SEISMIC EVALUATION PROCEDURE FOR SUSPENDED CEILINGS AND COMPONENTS NEW EXPERIMENTAL APPROACH

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SUMMARY
Suspended ceilings, a prevalent nonstructural feature of modern buildings worldwide, have suffered extensive in the past earthquakes. To address this vulnerability, building codes now include prescriptive design and installation requirements and they permit for shake table testing evaluation. The tests to date have had a narrow scope focused certification of manufacturer's proprietary systems. As such, the tests used limited instrumentation and little attempt was made to develop performance states. To address this issue, an experimental and evaluation program has been developed to: a) develop performance states b) provide a methodology for correlating experimental data to code requirements c) develop static experimental program to complement the shake table tests, and d) standardize the minimum instrumentation requirements. As a case study, a critical component of suspended ceiling system was evaluated using the proposed protocol and the component was qualified for use in regions of high seismicity.

Keywords: Suspended ceiling, earthquake simulator testing, seismic evaluation, new test methodology, building code assessment

1 INTRODUCTION

Directly hung suspended ceilings have been a main feature of modern buildings staring in late 1960s. In office or commercial applications, typical ceiling areas are 10 x 10 m. In warehouses or other commercial buildings, such as distribution centers, much larger ceilings are used; see Figure 1. A grid system, panels, and various attachments such as light fixtures, air diffusers, and sprinklers constitute the components of typical suspended ceilings. Most installations consist of lay-in panels; first the grid is assembled, then the panels are placed. Suspended ceilings are classified as nonstructural components. The seismic performance of nonstructural components greatly depends on the adequate design, anchorage, and on the proper installation.

1.1 Components of Suspended ceilings

Suspended ceilings consist of a grid, hanger wires, and the perimeter and lateral restraints. Lay-in panels and attachments contribute additional seismic mass to the ceiling grid; see Figure 2. The grid consists of main runners spanning in one direction and cross runners framing to these runners orthogonally. Vertical wires are used to suspend the ceiling from the main structures. Mechanical connections are used to splice main runner beams. The connection between the main and cross runners is typically a riveted mechanical tab connector installed on the cross runner by the manufacturer. The grid members are typically light-gauge hot-dip galvanized tee sections.

Figure 1. Commercial store suspended ceiling

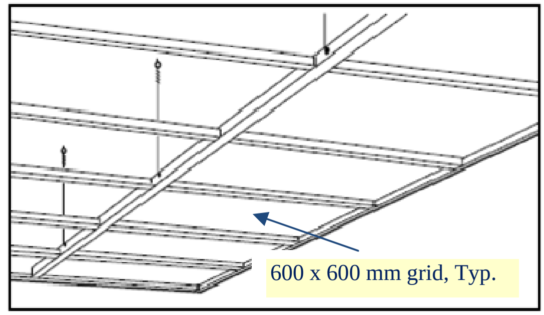

Figure 2. Components of suspended ceilings

2 BUILDING CODE REQUIREMENTS

2.1 Past Seismic Performance

Past earthquakes have demonstrated the susceptibility of suspended ceilings to failure during seismic events. Staring from 1971 San Fernando Earthquake, damage to these components has been surveyed and documented. The damage and failure of suspended ceilings have occurred even in smaller events and even for cases for which buildings, constructed using the more recent seismic code requirements, and have performed well with no or minor structural damage. The failure of these components can be a life safety hazard and result in financial losses and business interruptions. Examples of damage to suspended ceilings are the partial collapse of the system at the Santiago Airport during the 2010 Chile Earthquake; see Figure 3 (from University at Buffalo) and observed damage to a commercial building during the 2011 Christchurch (New Zealand) Earthquake; see Figure 4.

