12th Canadian Conference on Earthquake Engineering
12ème Conférence canadienne du génie parasismique
June 17-20, 2019 / 17-20 juin 2019
Château Frontenac, Québec, QC.
CCEE 2019

Performance of Suspended Ceilings during Seismic Events

Geoff Davidson[1], David Lau[2], Jeffrey Erochko[2], Kazuhiko Kasai[3]

[1] Master's Student, Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.

[2] Professor, Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.

[3] Professor, Urban Disaster Prevention Research Core, Tokyo Institute of Technology, Yokohama, Japan.

ABSTRACT

Suspended ceilings are often found in commercial buildings as part of the building contents. They are classified as non-structural or operational and functional components in a building because they provide important services or functions to the occupants of the facilities. Non-structural components typically are not designed as part of the primary seismic force resisting system; however, these components have an impact on the safety and seismic performance of the building because of their vulnerability and their contribution to the mass, stiffness, and interaction with the main structural system during earthquakes. Traditionally, the design of non-structural components, including suspended ceilings, does not consider seismic loads and the interaction effects with the supporting structure. The damage and disruption caused by failure of non-structural components can potentially represent a significant portion of the total economic loss in an earthquake. The performance of suspended ceilings, e.g. in hospitals and schools designated as post-disaster shelters, can be critical to emergency response, resilience and recovery during and after earthquakes. This paper reviews the state of the art of suspended ceilings performance during an earthquake. The paper investigates the development of both experimental and numerical research on suspended ceiling seismic performance. This paper also presents a current international joint collaborative research project that is being carried out by researchers in Japan, China and Canada on the seismic performance of suspended ceilings in supertall buildings. This includes both shake table testing and computer simulations program to evaluate the behaviour and performance of suspended ceilings subjected to the floor input motions of tall building structures. The aim of the research is to better understand the response and failure mechanisms of suspended ceilings, to improve their performance and design, and ultimately to develop a standardized seismic design methodology for suspended ceilings in tall buildings.

Keywords: suspended ceiling, international research project

INTRODUCTION

Suspended ceilings are often found in commercial buildings as part of the building contents. Suspended ceilings are classified as *non-structural*, or *operational and functional* components in a building that provide important services to the building occupants. Suspended Ceilings are made up of four main components; hanger rods, main beam, cross beam and ceiling tiles. The rods hang from the floor slab above, these rods hold up the main beams and cross beams. The ceiling tiles are simply placed on top of the beams and are not fixed in place. Non-structural components are not typically designed as part of the primary structural resistant system; however, these components do have an impact on the seismic response of the building through the contribution and distribution of mass, stiffness, and interaction of the non-structural components with the main structural system. In collaboration with Japan and China, Carleton University will be testing suspended ceilings using their multiple mobile shake tables. This will allow for the observation of the seismic performance of the system when subjected to different input excitations. This paper provides a review of design and performance issues associated with suspended ceilings and briefly describes the plans of the on-going collaborative research project.

Background

During a seismic event, structures are subjected to high levels of ground acceleration. Current structures are designed to withstand these events, however in some buildings structural and non-structural systems and components can be severely damaged. A study conducted in 2011 by Dhakal et al [1], observed the damage produced by the 6.2 magnitude earthquake in Christchurch, New Zealand. The findings have shown that some tall buildings built according to older design codes suffered both structural and non-structural damage whereas, even in shorter buildings where the structural components were intact, the non-structural components such as suspended ceilings were severely damaged [1].

Japan has witnessed many earthquakes in its past, including the Tohoku earthquake that took place on March 11, 2011. This earthquake was a magnitude 9.0 with many foreshocks and aftershocks reaching above M7.0 and caused a devastating tsunami. Both events injured and killed thousands of people. Along with the impact on human life, these events also caused billions of dollars in damages. Some buildings not designed to current codes collapsed during the earthquake but many buildings that were designed to modern standards still suffered damage to their dampening systems and non-structural elements [2]. Another more recent earthquake in Japan took place in 2016. With a magnitude of 7.0, the Kumamoto Earthquake caused some deaths and collapses of structures. Of particular interest though, the failure of non-structural elements in structures caused huge social-economic losses and caused injuries that increased the burden on emergency resources. As a result of the earthquake, many factories had to shut down until repairs were done to make the structures safe again. Most of these repairs consisted only of failed non-structural elements. The damage to a major sensor factory and impact on production due to repair down-time cost the owner of the factory an estimated 1 Billion dollars. Figure 1 below shows the failure of non-structural elements in the plant.

