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Shake Table Testing of Unique Restraint Systems 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 202 and EQRT 201, 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 Accelerations exceeded 1.21g and 1.43g in the two orthogonal horizontal directions, and 0.6g in the vertical 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, AC156 Seismic Certification, Seismic Rehabilitation.

INTRODUCTION

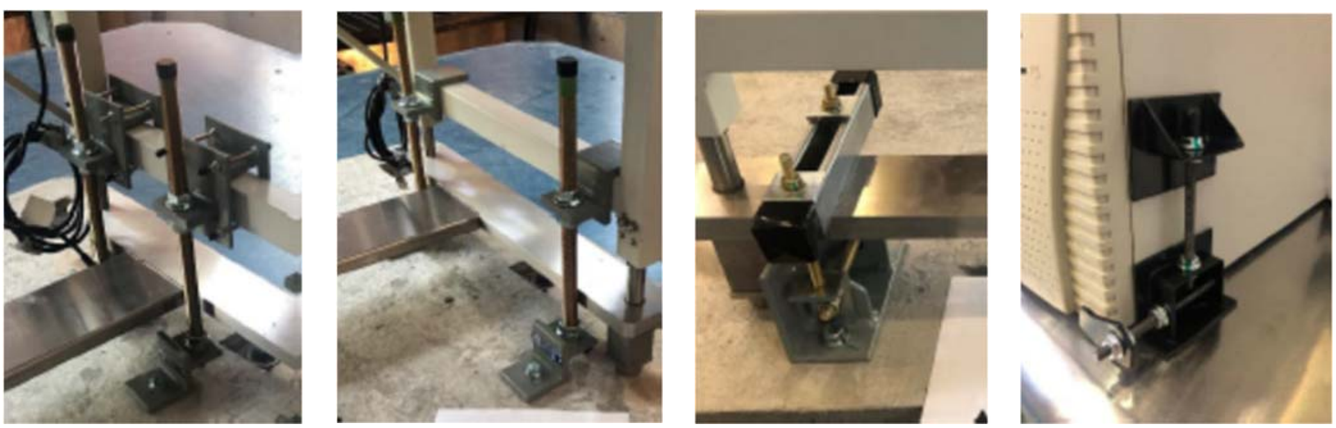
Nonstructural components of a building are those systems, parts, elements, or components that are not part of the structural load-bearing system but are subjected to the earthquake [1]. Typical examples of nonstructural components include architectural partitions, piping systems, ceilings, building contents, 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 202 and EQRT 201, 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 July 26th to 28th, 2021.

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 201, EQRT 202, and EQRT 203 units) 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, telecommunication units or components such as vending machines. The EQ Restraint System (EQRT 202 and EQRT 203), as the Unit Under Test in this testing program, consists of four (or eight) base units mounted to the base floor with anchor bolts, w/12" threaded rods, and top brackets. This combination of anchored units provides lateral and vertical restraint of the equipment and prevents any possible sliding, rocking and overturning of the equipment during an earthquake event. The EQ Restraint System (EQRT 201) was also used to restrain a computer desktop to the tested equipment during all tests. The units are constructed of Fy =300 MPa steel components, Fy=200 MPa for threaded rod and HILTI Screw Anchor KH-EZ ½"φ x 2-1/2" anchorage bolts. The EQ Restraint System 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 EQRT 201, 202, and 203 units.



(a) (b) (c) (d)

Figure 1. Overview of the EQ Restraint components assemblies used in the qualification tests: (a) EQRT 202 with confinement, (b) EQRT 202 without confinement, (c) EQRT 203 with Unistrut, (d) EQRT 201.

A set of EQ Restraint units (EQRT 202) 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.

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.

Table 1. Test Article characteristics.

