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THE SEISMIC VULNERABILITY OF ART OBJECTS

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ABSTRACT

The seismic vulnerability of art objects was investigated at three museums in Montréal. Research was focused on the seismic behavior of three unrestrained display cases, storage shelves, and a 6m long dinosaur skeleton model structure. Particular attention was paid to the support conditions, the effects of modified surface conditions, the sliding and rocking response in the case of unrestrained display cases, the location (floor elevation) of the display case and/or storage shelves, art object mass, and the dynamic properties of the display cases/storage shelves. The seismic vulnerability of art objects was evaluated based on the seismic response of the display cases/storage shelves at the level of art object display. The display cases were investigated experimentally using shake table testing. Computer analyses examined the seismic behavior of storage shelves, and the seismic sensitivity of the dinosaur structure was determined via vibrational analyses. Adequate instrumentation to determine sliding and/or rocking displacements of the unrestrained display cases was crucial. The distribution of content mass had a large impact on the response of the shelving system. The shelving system response was improved by increasing its stiffness. As a result of experimental and analytical analyses, recommendations and/or simple mitigation techniques are provided to reduce the seismic vulnerability of objects of art.

Introduction

According to the CSA S832 standard *Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings* (CSA 2005) building elements can be divided into two groups: structural components and operational and functional components (OFCs). Experience from past earthquakes has shown that damage from these components can be substantial and can pose significant life safety hazards. Even though research on the seismic-resistant design for nonstructural components has increased over the past decade, the need to research specific topics still exists.

Examples of 20th century earthquakes give an indication of the extent of art objects damaged and sometimes destroyed. Review of research efforts on the protection of art in earthquakes indicates that the seismic mitigation for art objects is still a challenge. The challenge arises in the fact that certain physical characteristics and inherent damages render art objects, either on display or in storage, particularly vulnerable to strong shaking. Conventional mitigation techniques can furthermore not always be utilized, as they might be of particular concern to the object surface and interfere with desired display characteristics.

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It appears that the first scientific studies on the earthquake behavior of art objects were undertaken by the Getty Conservation Institute in collaboration with the University of Southern California in 1988 (Agbabian and Masri 1988) and 1990 (Agbabian and Ginell 1990). The purpose of these studies was to evaluate current seismic mitigation methods based on analytical as well as experimental analysis techniques for the development of museum guidelines. Other studies on this subject followed at the University of Rome, in Italy (Augusti, Ciampoli, and Airoldi 1992; Augusti, Ciampoli, and Sepe 1995). These studies were conducted for the purpose of evaluating display cases restrained to the floor, and investigating the effect of ground motion parameters on unrestrained art objects exhibited in these display cases. Further research has been conducted to develop base-isolation devices to control the vibrations of art objects as a result of base excitations (Calio 2003, Vestroni 2000). Although base isolation is considered an effective means of reducing seismic forces, its application is usually limited to heavy statues and other objects of art of particular cultural significance.

The seismic behavior of art objects has been investigated in these studies by analyzing the dynamic response of rigid bodies. To mitigate the seismic risk for museum contents, it was emphasized that rocking and consequential overturning of objects should always be prevented, and sliding limited to acceptable values (Augusti and Ciampoli 1992). Each specific rigid body motion for a given object is governed by the surface friction coefficient.

This project was initiated to continue research on the protection of art in earthquakes and was conducted in collaboration with three museums in Montréal, Canada. The seismic hazard for Montréal and representative museum floor motions were simulated for that purpose. It is the scope of this research to investigate the seismic vulnerability of selected museum display cases, the dynamic behavior of storage shelves containing fragile contents, and the seismic sensitivity of a dinosaur skeleton model structure.

Computer analyses were performed to investigate the seismic behavior of a museum storage shelf system, which was identified as being seismically vulnerable due to its brittleness and large content weight. A parametric study, investigating effects of ground motion characteristics, building elevation of storage shelf location, content mass distribution, and shelving system stiffness, was conducted to determine structural vulnerability and structural improvement is recommended based on the simulation outcome. Content mass seismic behavior is predicted based on accelerations at the level of the shelves, and surface friction conditions between the contents and the shelves.

