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Development of New Seismic Testing Program for Suspended Ceilings

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ABSTRACT

Damage to suspended ceilings is one of the most observed types of earthquake damage to non-structural components. Despite the extensive damage observed in past earthquakes, there is still a lack of thorough investigation on understanding the behaviour and failure mechanisms of suspended ceilings during earthquakes. This paper describes the development of a new testing program to investigate the failure mechanisms and seismic performance of suspended ceilings, including the influence of the vertical and rotational components of building floor motions. While there have been previous shake table tests on suspended ceilings, most of these tests considered only the horizontal motions and only limited studies have also included the vertical component of floor motions. New state-of-the-art testing facilities at Carleton University utilize four mobile shake tables which allow for movement in all six degrees-of-freedom and can more realistically simulate the configuration and support conditions and seismic excitations of complex suspended ceiling layouts. Behaviour and performance of suspended ceilings in buildings of different heights including super-tall buildings are investigated. Super-tall buildings are more flexible and deflect more as part of their design strategy to dissipate seismic energy during earthquakes. As a result, especially at high floor levels, the floor vibration response includes more pronounced vertical and rotational components. Consequently, the vertical and rotational floor motion component may have a significant impact on the performance of suspended ceilings in super-tall buildings making them more vulnerable to seismic damage and failure. Existing testing procedures for non-structural components have not adequately accounted for different types of floor motions. A new testing program for suspended ceilings is developed to better understand the failure mechanisms of suspended ceilings and the effects of different types of floor motions.

Keywords: Suspended Ceiling, Non-structural Component, Shake Table, Floor Motion, Tall Buildings.

INTRODUCTION

Over the past decades there have been significant advancements in earthquake engineering in building design, resulting in stronger, more resilient, and safer structures. However, over the same period there has been more limited development of improvement in other areas concerning building safety, especially in the performance of non-structural building components during earthquakes. A modern structure designed in accordance with current building codes can be expected to survive a significant earthquake, remaining intact even though it may suffer a controlled amount of damage. In contrast, experiences from recent major earthquakes, such as the 1994 Northridge [1], 2011 Christchurch [2], 2011 Tohoku [3], and 2018 Anchorage earthquakes [4], have clearly demonstrated that non-structural components are susceptible to suffer significant damage which affect the operation and functional performance of their hosting structures. For example, Norton et al. [1] observed that of the commercial buildings within the epicentral area of the 1994 Northridge earthquake, only 2% experienced structural damage whereas 15% suffered non-structural damage significant enough to deem the building unoccupiable. Similarly, during the 2011 Christchurch earthquake severe non-structural damage was observed in low-medium rise buildings despite only minor structural damage [2]. In a survey study, Taghavi and Miranda [5] pointed out that non-structural components represent significant asset value which can account for 65% to 85% of the total cost of commercial buildings. Filiatrault and Sullivan [6] noted that earthquake losses from damage to non-structural components has been shown to exceed losses from structural damage, resulting in billions of direct (damage) and indirect (business disruption and downtime) economic losses.

Suspended ceilings are among the many types of non-structural components commonly used in commercial, office and institutional buildings such as schools and some medical facilities. Ceiling failure poses a major life safety hazard as falling ceilings are a serious threat to building occupants and can cause significant damage to other collocated components like electrical wiring or gas lines, resulting in loss of building function or possibly starting fires within the building. Furthermore, fallen ceilings create additional hazards as they can severely impede evacuation of the building and subsequent emergency search and rescue response. Damage to suspended ceilings has been reported as one of the most commonly observed types of damage to non-structural components even in moderate earthquakes that have higher probability of occurrence [7]. Examples of ceiling failure causing detrimental business disruption include the shutdown of the San Francisco International Airport during the 1989 Loma Prieta earthquake [8] and school closures after the 2018 Anchorage earthquake [4]. Despite their observed poor performance and the impact of failure on life safety, there is a lack of thorough investigation on understanding the behaviour and failure mechanisms of suspended ceilings during earthquakes.

A suspended ceiling is typically attached to the underside of a floor slab in a multi-storey high-rise building. The acceleration motion imparted to the suspended ceiling is influenced by the building's dynamic vibration characteristics and its response to the earthquake ground motions at its foundations. Consequently, the location of the ceiling in relation to the height of the building and the stiffness of the ceiling systems relative to the building can significantly influence the performance of the ceilings during earthquakes. Earthquake ground motions are three dimensional, but typically in earthquake engineering design practice, only the effects of the usually dominant horizontal ground motion components are considered. This ignores the potential significance of the vertical ground motion component. However, recent near-fault earthquakes have recorded vertical ground shaking components that are greater than the horizontal ground motion components [9]. Recent studies on seismic performance of suspended ceilings show that the vertical component of earthquake shaking may have a significant effect on the behaviour of suspended ceilings [10][11][12]. The extent and severity of dislodgement of ceiling panels from the supporting grid may be influenced by the direct vertical motion of the building. As the ceiling panels are critical in maintaining the in-plane rigidity of the suspended ceiling system, the loss of ceiling panels can lead to failure of the ceiling grid and complete collapse of the entire suspended ceiling system.

Because of advances in design and construction technologies in recent years, a new generation of super-tall buildings are being constructed in major cities around the world. Because most of these super-tall buildings have not been subjected to any major earthquakes [13], there is limited information regarding the performance of suspended ceilings in super-tall buildings. These super-tall buildings are more flexible and deflect more as part of their design strategy to dissipate seismic energy during earthquakes. As a result, especially at high floor levels, the floor vibration response includes more pronounced rotational components. Consequently, this rotational floor motion component together with the vertical motion component may have a significant impact on the performance of suspended ceilings in super-tall buildings making them more vulnerable to seismic damage and failure.