Unit Under Test	Description	Overall Dimensions	Weight
EQ Restraint System EQRT 202 with Confinement	EQRT 202 confined system, consisted of base unit, threaded rod, top bracket, and anchor bolt and confinement plates	76 mm wide x 76 mm long brackets with w/12” long threaded rod	35 N
EQ Restraint System EQRT 202 without Confinement	EQRT 202 standard system, consisted of base unit, threaded rod, top bracket, and anchor bolt	76 mm wide x 76 mm long brackets with w/12” long threaded rod	25N
EQ Restraint System EQRT 203 with Unistrut	EQRT 203 Standard system, consisted of base unit, threaded rod, top bracket, and anchor bolt and unistrut	76 mm wide x 76 mm long brackets with w/12” short threaded rod	25N
EQ Restraint System EQRT 201	EQRT 201 Standard system, consisted of base unit, threaded rod, top bracket, and sticky pads	25 mm wide x 28 mm long brackets with w/12” short threaded rod	3N
Restrained Equipment	Biosafety Cabinet	1830 mm long x 1524 mm wide x 1700 mm high	3333N

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. The surface of the concrete slab simulated a typical concrete surface in an industry or hospital building. Figure 2 illustrates the test setup, concrete slab and the EQ Restraint units installed on the equipment prior to testing. A supporting frame with dimensions of 1473 (L) x 762 (W) x 813 (H) mm and weight of 578 N was used to hold the support for the test equipment. Instrumentations layout is shown in Figure 3 and the instrumentations used in the testing program are illustrated in Figure 4.

Figure 2. Test setup and EQRT 202 System installed on the equipment prior to testing.

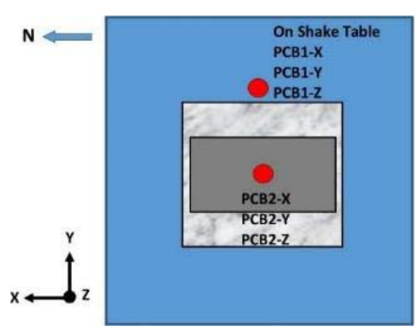


Figure 3. Instrumentations layout.

(a) *(b)*

Figure 4. Instrumentations used in testing program: (a) PCB1 Sensors, (b) PCB2 Sensors.

TEST EXCITATIONS

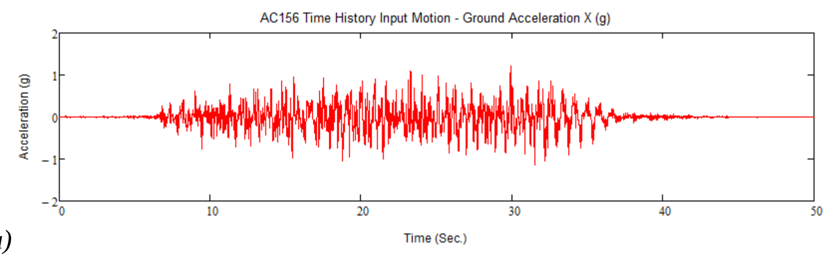
The Test Article was subjected to resonant frequency search tests and time history tests for the test program. The following sections describe the details of both excitations.

Resonant Frequency Search Tests

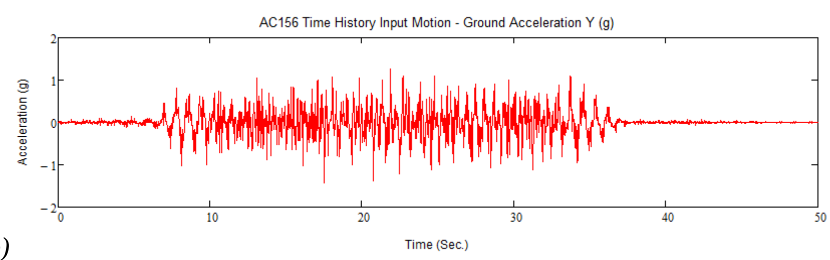
The resonant frequency tests were used to search for the resonant frequencies of the Test Article. A low-level amplitude, single-axis, sinusoidal sweep from 1.3 to 33 Hz was used in three principal directions of the Test Article, individually, to determine the resonant frequencies in this frequency range. 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 amplitudes of the input motions were adjusted such that the calculated Test Article Response Spectrum (TARS) envelopes the Required Response Spectrum (RRS) for each test between 1.3 to 33 Hz. The triaxial motion records used for time history tests are shown in Figure 5.