Figure 3. Santiago, Chile (2010) (From University at Buffalo)

Figure 4. Christchurch, New Zealand (2011)

2.2 United States Building Code Provisions

To address the seismic vulnerability of suspended ceilings, design codes have incorporated specific design and installation criteria for suspended ceilings. For example, the building code (ASCE 2005) requires that the grid connections have a minimum capacity of 800 N, hanger wires be used at 1.2 m maximum spacing and tied with a minimum of three turns and have a minimum capacity of 450 N. In addition, installation requirements for the attachment of the ceiling system to adjacent building walls are specified, and the light fixture require independent attachments. Finally, for ceilings area larger than 100 m^2 in area, lateral restraints are required and for ceilings larger than 250 m^2, separation joints are prescribed.

Because these units are difficult to analyze numerically, earthquake simulation testing can be used to assess the seismic performance of suspended ceilings. Testing and evaluation of data (Gilani and Takhirov 2011) have shown that the code-prescribed installation had an acceptable performance. However, the analysis of test data also revealed the shortcomings of the current experimental and evaluation methodology that require revisions.

2.3 Innovation and Evaluation

Ceiling and grid manufacturers continue to innovate and introduce new products that are requested by engineers and architects but are not addressed in the code. Therefore, it is necessary to have the proper means to evaluate such products. Currently no single standard for seismic qualification and evaluation of suspended ceilings exists. To address this shortcoming, the authors have developed an experimental procedure and a performance matrix based on limit states that can be used to evaluate and qualify innovations and to assess quantitatively the efficacy of various code prescribed design and installation requirements. The application of this procedure to an alternate installation was then undertaken as a case study.

3 PROPOSED EVALUATION METHODOLOGY

In the past, suspended ceiling specimens were evaluated using only a comparative method. However, this approach has limitations (for example lack of definition for acceptable performance states and qualification levels) and thus cannot be universally applied. The proposed evaluation methodology intents to address these shortcomings and has three key components: static testing, earthquake simulator testing with enhanced instrumentation, and use of performance levels.

3.1 Static Test Procedure

3.1.1 Overview

ICC-ES AC368 (ICC 2007) provides specific requirements for evaluation of ceiling grid intersections. However, currently neither this document nor any other standards specify acceptance criteria for the main runners in compression. To address this issue, a static test procedure has been developed. Tests are conducted to assess the strength and stiffness of the main runners. In addition, sufficient number of sensors (strain gages) is recommended to correlate the data with applied loading. This in-turn will be used to calibrate the results obtained from shake table tests described in the next section.

The proposed test assembly is indented to represent a portion of ceiling installation. As such, main runners, cross tees, panels, and hanger wires are used and the ceiling system is installed using procedures used in the field. This contrasts with conducting direct compression tests on a selected length (for example 1.2 m) portion of a main runner.

To capture the response of the main runners accurately, it was important to simulate field installation boundary conditions. This included the support condition of main runners and the ceiling system. The U.S. code (ASCE 2010) requires that two adjacent edges of a ceiling be connected to the perimeter members and two other sides are unrestrained. For the static tests, the main runners were attached on the reaction side and free to slide on the loading side. On the sides perpendicular to the main runner longitudinal axis, the cross tees were not attached to the wall angles. This conservative approach allows for symmetry in the tests. To ensure that only the center main runner is loaded, the adjacent main runners are cut approximately 25 mm short. The panels on the loading side are cut short to allow for loading to be applied to the main runners only. To provide fixity and prevent local buckling of the main tee at the loading and reaction points of the main runner, clamping was provided at the two ends.

3.1.2 Test Setup

The 4.9x4.9 m test frame used for shake table testing of suspended ceiling systems can be modified for static tests. The modification is needed to allow application of horizontal load using a loading platform. In this setup a suspended ceiling system was pushed from a loading frame through the opening. The loading frame is a stiff independent unit with a platform plate, installed on the side of the test frame. The test specimens are loaded along the longitudinal axis of the main runners using a ram supported on the loading platform plate using two lines of linear bearings. The linear bearings serve two purposes: the loading platform is restrained to move only along the longitudinal axis of main runners and it restrains all rotations at the loading point which can lead to local buckling. The friction in the linear bearing system was nominally small (approximately 90 N). A photograph of the test setup depicting the modified frame, loading platform, and installed ceiling specimen is shown in Figure 5. and Figure 6. Shows the schematics of the test setup and a sample test specimen.