The seismic sensitivity of a 6m long dinosaur skeleton model display is investigated. The seismic vulnerability is determined based on the natural frequency extracted from the measured accelerations of the dinosaur structure left in free vibration after being excited by a small impact. The seismic design force obtained based on the frequency properties is compared to that recommended by the 2005 NBC.

Finally, experimental testing of three display cases was performed on the shake table at the structural testing facility of École Polytechnique. Effects of display case stiffness, ground motion characteristics, location (floor elevation) of display cases, floor contact surface conditions, and art object mass are investigated. The experimental program to investigate these effects is presented in this paper. Ultimately, the dynamic behavior of unrestrained display cases will be evaluated and accelerations developed at the level of art object display will be assessed.

Montréal Seismic Hazard

The earthquake records for the experimental and analytical studies have been selected to match the seismic hazard in Montréal. Time history records have been simulated for different levels of probability of exceedance (Atkinson 1998). The seismic hazard is represented in terms of most likely magnitude (M) – hypocentral distance (R) scenarios and has been modified with a fine-tuning scale factor to match the target uniform hazard spectrum (Filiatrault 2004). The records have been selected to characterize small to moderate earthquakes at close distances (contributing to the short-period ground motion hazard) and larger events at greater distances (contributing to the long-period ground motion hazard). To account for the fact that the response of the display cases and shelving unit depends on their location of building elevation, floor time histories were generated at building elevations of z = 5m and z = 10m to represent floor levels 1 and 2 respectively with respect to ground level at z = 0m. A low-rise concrete building which has been modeled and validated with in situ measurements (Assi 2006) was considered to serve as a representation of the dynamic properties of the museum for the purpose of generating the floor acceleration records.

Table 1 summarizes the peak horizontal accelerations (PHA) and duration of shaking of the ground and floor motions and introduces their notation which will be used hereafter. Fig. 1 depicts floor acceleration spectra (FAS) for two base motions to demonstrate their variation in frequency and intensity content and the filtering effect that the dynamic response of the building has at different floor elevations. Significant peaks emerge in the spectrum at a period corresponding approximately to the fundamental period of vibration of the building at 0.30s.

Table 1. Summary of base motions

z (m)	Base Motion Notation	PHA (g)	Base Shaking Duration (s)	Base Motion Notation	PHA (g)	Base Shaking Duration (s)
	Probability of Exceedance: 10% in 50 yrs.			**Probability of Exceedance: 2% in 50 yrs.**		
0	10 M5.5R30	0.153	4.9	2 M6R30	0.396	6.3
5	10 M5.5R30	0.126	4.9	2 M6R30	0.371	6.3
10	10 M5.5R30	0.161	4.9	2 M6R30	0.404	6.3
0	10 M7R150	0.113	19.1	2 M7R50	0.307	16.9
5	10 M7R150	0.110	19.1	2 M7R50	0.352	16.9
10	10 M7R150	0.142	19.1	2 M7R50	0.483	16.9
0	10 M7R300	0.0712	25.1	2 M7R70	0.286	20.1
5	10 M7R300	0.0883	25.1	2 M7R70	0.347	20.1
10	10 M7R300	0.154	25.1	2 M7R70	0.414	20.1