This paper describes the development of a new testing program to investigate the failure mechanisms and seismic performance of suspended ceilings. This includes the development of appropriate floor response motions from a typical super-tall building to determine the influence of the vertical and rotational components of building floor motions. The research is being performed as part of a joint research project with Tokyo Institute of Technology and Tongji University which includes larger scale bi-directional suspended ceiling tests performed at Tongji University [14][15]. The goal of the present research is to further advance the knowledge of seismic performance of suspended ceilings, including the understanding of the effects of rotational motions, which has not been included in any previous studies. This is particularly important for determining the resilience of suspended ceilings in super-tall buildings that experience significant rotation on the high floors during earthquakes.

SEISMIC PERFORMANCE OF SUSPENDED CEILINGS

Suspended ceilings are any ceilings that are hung from the structure above, typically from a floor or roof slab. Two common types are suspended drywall ceilings or suspended lay-in tile ceiling systems, but other more specialized types exist as well. In the context of this paper, the term suspended ceiling will typically refer to suspended lay-in tile ceiling systems which are commonly known as T-bar ceilings. These systems consist of a light gauge metal grid system suspended from the structure with hanger wires and lightweight ceiling panels which are laid into the grid system typically without any physical connection. They are typically supported at the perimeter by a light gauge metal angle fastened to the partition walls. It is common in areas of moderate or high seismicity to have more robust or stringent seismic requirements at the perimeter connections and/or lateral braces for the ceiling grids. The lateral braces typically consist of a compression post (such as a light gauge steel stud) and four 45° splay wire braces.

Failures of suspended ceilings have been observed in many past earthquakes and are often identified as the most common type of damage to non-structural components. The types and severity of the damage observed have varied between earthquakes and the types of buildings the suspended ceilings were located in. The full extent of the damage and a detailed description of all of the ceiling damage can be difficult to capture following an earthquake. Seike et al. [16] noted during their field review after the 2011 Tohoku earthquake that it was difficult to gain access to many buildings and they found that damaged non-structural elements had been removed from many buildings before their review could take place. Because of these limitations and the vastness of non-structural damage, many of the reconnaissance reports of non-structural damage are not complete or do not have detailed information on the failure mechanisms. It has been observed after several earthquakes including the 1994 Northridge earthquake [1], 1998 earthquake in southern Taiwan [8], and the 2011 Christchurch earthquake [2], that damage is often initiated by failure at the perimeter connection. Suspended ceiling earthquake damage has also been attributed to strong vertical accelerations of the supporting structure. Significant ceiling damage was observed during the 2011 Tohoku earthquake. Motosaka and Mitsuji [3] observed the loss of ceiling boards in large span structures. They investigated the vibration characteristics of one of these structures and found that significant vertical motions were induced in the roof structure from horizontal input motions. They noted that based on the observed damage it appeared that the ceiling design did not account for the vertical motions experienced. Seike et al. [16] observed suspended ceiling damage in large space buildings, such as auditoriums or gymnasiums, office buildings, and low-rise commercial buildings. Hisada et al. [17] reviewed the damage in high-rise buildings in Tokyo during the Tohoku earthquake and found that ceiling damage occurred on the middle to upper floors. This was despite a relatively low severity of ground shaking in the area.

Various studies including experimental testing of the seismic performance of suspended ceilings have been performed throughout the years. The studies have included a range of ceiling types, sizes, configurations, and input motions. While the studies explore many different aspects of seismic performance of suspended ceilings, they have tended to focus on the effectiveness of lateral braces and have produced conflicting results regarding their effectiveness. Yao [8] found that lateral braces did not increase the seismic performance of the suspended ceilings, but the installation of transverse supports at the perimeter of the ceiling that prevented the lateral spread of the grid system did. Gilani et al. [10] observed the dislodgement of ceiling panels at the center of their test specimen and almost no damage at the perimeter. The observed damage was largely attributed to the flexibility of the test frame which resulted in amplification of the vertical input motions and unexpected large vertical accelerations at the center of the test frame. During tests performed with a full-scale five-storey building, Soroushin et al. [12] observed that when subjected to vertical accelerations greater than 1g, the lateral braces, originally intended to enhance the seismic performance of the suspended ceiling, actually had a negative impact. This was observed to be because the lateral braces provide a rigid connection between the floor structure and the ceiling grid. When the floor structure acceleration is greater than 1g downwards, the floor and ceiling grid move together but the unconnected ceiling panels only experience acceleration due to gravity and become separated from the grid system. When acting together with acceleration motions in the horizontal direction, this results in the ceiling panels becoming easily dislodged. In contrast, Ryu and Reinhold [11] found that the use of lateral restraints improved the performance of the suspended ceiling in their large-scale ceiling tests but noted that the effects of the vertical amplification of the supporting structure was not assessed due to the relatively high stiffness of the test frame in the vertical direction.

The observations of ceiling performance from past earthquakes and previous experimental seismic testing of suspended ceilings have indicated that the perimeter connections are a vulnerable component of the suspended ceiling system. They have also shown that vibration characteristics of the supporting structure can result in large vertical accelerations that have a significant impact on the performance of the suspended ceiling. This emphasizes the importance of the proper determination of the floor motion responses which ceilings could be subjected to, including the potential significant influence of the vertical motion component imparted to the ceiling system from the supporting structure as well as the importance of proper test setup and equipment that can realistically and accurately replicate the proper floor response motions. While previous studies have included the effects of vertical accelerations, the ratio of horizontal to vertical motions has not been clearly established. In addition, there have been no studies that have also included the effects of rotations.

FLOOR MOTION RESPONSE OF SUPER-TALL BUILDING

In order to properly simulate earthquake motions experienced by suspended ceilings it is essential to consider also the dynamic properties of the building and floor structure which will support the ceiling.