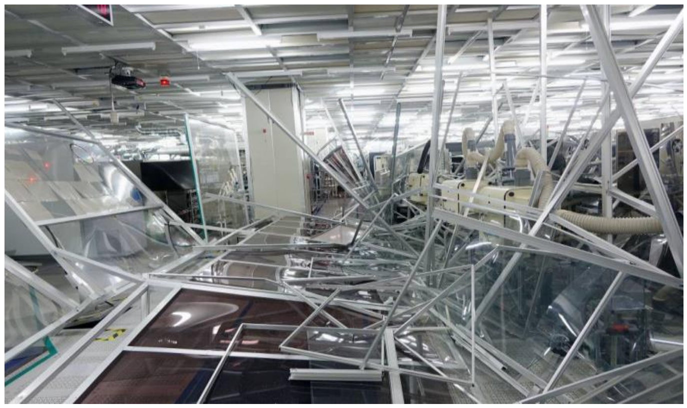

Figure 1. Non-structural Element Failure Inside Sony's Sensory Plant [3]

On November 30, 2018 a 7.0 magnitude earthquake hit South Central Alaska. There were multiple aftershocks that took place following the earthquake, with some reported magnitudes above 5.0. This recent seismic event has further shown the importance of the performance of non-structural elements. Schools in South Central Alaska suffered significant damage, mostly due to the failure of their suspended ceilings. Although there were no reported injuries, many of the schools had to be closed for a week. Two schools were damaged so severally that it is unlikely the schools reopen this school year and possibly the next. The figures below show the collapse of suspended ceilings located in the classrooms of Hanshew and Houston Middle School, Figure 2 and 3 respectively [4].

Figure 2. Classroom of Hanshew Middle School [4]

Figure 3. Classroom of Houston Middle School [4]

Failure or poor performance of non-structural elements in earthquakes can lead to huge socio-economic losses after an earthquake. Non-structural elements make up approximately 60% of the costs of constructing a building dependent on type of structure (e.g. hospitals contain a much higher percentage of non-structural elements). Depending on the structure failure of these elements also increases the recovery time required for a building to be functional post-earthquake, creating a large additional expense for the owner. It is observed in a previous study that nonstructural systems account for an estimated 78% of the total annual earthquake loss in the United States [5]. In Figure 4 below, the repair cost to a building and all its components are compared after an earthquake. As seen, the majority of repair costs are associated with non-structural elements [6].

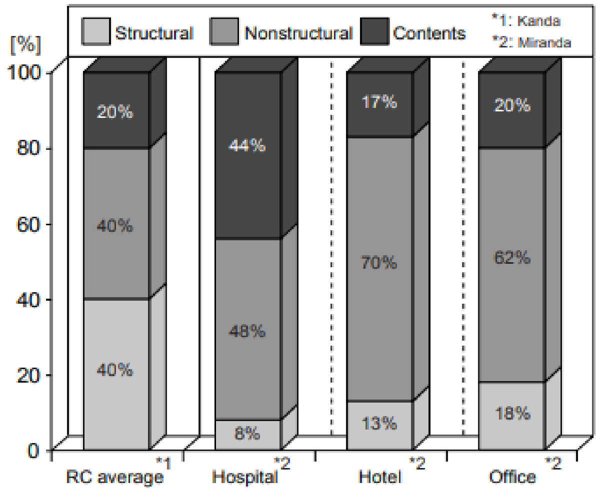

Figure 4. Repair Cost of Building Components after Seismic Event [6]

During a seismic event, failure of non-structural elements can pose a threat to health and safety. In terms of the non-structural elements focused on in this paper, failure of suspended ceiling components pose a higher risk to human life as these elements are positioned above head height and therefore become dangerous when falling. Fallen components of suspended ceilings can also create a tripping hazard during evacuation and, in some cases, may completely block exits. Failure of these elements also leads to an occupant perception that the building is unsafe and may collapse. The occupant's instinct is to then evacuate the building which causes mass congestion and panic in the streets, reducing the ability of first responders to travel and address emergencies. It may lead to better outcomes if the occupants feel safe to stay inside of buildings. An example of this behavior can be seen in Figure 5; this image shows the panic and congestion in the streets of Mexico after an earthquake hit in 2017.