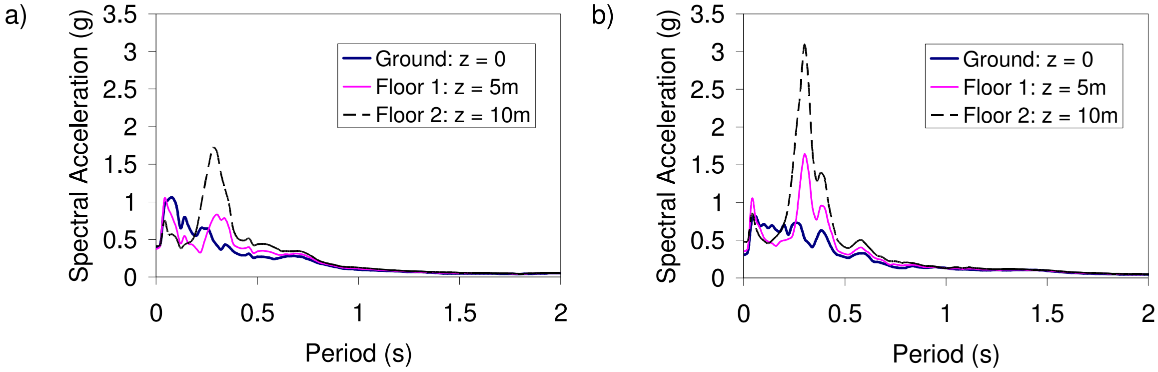

Figure 1. FAS for base motions a) 2 M6R30, and b) 2 M7R50

Case Study 1: Storage Shelf System

The seismic behavior of a museum storage shelf system containing fragile contents is investigated. The shelves are loaded with glass negatives, individually stored in paper envelopes. The shelving system, where every shelving unit weighing approximately 0.8 KN is loaded with contents weighing a total of 113 KN, was identified as being seismically vulnerable due to its brittleness and large content weight. Several parameters are varied in the analysis to investigate their effect on the shelving system response. The overall dynamic response is described by the maximum accelerations and deflections. The structural vulnerability is determined based on the simulation outcome and structural improvement is recommended as a result. Finally, the art object response is predicted.

Model Description

The shelving system was modeled using SAP2000 and the wire mesh of the model is shown in Fig. 2. The shelving system was modeled as a series of parallel linear elastic 2D steel frames (Hermitian elements) connected at the top of some columns to adjacent rows via small channel sections as indicated by dashed lines in Fig. 2b. These link elements do not provide effective horizontal bracing for the shelving system. The shelf beams are cold formed steel members and the columns are perforated open sections to allow the aluminum hooks of the beam-end to form a beam-column connection. Equivalent section properties were calculated for all members. Braces exist at intervals in the longitudinal direction of the shelving system. The mass of the contents was added to the shelves and were lumped at nodes at shelf beam mid span.

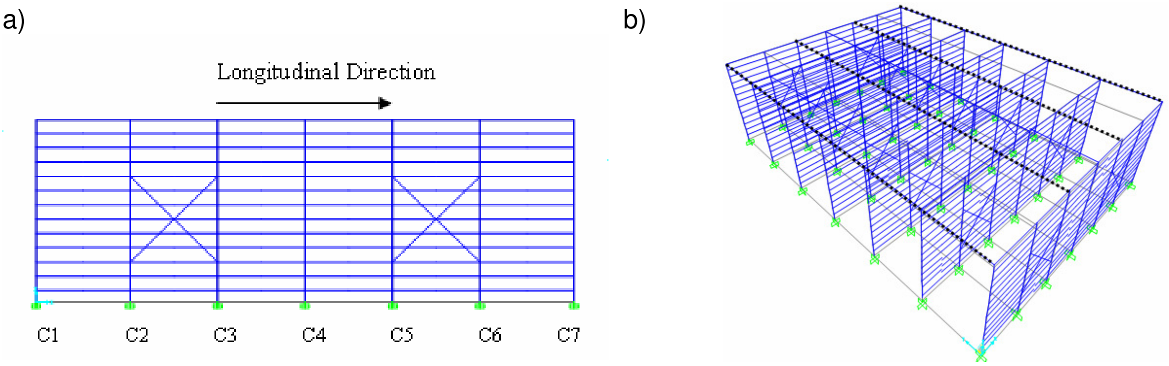

Figure 2. a) 2D elevation and b) 3D view of the shelving system model

Ideally the stiffness and performance of the connections would have been evaluated experimentally. Since this case study is strictly a numerical investigation, the model was initially analyzed with pinned as well as fixed beam-column connections. Significant differences in modal frequencies and mode shapes between the pin and fixed connections were not determined. Therefore, pinned connections were used in subsequent analyses.

