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Experimental Modal Analysis and Seismic Mitigation of Statue-Pedestal Systems

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Abstract

The seismic protection of cultural heritage, particularly statues, is a critical issue due to its high cultural significance, difficulty to repair or replace artifacts, and observed poor behavior during past earthquakes. Recent research has explored analysis techniques and methodologies for predicting the seismic response of statues; however, these studies typically assume the statue to be either freestanding or rigidly attached. The seismic response of statues with these different boundary conditions varies widely and therefore accurate characterization is critical. While modern mounting techniques aim to rigidly attach a statue to the floor or to a pedestal, the degree of rigidity of the as-built system may vary greatly, particularly for large and heavy statues, which are difficult to mount. To this end, experimental modal analysis and system identification were conducted on six statues while in their installed condition at the Asian Art Museum in San Francisco, California. The tested statues were large, typically stone, and restrained with different mechanisms for comparison. The statue-pedestal-restraint systems were observed to be quite flexible with natural frequencies as low as 3 Hz. However, certain systems, which incorporated an embedded base of the statue, were much stiffer with frequencies around 14 Hz. It is noted that

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this type of testing requires significant contact and excitation of the statue. This rare opportunity to work directly with the statues resulted in a valuable dataset summarizing their dynamic characteristics for museum engineers and curators. In cases where rigidity is not attained, there is concern that the statue's natural frequency may be too close to that of the anticipated floor motions. For this reason, a simple and non-intrusive base isolation system is detailed. This system was further verified through shake table testing and is shown to sufficiently reduce earthquake demands to the statue.

Keywords: system identification, museum contents, statue, experimental modal analysis, seismic isolation, cultural heritage

1. Research Aims

The aim of this research was to quantify the dynamic characteristics of typical statue-pedestal systems which incorporate modern mounting techniques. While art objects are often intended to be fixed to their pedestal and/or the museum floor, the degree of rigidity of the constructed system is generally unknown. This variability can have a significant impact on the seismic response of the statue-pedestal system. Therefore, experimental modal analyses were conducted on six large, human-form statues while in their installed condition at the Asian Art Museum in San Francisco, California (USA). These statues were full-scale, typically stone, and incorporated various restraint systems. Experimental procedures, such as this, are very rarely allowed due to the full-contact nature of the testing; and, as such, this manuscript is not intended to provide a comprehensive methodology for the seismic assessment of any arbitrary statue. Rather, the dataset can be used for qualitative guidance on the dynamic characteristics of statue-pedestal systems with modern restraints. Furthermore, a simple seismic isolation system is presented, which can be incorporated for statues unable to achieve rigidity.

2. Introduction

The preservation and seismic protection of cultural heritage has become a particularly important focus of both the earthquake engineering and museum communities. Damage to cultural heritage, particularly large, human-form or other slender, heavy statues, can be particularly devastating because the artifacts are not only historically significant but also unique and irreplaceable. Moreover, catastrophic toppling or other excess movement may pose significant safety hazards during an earthquake. Damage to heritage statues has been observed repeatedly following earthquake events around the world, such as the 2009 L'Aquila (Italy) [1], 2014 South Napa (USA) [2], and the most recent 2015 Gorkha (Nepal) earthquakes [3]. As a result, it is critical to understand how the statues interact with their pedestals and restraint systems when subject to earthquakes. Provided this understanding, seismic mitigation methods can be proposed and implemented in an effort to protect cultural heritage.