(a)



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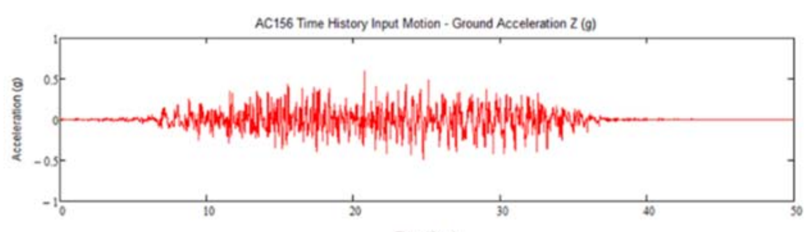
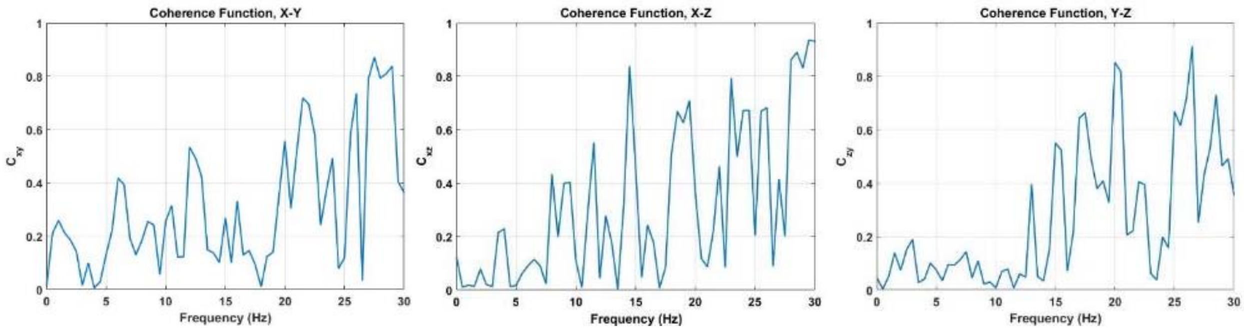


(c)

Figure 5. 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 6. 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.



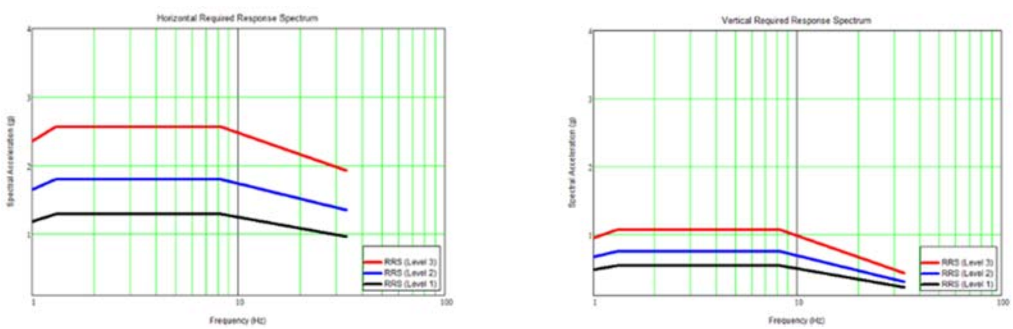
(a) *(b)* *(c)*

Figure 6. Coherence Function for the triaxial time history motion: (a) Cxy, (b) Cxz, (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 2. All three levels of shake table test were considered to achieve the target of S_{DS} =0.80g, 1.13g and 1.60g for roof top installation in a high-risk seismicity area. 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 7.

Table 2. 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	2.40	1.60	2.56	1.92	1.07	0.43



(a) (b)

Figure 7. AC 156 Required Response Spectrum (RRS) for time history tests, 5% Damping: (a) Horizontal, (b) Vertical.