Structural Analysis

Static stability of the model was initially verified and found acceptable. The dynamic analyses were performed with seismic base motions as presented in Table 1 and applied in the transverse direction (weak axis) of the shelving system. An eigenvalue analysis of the loaded shelving system was performed on the lowest 30 modes of vibration. All 30 modes were found to have frequencies below 10 Hz; spanning the usual frequency range of earthquakes, indicating the possible seismic sensitivity of the structure. The first mode was found at a period of vibration of 0.74s.

Parametric Study

The analysis was conducted with input ground and floor motions of different intensity-frequency content. Floor motions at level 2, the location of the shelving unit, are of particular interest. The glass negatives of varying size are stored on the shelving system systematically according to historical context. The resulting mass concentration at some shelves can possibly induce torsional response due to eccentricities with respect to the center of stiffness. The shelving system was thus analyzed with content mass distributed among the shelving system in five different configurations to investigate if torsion dominates and possibly identify if contents can be stored in a configuration such as to improve the system response. Initially, the system was investigated with content mass evenly distributed among shelves. To investigate the torsional effect, heavy masses have been concentrated at the bottom right and top left corners of the shelving system in plan view, and the lighter masses have been concentrated at the remaining corners. The system was then analyzed in two configurations of content mass once increasing and once decreasing with increasing shelf height. Another configuration considered heavy masses concentrated at the center column of the shelving system. The shelving system consists of rows of shelves interconnected out-of-plane by a link (a small C-shape or a HSS). The stiffness of this link is varied in the analysis to determine its effect on the overall system response. The actual links (HSS 25*25*2) were replaced with HSS 51*51*6.4 sections, and solid rectangular steel sections of size 100mm*100mm to represent a very stiff link.

Analysis Results and Discussion

Analysis results were obtained in terms of the maximum absolute acceleration and the maximum relative displacement. The following observations were made:

- The shelving system experienced a peak acceleration of 0.92g under ground motions corresponding to events of high-frequency content. The responses were significantly increased at ground motions of higher intensity, with an increase of 75% for short-frequency content events.
- The acceleration response decreased at floor level 1 with respect to ground level due to the building response. Accelerations increased from floor level 1 to floor level 2 by a range of 12% to 33%. Deflection responses consistently increased with increasing floor elevations by up to 30% between floors of an intermediate-frequency content base motion. As a result of decreased accelerations at floor level 1 the impact of varied frequency content at floor level 2 was not significant.
- Placing the heaviest glass negatives at the bottom shelves had a negative impact on the shelving response, causing an increase in acceleration response of 52% compared to the case of even mass distribution. This is due to the fact that the period of vibration of the shelving system has decreased because of the lowering of its center of mass. As a result, according to the response spectrum, the response of the system has shifted into a zone of increased acceleration response.
- The shelving system was loaded asymmetrically in an attempt to induce torsional eccentricities. The resulting acceleration response increased on average by 12% which would indicate insignificant torsional response. This is in accordance with the lack of a torsional mode identified in the low frequency range. It appears that the distributed nature of the support points ensures good seismic behavior in this respect.
- The acceleration response of the shelving system can be reduced by connecting the shelving rows with adjoining rows via links of increased stiffness. By replacing the existing links with solid sections, the acceleration was decreased on average by 27% for different base motions.
- The maximum horizontal acceleration and displacement occurred at the top shelf at the center of the shelving unit, when the contents were equally distributed.
- The amplification of acceleration of the top shelf with respect to the acceleration at the base (Maximum absolute acceleration/Maximum input base acceleration) ranges from approx. 1.5 to 3.0. Amplifications of up to 4 were obtained when the system was loaded such that the heaviest glass negatives are located at the bottom. Note, however, that amplification factors are not obtained from synchronous values.
- A maximum deflection of 0.077 m at the top of the shelf was calculated. This corresponds to a drift of 3.4% of the total height. The lateral deflection limits for buildings are limited to 2.5% of the overall height, according to Cl.4.1.8.13 of the 2005 NBC, but this requirement would not apply to such a structure. Since the shelving system under consideration is not located too close to the wall, pounding is not a problem and stringent drift limitations are not necessary.
- On most shelves the glass negatives, stored in paper envelopes, are filed tight enough to avoid impact with adjacent glass negatives or the sides of the shelving system. The envelopes are filed so that the shorter side is along the depth of the shelf. No measures have been implemented to prevent contents from sliding off of shelves in the transverse direction. Due to the low coefficient of friction between the

paper envelopes and the steel shelves, the glass negatives will most likely start sliding transversely on the shelves and topple on the floor under even small base motions.