As mentioned previously, there has not been any field experience of super-tall buildings subjected to major earthquakes [13] and, therefore, there is limited information regarding the response of super-tall buildings to actual seismic events. In this study, two prototype building models were used to produce simulated floor response motions. The first is a model of the 128-storey Shanghai Tower, one of the tallest buildings in the world. The second is a model of a ten-storey building located on the Carleton University campus in Ottawa, Ontario, Canada. The buildings were chosen as representatives of a typical super-tall and a mid-rise building, respectively. The intention of these two models is to observe the different characteristics in floor responses between mid-rise and super-tall buildings in order to determine the impact of the influence of the characteristics of super-tall buildings on the seismic performance of suspended ceilings.

The model of the Shanghai Tower is a nonlinear model using PERFORM-3D software developed by Lu et al. [18] as a benchmark model for seismic performance of super-tall buildings. The structure consists of a central core made of reinforced concrete shear walls with steel embedded reinforced concrete columns at its perimeter, and steel outrigger trusses in between [13]. Analysis of the building found that the fundamental vibration modes were approximately 8.93s in both horizontal directions and 0.60s in the vertical directions.

The model of the 10-storey building [19] is a linear model created in ETABS software. The structure consists of reinforced concrete slabs supported by reinforced concrete shear walls to provide lateral load resistance in both directions. Analysis of the building found that the fundamental vibration modes in the long, short and vertical directions were approximately 0.47s, 0.31s and 0.08s respectively.

Both models were subjected to two ground motion records [18]. The first, SHW6, is a ground motion record from the 1999 Chi-Chi earthquake specified in the Shanghai seismic design code **Error! Reference source not found.**. This ground motion was used for development of the floor motions used in the Tongji tests [14][15] and has only horizontal components. The second is a ground motion record from the 1985 Mexico City earthquake which contains components in both horizontal directions and the vertical direction. For the simulation study here, the building models were subjected to ground motions scaled to peak acceleration levels of 0.2g or 0.4g in the horizontal X direction and the horizontal Y and vertical Z components scaled to 85% and 65% of the peak value respectively. The roof level response was analyzed for both building models. The displacement and acceleration time histories were recorded at nodes which represent the top of vertical supports at the sides of each building to ensure the values represent the movement of the building as a whole and are not amplified by the out-of-plane vibration of the floor slabs. The horizontal and vertical acceleration time histories from each model subjected to the ground motions scaled to a peak acceleration of 0.4g are shown in Figure 1 through Figure 4.