3.1.3 Required Instrumentation

The proposed minimum instrumentation for the static tests consisted of a load cell, displacement transducers, and strain gages. The load cell and displacement transducer on the loading side were used to estimate the capacity and stiffness of the main runners. The strain gage on the main runner was used to correlate the applied load to the measured stress (load) in the member to ensure that loading was transferred to the main runner. The strain gages on the hanger were used to monitor the incipient buckling.

Figure 5. Static test frame and loading frame

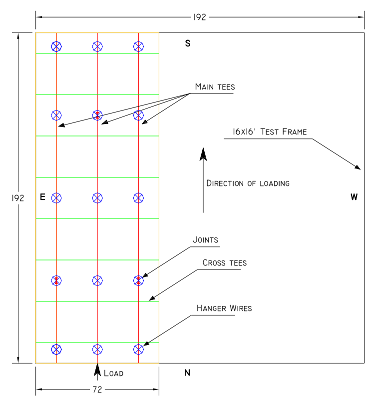

Figure 6. Line drawing of test setup

3.2 Earthquake Simulator Test Procedure

In the U.S., earthquake simulator tests of suspended ceiling systems have been conducted using a 4.9x4.9 m test frame (Badillo-Almaraz et al 2007 and Takhirov 2009); see Figure 7. The frame is intended to mimic a portion of ceiling installed in the field. Previous tests have used instrumentation primarily based on the ICC-ES AC156 (ICC-ES 2010) test protocol. However, for the tests used as part of the proposed evaluation methodology, significantly more channels of data were used. One key addition was the requirement for the use of strain gages placed on key components (see Figure 8.) to allow for experimental measurement of strain (force) in components of the test specimens. Such data were in-turn used to assess the performance of systems and provide comparison with the design values prescribed in the building codes.

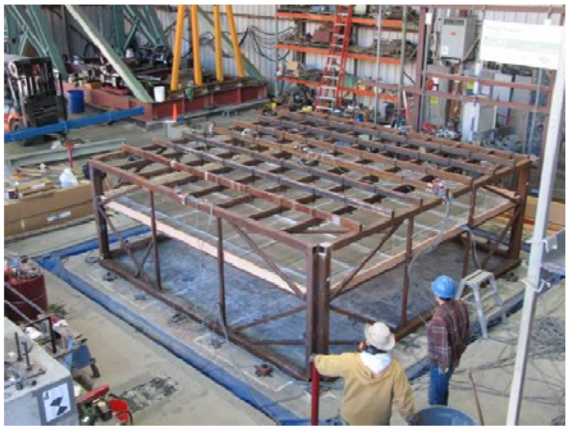

Figure 7. Suspended ceiling system mounted on the test frame prior to experimentation

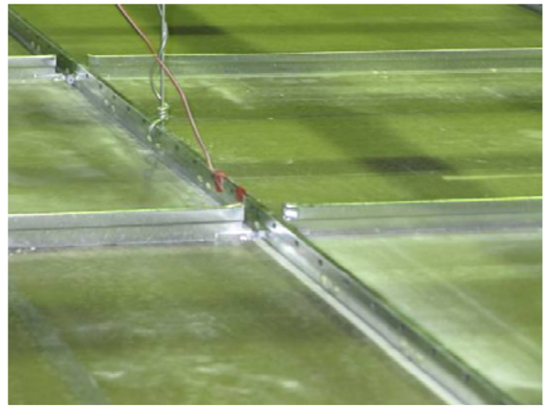

Figure 8. Strain gage placed on the main runner

3.2.1 Required Instrumentation

The proposed instrumentation for the dynamic tests consisted of triaxial accelerometers, displacement transducers, and strain gages. The strain gages were used to measure the force in the main runners and hanger wires and will be used to ensure that the demand on these components is below their capacity. The motion at the floating ends was measured by means of position transducers to account for pounding of grid to support frame if any.

