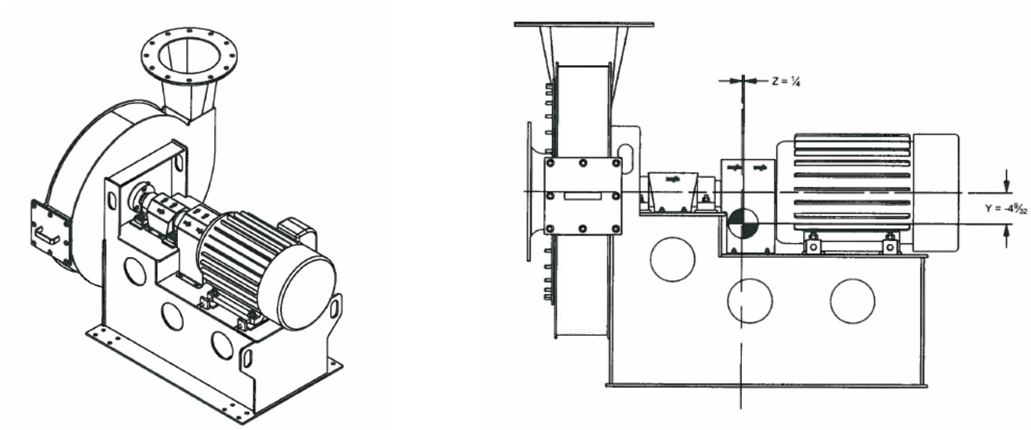

Figure 1: Isometric and elevation views of PB test fan assembly.

Test Summary

The test fan assembly (Figure 2) was directly bolted to the shake table and instrumented using three control accelerometers mounted to the seismic table and 15 response accelerometers mounted at various locations of the test assembly. The control accelerometers served as a baseline reference for the response accelerometers. The 15 response accelerometers monitored and recorded acceleration levels throughout the seismic testing.

The PB fan was subjected to the following seismic test sequence in addition to normal operating temperature and pressure:

- Resonance Search
- Operating Basis Earthquake (OBE)
- Safe Shutdown Earthquake (SSE)

The qualification program included a post-test inspection, which verified the performance requirements. Based on the resonance testing, the dominant frequencies are measured as 42.7 Hz, 56.6 Hz, and 86.7 Hz along the front-to-back (Y-direction in analysis), side-to-side (X-direction in analysis), and vertical (Z-direction in analysis) directions, respectively. Analytically, these frequencies are calculated as 40.6 Hz, 53.7 Hz, and 77.3 Hz along the same directions. The measured and calculated dominant modes show good correlation, which substantiates the adequacy of the analytical model and its use for extended evaluation.

The shake table tests demonstrated the structural integrity and functionality of the test fan assembly. Based on OBE and SSE testing, the fan successfully withstood the seismic test response spectra (TRS). The TRS represent the envelope of the 3-percent (%) damped design-basis floor response spectra (EFRS) at the equipment locations.

Figure 2: Final mounting of the PB test fan assembly.

Analysis Summary

The seismic qualification analysis is based on a finite element model of the fan assembly. The stress analysis of the fan assembly for all loading conditions is based on a static stiffness formulation assuming linear elastic behavior. Figure 3 presents the finite element model of the test fan assembly generated in ANSYS.

Seismic loads on the fan assembly are represented as pseudo-static loads obtained by multiplying the prescribed seismic accelerations for either the OBE or SSE by the mass of the fan components. The calculated static response due to seismic loads is combined with the response due to operating and/or accident loads on the fan assembly. The operating loads include the self-weight of the fan components, operating pressure, and thermal loads, while the accidental loads include the accident condition thermal loads.

Based on the mode-frequency analysis, the fundamental mode of vibration occurs at a frequency of 24.73 Hz and represents rotational displacements of the fan wheel about the transverse horizontal and vertical axes. However, this is not the dominant mode. The mode with the highest mass participation occurs well into the rigid range of frequencies. Therefore, the equivalent static accelerations are determined from zero-period acceleration (ZPA) and scaled by a factor of 1.5 to account for multi-mode effects. These accelerations, 0.60g in horizontal and 0.75g in vertical directions, are applied in the equivalent static cases at the center of gravity of the fan assembly.

Nineteen load combinations are considered: two sets of eight load combinations include the OBE and SSE each, and three other combinations include the gravity loads, operating pressure, and normal or accident temperature, based on Table Q1.5.7.1 of American Institute of Steel Construction (AISC) N690-1994 (ANSI/AISC,1994).