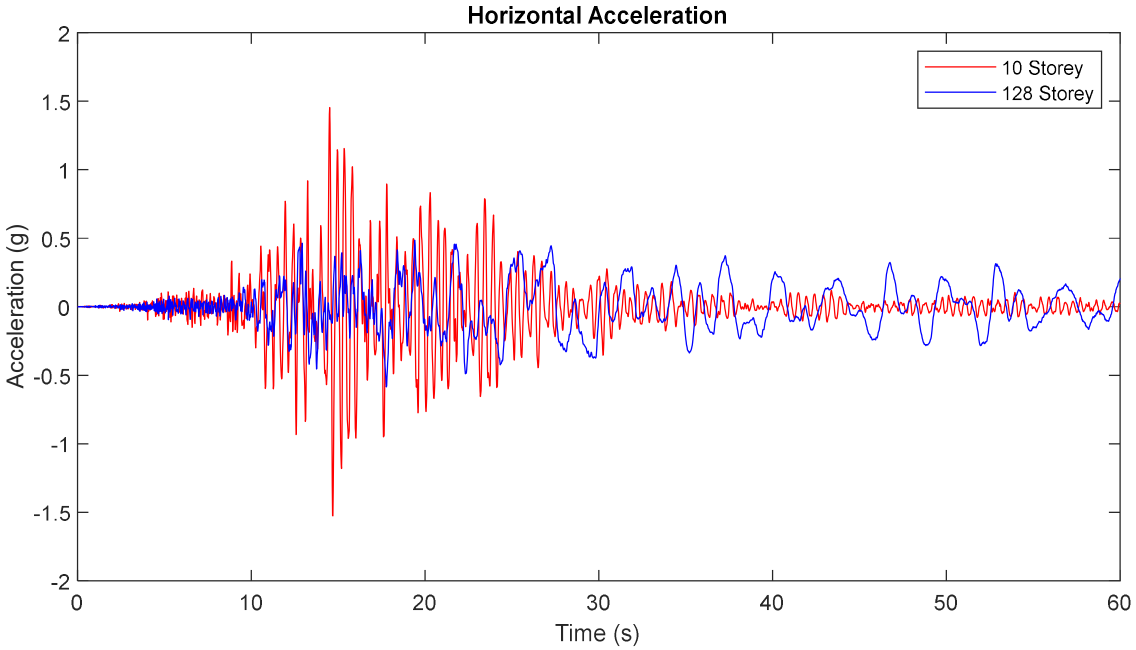

Figure 1: Horizontal acceleration due to SHW6 ground motion

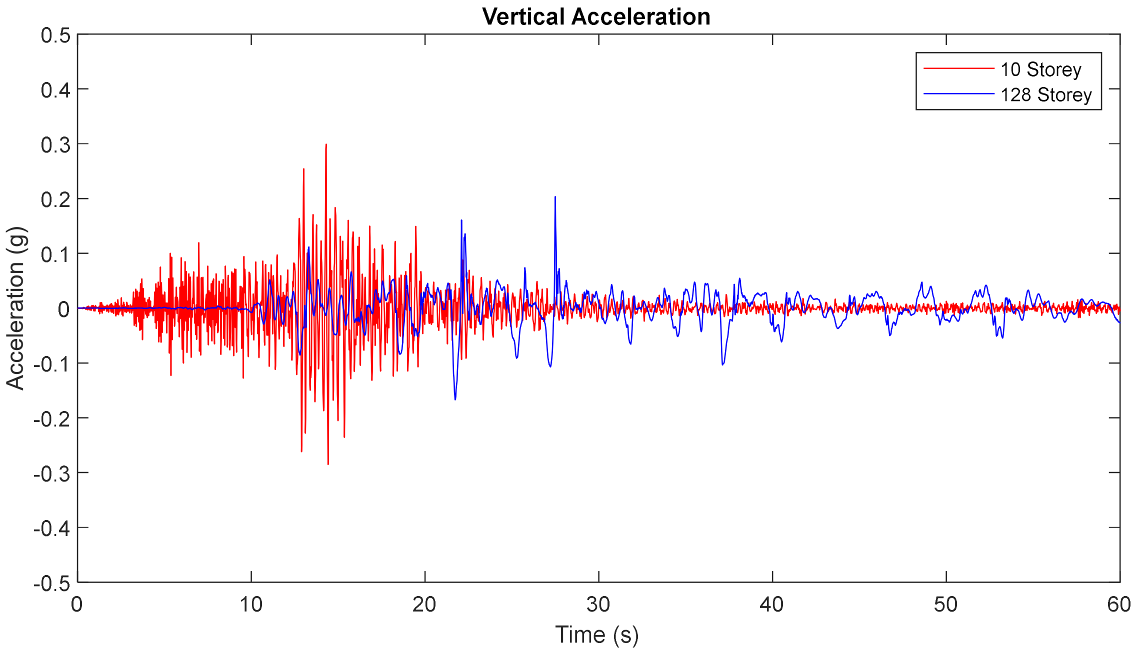

Figure 2: Vertical acceleration due to SHW6 ground motion

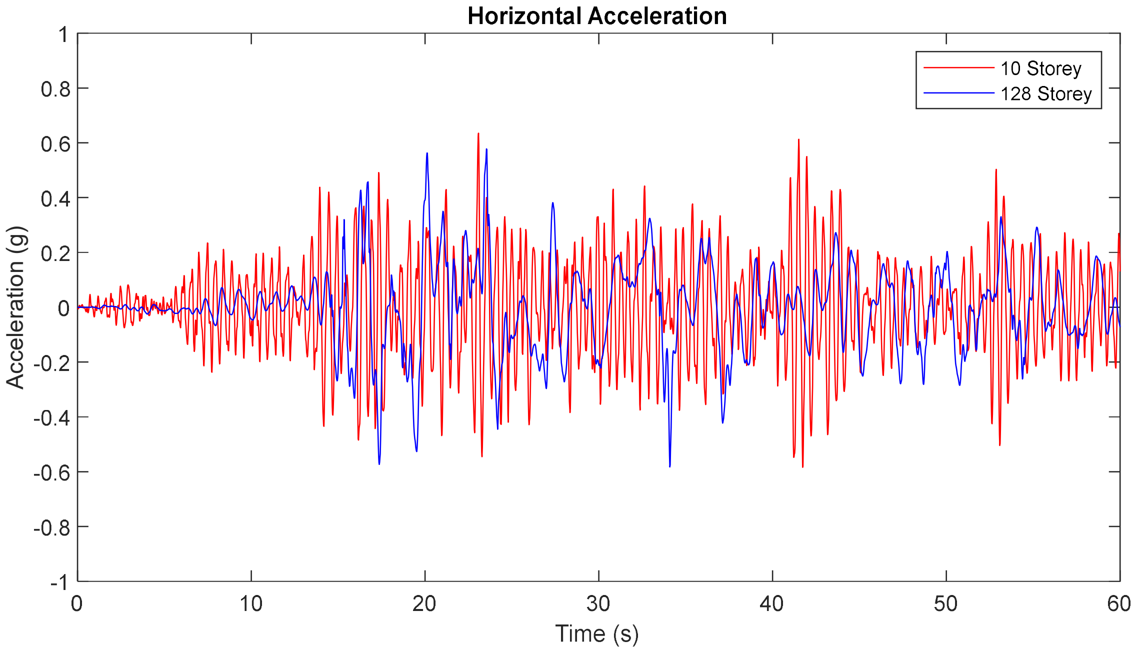

Figure 3: Horizontal acceleration due to Mexico City ground motion

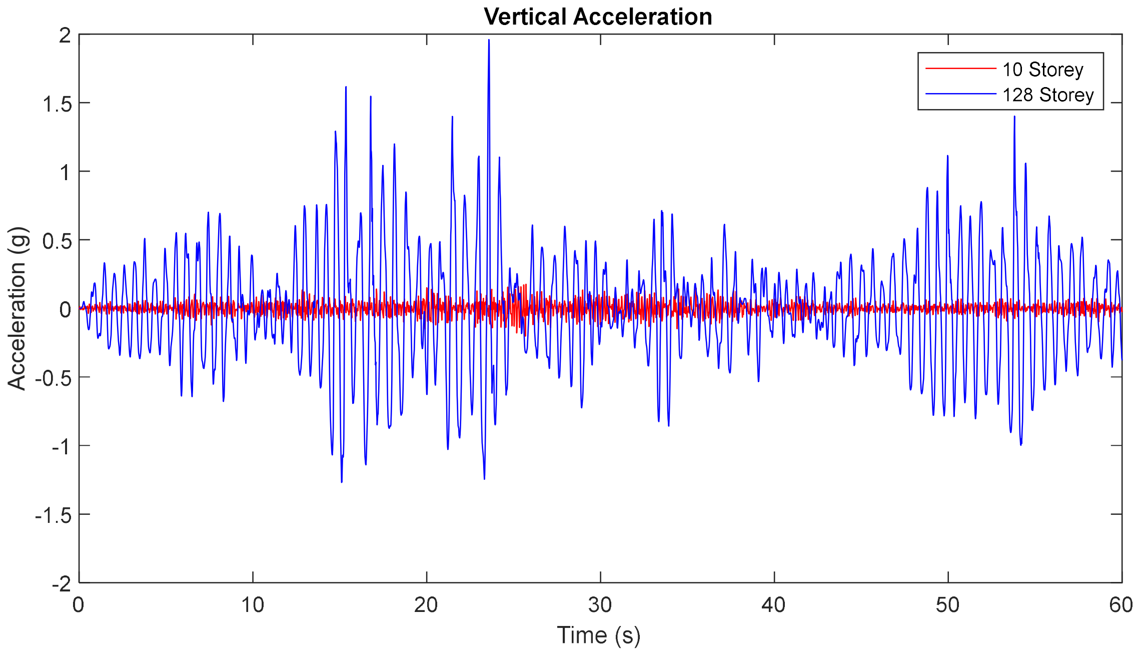

Figure 4: Vertical acceleration due to Mexico City ground motion

When subjected to the SHW6 ground motion, the horizontal accelerations are amplified much more in the 10-storey building than the 128-storey building. Vertical accelerations are observed in both buildings despite no vertical component in the input motion but the vertical accelerations are much lower than the horizontal accelerations. These vertical accelerations are recorded at the perimeter of the building and are mostly due to the slight rotation in the building caused by horizontal movement.

The horizontal accelerations of both buildings reach a similar peak due to the Mexico City ground motion. This is likely due to the higher low frequency content in the ground motion. The vertical accelerations observed in the buildings when subjected to the Mexico City ground motion indicate that there is very significant vertical amplification in the 128-storey building resulting in vertical accelerations that were several times higher than the peak vertical acceleration of the ground motion excitation. In contrast, the vertical accelerations at the top of the 10-storey building were less than the peak vertical acceleration of the ground motion excitation indicating that there was no vertical amplification of the ground motion. To further evaluate the effect of the vertical ground motion component to the rotational response of the floor and the associated vertical floor displacement at the building perimeter, the building models were subjected to the Mexico City ground motion record with and without the vertical component of the ground motion excitation. The results of this and several additional analyses performed on the models and the results are summarized in Table 1.