Figure 5. Mexico Street after 2017 Earthquake [7]

Experimental Studies

Due to the non-structural title of suspended ceilings, there has been insufficient testing on their seismic performance. Experimental research on the ceiling system and their components has slowly progressed from the 1980's. There have been studies investigating the failure mechanisms of the system, the effects of size and boundary conditions and the capacities of the individual components. However, due to the nature of these suspended ceilings and the amount of possible variability in the system this research has been insufficient.

In 1983, ANCO Engineers Inc. [8] conducted a shake table test on a suspended ceiling. The size of their system was 3.6m x 8.5m made up of the typical 0.6m x 1.2m ceiling panels. They were trying to examine the effects of various restraints used in a system and were also examining the interaction of the system with light fixtures. The results from the test indicated that splay wires and compression struts had no impact on the dynamic response of the ceiling. They also concluded that safety lines were an easy and feasible method to support drop in light fixtures [8].

In 1984, Granneman et al [9], performed shake table tests to research the impact of partitions attached to suspended ceilings. The system was 3.6m x 4.8m with typical 0.6m x 1.2m ceiling panels. They used a uniaxial sinusoidal input with a peak acceleration of 2.2g. The three main types of damage that occurred in the system were separation of cross tees from main tees, splice damage in the main tees, and stretching of splay wires [9]. The ceiling system was built according to the code at the time which is now over 30 years ago. Also, as seen in later tests, damage is more severe when subjected to multi-directional components of the input excitation.

In 2000, Yao et al [1], performed a shake table analysis on a 2m x 4m system. The results of the test were used to develop a numerical model. Three conclusions were made from the results. First, splay wires did not improve seismic performance as also seen in previous studies [ANCO, 1983]. Secondly adequate edge connectivity can increase the capacity of the system during an earthquake. Finally, transverse supports increased the seismic capacity in large ceilings [1]. Like previous studies only a small ceiling system was tested under a uniaxial input.

In 2006, three studies had been conducted, two at the University of Buffalo and one in Japan. Badillo-Almaraz et al [10], performed shake table tests of ceiling assemblies at the University of Buffalo. These tests investigated a variety of perimeter and panel configurations. The results showed that connections in between members were more flexible than the member itself. This characteristic leads to the dislodging of panels. When hold down clips were implemented on the system to keep panels from dislodging, a failure in the grid members had a greater chance of developing. Another conclusion is that the size of the panel greatly influenced how many panels dislodged [10]. The other study at the University of Buffalo was performed by Lavan et al [11]. The purpose of these tests was to set up the test frame and observe the common failure mechanisms of the system along with their influence on the structure. The results indicated that for a 4.9m x 4.9m ceiling system the vertical fundamental frequency of the frame was reduced by approximately 2Hz from its pre-ceiling frequency of 7.5Hz. The ceiling had a negligible effect of the fundamental frequency in the horizontal direction of the frame. In the tests conducted, panels only dislodged near the middle of the system. This result was not consistent with the damage observed in past earthquakes where ceiling damage occurred along perimeter. As mentioned by the researchers, this variance could be due to ceiling system being larger in the field. Also, further investigation is required on the vertical flexibility in the roof and the selection of $z/h = 1$. The variable z/h represents the ratio of the component height compared to the ceiling height. Due to the system being connected to the ceiling the value of $z/h = 1$, however this might not accurately represent the input forces due to the locations of the boundary conditions of the suspended ceiling. These factors may have led to the large amplification of the vertical accelerations in the roof of the testing frame. Both these tests were conducted with multi-directional input excitations with a max spectral acceleration of 3g [11]. Maseki et al [1] conducted shake table tests on the Japanese Suspended Ceilings. The specimen was 4.5m x 4.5m and the research was directed towards comparing the conventional ceiling design with a newer proposed design. There are a couple variations with the components used in Japan's Ceilings as compared to Canada's Ceilings, one of the variations is the use of a steel angle as a lateral brace to replace the Canadian compression post and splay wires. The findings of the study were that the proposed design performs much better than the conventional design [1].