Due to the importance of heritage protection, numerous studies have been presented in the literature focusing on the prediction of the seismic response of statues. To the authors' knowledge, the earliest, most profound major study in this area was conducted at the J. Paul Getty Museum in Los Angeles, California (USA) [4]. In this study, the seismic vulnerability of the museum contents was determined based on rigid body dynamics and estimated geometric properties. More recently, a multi-disciplinary diagnostic analysis of Michelangelo's *David* was conducted to assess the current state of health of the statue [5]. While the investigation focused on understanding the existing crack distribution, laser vibrometry was also conducted in an effort to gage the dynamic properties of the restrained statue and predict its seismic response. Building upon previous works, a comprehensive interdisciplinary methodology for the seismic assessment of statues was presented by Berto et al. [6] as they combined historical, material, and structural analyses. Using highly accurate geometric data, the authors used static analyses to determine the acceleration of the ground necessary to induce rigid body motions of the statues. They further studied the effect of rigid restraint systems through dynamic finite element analyses. Most recently, Aktaş and Turer incorporated modal analysis and system identification of the large freestanding Nemrut monuments in Turkey [7]. The determined modal frequencies were used to calibrate a detailed finite element model, which was subsequently used to assess the monuments' vulnerability and guide seismic mitigation strategies.

While much of the literature proposes methodologies targeting the application of freestanding statues, many statues are also supported with modern restraint systems, such as those detailed by Lowry et al [8]. These restraints are intended to prevent overturning of the statue, which may occur during an earthquake or by an accident. At the same time, the presence of the restraint system should not detract from the ability to view the statue or artifact. As a result, the restraint likely has some degree of flexibility and is not perfectly rigid, particularly for large, heavy statues. This flexible statue-restraint system may have fundamental periods of vibration that are close to those of the floor-level earthquake motion, which may potentially impose significant forces causing damage to the statue system.

In an effort to expand upon previous methodologies for the seismic assessment of statues, experimental modal analyses of six large statues are presented in this paper. The statues studied were mounted in a museum incorporating various types of modern restraint systems. The determined natural frequencies are correlated to the rigidity of the as-built statue pedestal system. The natural frequencies are then compared to the anticipated input assuming a maximum considered earthquake hazard. A simple and non-intrusive base isolation system is then utilized as a means of seismic isolation for those statues found to be particularly vulnerable.

3. Description of Museum and Statues Tested

Testing of six statues was conducted on-site at the Asian Art Museum in San Francisco, California, in October 2014. San Francisco is a region of particularly high seismicity and therefore special attention is needed to protect the museums and their contents. This particular museum building is a historic, three-story structure, which was originally the San Francisco Old Main Library. The building was heavily damaged in the 1989 Loma Prieta earthquake and subsequently underwent significant seismic retrofitting and base isolation prior to becoming the home of the museum. Design and analysis of the retrofit of the building, by Forell/Elsesser Engineers, indicates the newly base isolated building would have a period of 2.4 seconds (frequency of 0.42 Hz), dramatically protecting it from damaging earthquake motions [9].

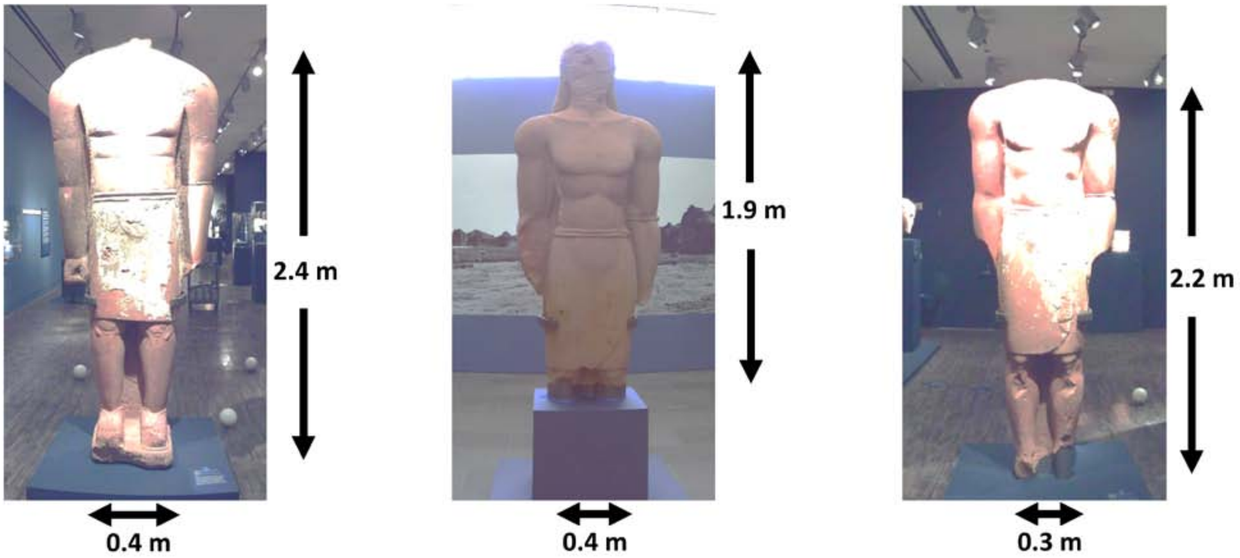
The museum's primary collections include both modern art and ancient archaeological artifacts from all areas of Asia. In addition to these collections, at the time of this study, the museum was host to the *Roads of Arabia* exhibition sponsored by the Smithsonian Institute.