Table 1: Results of ground motion analysis of building models

	Building Model		**Peak Ground Acceleration**			**Peak Floor Acceleration**	
# of Storeys	**Ground Motion**	**Floor Level**	**X (g)**	**Y (g)**	**Z (g)**	**X (g)**	**Z (g)**
128	SHW6	128	0.2	0.17	0	0.35	0.09
128	SHW6	128	0.4	0.34	0	0.46	0.20
128	SHW6	70	0.4	0.34	0	0.22	0.13
128	MexC	128	0.2	0.17	0.13	0.59	0.72
128	MexC	128	0.4	0.34	0.26	0.58	1.94
128	MexC	70	0.4	0.34	0.26	0.31	1.49
128	MexC	128	0.4	0.34	0	0.51	0.14
10	SHW6	10	0.4	0.34	0	1.52	0.30
10	MexC	10	0.4	0.34	0.26	0.63	0.20
10	MexC	10	0.4	0.34	0	0.63	0.08

When subjected to the Mexico City earthquake with no vertical component the 128-storey building has very small vertical accelerations at its roof level. This indicates that the high vertical accelerations experienced by the building when subjected to the Mexico City ground motion with a vertical input ground motion component are mainly due to amplification of this vertical component and not the horizontal component or rotation of the building.

The floor response was also recorded at the 70th floor of the 128-storey building to observe how the response varies along the height of the building. The results show that horizontal and vertical accelerations increased along the height of the building as expected.

In addition to floor accelerations, the floor rotation time history was plotted for both buildings as shown in Figure 5 and Figure 6. The 10-storey building experiences almost no rotation while the 128-storey building experiences a top floor rotation of almost 0.5 degrees due to both ground motions.