The structural integrity of the fan is maintained when the stress and the displacement levels are within the applicable code allowable limits. AISC N690-1994 is selected as the applicable code and basis for defining the stress acceptance criteria. The maximum permissible deflection (fan wheel and inlet cone) is checked based on ASME AG1 Section AA-4231 acceptance criteria.

Stress acceptance criteria vary, depending on whether or not secondary stresses are present. Examples of secondary stresses are thermal loads and bending stresses at gross structural discontinuities. In these calculations, thermal stresses are considered as the only source of the secondary stresses. In the case of secondary stress existence, the allowable criteria are magnified by a factor depending on the type of stress considered. The calculated stresses in the critical structural components of the test fan are within allowable ranges and meet the acceptance criteria of AISC N690-1994.

Extrapolation for Similar Equipment

Consistent with IEEE 323, seismic qualification by similarity uses extrapolations of qualification results (experience data) based on similarity of excitation, physical system, and safety function (operability).

The similarity analysis needs to demonstrate that 1) the test environment (excitation) and the reference fan analysis basis meet or exceed the project-specific requirements; 2) the reference fans are physically similar in size, weight, mounting arrangement, and dynamic characteristics; and 3) test performance in terms of function or operability meets or exceeds project-specific requirements.

Table 1 also compares the physical characteristic of the PB fans and the Shake 1 fan, providing the basis to judge that the seismic response of the PB fans is similar to the seismic response of Shake 1. This is confirmed by comparing the analytically predicted response of the tested fan to select fans from the remainder of the supply. The seismic qualification tests demonstrate that the equipment performed the safety function(s) during and after the earthquake in accordance with the requirements for qualification by testing. Based on similarity in physical characteristics as well as dynamic response characteristics, all fans identified in Table 1 are also expected to perform satisfactorily, subject to TRS.

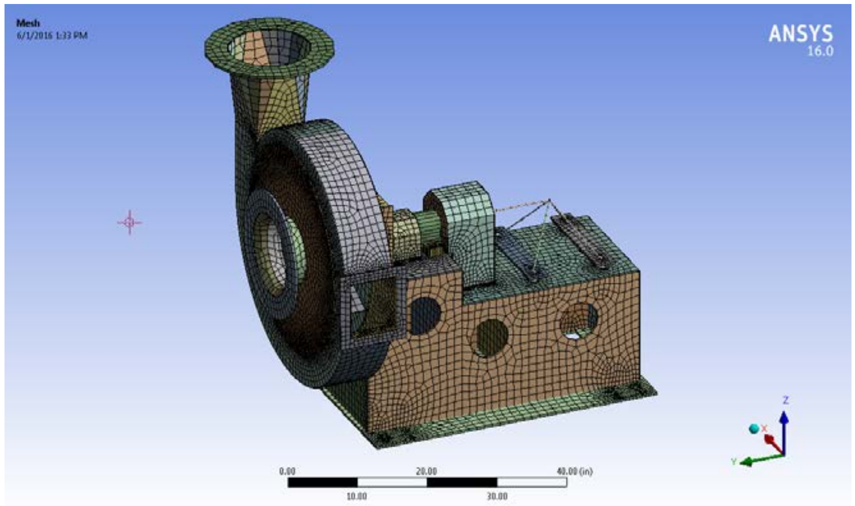

Figure 3: Isometric view of the meshed PB test fan assembly.

QUALIFICATION BY COMBINED ANALYSIS AND TESTING OF A BATTERY RACK

As another example, the seismic qualification of a battery rack is described here to demonstrate the qualification by combined analysis and testing. In this case, the seismic qualification by testing, performed for a 2-step 3-frame battery rack with 8 cells, is used for the qualification of a 2-step 5-frame battery rack with 20 cells. This qualification is justified by first performing modal analysis of the 2-step 3-frame battery rack with 8 cells. The purpose of this analysis is to calibrate its finite element representation by comparing the analytically predicted fundamental frequencies in three orthogonal directions (f_x, f_y, and f_z) to those measured during the seismic qualification test.