In 2010, Paganotti et al [12], conducted experimental research at the University of Canterbury to produce fragility curves for the components of the ceiling system. In their studies, grid member components were tested in both compression and tension. The fragility curves were derived by the failure loads. These results were used to create a simple model to produce a fragility curve of the whole system [12].

In 2011, Dhakal et al [1] published a study that investigated the damage to suspended ceilings from the 2011 Christchurch earthquake. The major findings of the investigation have shown that tall buildings not designed to the current code experienced both structural and non-structural damage. However, even in low rise buildings where the structural systems remained intact, the non-structural systems were severely damaged. The majority of suspended ceilings installed do not typically use panel hold downs, as such it was found that vertical accelerations above 1.0g will cause the panels to lift from their supporting members and possibly dislodge. That being said, it was observed that horizontal accelerations cause more damage than vertical accelerations. There were three main types of failure mechanisms that were observed in the suspended ceiling systems. One mode of failure in the system is the separation of members from the perimeter angles, this was a result of insufficient capacity in the rivets. This mode caused damage in the perimeter of the ceiling sometimes leaving the middle section intact. The second common type of failure occurred due to additional forces caused by movement of ceiling services.

These services include HVAC and sprinklers. The issue with HVAC is that sometimes due to the layout of the system, the suspended ceiling must be hung directly from the ventilation ducts which will not move in unison with the rest of the ceiling. Sprinkler heads are usually placed through a ceiling panel and it was observed that with an insufficient gap the rigid sprinkler would put extra force of the moving panels. Finally, from the observed results after the earthquake, it was shown that the typical failures in the grid components were identical to that observed during previous experimental studies. These failures included separation of cross-tee from the main-tee, failure of the main-tee splices and buckling of main-tees members. This research concluded that suspended ceilings create a "Domino effect" upon failure of a single component [1]. This effect means that after the failure of a single grid component the damage would be progressive and potentially may lead to collapse of the entire system. This is important in understanding the overall ceiling performance in previous and current research. Experiments may only produce results that indicate single component failure due to the optimization of installation in the labs compared to that in the field. From a systems performance characteristics, a single component failure can be an indication that the entire ceiling system in today's buildings may be vulnerable to collapse during earthquakes, especially over mildly long duration shaking in supertall buildings.

In 2012, Reinhorn et al [13], conducted shake table testing of a large area ceiling measuring 6.1m x 16.3m. The goal of this research was to identify failure mechanisms and investigate effects of various systems. The results from the test concluded that ceiling systems were more vulnerable to three-directional inputs compared to one or two directional. Also, the weight and size of the system directly impacted the probability of system failure. Finally, lateral restraints improved seismic performance as also shown by tests conducted by Yao et al [Yao, 2000] [13]. Another study performed in 2012 by Soroushian et al [14], inputted two and three-directional excitations on a five-storey steel frame with both base-isolated and base-fixed configurations. This research aimed to investigate more into the seismic performance of sprinkler systems, however suspended ceilings were also considered in this experiment. The results of this experiment followed that of previous tests, the findings have shown that lateral bracing did not improve seismic performance and sprinkler heads caused considerable damage to ceiling panels [14].

In 2016, static tests on ceiling components were performed in New Zealand by Soroushian et al [15]. These tests were performed on both the grid members and their connections. The fragility curves from these tests have shown that in both tension and compression, cross-tee connections are the weakest part of the ceiling system. It was also shown that all components except for splices were weaker in compression compared to tension. The conclusion of the test was connections would fail before the member reached its capacity causing failure of the system before design loads of the members can be reached. A limitation as mentioned in the study, was that the standardized code in New Zealand had no specific standard in terms of compression testing and no methods are provided to test connections [15]. A study was also performed in China by Wang et al [16], to reproduce the damage observed during the Lushan Earthquake with shake table testing. The set up consisted of a single storey reinforced concrete frame with a 3.1m x 3.7m suspended ceiling. The input to the shake table was a three-dimensional ground motion record of the 2008 Wenchuan earthquake, with a peak ground acceleration horizontally of 1.10g. These tests did produce similar damage to that observed from the Lushan Earthquake, however there were some discrepancies with previous shake table studies that resulted in lower fragility curves. The reasons behind the discrepancy is due to the scale of the specimen and the measured roof spectrum significantly varying from the required roof spectrum outlined in AC156 [16].