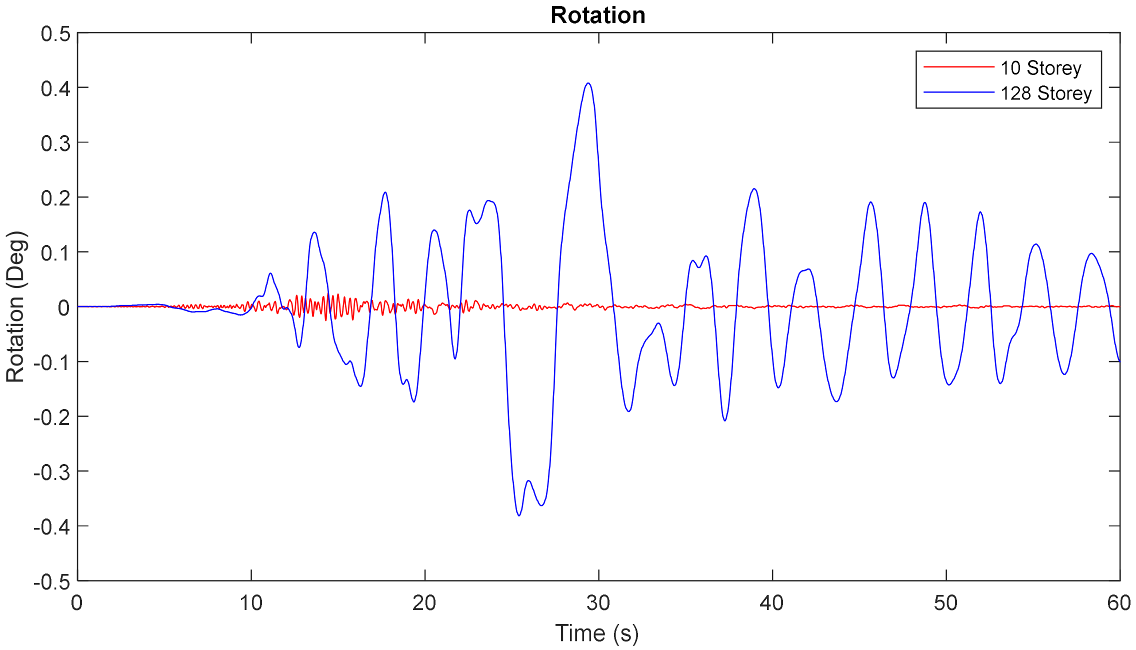

Figure 5: Top floor rotation due to SHW6 ground motion

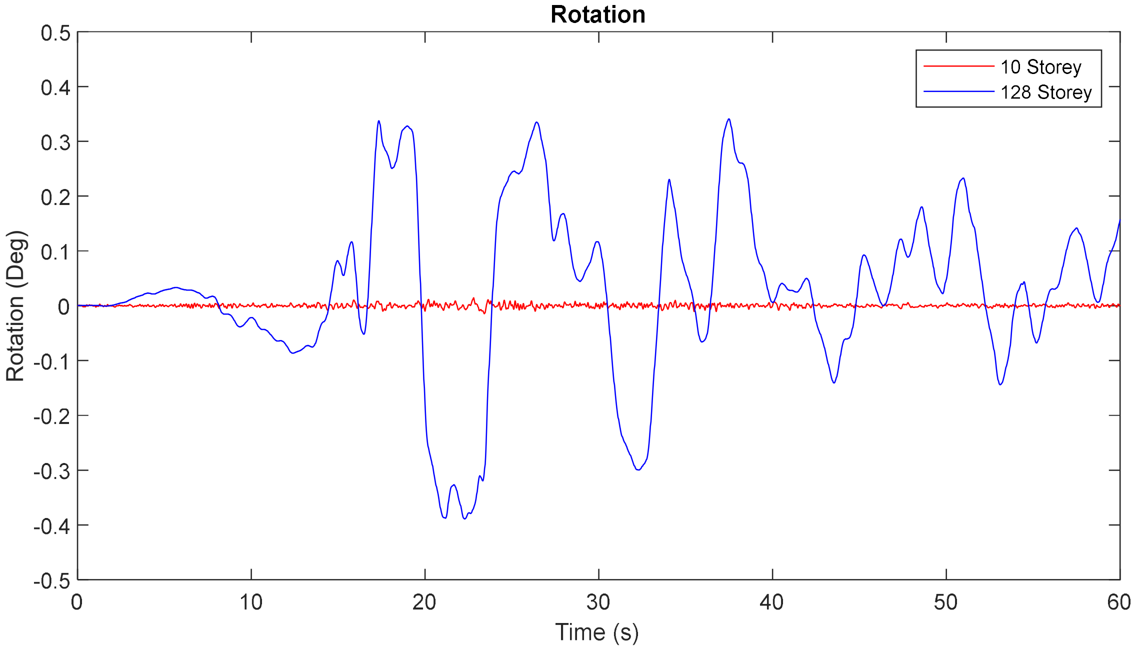

Figure 6: Top floor rotation due to Mexico City ground motion

EXPERIMENTAL SEISMIC TESTING OF SUSPENDED CEILINGS

Several different methods have been used in experimental seismic testing of suspended ceilings. Some tests have used acceleration time histories based on a building design spectrum [8], others have used acceleration time histories generated from the recommended required response spectrum (RRS) in ICC-ES AC156 (AC156) [10][11], and some tests have been performed on full-scale buildings subjected to ground motions [12]. Testing of non-structural components using direct ground motions or a building design spectrum is less realistic because the amplification or filtering effect due to the dynamic response of the building structure are not taken into account. Testing with full building models will most closely replicate the loading conditions of suspended ceilings in the field but is likely prohibitively expensive and impractical for large buildings. A viable alternative approach is to use floor response motions determined from computer models of buildings as the input excitations to the suspended ceilings in shake table tests of the non-structural components. The influence of different buildings characteristics and parameters on the response behaviour of suspended ceilings can be investigated by a rigorous testing program using floor response motions of different building types and characteristics obtained by computer simulation of building models.

The AC156 [21] testing procedure has been used by ceiling manufacturers for testing suspended ceilings [22], and was also used to develop the fragility curves in FEMA P-58 [23]. AC156 is a testing standard procedure for seismic certification of non-structural components, which is referenced in ASCE 7-22 [24] as a possible alternative to the force design procedures. The AC156 procedure involves development of a RRS to generate random excitations to be used as the input motions for shake table tests. The RRS is constructed using the horizontal spectral acceleration values for flexible components (A_{FLX-H}) and rigid components (A_{RIG-H}) specified in AC156. The equations for these factors are based on the horizontal force equation for the design of non-structural components in ASCE 7-16 [25], Eq. (1).

$$F_p = \frac{0.4 a_p S_{DS}}{(R_p/I_p)}(1 + 2\frac{z}{h})W_p \qquad (1)$$

where: a_p is the component amplification factor, S_{DS} is the short period spectral acceleration, R_p is the component response modification factor, I_p is the component importance factor, z is the height of the component attachment point, h is the height of the building, and W_p is the weight of the component. This equation has factors that account for the component response, the seismicity of the area and the relative height of the component with the building but there are no factors that account for the seismic response of the building. As a result, the design force for a component will be the same whether it is attached to the roof of a single-storey shear wall structure or the roof of a 50-storey moment frame structure. This results in a large advantage of the AC156 testing procedure in that it can be used to verify that an installation setup will be in accordance with ASCE 7-16 for any building with an S_{DS} lower than the value used to develop the required response spectrum. The equations for the component spectral accelerations specified in AC156 are shown in Eq. (2) and Eq. (3) respectively. These values represent the maximum spectral accelerations experienced by flexible components, defined as a component with a fundamental frequency less than 16.67 Hz, and rigid components, defined as a component with a fundamental frequency greater than or equal to 16.67 Hz [21].