This exhibition contained hundreds of pre-Islamic artifacts from Saudi Arabia. Six total statues were tested with three from the primary collections and three from the *Roads of Arabia* exhibit (*Colossi* statues). The three *Colossi* statues were chosen due to their cultural significance, size, and weight. The three statues from the primary galleries were chosen due to their unique restraint systems, which in particular allowed a comparison to that of the *Colossi*. Similar to the *Colossi*, these statues are also considered quite significant and were also considered vulnerable by the museum due to their massive size and weight.

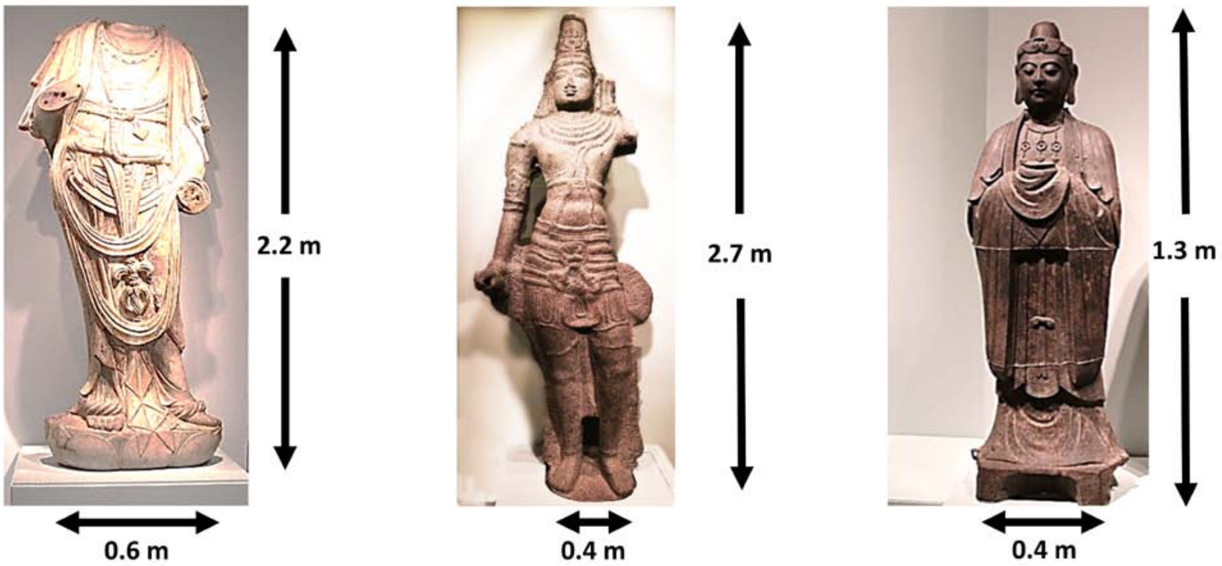
Historical and physical details of the selected statues are included in Table 1. Images of each of the statues and the statue restraint systems are included in Figs. 1 and 2, respectively. It is noted that each of the statues is monolithic and did not exhibit visible signs of damage, such as surface cracking or otherwise excessively deteriorated regions. The *Colossi* statues ranged in height from 1.9 – 2.4 m and are constructed of solid sandstone. These statues are restrained laterally using contoured arms, which surround the statue on roughly three sides at the approximate "waist" of the statue (20 – 40% of the height of the statue; Fig. 2a-c). These arms are attached to a separate steel post to the pedestal upon which the statues rest. Due to the uneven bases of the statue, a molded foot was custom constructed for

Table 1. Historical and physical attributes for each of the tested statues.