Case Study 2: Dinosaur Skeleton Model

The objective of this case study is to investigate the seismic sensitivity of a 6m long dinosaur skeleton model display, as illustrated in Fig. 3. The seismic vulnerability is determined based on the natural frequency extracted from the measured accelerations of the dinosaur structure left in free vibration after being excited by a small impact. The seismic design force for the dinosaur is determined according to the resulting frequency properties, and compared to the horizontal seismic design force as recommended by the 2005 NBC.

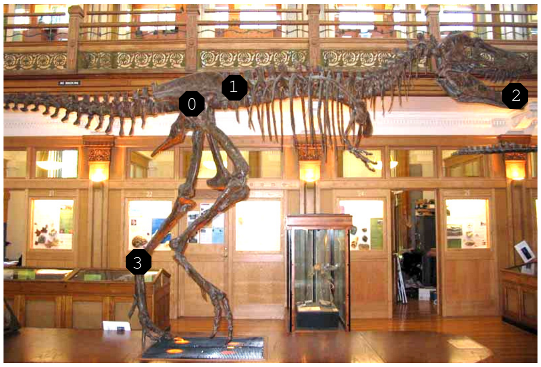

Figure 3. Albertosaurus Rex and accelerometer location and identification

Test Specimen

The vertebrae, ribs, skull, and arms of the composite skeleton structure are made from water extended polyester and the long bones are made up of polyester gel coat and fiberglass. The entire skeleton is painted with acrylic paint. A schedule 80 steel pipe runs through all the vertebrae and legs and serves as the connection to the base. The manufacturer estimated the weight of this structure at 2.67kN.

Testing Program

The dinosaur structure is set into free vibration by small impacts such as touching the skeleton lightly, jumping nearby, or applying a small impact at the base. Acceleration measurements were taken while the structure was in free vibration. The location and identification of four accelerometers are shown in Fig. 3. The placement of the accelerometers was chosen to capture a representation of the overall vibrational behavior of the dinosaur structure. Accelerometer 3 has been placed to measure the response in the vertical direction while the other instruments measure the horizontal accelerations in the longitudinal direction of the skeleton.

Test Results

A Fast Fourier Transform (FFT) analysis was carried out on the acceleration response curves for each test run at a point after the impact to determine which frequencies were excited by impacts. To simulate earthquake excitation, a small impact was imparted to the base in the horizontal direction. Fig. 4 presents the FFT curve for that acceleration response.

Seismic Vulnerability

The FFT curves that were obtained for each of the test runs from the free vibration analysis demonstrate that for a complex structure like this skeleton model there are many significant modes of vibration. For example, accelerometer 2, which is located in the mouth of the dinosaur at an outermost point of the structure, has a frequency content which differs significantly from that at other locations due to local articulation effects. The results reveal that due to small impacts, the frequencies that are excited range from approximately 1 to 20 Hz. Since earthquakes are expected to excite frequencies up to 10 Hz, it can be concluded that the skeleton is possibly vulnerable to seismic excitation.