$$A_{FLX-H} = S_{DS}(1 + 2\frac{z}{h}) \leq 1.6 S_{DS} \qquad (2)$$

$$A_{RIG-H} = 0.4\, S_{DS}(1 + 2\frac{z}{h}) \qquad (3)$$

The RRS is then constructed with the value of $A_{FLX-H}/10$ at a frequency of 0 Hz, A_{FLX-H} from frequency of 1.3 Hz to 8.3 Hz and A_{RIG-H} at a frequency of 33.3 Hz. The vertical RRS is taken as equal to two-thirds the horizontal RRS with the value of z set to 0. The required response spectra for a region with $S_{DS} = 1$ is shown in Figure 7

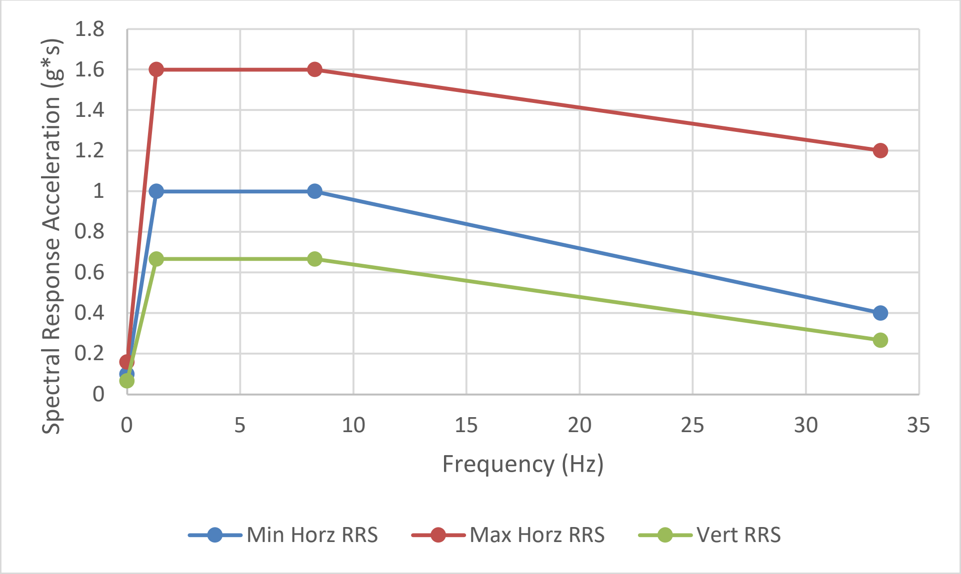

Figure 7: Required response spectra for $S_{DS} = 1$ *(based on AC156 Figure 1) [20]*

The equation for the vertical force applied to non-structural components in ASCE 7-16 is shown in Eq. (4) [25]. This equation simply accounts for the components weight and the seismicity of the area the building is located. There are no factors to account for the building type, the location of the component within the building, or even the component type. Therefore, the vertical force on a nonstructural component will be the same for any component located anywhere within any building with the same seismicity. This equation is also equal to two-thirds of the minimum value that can be taken for the horizontal force in ASCE 7-16 and as a result, the vertical response spectrum in the AC156 procedure will always be more conservative than the vertical force equations.

$$\pm 0.2\ S_{DS} W_p \qquad (4)$$

This horizontal force equation has since been updated in ASCE 7-22 [24] with factors that account for the period and ductility of the building supporting the component. The updated equation was based on the recommendations in NIST GCR 18-917-43: “Recommendations for Improved Seismic Performance of Nonstructural Components” [26]. The recommendations were developed based on a number of studies including both acceleration floor response data from instrumented building subjected to real ground motions and numerical computer models. Acceleration floor response data from a total of 44 individual buildings was used in the study, most of which were low-rise buildings. Only four buildings with more than 30 storeys were included with the tallest building being 52 storeys with a roof height of approximately 218 m [27]. Some of the main findings of the study were that an increase in building period or ductility generally results in a reduction of the amplification of the peak ground acceleration and that the previous approach of linear increase in force along the height of a building was conservative [26]. The NIST report did note that vertical forces were not investigated as part of the project mainly due to the lack of or poor placement of vertical accelerometers in buildings. As a result, the equation for the vertical force applied to non-structural components was not changed [24] and remains as shown in Eq. (4).

The use of the AC156 procedure for shake table testing of suspended ceilings has been found to produce results that do not match the typical failures observed in the field [22]. Since the procedure uses the ASCE 7-16 force equation to develop the RRS, no properties of the supporting structure are considered when developing the input motions. The requirement for the vertical RRS to be two-thirds of the horizontal RRS for the base level of the building also results in higher vertical components than is considered by code. However, as discussed, the vertical force component on non-structural components is not well understood and will not be the same for all buildings. Since it has been shown that suspended ceilings are susceptible to vertical accelerations it is evident that new procedures should be developed for the seismic testing of suspended ceilings.

NEW TEST PROGRAM

A rigorous seismic testing program has been developed to investigate the seismic performance of suspended ceilings subjected to floor motions from different types of buildings including super-tall buildings.

