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Shake Table Testing of a Unique Restraint System for Seismic Rehabilitation of Nonstructural Components

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ABSTRACT

A series of shake table tests were conducted on a unique restraint system, which is a restraining system product line manufactured by EQ Restraint Technologies Inc in BC, Canada. The tests were performed on the Multi Axial Shake Table at the Earthquake Engineering Research Facility of the University of British Columbia, Vancouver, BC. The objective of the testing program was to determine the seismic performance and withstanding capacity of the EQ Restraint System EQRT 203-7, using shake table tests. The performance of the configuration was tested in a realistic context, as it would be in a typical post disaster facility like a hospital. The tri-axial shake table tests were carried out in accordance with the selected requirements of ICC-ES – AC 156-2012, Acceptance Criteria for Seismic Certification by Shake Table Testing of Nonstructural Components. The seismic test program consisted of pre-test structural functionality inspection, resonant frequency search tests, time history tests at three levels; and post-test structural functionality inspection. At the highest intensity of shaking, the Test Response Spectra enveloped the Required Response Spectra in all directions, and at all locations, between 3.5 and 33 Hz. The Peak Shake Table Acceleration exceeded 1.21g in the X direction, 1.43g in the Y direction, and 0.6g in the Z direction, at the highest level of shaking. In time history tests, no damage or deformation was observed during the tests. The Test Article did not pose a life or limb safety hazard due to collapse, damage, instability, rocking, sliding or overturning at any test level. EQ Restraint system remained connected, integrated, and did not cause loss of function or present a safety hazard. No subassembly separation, failure, elongation, or bending was observed in any part of the units. In conclusion, the test results confirmed that Test Article passed the seismic tests and can be qualified for AC 156 seismic certification.

Keywords: Seismic Restraint System, Nonstructural Components, Shake Table Test, AC 156 Seismic Certification, Seismic Rehabilitation

INTRODUCTION

Nonstructural components of a building are those systems, parts, elements, or components that are not part of the structural load-bearing system but are subjected to the earthquake [1]. Typical examples of nonstructural components include architectural partitions, piping systems, ceilings, building contents, mechanical and electrical equipment, and exterior cladding. Nonstructural components represent a substantial percentage of the value of most buildings. Much of the economic loss from past earthquakes can be attributed to damage to nonstructural components and contents [2]. Therefore, it's very important to protect the non-structural components in case of earthquake and reduce the level of loss due to heavy damage in non-structural components caused by major earthquakes. There are many techniques used for seismic rehabilitation of non-structural components that have been discussed in the literature [3, 4]. This paper presents a unique restraint system for seismic rehabilitation of industrial equipment. A series of shake table tests were conducted on the EQ Restraint System EQRT 203, manufactured by EQ Restraint Technologies Inc. in BC, Canada, which is a seismic product to restrain and secure the nonstructural elements against earthquake motions, The tests were performed on the Multi Axial Shake Table (MAST) of the Earthquake Engineering Research Facility (EERF) of the Department of Civil Engineering at the University of British Columbia (UBC) located in Vancouver, BC, on January 31st, 2018.
The objective of this testing program was to determine the seismic performance and withstanding capacity of the EQ Restraint System. The shake table tests were carried out in accordance with the selected requirements of ICC-ES–AC 156-2012, Acceptance Criteria for Seismic Certification by Shake Table Testing of Nonstructural Components [5].

The testing program was coordinated by the EERF Research Group in collaboration with EQ Restraint Technologies Inc. from Vancouver, BC. The EQ Restraint units were installed by Seismic Solutions Inc. from Vancouver, BC. The tests were conducted by the EERF Research Group and the test report was prepared by the EERF Test Engineer according to the procedures specified by ICC-ES – AC85-2012, Acceptance Criteria for Test Reports.