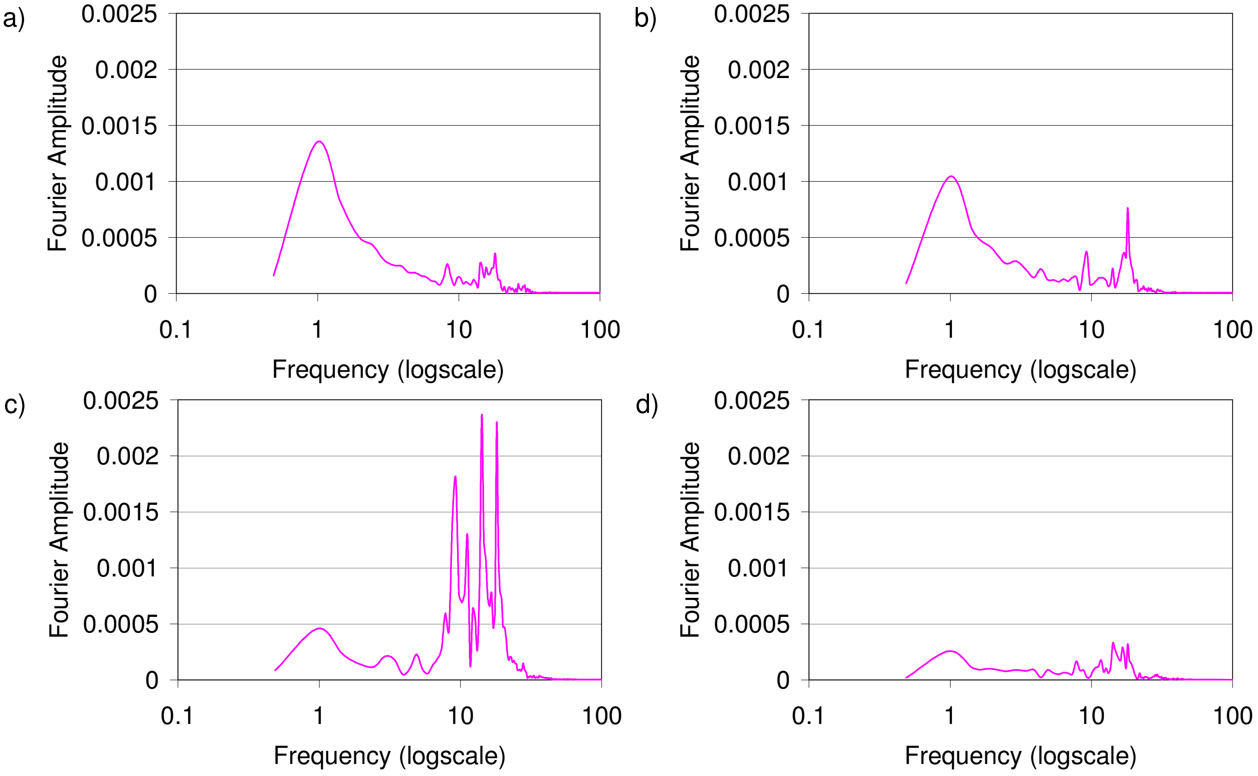

Figure 4. FFT for acceleration response of accelerometer a) 0, b) 1, c) 2, and d) 3

Seismic Force Calculation

As part of the seismic design requirements for nonstructural components, the 2005 NBC determines the horizontal seismic design force equal to 1287 N. Based on the frequency properties obtained from the measurements the design force is calculated at 267 N. This reveals that the code requirements are for the maximum anticipated forces and are therefore conservative design requirements for this example.

Case Study 3: Display Cases

This section introduces the experimental testing program that was conducted to investigate the seismic vulnerability of three unrestrained museum display cases. A series of shake table tests were conducted at the Structural Laboratory at École Polytechnique in Montréal for that purpose.

Test Specimens

The three display cases are shown in Fig. 5. They are made of high-density fiber board. The maximum dimensions for display cases 1, 2, and 3 (excluding the height of the Plexiglas cover) are 1.85*1.50*0.91m, 1.59*0.77*0.91m, and 0.68*0.68*1.07m respectively. The total mass (including the

Plexiglas cover) was found to be 147kg, 70kg, and 55kg for display cases 1, 2, and 3 respectively. Display cases 2 and 3 are symmetric in geometry, whereas display case 1 is constructed so that its supports are asymmetric with respect to the table top. The support conditions of display cases 1 and 3 have been modified with additional plastic supports.