TEST PROCEDURES

The Test Article was subjected to a seismic test program in four setups consisting of: (1) pre-test structural functionality inspection, (2) resonant frequency search tests, (3) time history tests at designated levels, and (4) post-test structural functionality inspection.

Upon arrival at the test facility, the EQRT 201, 202, and 203 units were visually examined to verify that no damage had occurred during shipping and handling.

For each pre-test and post-test inspection, the EQRT units were visually checked for evidence of structural damage per acceptance criteria.

The resonant frequency search tests were performed on the Test Article in the three principal axes separately to determine the resonant frequencies within the range of 1.3 to 33 Hz.

The time history tests were performed tri-axially. The test for the Article at each test level was performed after the required inspections.

The following structural Functionality acceptance criteria were checked before, during, and after each time history test:

1) TARS shall envelope RRS for each test in all locations between 1.3 and 33 Hz;
2) The Test Article shall not pose a life or limb safety hazard due to collapse, major damage, instability, rocking, sliding or overturning. EQ Restraint system shall not become disconnected or loose enough to cause loss of function or present a safety hazard;
3) Overall structural stability of the Test Article shall be maintained. Metal parts shall not fail enough to cause loss of function or present a safety hazard. Metal and connection parts may, however, elongate or bend and shall be allowed minor fractures and anomalies;
4) Structural integrity of the component attachment system shall be maintained. Connection anchor bolts shall not be broken, shear off or pulled out from the concrete slab.

Table 3 presents the list of the tests performed for the seismic testing program.

Table 3. List of the tests conducted on Test Article #3.

Test Setup	Type and Number of used EQ Restraint System	Waveform Record	Test Date	Time (PST)
Setup 1	EQRT 202 – with Confinement (Qty. 6)	Sine Sweep (X)	July 26th, 2021	13:57
		Sine Sweep (Y)		14:07
		Sine Sweep (Z)		14:20
		Time History Test (Level 3)		14:39
		Time History Test (Level 3)-Repeated	July 27th, 2021	12:29
Setup 2	EQRT 202 – with Confinement (Qty. 4)	Sine Sweep (X)	July 27th, 2021	15:08
		Sine Sweep (Y)		15:18
		Sine Sweep (Z)		15:36
		Time History Test (Level 2)		15:47
Setup 3	EQRT 202 – without Confinement (Qty. 4)	Sine Sweep (X)	July 28th, 2021	10:44
		Sine Sweep (Y)		10:54
		Sine Sweep (Z)		11:05
		Time History Test (Level 1)		11:18
		Time History Test (Level 2)		11:40
		Time History Test (Level 3)		11:58
Setup 4	EQRT 203 – with Unistrut (Qty. 4)	Sine Sweep (X)	July 28th, 2021	13:51
		Sine Sweep (Y)		14:19
		Sine Sweep (Z)		14:29
		Time History Test (Level 1)		14:40
		Time History Test (Level 2)		15:00

TEST RESULTS

The following sections describe the results of the seismic tests and inspections.

Resonant Frequency Search Tests

Fourier Amplitude and Transmissibility functions for sweep tests performed on the Test Article are provided in Figure 8 as an example.

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 4 presents the resonant frequencies found within the frequency range of interest for the Test Article during the sweep tests in X, Y and Z directions.