Figure 4 shows elevation views of the 3-frame rack that illustrate its configuration. This rack is designed to support 8 cells, and its overall plan dimensions are 72.00 inches x 49.25 inches. The rack is a 2-step design in which 4 cells are mounted on each step. The rack height is 28.81 inches, measured from the point of support to the top of the upper step. In the side-to-side direction (long direction), the rack has two 28.25-inch-long spans between transverse frames and two approximately 8-inch-long cantilevers. The transverse frames comprise columns of structural tubes connected by angles in the front-to-back direction (short direction). The front-to-back angles form the upper step and are supported by rectangular bracing members. Each frame has four holes for securing the rack to the floor. The rack components are made of A-36 steel, with the exception of channels, which are made of SAE 1010 steel. Rectangular cross bracing members are used support the frame in the side-to-side direction (long direction). In addition, channel sections are used to support the battery cells on the structural framing members as well as on the sides to restrain cell movement in horizontal directions.

The rack is a modular design, which means it can be expanded by adding frames to accommodate more cells. Therefore, the 5-frame rack can be modeled by expanding the 3-frame rack model after close agreement is reached between the numerical and test results for the 3-frame rack fundamental frequencies.

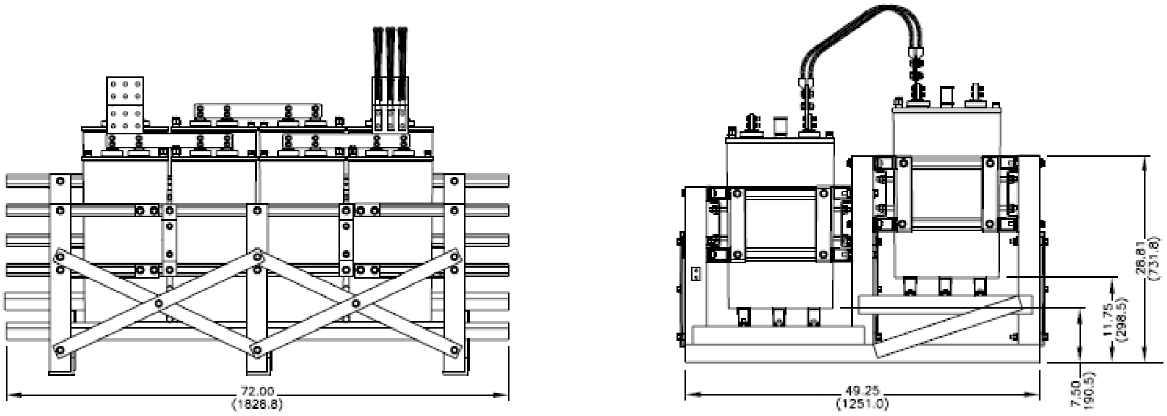

Figure 4: Elevation views of 2-step 3-frame battery rack.

Test Summary

The 3-frame rack was directly welded to the shake table and instrumented using control accelerometers and several response accelerometers, as shown in Figure 5. The control accelerometers were mounted to the seismic table and monitored the table accelerations in each of the three orthogonal axes. The response accelerometers were mounted at various locations on the test assembly and monitored and recorded acceleration levels throughout seismic testing. The control accelerometers served as a baseline reference for the response accelerometers.

The 3-frame rack was subjected to the following seismic test sequence: resonance search, plant-certified seismic design response spectra (CSDRS), and hard-rock high frequency (HRHF) spectra. The qualification program included a post-test inspection, which verified performance requirements.

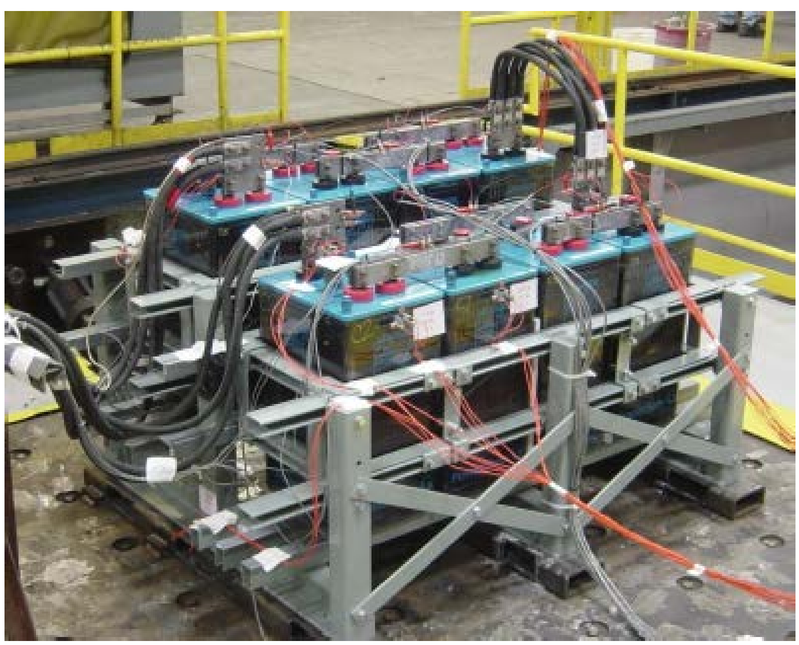

Figure 5: Testing of the 2-step 3-frame battery rack.