DESCRIPTION OF THE EQ RESTRAINT SYSTEM, EQRT 203

The EQ Restraint System, EQRT 203 manufactured by EQ Restraint Technologies Inc, is a seismic restraint system designed to secure a wide variety of nonstructural components such as specialized equipment in medical labs and hospitals, as well as mechanical units, electrical units and telecommunication units, and components such as vending machines. The EQ Restraint System, as the Unit Under Test in this testing program, consists of four base units mounted to the floor with anchor bolts, threaded rods, threaded rod sleeve and tie down straps hooked up around the subject equipment and connected to the base units at the bottom. This combination of anchored units and straps provides a lateral and vertical restraint of the equipment and prevents any possible sliding, rocking and overturning of the equipment during an earthquake event. The units are constructed of Fy =300 MPa (43.5ksi) steel components, Fy=393 Mpa (57ksi) for Threaded Rod and HILTI Screw Anchor KH-EZ ½" ϕ x 2 ½" anchor bolts and the tie down straps with 44.5 KN (10kip) breaking strength. The EQ Restraint System, EQRT 203 is a relatively cost-effective solution for the seismic upgrading of nonstructural component performance and does not require special expertise for installation. Figure 1 shows the view of the assembled EQ Restraint units.

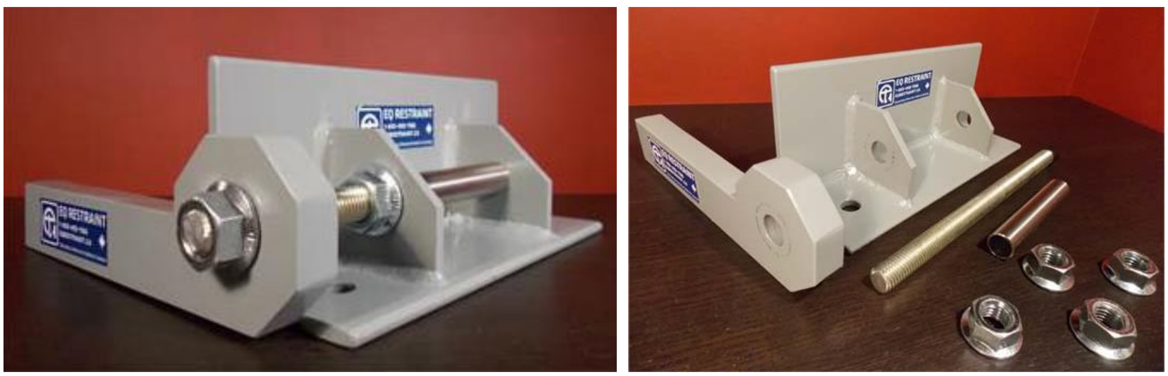


Figure 1. Overview of the EQ Restraint EQRT 203-7 components assemblies.

A set of EQ Restraint units (EQRT 203) was selected and designed to adequately represent the entire component product line by restraining a piece of equipment. The restrained equipment and the EQ Restraint System herein is identified as Test Article (test specimen). Table 1 describes the characteristics of the selected units and the equipment for the testing program.

Table 1. Test Article characteristics.

Unit Under Test	Description	Overall Dimensions	Weight
EQ Restraint System	EQRT 203-7 Standard system, consisted of base units, threaded rods, rod skins, anchor bolts and tie down straps	75 mm (3") wide x 178mm long (7") x 100 mm (4") high bracket and 220mm (8 11/16") x 20mm (3/4") confinement lip	32.5 N (7.31 lbf)
Restrained Equipment	Sanyo Hospital Freezer	860 mm (33 7/8") wide x 1016 mm (40") deep x 1981 mm (78") high	3373 N (728.28 lbf)

The assembly was installed by Seismic Solutions Inc. personnel under supervision of the Test Engineer from UBC, and the Supervisor from EQ Restraint Technologies Inc. The equipment was mounted in the in-service configuration and oriented in the normal upright position, such that its principal axes were collinear with the axes of the excitation of the shake table. A subfloor concrete slab was used underneath to simulate the real boundary condition, and the EQ Restraint units were installed as it would be in a post disaster facility such as hospital building. Figure 3 shows the assembly of the EQ Restraint units prior testing.

TEST SETUP

The test setup was designed and provided by EERF Test Engineer according to the requirements as specified by AC 156. A subfloor concrete slab, 1500 mm (5') long, 1500 mm (5') wide, and 150 mm (6") high was constructed and installed on the shake table after concrete curing to represent the boundaries of an equipment room in an industry or hospital building, which will naturally constrain the motion of the equipment. The same concrete slab was used for all the runs. Figure 2 shows the general view of the concrete slab constructed and installed on the MAST prior to positioning the equipment and installing the EQ Restraint units (EQRT 203).