Statue	*Date*	*Origin*	*Material*	*Restraint Description*[1]	*Mass [kg]*	*Statue Height [m]*	*Height of Lateral Restraint [m]*
Colossi 111	4th – 3rd c. BCE	Saudi Arabia	Sandstone (monolithic)	(2) contoured arms along height; custom-mold base	1100	2.48	0.95
Colossi 112	4th – 3rd c. BCE	Saudi Arabia	Sandstone (monolithic)	(2) contoured arms along height; custom-mold base	725	1.98	0.40
Colossi 113	4th – 3rd c. BCE	Saudi Arabia	Sandstone (monolithic)	(2) contoured arms along height; custom-mold base	700	2.25	0.95
Bodhisattva	10th-11th c. CE	China	Marble (monolithic)	embedded epoxy anchor tensioned at base via turnbuckle	850	2.16	0.0
Rama	14th-16th c. CE	India	Granite (monolithic)	embedded base within pedestal	550	2.69	0.0
Attendant	15th-16th c. CE	China	Iron (monolithic)	(3) contoured clips at base	<100	1.35	0.0



(a) ***Colossi 111*** **(b)** ***Colossi 112*** **(c)** ***Colossi 113***

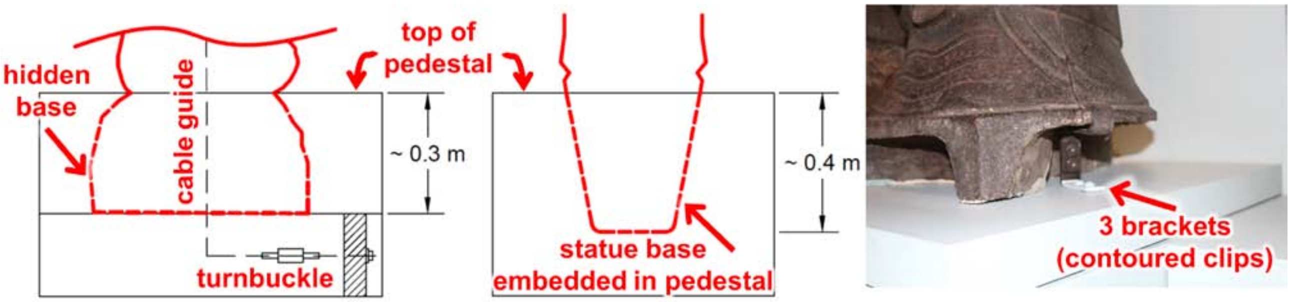


(d) ***Bodhisattva*** **(e)** ***Rama*** **(f)** ***Attendant***

Fig. 1. Tested statues at the Asian Art Museum from (**a-c**) the *Roads of Arabia* exhibit, and (**d-f**) the primary museum collections.

the statue to rest. The first of three primary gallery statues is a 2.2 m marble statue of the Chinese *Bodhisattva*. This statue has an embedded epoxy anchor approximately 0.3 m from its base. This anchor is tensioned by way of a cable and turnbuckle system below the statue base (within the hollow pedestal; Fig. 2d). The second primary gallery

(a) ***Colossi 111*** **(b)** ***Colossi 112*** **(c)** ***Colossi 113***



(d) ***Bodhisattva*** **(e)** ***Rama*** **(f)** ***Attendant***

Fig. 2. Images and drawings detailing the restraint mechanisms of each of the tested statues. Note that the restraint system was typical across the *Colossi* statues.

statue is a 2.7 m granite statue of the Indian god *Rama*. The tapered base of this statue is placed within a solid concrete pedestal with corresponding tapered hole (no epoxy or drilling of the statue). The final statue is a 1.3 m iron statue of a Chinese *Attendant*. This statue is restrained using contoured bracket clips at three points along its base. While these clips are bolted to the pedestal, they are not bolted to the statue and are snug against the statue base. All of these unique statues systems are evaluated by way of experimental modal analysis, as presented in the following section.