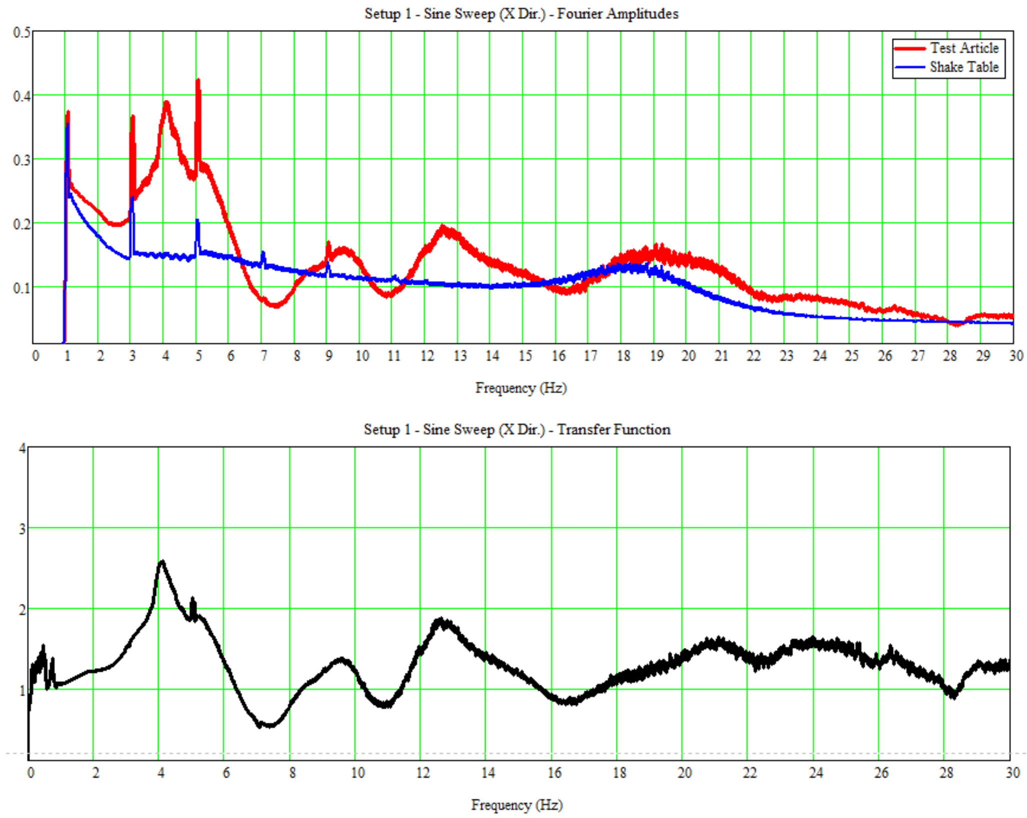


Figure 8. Fourier Amplitudes and Transmissibility Function for Setup 1 in X Direction.

Table 4. Test Article First Resonant Frequency search.

Test Setup	Side-to-Side (X)	Front-to-Back (Y)	Vertical (Z)
Setup 1	4.19 Hz	5.7 Hz	15.05 Hz
Setup 2	4.61 Hz	5.81 Hz	14.92 Hz
Setup 3	4.00 Hz	4.96 Hz	15.01 Hz
Setup 4	3.97 Hz	4.00 Hz	13.41 Hz

Time History Tests

The time history test results, pre-test, and post-test inspection checks are presented in this section. The overall views of the Test Article before and after the test in all Setups are illustrated in Figures 9 to 12. Figure 13 shows the Test Response Spectra (5% Damping) of the Shake Table for Setup 1 at level 3 as an example. Table 5 presents the Peak Shake Table Acceleration in all Test Setups.

(a) *(b)*

Figure 9. View of the Test Article in Setup 1 at Level 3: (a) Before test-general view, (b) After test-close view.