Experimental Setup

The display cases are left unrestrained on museum floors. To simulate the surface friction conditions of the museums, hardwood and carpet floors were constructed and bolted on the shake table. The specimens were positioned on top of the shake table so that the short dimension of the display case is in the direction of shake table excitation.

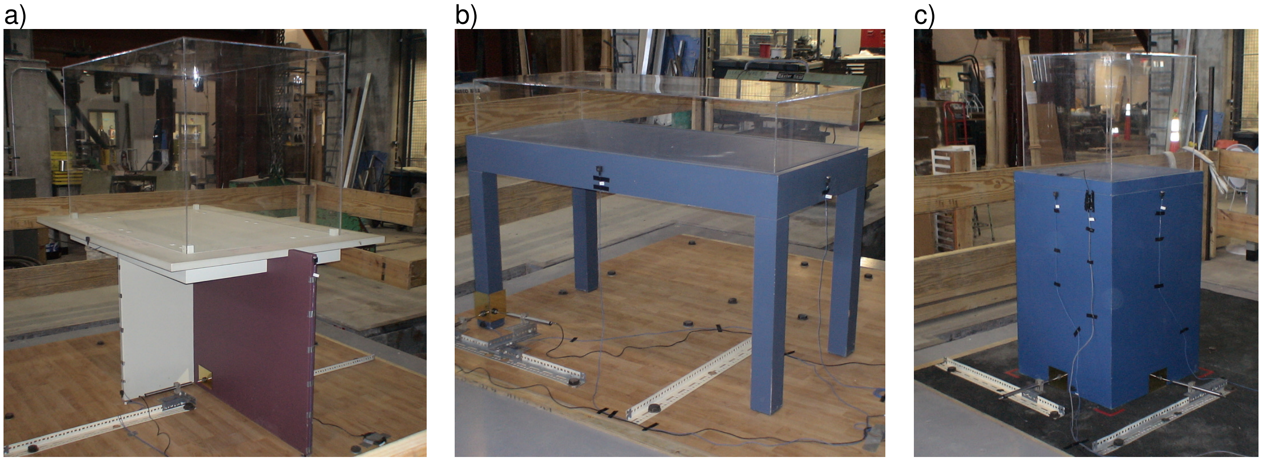

Figure 5. a) Display case 1 on wood, b) display case 2 on wood, and c) display case 3 on carpet.

Instrumentation

Instrumentation for each shake table test included accelerometers to determine acceleration responses and Linear Variable Displacement Transducers (LVDTs) to determine displacements. A film camera was set up to record each test series. The accelerometers were installed to measure the absolute horizontal acceleration of the shake table and to monitor the acceleration response of the display cases at the base of the display case and at the top of the display cases in the horizontal plane in the direction of excitation and perpendicular to it. For display cases tested on carpet, an additional accelerometer was installed to measure the acceleration response in the vertical direction. The acceleration response of greatest interest is that at the top of the display case, at the location of art object display, in the direction of shake table excitation. The results of the remaining accelerometers are important to monitor the overall behavior of the display cases.

Even though the shake table excitation is in one direction only, sliding and/or rocking/jumping of the display cases can occur in two horizontal directions. LVDTs were therefore installed parallel and perpendicular to the horizontal base motion. Small magnets were installed at the end of the LVDTs and steel plates were fastened to the display cases as target points, as illustrated in Fig. 6. This ensured that LVDTs remain undamaged due to sideways motion of the display case. The LVDTs were fixed to the floor surface of the shake table to determine the relative displacement between the display case and the shake table.

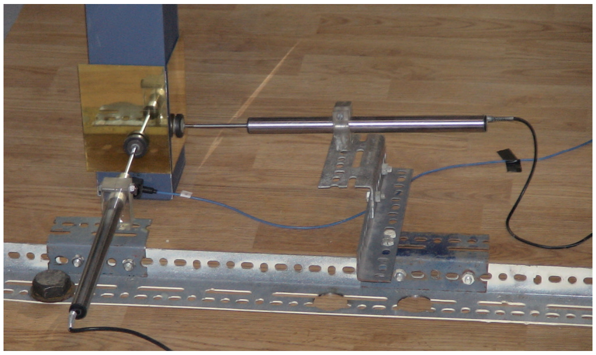

Figure 6. Installation of LVDTs, modified with magnets.