4. Experimental Modal Analysis

Experimental modal analysis (EMA) is a technique used to determine the natural frequencies and modes of vibration of a structure. Similar to operational modal analysis, the process consists of measuring the acceleration of a structure at numerous points. In contrast to operational modal analysis, EMA provides a known input to excite the vibration of the structure and increases the signal-to-noise ratio. While this input can be applied as harmonic input from a portable shaker or an impulse from an impact hammer, portable shakers may inadvertently excite other objects in the vicinity of the intended test specimen, in addition to the target. As a result, EMA with an impact hammer is the ideal choice for determining the natural frequencies of the as-built statue-pedestal-restraint systems. It should be noted that this technique not only requires multiple sensors to be in direct contact with the statue, but also requires contact at the point of impact of the hammer. For this reason, EMA is typically not permitted by museums and the analyses described in this paper are exceptionally rare.

4.1. Test Setup and Procedure

Due to the sensitive nature of testing culturally significant statues, the test setup is described in particular detail as it deviates from traditional structural monitoring. Images of a representative test setup are included in Fig. 3 for *Colossi 112*; however, sensor attachment and general sensor placement were consistent for all tests reported. Each statue was instrumented with seven small, lightweight, uniaxial accelerometers along the height of the statue as well as along any restraint system. The accelerometers are piezoelectric sensors with a dynamic range of 0.5 – 10,000 Hz at 500 g. Firm attachment of the sensors is critical for direct measurement of the statue acceleration. However, use of harsh adhesives or drilling into the statue is clearly not permitted. As a result, the sensors were held in place by a rubber strap. In addition, to avoid introducing or removing any particulates from the surface of these artifacts, a polyethylene wrap was placed beneath the rubber straps with a small hole to allow only the sensor to come into contact with the statue. Where permitted, such as on the modern restraint system, magnetic tips were used to affix the sensors to the structure. A 0.90 kg modally-tuned hammer was used to tap the statue and excite its natural frequencies. The hammer has a hard rubber tip to avoid localized surface damage. The force of the hammer and acceleration of the sensors were recorded by a laptop-controlled portable signal conditioning and data acquisition system. The testing procedure consisted of tapping the statue and recording the

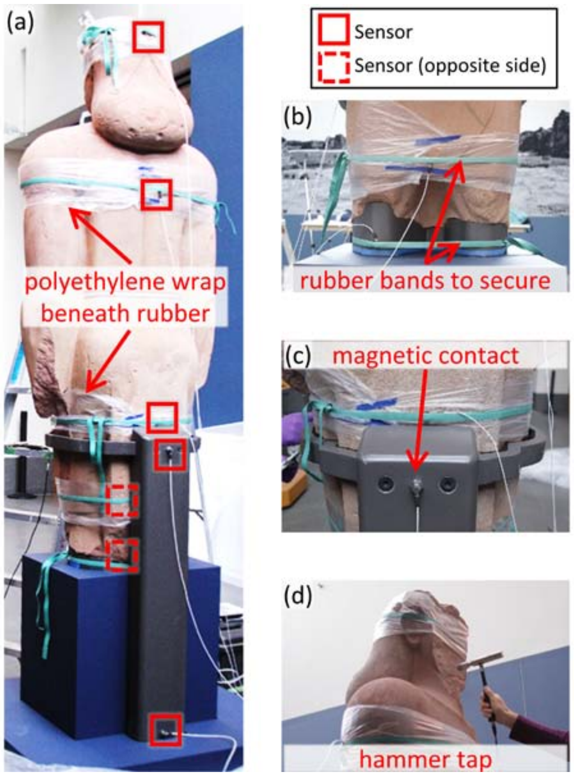


Fig. 3. Sensor placement for a sample test along statue and restraint system: (**a**) *Colossi 112* with 7 accelerometers attached and wrapped polyethylene beneath (**b**) rubber bands securing the sensors to the specimen; (**c**) magnetic tips were used to secure the sensors to steel posts; and, (**d**) hammer tap at a relatively flat surface at the top of the statue.