3.2.2 Performance States

ASCE/SEI 41-06 (ASCE 2006) defines three performance levels (based on level of damage) for suspended ceilings; see Table 1. . It is noted for the operational level of a building, it is anticipated that a few panels would fall. At the life safety performance (the 475-year return event which is basis of building code prescribed seismic design), the standard anticipates that many panels would fall. FEMA HAZUS (NEHRP 2010) defines four levels of damage and the expected type of damage as listed in Table 2. For a slight level of damage—what can be expected during a minor earthquake for operational performance of ASCE/SEI 41—the document anticipated that a few panels would fall.

Table 1. Adapted from ASCE/SEI 41-06 performance states for suspended ceilings

	Operational	Immediate Occupancy	Life Safety
Overall damage	Negligible	Minor	Extensive
Panel dislocated	Few	Some	Yes
Panel fallen	No	Few	Many

Table 2. Adapted from FEMA HAZUS damage states for suspended ceilings

	Damage state			
Damaged item	Slight	Moderate	Extensive	Complete
Panel dislocation	Few	Extensive	Extensive	
Panel fallen	Few	Extensive	Many	
Light fixtures		Some		
Grid buckling	None	Some	Extensive	throughout
Member disconnection	None	Some	Many	Extensive
Ceiling system collapse	None	None	Partial	Full or extensive
Repair/replacement	Minor or none	Localized	most of area	Complete

Based on the above references, quantitative performance states are proposed to assist with seismic evaluation of suspended ceilings and to provide uniformity when systems are tested at different facilities. These states are in-turn depended on the following limit states: a) dislodging of panels (expressed in percentage of total number of panels), but remaining on grid, b) fall of a panel, c) perimeter failure such as screw shearing off, d) connection failure such as cross tees disconnecting from main tees, and e) grid failure such as buckling of grid members. Based on these limit states, performance states were developed; see Table 3. The application of these values is restricted to typical commercial buildings and for acoustic in-lay panels. When an enhanced performance is desires, such as for ceilings installed in structures with higher risk factors, or for ceilings with heavy metal the failure of a single panel might constitute unacceptable performance and thus not considered herein.

Table 3. Definition of performance states used in this paper

	Performance state				
Damaged item	I	II	III	IV	V
Panels dislodged	No limit	No limit	No limit	No limit	No limit
Panels fell	None	<5%	5-20%	20-50%	>50%
Grid failure of buckling	None	None	None	1 or 2	>2
Connection failure	None	None	1 or 2	3 to 5	>5
Perimeter failure	None	None	1 or 2	3 to 5	>5
System failure	None	None	<20%	20-50%	>50%

For the purpose of evaluation of specimens, the pass level is set as class I or II: no structural damage, but allowing for dislodging of panels and falling of up to 5% of panels. The 5% limit is selected as representative of what is typically allowed in design and accounts for uncertainties in design and installation, for example, panels not cut to size or hanger wires not being uniformly taut.

4 CASE STUDY: APPLICATION TO GRID MAIN RUNNERS

4.1 Overview

The current edition of the building code in the U.S. [reference here] requires that heavy-duty main runners be used in the grid assemble in regions of high seismicity. In addition, the code also describes alternate means and methods, and allows for the use of shake table testing in lieu of analytical investigation. The grid rating is a measure of applied uniform loading to a 1.2-m simply supported member that causes a deflection of L/360 (3.5 mm). To meet the heavy- or intermediate-duty rating, this load should be greater than 0.8 and 0.5 kN/m2, respectively [is it 16 pounds per linear foot for HD: 16*0.45*9.81/0.3 = 235 N/m?] [reference here]. The procedure developed by the authors and described in Section 3 was applied to a case study. This example focused on the use of intermediate duty main runners in high seismic regions. The two specific systems used in testing and evaluation are referred to as the 11C (heavy-duty) and 11A (intermediate-duty) systems in this paper.

4.2 Connection Splice Capacity

Connection tests of the main runner splices, cross tee intersections, and wire pullout were conducted using the ICC-ES AC368 protocol. As shown in Table 4. , both systems had significantly more reserved capacity beyond the code minimum prescribed value (at least 160%) and that the change from 11C to 11A did not reduce the connection capacity (at most 1%).