Based on the resonance testing, the dominant frequencies are measured as 10.0 Hz, 12.0 Hz, and 30.0 Hz along side-to-side (direction spanning 4 cells and designated as the Y-direction in the analysis), front-to-back (direction spanning 2 cells and designated as the X-direction in the analysis), and vertical (Z-direction in the analysis) directions, respectively.

The shake table tests demonstrated the structural integrity and functionality of the 3-frame rack, and based on the CSDRS and HRHF testing, the 3-frame rack successfully withstood the seismic TRS.

Analysis Summary

A three-dimensional (3D) finite element model is first developed for the 3-frame rack in STAAD.Pro software. The model is created using beam members, with the front-to-back direction of the rack aligned with the global X-direction, the side-to-side direction aligned with the Y-direction, and the vertical direction aligned with the global Z-direction. Bracing members along the front-to-back direction and the cross-bracing along the side-to-side direction are modeled as truss members. Figure 6 shows the rendered 3D view of the 3-frame rack model created in STAAD.Pro.

The battery cells are modeled as lumped masses acting at the center of gravity (C.G.) of each cell. The masses are connected to the channel rails through links (elastic elements) representing the rigidity of the cells. The links are modeled as truss elements that can carry only axial loads. The stiffness of the links would then depend upon their modulus of elasticity (E), their cross-sectional areas (A), and lengths (L). The E and A of the link members are adjusted to provide natural frequencies within ±10% of the natural frequencies observed during the seismic test of the 3-frame rack.

The evaluation of the tested configuration includes a static analysis due to the dead weight (DL) of the rack and battery cells and a response spectrum analysis considering the CSDRF and HRHF response spectra. The modal analysis performed as part of the response spectrum analysis showed that the modes are closely spaced. Therefore, instead of the square-root-of-the-sum-of-the-squares (SRSS) method, the grouping method described in United States Nuclear Regulatory Commission (USNRC) Regulatory Guide (RG) 1.92, Revision 1 is used to combine modal responses.

A code check is performed for all of the frame members for four load combinations, which include DLs and seismic loads. The seismic loads are obtained from the SRSS combination of the combined modal response in the spatial directions. In these load combinations, the DL is combined with the positive and negative SRSS'ed CSDRS and HRHF response spectrum loads. The DL of the rack is applied directly and is based on the geometric and material properties defined for the cross-sections of the rack components. On the other hand, the cells' weights (480 pounds [lbs] each) are applied as concentrated static loads at the C.G. of each cell. The weight of the elastic link members that connect the cell's mass to the rack rails is not considered in the self-weight calculation of the model.

Because the condition of the horizontal battery restraints is unknown, the properties of the elastic link members connecting the masses of the battery cells to the rack are adjusted using the measured frequencies. The finite element model frequencies are considered acceptable when they are within the ±10% of the experimental frequencies. Other factors considered in modeling the 3-frame rack are the mass participation factors in the modal analysis and the compliance of the rack members' design to the Manual of Steel Construction, Part 5, Specification for the Design, Fabrication and Erection of Structural Steel for Buildings (Manual of Steel Construction) by AISC (AISC, 1989). The sum of the mass contributing to the modal response must be greater than 90% of the total mass. If sum of the modal mass up to the cutoff frequency does not include sufficient mass, the static seismic response of the higher frequency modes shall be combined with the response for the modes below the cutoff frequency.

The fundamental frequencies obtained from the analysis are within 10% of the measured test frequencies. The measured and calculated dominant modes show close agreement, which substantiates the adequacy of the analytical model and its use for extended evaluation. The mass in the Y-direction is less than the 90% criterion, and therefore, the static seismic response was considered in the response spectrum analysis.

Since the 3-frame rack finite element model is the basis for developing the 5-frame rack finite element model, all code checks required for the 5-frame rack according to the Specification of the Manual of Steel Construction (AISC, 1989) are performed first for the 3-frame rack.