free vibration for 8 seconds. Each test was repeated five times. In an effort to identify all primary modes important for response during an earthquake, taps were applied in two orthogonal horizontal directions both at the top of the structure and at approximately mid-height. Due to the highly irregular geometry, it is recognized that the same modal frequencies may be identified following taps in each direction. However, the relative amplitude of the modal response will vary according to the direction.

4.2. Data Processing

To understand the vibrational response of the statues, the time histories of acceleration are transformed to the frequency domain via Fast Fourier Transform (FFT). The magnitude (absolute value) of the

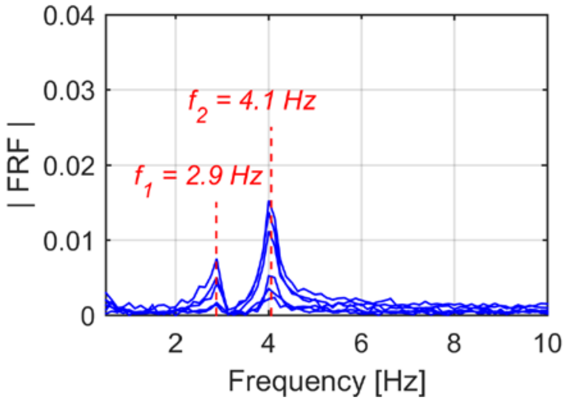


Fig. 4. Magnitude of the frequency response function (FRF) for each sensor on *Colossi 112*.

ratio of the FFT of the output (measurement on the statue) to that of the input (that on the hammer tip) is known as a Frequency Response Function (FRF), or more commonly via its short name as a transfer function. To increase the resolution of the transfer function, the FRF is taken as the average of the five trials of each test. Relative peaks in the final FRF indicate the presence of a natural frequency or mode. The mode is considered global if all of the sensors along the system align at the peak. If only a few of the sensors align at the peak, the mode would be considered local. The FRFs of all sensors for a representative test, corresponding to the setup of *Colossi 112*, are overlaid in Fig. 4. In this figure, each FRF clearly contains peaks at frequencies of 2.9 Hz and 4.1 Hz indicating global modes. This process was repeated for all test configurations and all statues.

5. Results

The goal of the modal analysis was to determine the lowest natural frequencies or modes of the constructed statue-pedestal-restraint systems, as these may be activated during an earthquake. Higher modes are not considered in this study because they are difficult to excite in testing due to the low amplitude excitation. The following test results are presented in terms of the two lowest observed natural frequencies or modes, f_1 and f_2, regardless of direction. Mode shapes are not presented for these frequencies, as they are not essential for the current test objectives. Furthermore, the imperfect surfaces did not allow the sensors to be in precisely the same direction. However, the modal data provide evidence that global modes involving the statue, pedestal, and restraint system exist as seen in Fig. 4. While each mode may have been more significantly excited due to impact in one direction, both modes were discernible when the statue was excited in either of two orthogonal horizontal directions at both the top of the statue and at mid-height.

5.1. As-Built Restraint Systems

A scatter plot of the two lowest natural frequencies (modes 1 and 2) of each of the statue-restraint systems is presented in Fig. 5. In this graphic, mode 1 is associated with the lowest observed natural frequency and mode 2 with the second lowest. Each of the plotted modes was observable when excited in either horizontal direction and is not associated with a specific axis of vibration. Both modes for each statue