(a) *(b)*

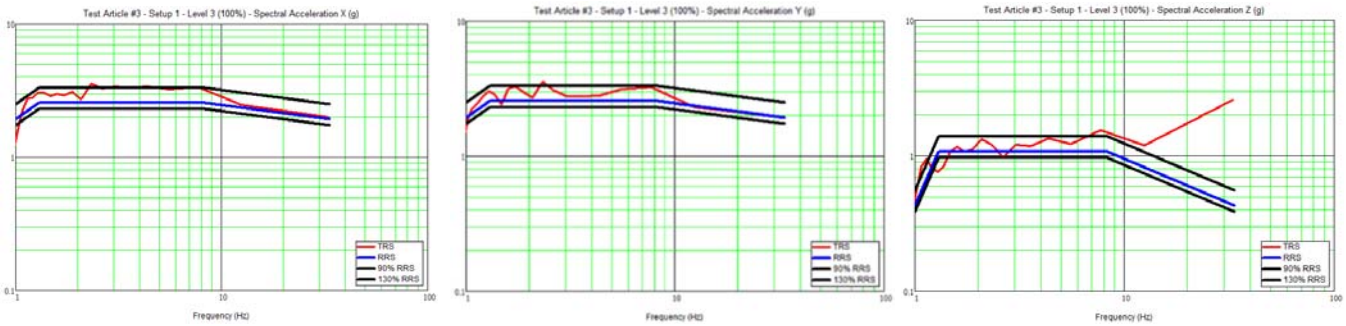
Figure 10. View of the Test Article in Setup 2 at Level 2: (a) Before test-general view, (b) After test-close view.

(a) *(b)*

Figure 11. View of the Test Article in Setup 3 at Level 3: (a) After test-general view, (b) After test-close view.

(a) *(b)*

Figure 12. View of the Test Article in Setup 4 at Level 2: (a) After test-general view, (b) After test-close view.



(a) *(b)* *(c)*

Figure 13. Test Response Spectrum of the Shake Table in Setup 1 at Level 3- (5% Damping): (a) X Direction, (b) Y Direction, (c) Z Direction.

Table 5. Peak time history acceleration of the shake table in all setups (g).

		X Direction	**Y Direction**	**Z Direction**
Setup 1	Level 3	1.35	1.48	1.19
Setup 2	Level 2	1.11	1.15	1.04
Setup 3	Level 1	0.86	0.78	1.13
	Level 2	1.12	1.12	1.02
	Level 3	1.37	1.65	1.32
Setup 4	Level 1	0.84	0.75	0.76
	Level 2	1.12	1.13	1.02

RESPONSE OF THE RESTRAINED EQUIPMENT

The motions of the Test Article, subjected to shake table tests at all shaking levels, were recorded by the sensors installed at top of the equipment. Table 6 shows the peak acceleration of the Test Article in all setups in the time history tests.

Table 6. Peak acceleration of the Test Article in all setups in the time history tests (g).

		X Direction	**Y Direction**	**Z Direction**
Setup 1	Level 3	3.82	4.39	2.97
Setup 2	Level 2	3.62	3.16	2.25
Setup 3	Level 1	1.35	1.85	1.24
	Level 2	2.25	2.58	1.36
	Level 3	3.79	4.97	2.81
Setup 4	Level 1	1.58	3.21	2.37
	Level 2	2.81	4.40	2.67

CONCLUSIONS

Seismic tests of the EQRT 201, 202, and 203 Restraint systems, 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:

The sweep tests showed the resonant frequencies at 4.19 Hz, 5.70 Hz, and 15.05 Hz in X, Y and Z direction, respectively for Setup 1. The resonant frequencies were found as 4.61 Hz, 5.81 Hz, and 14.92 Hz in X, Y and Z direction, respectively for Setup 2. The resonant frequencies in Setup 3 identified at 4.00 Hz, 4.96 Hz, and 15.00 Hz in X, Y and Z direction, respectively. Also, the resonant frequencies were found as 3.97 Hz, 4.00 Hz, and 13.41 Hz in X, Y and Z direction, respectively for Setup 4.

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;

The Peak Shake Table Acceleration reached 1.37g, 1.65g and 1.32g in X, Y, and Z direction, respectively in Level 3 at Setup 3. Likewise, the Peak Acceleration at top of the Test Article was recorded in this level of shaking at Setup 1 as 3.82g, 4.39g and 2.97g in X, Y, and Z direction, respectively;

The Test Articles did not pose a life or limb safety hazard due to collapse or major damage, instability, rocking, sliding or overturning. EQ Restraint system in all setups maintained connected and integrated and did not cause loss of function or present a safety hazard;

Any subassemblies separation, failure, elongation or bending was not observed in any metal part of the EQ Restraint Units;

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.

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

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