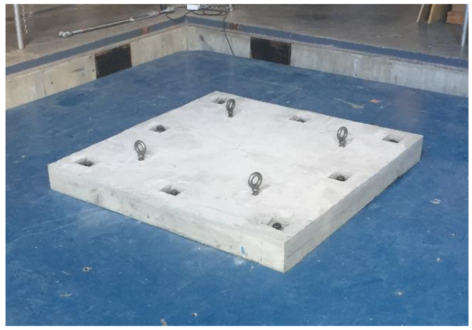


Figure 2. Concrete slab installed on the Shake Table.

The surface of the concrete slab simulated a typical concrete surface in an industry or hospital building. The Figure 3 illustrates the test setup and the EQ Restraint units installed on the equipment prior to testing.

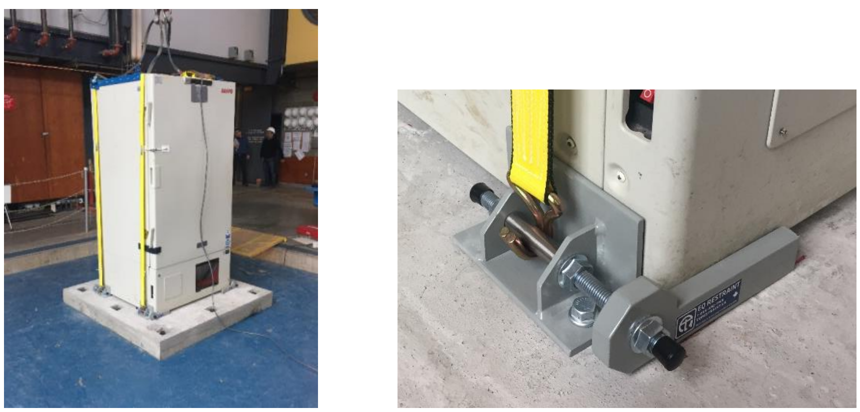


Figure 3. Test setup and EQ Restraint System (EQRT 203-7) installed on the equipment prior to testing.

TEST FACILITIES AND EQUIPMENT

The testing facilities and equipment belong to the University of British Columbia, Department of Civil Engineering and are located at the EERF.

The EERF testing facilities used for test program include a strong floor, a crane, a multi axial shake table, various types of instruments, data acquisition systems, and video systems. The size, capacities, and characteristics of the MAST are presented in Table 2.

Two sets of instrumentation were used to measure the response of the shake table and the Test Article. There was one set of uniaxial piezoelectric accelerometers (PCB1), mounted at central location at the base of the shake table, and used to measure motions in the horizontal and vertical directions and develop the Test Article Response Spectrum (TARS). There was also one triaxial accelerometer (AC1) placed on top of the Test Article and used for resonant frequency search. Table 3 presents the characteristics of the sensors used for the tests. The instrumentations' layout is shown in Figure 4. A photo of each set of sensors is shown in Figure 5.

Table 2. Multi Axial Shake Table (MAST) characteristics.

Size	4 m x 4 m (13 ft x 13 ft)
Payload	10 t (20,000 lb)
Degrees of Freedom	6
X Horizontal Displacement (max.)	Static: ±242 mm (±9.5 in) dynamic: ±216 mm (±8.5 in)
Y Horizontal Displacement (max.)	Static: ±152 mm (±6.0 in) dynamic: ±120 mm (±5.0 in)
Z Vertical Displacement (max.)	Static: ±84 mm (±3.3 in) dynamic: ±76.2 mm (±3.0 in)
X Horizontal Velocity (400gpm)	1.67 m/s (65.9 in/s)
Y Horizontal Velocity (300gpm)	1.25 m/s (49.4 in/s)
Z Vertical Velocity (150gpm)	2.08 m/s (82 in/s)
X Horizontal Acceleration	20kip payload: 1.24g (12.2m/s^2) bare table: 3.8g (37.3m/s^2)
Y Horizontal Acceleration	20kip payload: 2.47g (24.2m/s^2) bare table: 5.2g (51.0m/s^2)
Z Vertical Acceleration	20kip payload: 0.47g (4.61m/s^2) bare table: 2.1g (20.6m/s^2)
Operating Frequency	40 Hz
Table Weight	9 t (18,000 lb)
X Horizontal Dynamic Force	static: 70,000 lb dynamic: 47,000 lb
Y Horizontal Dynamic Force	static: 140,000 lb dynamic: 94,000 lb
Z Vertical Dynamic Force	static: 84,000 lb dynamic: 56,000 lb

Table 3. Acceleration sensor's locations and characteristics.