Extending The Qualification

The 5-frame rack is designed to support 20 cells and has overall dimensions of 132 inches x 49.25 inches. As described above, the rack is a modular design, and a 5-frame model can be developed by expanding the 3-frame model. In the side-to-side direction, the 5-frame rack has four 28.25-inch spans and two cantilevers with 9.88-inch and 9.13-inch lengths, as shown in Figure 7 below. The rack is a 2-step design where 10 cells are mounted on each step. The column, angle, and channel rail sections of the 5-frame rack are the same sections used in the 3-frame rack.

The calculated stresses and forces of the components are checked with allowable limits according to the Manual of Steel Construction (AISC,1989). In addition, the code checks based on the AISC-1989 specifications are only supported for prismatic sections in the software used, and consequently, the code checks for the bracing and the cross-bracing members of the 5-frame rack are performed in separate calculations based on the maximum forces and stresses obtained from the response spectrum analysis results.

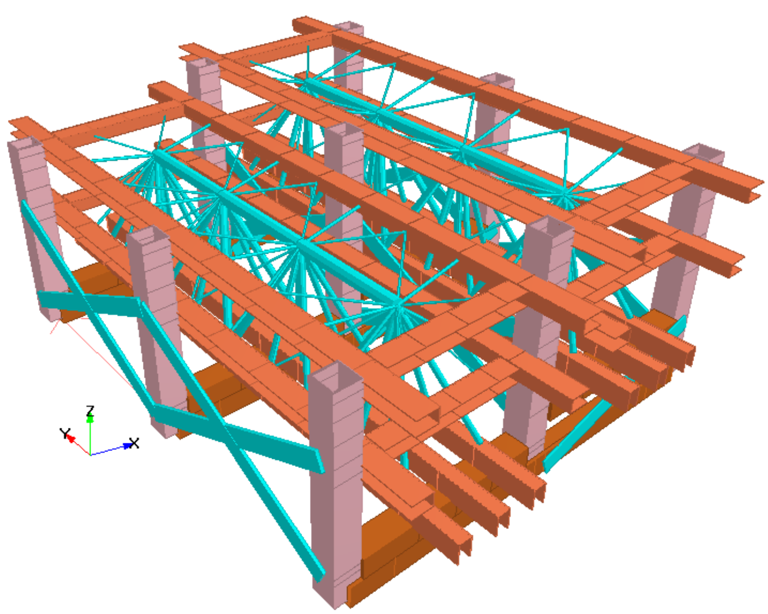

Figure 6: Isometric view of the 2-step 3-frame battery rack model.

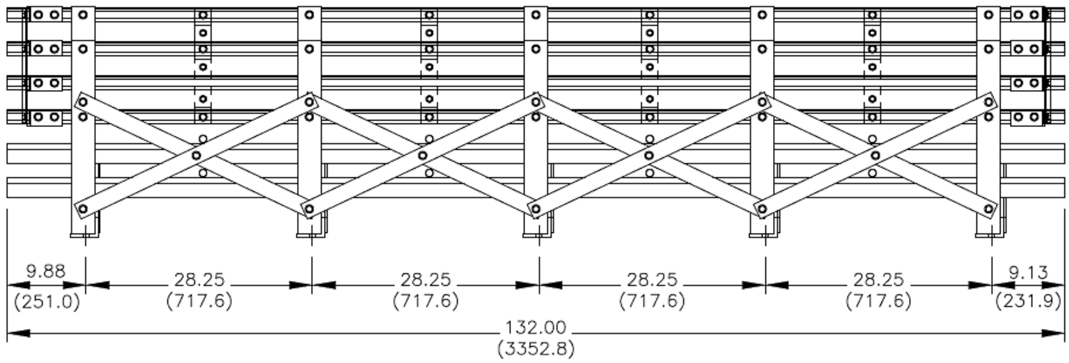

Figure 7: Side-to-side elevation view of the 2-step 5-frame battery rack.

CONCLUSION

Consistent with IEEE-344, the paper describes the use of correlation between test and analysis results to extend the qualification by testing or by combined testing and analysis to the similar components. This approach uses similarity in physical configuration, dynamic characteristics, and analytically predicted response quantities. The paper describes the implementation of this approach to qualify several PB fans based on qualification by testing and analysis of a sample.

Additionally, the paper illustrates the viability of qualification by analysis of large modular components such as battery racks, supported by calibration and validation of the numerical finite element models of smaller tested samples.

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