Numerical Models

There have been very few numerical models created for suspended ceiling systems, for various reasons such as the difficulty in modelling the separate components and accurately representing the total collapse of the system. Starting in 2012, Soroushian et al [14] created an numerical model using SAP2000. This model used elastic elements to represent the main-tees and cross-tees. The panels were modeled as an x-shape with a lumped transitional-rotational mass at the center. The hanger and sway wires were modeled using a hook-link with a determined stiffness to only resist tensile loads. The compression posts were represented as channel frames with the measured cross section. The splice in members were modelled with Linear Links. The gaps in panels on the tees and free boundary conditions were represented by a horizontal T/C Friction Isolator Link. Once the model was created the researchers performed a sensitivity analysis to correct friction values, tile weight and supporting deck frequency. This model was able to produce fragility curves to show the seismic performance of an entire suspended ceiling system. The limitations of the model included the exclusion of the non-linear characteristics of the ceiling components. The other limitation as mentioned in the study was the inability to model the progressive collapse of the system [14].

In 2012, Reinhorn et al [13] created an numerical model to verify their experimental results. The suspended ceiling was modeled as a unidirectional simplified system. This model was constructed as multiple pendulums in series with springs representing splices and springs representing the pop rivets. The researchers mentioned the possibility of using slip-lock springs to represent the joints. This could be done using a hysteretic spring in series with a "Gaussian Pinching Model", however the researchers did not consider non-linearity and therefore did not use this method [13].

In 2015, Soroushian et al [16] performed testing to evaluate the non-linear axial behavior of joints in order to create a detailed numerical model to represent this behavior. The joints were tested in both monotonic and reverse cyclic tests in order to produce fragility curves and to verify the numerical results. All fifteen cross-tee latches were tested and the different failure mechanisms in the joint were noted in the study. The researcher mentioned the limitations of the experiment which might have affected the results. Such limitations include the absence of ceiling panels, the boundary conditions and the member alignments. Opensees was the analysis software used to model the hysteretic behavior of the joints. The was done by assigning a uniaxial material "Pinching4" to a zero-length element. A sensitivity analysis was performed in order to determine all 39 parameters. This analysis was limited to keeping the maximum cumulative hysteresis energy within 10% of the experimental results. During the study it was found that 23 parameters were independent and could be set to a constant value. For the simplicity of adding this element into future system models, a generic model was produced in order to avoid accounting for all the small discrepancies in each test [16].

Both Jiang et al. (2015) and Soroushian et al. (2016) have developed direct spectra-to-spectra methods for estimating the response of non-structural components in nuclear power structures. These methods are very complex, so Kasai et al. (2016) developed a more efficient simplified procedure for predicting maximum response of non-structural components based on the vibration of the building structures excitation input. This model considers both the effects of the frequency content as well as the ground motion duration. This method does not require time-history analysis, just mode shapes, modal frequencies, damping ratios and ground response spectra.

Current Canadian Design Codes

Currently, Canada's design standards for non-structural components is very limited as there has been an insufficient amount of research. New Zealand follows a similar design approach of NBCC 2015. However, as mentioned in the study by Pourali et al [17], New Zealand's design code mainly requires the design for serviceability limit states. There are other such standards that are used to specifically design and install suspended ceilings such as FEMA, CISCA, and ASTM C635 [17]. Manufacturers of ceilings provide their own design and installation standards that meet at least the minimum requirements as specified by the code [17]. The design equations of NBCC 2015 [19] for non-structural components are summarized below. Suspended Ceilings systems are designed to the seismic design loads determined using Eq (1):

$$V_p=0.3*I_{e*}F_a*S_a\,(0.2)*S_p*W_p \tag{1}$$

Where S_p is the component response factor. This factor is supposed to account for some of the effects a suspended ceiling encounters during an earthquake based on its natural dynamic properties. This factor is calculated using Eq (2):

$$S_p=C_p*A_r*A_x/R_p \qquad \text{limits } 0.7<=Sp<=4. \tag{2}$$

Where C_p is based on the associated risk during failure of the component. For a suspended ceiling system this factor will be 1.0. The variable A_r is the dynamic amplification, based on the ratio of the natural period of the component and the fundamental period of the building. A_x is given by Eq (3):

$$A_x=(1+2h_x/h_n) \tag{3}$$

This formula considers the amplification of the base acceleration to the acceleration at which the component is attached to the structure. Finally, R_p accounts for any energy dissipation in the connection of the component to the structure. Along with these formulas to determine the seismic design force, there are other codes in place to prevent impact between the structure and hanging components. The Canadian building code states that if the components can swing 45deg without impacting a structure then they can be designed as a pendulum system; otherwise sway braces can be used and designed to the required loads to restrain the sway movement of the components [18].