Sensor ID	Sensor Model	Serial No.	Location	Range		Date of Calibration
				Acc. (g)	Freq. (Hz)	
PCB1-X	Piezotronics 393A03	49497	Under the Table	±5	0.5-2000	11/27/17
PCB1-Y	Piezotronics 393A03	49498	Under the Table	±5	0.5-2000	11/27/17
PCB1-Z	Piezotronics 393A03	49499	Under the Table	±5	0.5-2000	11/27/17
AC1-X	Triaxial IC 3026	X-1873-048	On the TA	±5	0.5-300	12/01/17
AC1-Y	Triaxial IC 3027	Y-1873-034	On the TA	±5	0.5-300	12/01/17
AC1-Z	Triaxial IC 3028	Z-1873-005	On the TA	±5	0.5-300	12/01/17

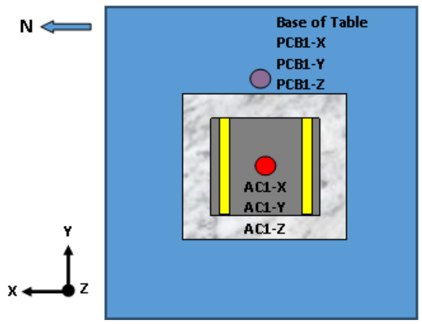


Figure 4. Instrumentations layout.

Two sets of video recorders, Synchronized Video Network Cameras, and JVC Video Cameras were used to monitor the seismic tests from X and Y directions, and from above the Test Article.

TEST EXCITATIONS

The Test Article was subjected to resonant frequency search tests and time history tests for the test program. The following sections describe the details of both excitations:

(a) *(b)*

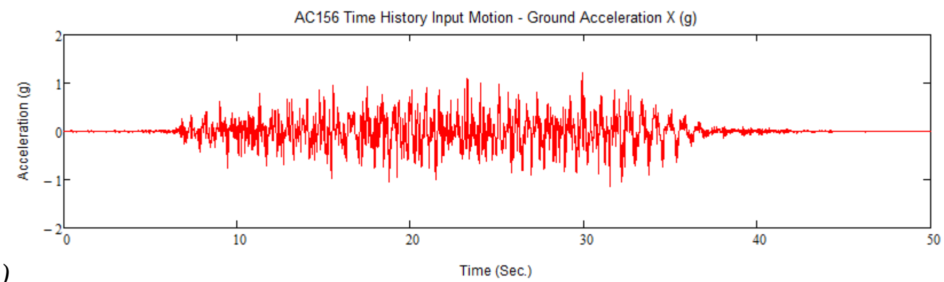
Figure 5. Instrumentations used in testing program: a) PCB1 Sensors; b) AC1 Sensors.

Resonant Frequency Search Tests

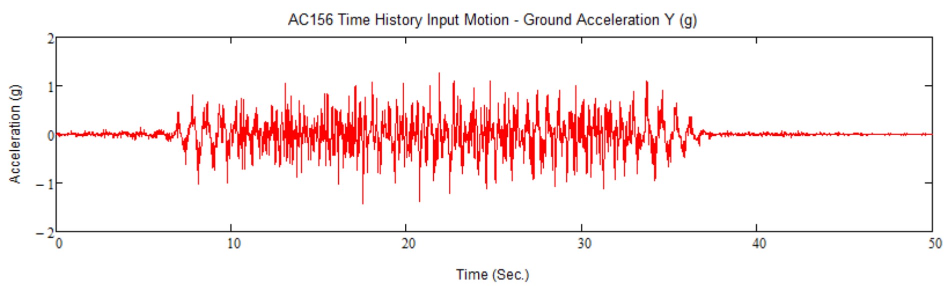
The resonant frequency tests were used to search for the resonant frequencies of the Test Article. A low-level amplitude single-axis sinusoidal sweep from 1.3 to 33 Hz was used in three principal directions of the Test Article individually to determine the resonant frequencies in this frequency range. The sweep rate was 1 octave per minute to ensure adequate time for maximum response at the resonant frequencies.