Table 4. Connection capacity (kN) from laboratory tests

Test	Main runner splice		Intersection		Wire pullout
	Tension	Compression*	Tension	Compression	Tension
11C	1.26	>2.22	1.76	1.30	2.03
11A	1.53	>2.22	1.76	1.30	2.02
Code minimum	0.80	0.80	0.80	0.80	0.89

*The load cell used in testing had a capacity of 2.22 kN. During the tests, the capacity of the load cell was reached without failure. Thus teh connection capacity is shown as >2.22 kN.

4.3 Main Runner Compression Tests

4.3.1 Experimental Program

Static testing of the main runners 11C and 11A were conducted using the protocol developed by the authors and described in Section 3. To ensure repeatability in results, three samples for each of the two specimens were tested. All systems experienced global out-of-plane buckling as their failure mode; see Figure 9. and Figure 10. .

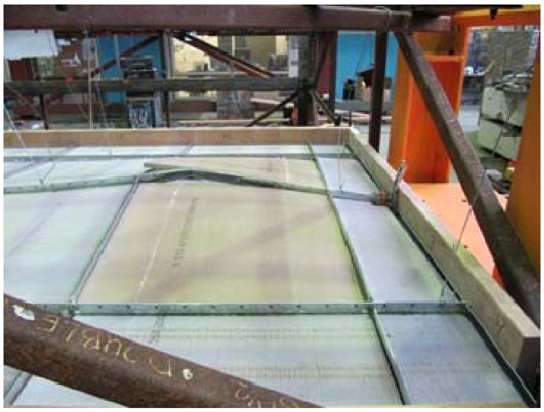

Figure 9. Global buckling, 11C

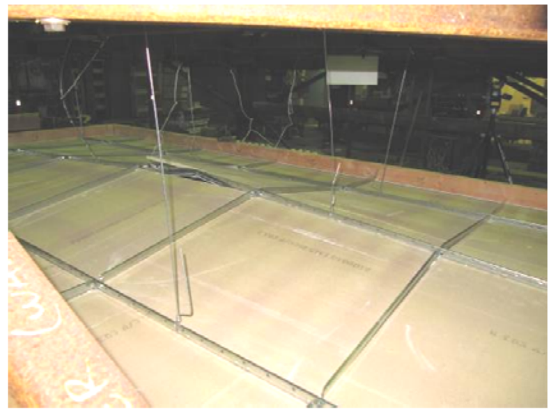

Figure 10. Global buckling, 11A

4.3.2 Experimental data

Figure 11. and Figure 12. present the force-displacement plots for specimens 11C and 11A, respectively (three samples per plot). The plots are shown up to the point of incipient buckling. The data for the three test samples are shown as solid line, and the dashed lines correspond to the idealized linear approximation to the plots used to compute the axial stiffness of the test specimens.

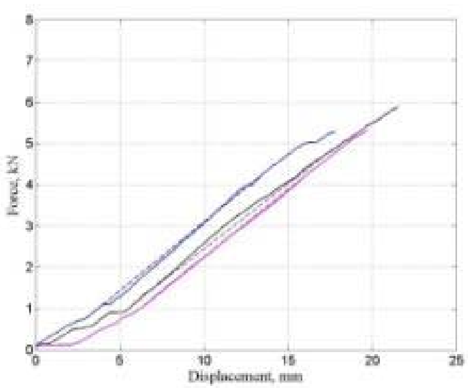

Figure 11. Force-deflection relation, 11C

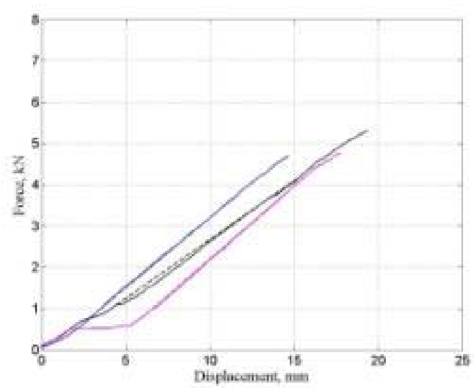

Figure 12. Force-deflection relation, 11A

Table 5. summarizes the experimental data. For each set of three tests, the data closely track and produce similar axial strength and stiffness with coefficient of variation (COV) of 11% or less. The reduction in axial strength and stiffness is approximately 11% and 2% between 11C and 11A. It is further noted that the main runners for both systems have significantly larger (over 200%) axial capacity that the spices in line with these members (see Table 4.); thus, the main runners are not the weakest element along the load path resisting lateral loading.