While these simplified equations provide an estimate of the load on a suspended ceiling system, they do not account for many common conditions including the effects of overall size, layout of attachment points, different boundary conditions, or changing stiffness due to dislodgment of ceiling tiles.

Current Research Project

Carleton University is collaborating with Tongji University and Tokyo Institute of Technology on this ILEE (International Joint Research Project of Earthquake Engineering) research project. The research program is being led by PI Prof. Kazuhiko Kasai of Tokyo Tech. and Co-PI Prof. Huanjun Jiang of Tongji University. Tongji University will be using two 30 ton shake tables to test full size suspended ceilings systems. These tests will involve different boundary conditions and observe the effect of seismic clips and dampeners. These tests will use ground motions recorded from the 2011 Tohoku and 2008 Wenchuan earthquakes that occurred in Japan and China respectively. The inputs will consider 10 to 100 storey buildings with a probability of exceedance ranging from 50, 10 and 2% in 50 years. Tokyo Institute of technology will be using Motoyui's (2014,2017) detailed finite element analysis to simulate the time-history responses of the suspended ceilings.

Carleton University will be using multiple mobile shake tables to test suspended ceilings systems. These tests will provide supplemental results for the large scale shake table testing at Tongji University. Using the mobile shake tables will allow Carleton to observe the performance of non-structural elements when subjected to different layouts with partitions and varying input excitements based on attachment locations. These tests will allow us to determine whether the current design standards are acceptable in all circumstances, and to determine if the code needs to account for the effects of multiple input excitations, boundary conditions, and varying support configurations

CONCLUSIONS

In conclusion, there has been research into testing individual components of a suspended ceilings and in creating numerical models. However, this research has been insufficient as there are many conditions that vary with suspended ceilings such as, supports, boundary conditions, size and layout. In order to improve the design standard all these factors will need to be considered and tested both in a laboratory and numerically. Previous Research has led to the following conclusions:

- Sway wires, compression posts, and lateral restraints do not improve the seismic performance of the ceiling system.
- All members except for main-tee splices are weaker in compression compared to tension. The cross-tee connection is the weakest part of the ceiling system.
- Common failure mechanisms include, cross-tee connection separation, main-tee splice failure and separation of members from perimeter angles due to failure of rivets.
- Member connections fail before member reaches its design strength.
- Grid component failure would likely lead to progressive failure of the entire suspended ceiling.
- Heavier and larger ceilings were more vulnerable to system failure. The use of panel hold-down clips subjected the system to fail in the grid members and not by panel dislodgement.
- Numerical models were produced to model the entire system behavior however, they did not consider non-linear behavior and were not able to capture the progressive ceiling failure. This is due to change in stiffness of the system upon failure of members or boundary supports.
- Member joints can be modeled using a generic hysteresis spring however, this is only a single component of the system and was limited to testing with the absence of a ceiling panel and variation in member alignment and boundary conditions

Even with the current improvement on the research of suspended ceiling systems, these systems are still currently failing as seen in the 2018 Alaska Earthquake. The aim of this joint research program is to observe the seismic performance of suspended ceilings tested both in a laboratory and numerically. The research will hopefully lead to improved design codes and standards for suspended ceilings.

ACKNOWLEDGMENTS

The Carleton University project is supported by the Canada Foundation for Innovations and the Natural Sciences and Engineering Research Council of Canada, as part of the international collaborative research project on suspended non-structural systems between Japan, China and Canada. The international collaborative research project is led by K. Kasai and H. Jiang sponsored by the International Joint Research Laboratory on Earthquake Engineering (ILEE). These supports are acknowledged.

REFERENCES

[1] Dhakal RP, MacRae GA and Hogg K (2011). "Performance of Ceilings in the February 2011 Christchurch Earthquake". Bulletin of the New Zealand Society for Earthquake Engineering, 44(4): 379-389.