Time History Tests

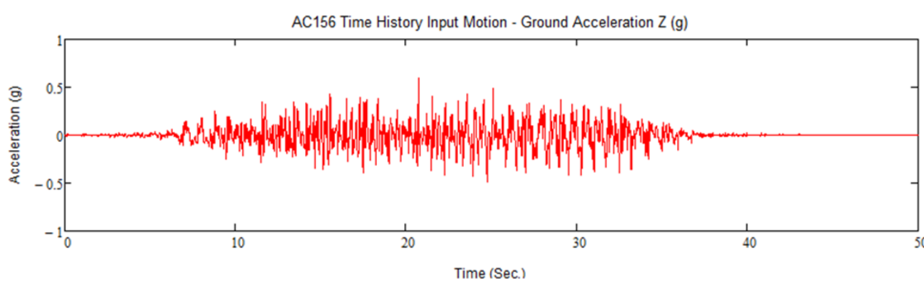
A triaxial synthetic time history seismic random motion was used for time history tests. The motion components were nonstationary broadband excitations having an energy content ranging from 1.3 to 33 Hz. The total duration of the input motion was 32 seconds by an input signal build-strong ground motion-decay envelope of 5 seconds, 22 seconds and 5 seconds, respectively to simulate the nonstationary nature of an earthquake event. The acceleration amplitude of the input motions was adjusted such that the calculated Test Article Response Spectrum (TARS) envelopes the Required Response Spectrum (RRS) for each test in all locations between 1.3 to 33 Hz. The triaxial motion records used for time history tests are shown in Figure 6.



(a)



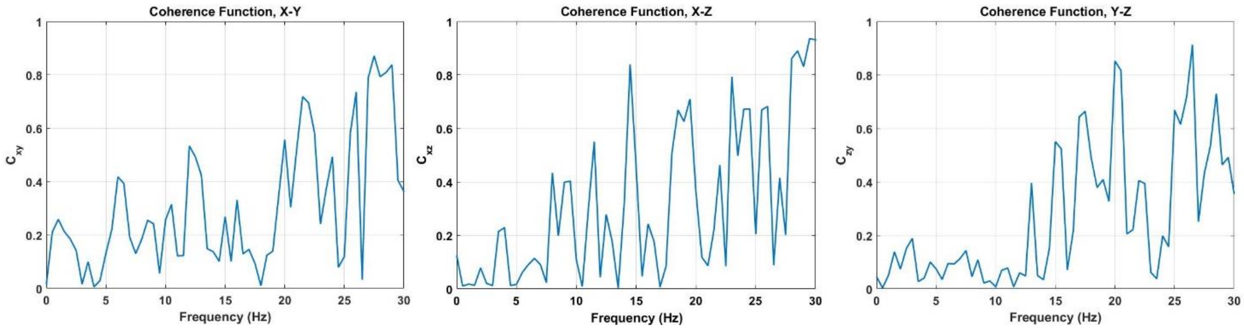
(b)



(c)

Figure 6. AC 156-time history motion records used for Shake Table tests: a) Horizontal X direction; b) Horizontal Y direction; c) Vertical Z direction.

The Coherence Functions between pairs of the recorded motions are shown in Figure 7. The Coherence Function verifies that simultaneous shake table motions in three orthogonal directions are phase incoherent if the value of this function is very low.



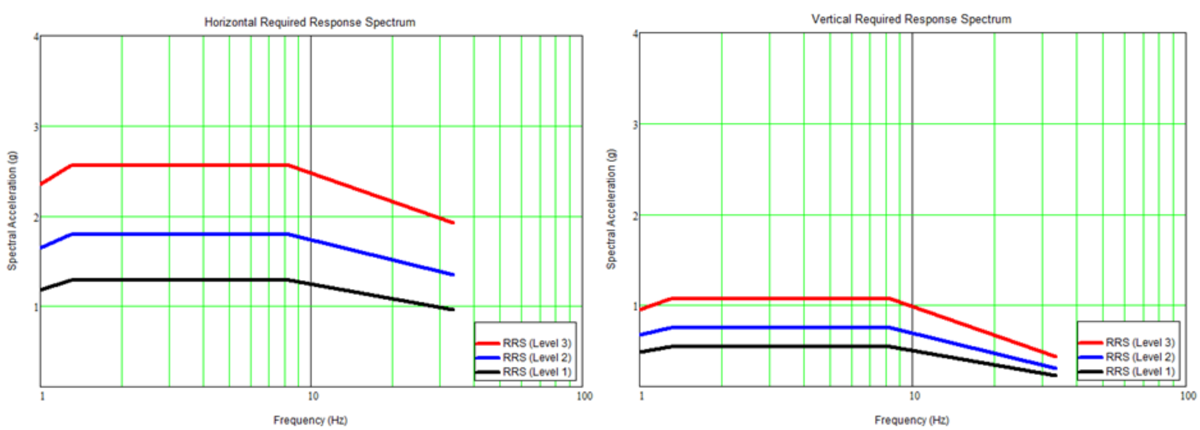
(a) (b) (c)

Figure 7. Coherence Function for the triaxial time history motion: a) Cxy; b) Cx; c) Cyz.