Table 5. Experimental results from static tests

Property	Compression capacity, kN			Axial stiffness, kN/m		
	Average	Std Dev.	COV	Average	Std Dev.	COV
11C	5.30	0.33	6%	332	15	4%
11A	4.70	0.33	7%	326	35	11%

4.4 Earthquake simulator tests

4.4.1 Observations

Table 6. summarizes the findings for the specimen 11A and 11C. For 11C, at test with S_s of 2.00 g, two panels fell, followed by four more panels falling at test with S_s of 2.25 g. At test with S_s of 2.50 g, large number of panels fell, followed by partial collapse of the grid. For 11A, at tests with S_s of 3.00 g, large number of panels fell, followed by extensive collapse of the grid. For both specimens, dislocation of the cross tee-to main runner connections precipitated the system failure

Table 6. Global performance of Specimen 11A and 11C

	11C						11A	
S_s , g	1.75	2.00	2.25	2.50	2.75	3.00	1.75 through 2.75	3.00
Panels dislodged	--	--	--	Y			--	Y
Panels fell	--	2	4	Y			--	Y
Grid buckling	--	--	--	--			--	--
Connection failure	--	--	--	Y			--	Y
Perimeter failure	--	--	--	--			--	--
System failure	--	--	--	Partial			--	Extensive
Performance level	I	II	III	IV			I	V

4.4.2 Spectral enveloping

Figure 13. and Figure 14. present the required response spectrum (RRS) for horizontal and vertical directions, and the target response spectrum (TRS) for X-, Y-, and Z- directions computed from experimentally measured earthquake simulator internal accelerometers for specimens 11C and 11A, respectively. The data is shown for a test with S_s spectral acceleration of 2.00g, the last test for which both systems met performance level of I or II. The resonance search data indicated that the systems had horizontal (X- and Y-) frequencies of approximately 18 Hz and vertical (Z-) frequency of 8.5 Hz. For both specimens, the TRS enveloped the RRS in all three directions past the filtering cutoff frequency which was significantly lower that the systems' resonant frequencies.

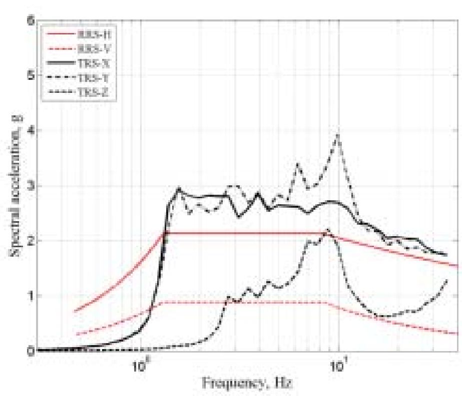

Figure 13. Spectral enveloping, S_S=2.00 g, 11C

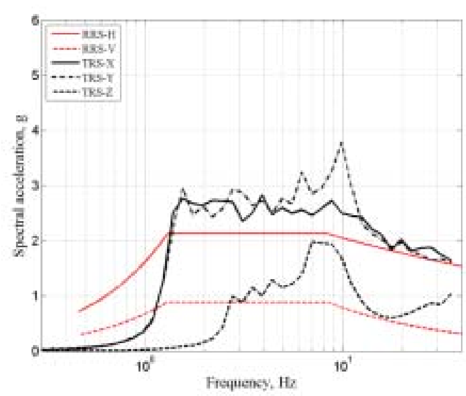

Figure 14. Spectral enveloping, S_S=2.00 g, 11A

4.4.3 *Building code evaluation*

The response of Specimen 11A was further evaluated using the building code provisions. Such evaluation was not necessary for Specimen 11C because 11C used main runners that met the building code requirements and thus can be used in regions of high seismicity. For Specimen 11A, the test with spectral acceleration of 2.75 g, the last test prior to failure was used for further evaluation.