Testing will be performed using a newly developed shake table system consisting of four independent mobile shake tables by MTS Systems Corporation and their subsidiary E2M Technologies B.V. Each table can duplicate motions in six degrees-of-freedom. The four tables can be controlled such that they move individually, each table’s movement independent of the movement of the other tables, or such that they move together as a single large platform in translation and rotation about one reference location. Since there are four separate mobile tables, they can be positioned in any configuration depending on the specimen shape and size being tested. For the suspended ceiling tests to be performed, the four independent tables are positioned in a square layout to support a 5.4m x 5.4m steel test frame from which the ceiling specimen is suspended.

The test frame, specially designed for testing non-structural components [19] is shown in Figure 8. The test frame is a steel braced structure with perimeter beams and open web steel joists forming the roof/floor structure. Steel angles can be installed on the perimeter of the test frame at varying heights below the underside of the joists to simulate the perimeter support conditions for suspended ceilings and allow for different suspension heights. The test frame was designed with the intention to reduce the amplification of the input excitations in both the vertical and horizontal directions and as such the bare frame's fundamental frequency in the horizontal and vertical directions was designed to be greater than 20 Hz. The relatively high stiffness of the frame will reduce amplification and therefore allow desired floor motion responses to be inputted directly and give greater control of the response motion to the researchers. In addition, if a lower vertical frequency is desired for specific testing, weight can be added to the roof of the frame to lower the frequency.

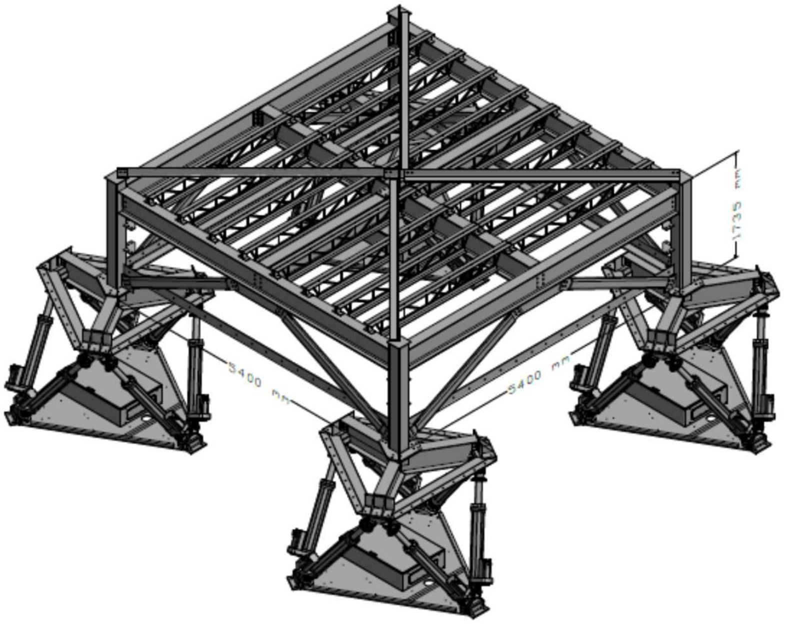

Figure 8: Test frame setup [19]

The testing will follow the procedures described in FEMA 461 "Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components" [28]. This document outlines protocols for shake table testing of structural or non-structural components. The recommended input motions for performance testing in the FEMA 461 approach are narrow-band random sweep acceleration records which sweep from a high frequency to a low frequency and have a relatively smooth response spectra. The benefit of using the FEMA 461 records with a frequency sweep is that the time of damage can be recorded and used to identify the frequency of the motion that caused damage. If a specimen has multiple failure modes, such as a suspended ceiling would, the frequency that caused damage can be notch filtered out of the input motion and the test can be repeated to identify other failure modes. The main goal of the testing will be to determine the effects of different ratios of the magnitude of horizontal to vertical input motions and to better understand the different failure mechanisms of suspended ceilings. This knowledge can then be used to access if the current practice is appropriate for different types of buildings. The accomplish this, instead of applying the vertical input motions at 80% of the horizontal input motions (as recommended in FEMA 461), the ratio of horizontal to vertical input motion will be varied across a series of tests. For comparison, tests will also be performed using the AC156 approach and using actual floor motions developed from computer modelling.

CONCLUSIONS

Previous earthquake experience has shown that earthquake damage to non-structural components, and especially suspended ceilings, can be a significant hazard to life and the continuing function of the building. Damage to suspended ceilings has commonly been the most reported type of damage to non-structural components and has resulted in large economic losses due to property damage and often more significantly the extended closure of business. Suspended ceiling performance in previous earthquakes and in experimental testing has shown that ceilings are susceptible to damage at their perimeter connections and that vertical acceleration of the supporting structure has a significant impact on the ceiling's performance.

Models of a typical super-tall and mid-rise building were used to develop floor response motions. The floor responses indicate that suspended ceilings at the top of super-tall buildings could be susceptible to earthquake damage. Large amplifications of the vertical component of the ground motion excitation were observed resulting in large vertical accelerations which suspended ceilings have been shown to be vulnerable to. In addition, floor rotations of up to almost 0.5 degrees were observed. This amount of rotation would result in the support location of a ceiling suspended 1200mm below the floor structure to move approximately 10mm away from the original location. This combined with the effects of the building drift, the additional vertical accelerations due to the rotations and the amplification of the vertical component of the ground motions will add stresses to the perimeter connections or cause more pronounced movements of the ceiling making them more susceptible to damage during earthquakes.

A seismic testing system was designed specifically for experimental testing of the seismic performance of non-structural components including suspended ceilings. The test system consists of six degree-of-freedom mobile shake tables supporting a rigid steel frame which can be used to accurately simulate the floor response of super-tall buildings including the rotational components of the motion. A new testing program is developed using the FEMA 461 procedure to investigate the effects of varying the ratio of horizontal to vertical input motions on the seismic performance of suspended ceilings. Testing will also be performed using the AC156 procedure and generated floor motions for comparison.

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