The level of time history tests and the shake table test parameters for RRS were provided by EQ Restraint LTD. and are presented in Table 4. The highest level of shake table test (Level 3) was considered to achieve the target of S_{DS} =1.60 for roof top installation in a high-risk seismicity area [6, 7]. The RRS were used to define the acceleration levels used during testing. The RRS developed for horizontal and vertical directions at the test levels are illustrated in Figure 8.

Table 4. Shake Table test parameters according to AC 156.

Sa	F_a	S_{MS}	S_{DS} (g)	Horizontal Acceleration (g)		Vertical Acceleration (g)	
				A_{FLX-H}	A_{RIG-H}	A_{FLX-V}	A_{RIG-V}
Level 1: 1.2	1.00	1.20	0.80	1.28	0.96	0.54	0.22
Level 2: 1.7	1.00	1.70	1.13	1.81	1.36	0.76	0.31
Level 3: 2.4	1.00	2.4	1.60	2.56	1.92	1.07	0.43



(a) *(b)*

Figure 8. AC 156 Required Response Spectrum (RRS) for time history tests, 5% Damping: a) Horizontal; b) Vertical.

Resonant Frequency Search Tests

Fourier Amplitude and Transmissibility functions for sweep tests performed on the Test Article are provided in Figure 9 to 11.

Transmissibility Functions between the shake table and test article motions show the resonance occurrence during the sweep tests. The peak values of the Transmissibility Functions show the resonant frequencies. Table 6 presents the resonant frequencies found within the frequency range of interest for the Test Article during the sweep tests in X and Y directions.

However, The Transmissibility Function in Z direction does not show any peak; that means no resonant frequency was found in vertical direction. Therefore, the result from this investigation in Z direction is stated as "Not Present" in Table 6.

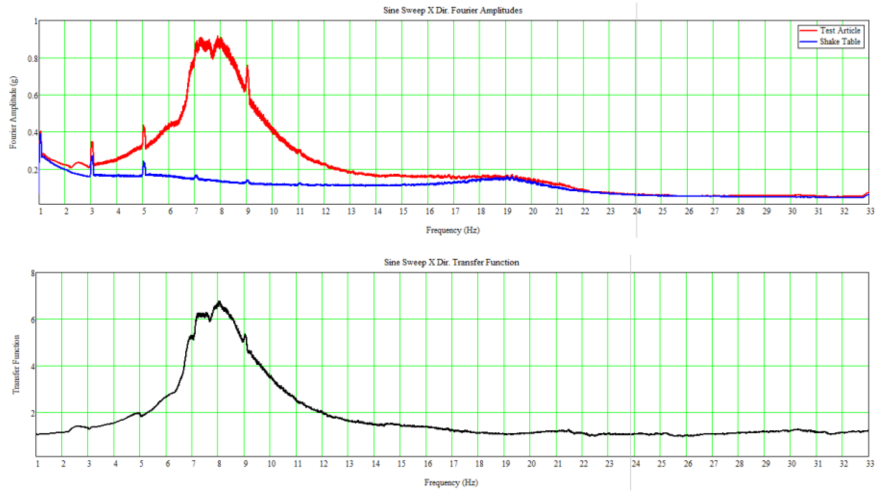


Figure 9. Fourier Amplitudes and Transmissibility Function for Test Article in the X Direction.