Figure 15. presents the motion of the grid relative to the test frame for the displacement transducers that monitor the grid response at the floating sides. Also shown in the figure is the dashed line representing the code prescribed clearance of 19 mm on the floating sides. Since the grid motion is significantly below this threshold, no impact of the 11A system at the floating sides is expected.

Figure 15. presents the forces measured in the main runners instrumented for the tests. The measured forces were computed as the product of the main tee area, steel Young modulus, and the strains recorded from strain gage data. Also shown in the figure are the dashed lines representing the tensile and compressive capacities of the main tee. The tensile capacity is computed using the yield strength of main tee obtained from laboratory tests. The compression capacity accounts for buckling and is based on the data measured as described in Table 5. Since the measured main runner forces are well below the capacity, yielding, or buckling of the main runner is not expected.

4.4.4 *Seismic qualification for 11A*

Specimen 11A was evaluated by the procedure developed in Section 3. The specimen underwent testing with spectral accelerations including the test equal to 2.75g. The TRS enveloped RRS beyond the filtering limit which was significantly lower than all resonant frequencies of the system, and the measured data were below the code prescribed values and the capacity of the main runner. Thus, 11A was qualified by experimentation to S_S of 2.75 g. Specimen 11A was qualified to a level higher than that of Specimen 11C. Because 11C is qualified for use according to the U.S. building code provisions, 11A is therefore qualified for use in place of 11C.

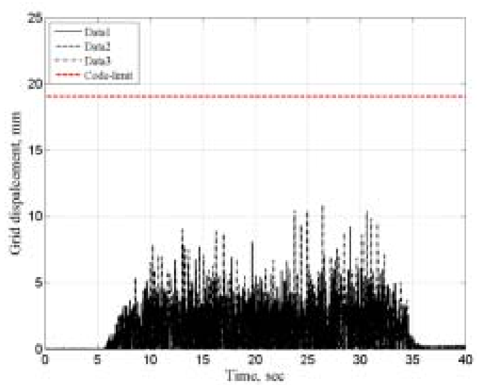

Figure 15. Figure 15 Edge displacement, S_S=2.75g,

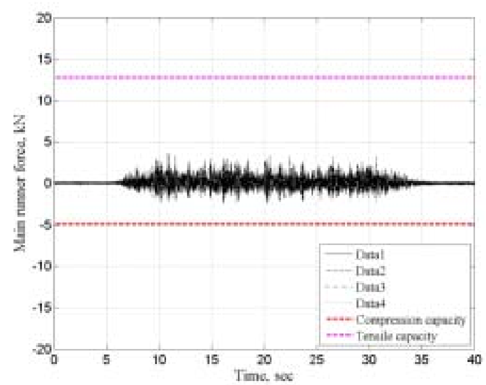

Figure 16. Figure 16 Main runner force, S_S=2.75g,

CONCLUSIONS

A new experimental procedure has been developed and proposed to assist in evaluation of suspended ceilings and alternate installation. This procedure includes both static and dynamic testing of representative systems installed to simulate field conditions. Extensive array of instrumentation, including strain gages to monitor the load in members, form an integral part of the new procedure. In addition, performance states have been developed to assist with and quantify response. As a case study, this procedure was applied to evaluation of systems of intermediate-duty main runners as a substitute to building code mandated heavy-duty members.

- The proposed evaluation procedure provides a rigorous approach than can be implemented for a wide range of alternate installation
- The development of the performance states forms a critical component of the seismic qualification document proposed for future development
- The measurement of the force in the system components such as the main runners and hanger wires provide data that is used to determine the margin of safety against component capacity as a function of input seismic intensity
- Experimental data showed that the substitution of intermediate- for heavy-duty main runners did not adversely affect the seismic response of the system

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