Test Series

The experimental program was conducted to investigate the effect of several parameters on the seismic response of the display cases. Three display cases of different geometry and mass were tested to investigate their seismic response and allow for comparison of varying stiffness and dynamic properties. The effect of ground motions of different intensity-frequency content were investigated for a seismic hazard at a probability of exceedance of 2% in 50 years. To account for the fact that the response of the display cases depends on the floor elevation, floor motions as presented in Table 1 were used as shake table input. Hardwood as well as carpet floor surfaces were investigated to determine the effect of modified surface friction conditions on unrestrained display cases. Cast iron plates of different weight were positioned on the display surface to represent art objects and determine if display case response is altered.

The test sequence was performed to investigate the effect of the change of a single parameter. Free vibration tests of the three display cases on each floor surface were performed prior to shake table testing to determine their fundamental frequency of vibration. For hardwood floor conditions, the fundamental frequencies of vibrations for display cases 1, 2, and 3 were 3.6Hz, 7.0Hz, and 13.7Hz respectively, and on carpet, the respective values were equal to 4.5Hz, 6.3Hz, and 10.7Hz.

Conclusions and Recommendations

Conclusions and recommendations are provided for the three case studies respectively.

Case Study 1: Shelving System

The seismic performance of the shelving system under investigation is twofold. It consists of the seismic performance of the shelves as well as the response of the stored contents. The shelves have to be adequately designed, installed, and loaded to resist earthquakes. Hence, shelves have to be designed to prevent collapse and overturning and contents should be restrained. Consistent with target performance levels, ground motions were chosen for the Montréal region to assess the seismic performance of the shelving system. The accelerations and deflections that the shelving system would experience under strong shaking were shown to be significant. Brittle glass negatives stored on the shelves with these levels of accelerations are expected to slide off and break. The current shelving system does not provide sufficient seismic resistance and is proven to be vulnerable to ground shaking. Some recommendations are provided that can be implemented to improve the seismic performance of the shelving system:

- Anchoring should be provided at the bases of the end and center columns to avoid overturning of the shelving system. Base plates, bolted to the floor, should be provided.
- To increase the out-of-plane stability of the shelving system, the shelves should be connected at their top to adjacent shelving rows with steel members stiffer than presently used.

- The shelving system is currently placed at a safe distance from the wall in the weak direction. The system experiences deflections up to approximately 8 cm at the top under strong shaking. Sufficient space between the walls and the shelving system is needed to ensure that impact is avoided.
- To prevent contents from sliding off the shelf, the contents should be secured on the shelves. Contents can be restrained simply by installing cables, chains, or straps at the front of the shelves.
- To avoid contents from breaking due to impact with adjacent objects or the end of the shelf, they should be stored tightly or restrained sideways.
- Care has to be taken to avoid overloading of the shelves. Increased masses will induce increased seismic forces imposed on the system.
- Contents of varying mass are currently distributed over the shelving system according to historical context. This random mass configuration should be maintained.

Case Study 2: Dinosaur Skeleton Model

Based on the frequency properties of the dinosaur skeleton model, it was concluded that the structure is seismically vulnerable. It was determined that the 2005 NBC provides a conservative seismic design force recommendation.

Case Study 3: Display Cases

The experimental program that was conducted to investigate the display cases was presented. The test series were aimed at investigating the effect of display case stiffness, earthquake motion characteristics, elevation of floor height, surface friction condition, and art object mass on display case behavior. Detailed results of these test series are not presented in this text but can be found in (Neurohr 2007). Of particular interest in the experimental setup was the installation of LVDTs. The LVDTs, modified with magnets at their ends, proved to be a very successful test setup to record the displacements due to sliding or rocking/jumping in the horizontal plane of the display cases in motion.

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