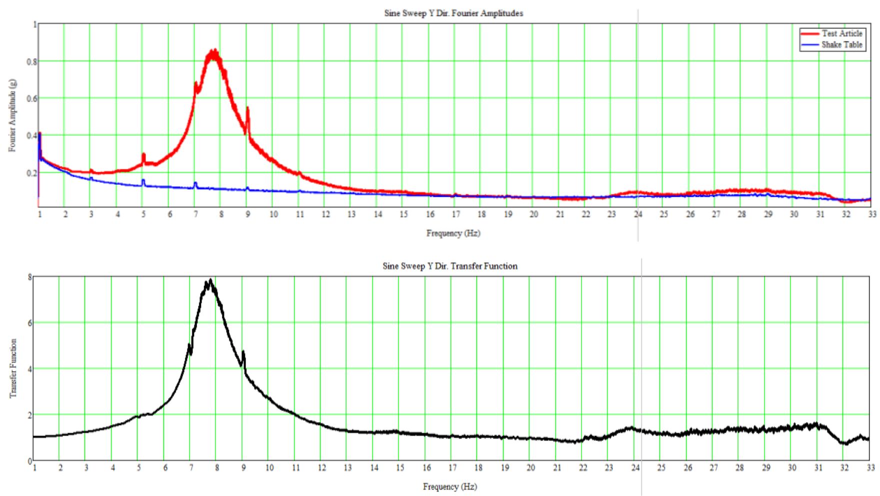


Figure 10. Fourier Amplitudes and Transmissibility Function for Test Article in the Y Direction.

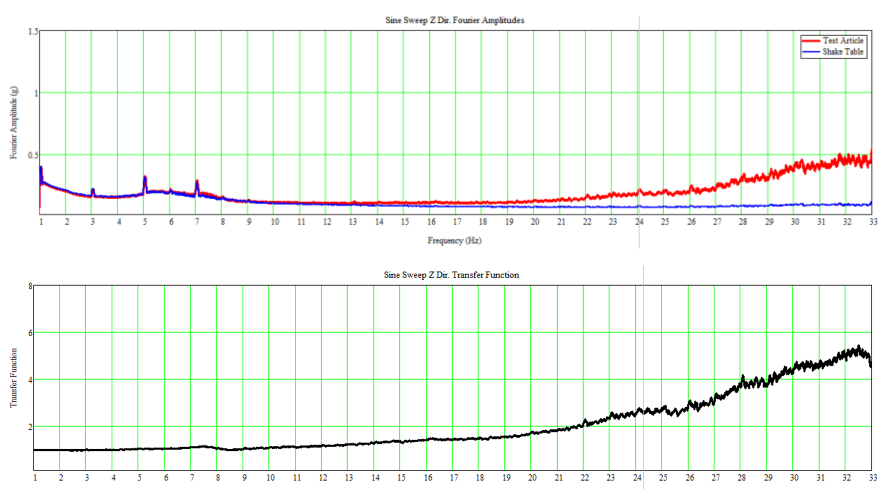


Figure 11. Fourier Amplitudes and Transmissibility Function for Test Article in the Z Direction.

CONCLUSIONS

Seismic tests of the EQ Restraint system, EQRT 203 consisting of pre-test and post-test structural functionality inspection, resonant frequency search tests, and time history tests were performed as part of this project. The following results were derived from the test program:

1. The sweep tests showed the resonant frequencies at 8 Hz and 7.8 Hz in X and Y direction, respectively but, did not show any resonant frequency in Z direction in the frequency range of interested;
2. At all test levels, the TARS enveloped the RRS in all directions in most of the regions between 1.3 and 33 Hz. However, the TARS do not fully envelop the amplified region of the RRS in frequency range lower than 3.5 Hz. As long as no resonance response phenomena exist below 5 Hz, the TARS is required to envelop the RRS only down to 3.5 Hz and the retest is exempted according to Section 6.5.3.1.1 of AC 156 Acceptance Criteria;
3. The Peak Shake Table Acceleration reached 1.21g, 1.43g and 0.6g in X, Y, and Z direction, respectively in Level 3. Likewise, the Peak Acceleration at top of the Test Article was recorded in this level of shaking as 2.82g, 3.17g and 1.01g in X, Y, and Z direction, respectively;
4. The Test Article did not pose a life or limb safety hazard due to collapse or major damage, instability, rocking, sliding or overturning. EQ Restraint system maintained connected and integrated and did not cause loss of function or present a safety hazard;
5. Any subassemblies separation, failure, elongation or bending was not observed in any metal part of the EQ Restraint Units;
6. Connection anchor bolts were not broken, shear off or pulled out from the concrete slab and the structural integrity of the component attachment system was maintained;
7. Straps components retained tight enough to maintain the functionality of the equipment and did not present a safety hazard. No tear off or damage was observed in any test level.

In conclusion, the test results confirmed that the Test Article passed the seismic tests and can be considered as qualified for AC 156 seismic certification.

ACKNOWLEDGMENTS

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