[2] Norio, O., Ye, T., Kajitani, Y., Shi, P., & Tatano, H. (2011). The 2011 eastern Japan great earthquake disaster: Overview and comments. *International Journal of Disaster Risk Science*,*2*(1), 34-42. doi:10.1007/s13753-011-0004-9

[3] Nakamura, Y., "A Year After Kyushu Quakes, Sony's Sensor Business Expands to AR, Robots." *Japan Times.* https://www.japantimes.co.jp/news/2017/04/14/business/corporate-business/year-kyushu-quakes-sonys-sensor-business-expands-ar-robots

[4] "Photos from inside Earthquake-Damaged Schools in Southcentral Alaska." *Anchorage Daily News*, Anchorage Daily News,www.adn.com/alaska-news/2018/12/04/eerie-photos-from-inside-earthquake-damaged-schools-in-southcentral-alaska/.

[5] Soroushian, S., Maragakis, M., & Jenkins, C. (2016). "Axial Capacity Evaluation for Typical Suspended Ceiling Joints". *Earthquake Spectra*,*32*(1), 547-565. doi:10.1193/123113eqs301m

[6] Takahashi, N., Shiohara, H. "Life Cycle Economic Loss due to Seismic Damage of Non-Structural Elements." 13th World Conference on Earthquake Engineering. Vancouver, B.C., Canada. August 1-6, 2004 Paper No. 203

[7] "People Flee to Streets after Mexico Earthquake." *ABC News*, 19 Sept. 2017, https://www.abc.net.au/news/2017-09-20/people-flee-to-streets-after-mexico-earthquake/8962660

[8] ANCO Engineers Inc. (1983). "Seismic Hazard Assessment of Non-Structural Ceiling Components: Phase I". Report No. 1249.12, Grant 8114155, National Science Foundation, Culver City, California, USA.

[9] Rihal SS and Granneman G (1984). "Experimental Investigation of the Dynamic Behavior of Building Partitions and Suspended Ceilings during Earthquakes". Report No. ARCE R-84-1, California Polytechnic State University, San Luis Obispo, California, USA

[10] Badillo-Almaraz H, Whittaker AS and Reinhorn AM (2007). "Seismic Fragility of Suspended Ceiling Systems". Earthquake Spectra, 23(1): 21–40.

[11] Gilani, A., Reihorn, A., Ingratta, T., Glasgow, B., & Lavan, O. (2008). Earthquake Simulator Testing and Evaluation of Suspended Ceilings: Standard and Alternate Perimeter Installations. *Structures Congress 2008*. doi:10.1061/41016(314)222

[12] Paganotti G, MacRae GA and Dhakal RP (2011). "Development of Typical NZ ceiling System Seismic Fragilities". Proceedings of the Ninth Pacific Conference on Earthquake Engineering, Building an Earthquake Resilient Society, Auckland, NZ, 14-16 April 2011.

[13] Ryu, K. P., Reinhorn, A. M., and Filiatrault, A., (2012). "Full scale dynamic testing of large area suspended", 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, Portugal 24–28 September 2012.

[14] Soroushian, S.; Ryan, K.L.; Maragakis, M.; Wieser, J.; Sasaki, T.; Sato, E.; Okazaki, T.; Tedesco, L., Zaghi, A.E.; Mosqueda, G.; Alvarez, D. (2012), "NEES/E-Defense tests: seismic performance of ceiling/sprinkler piping nonstructural systems in base isolated and fixed base building," 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, Portugal 24–28 September 2012.

[15] Soroushian, S., Rahmanishamsi, E., Ryu, K., Maragakis, M., and Reinhorn, A. (*2016*) Experimental Fragility Analysis of Suspension Ceiling Systems. Earthquake Spectra, 32(2), 881-908.

[16] Wang, D., Dai, J., Qu, Z., & Ning, X. (2016). "Shake table tests of suspended ceilings to simulate the observed damage in the M s7.0 Lushan earthquake, China." *Earthquake Engineering and Engineering Vibration*,*15*(2), 239-249. doi:10.1007/s11803-016-0319-z

[17] Pourali. A, MacRae GA and Dhakal RP (2014). "Seismic performance of suspended ceilings: Critical review of current design practice". NZSEE Annual Conference, Auckland, NZ, 2014.

[18] *User's guide* – NBC 2015, structural commentaries (Part 4) (2015). Ottawa. Canadian Commission on Building and Fire Codes, National Research Council of Canada