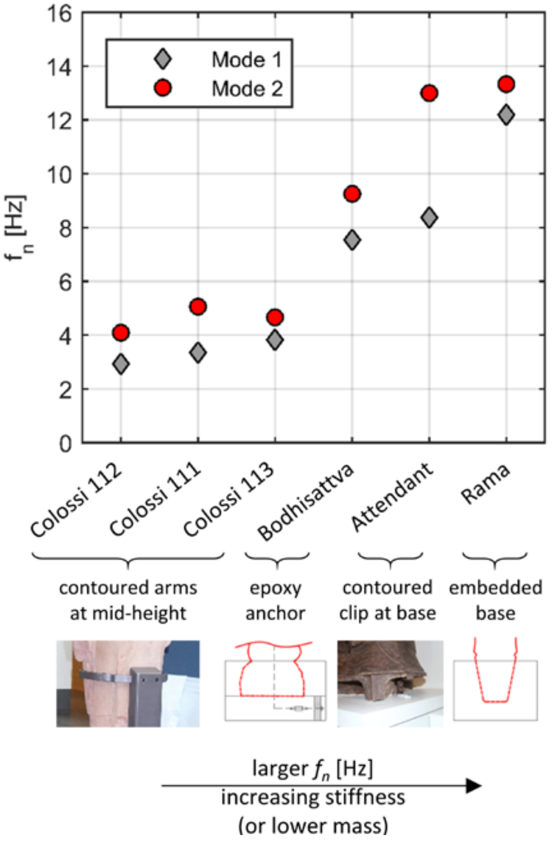


Fig. 5. First two natural frequencies of each of the tested statue-restraint systems.

were less than 16.67 Hz, which is a common lower bound identifying whether a system will behave rigidly during earthquake excitation [10]. It should be noted that the first bending mode associated with vibration of the fixed-base statues themselves would be an order of magnitude larger than the plotted frequencies, and the statues alone would be considered rigid. For example, a fixed-base *Colossi 112* is estimated (via hand calculation and finite element analyses not presented herein) to have a natural frequency around 40 Hz. This indicates that the experimentally measured frequencies are associated with a system-wide mode of the statue-pedestal-restraint system; and, that the system cannot be considered as rigid. Furthermore, this graphical representation of the results emphasizes the dramatically lower natural frequencies of the *Colossi* statues with frequencies less than 5 Hz. This indicates that these sculptures, in this installed condition, are much more flexibly attached than the other statues from the museum's primary collections. This system provides lateral restraint only at mid-height whereas the remaining statues were laterally restrained at their bases. However, the flexibility of the *Colossi* system is likely more dependent on the implementation and fit of the arms and less so on the location of the arms. This is further explored in the following section.

The statue of *Rama* in the primary galleries exhibits the highest natural frequencies with both greater than 12 Hz. The simple restraint system used for this statue consists of a solid concrete pedestal with a drilled hole. The drilled hole was custom fabricated to fit the base of the statue; and, the statue was placed in the hole without the use of epoxy or bolts. Not only does this system provide near-rigidity to the statue's restraint, but it also lowers the system's center of mass, which becomes critical in terms of overturning potential during an earthquake. The statue of *Bodhisattva* has a slightly more rigid system than the *Colossi* statues with frequencies around 8 Hz, but not quite as rigid as the installed *Rama*. In this case, the employed restraint system requires significant, irreversible modification to the statue in the form of drilling at the base and epoxied anchors. The final tested statue of the *Attendant* exhibited modes near that of both *Bodhisattva* and *Rama* at 8 Hz and 13 Hz. The restraint for this statue consisted of a simple, non-intrusive system with bracket clips providing lateral restraint at the base at three distinct points. While these clips are designed to contour to the base of the statue, they are bolted only to the display pedestal and require no drilling or modification to the statue. However, the rigidity of a statue mounted in this way would be strongly linked to how well the clips contour the base.

5.2. Modified Restraint Systems

Due to the relatively low natural frequencies associated with the first two modes of response for the *Colossi* statues, comparative tests with a loosened restraint system were performed on two of the *Colossi* statues. The primary restraint of these statues is provided by contoured steel arms, located at approximately one-third the statue height (i.e. waist of the statue), which were hand-tightened by the museum mountmaker (Fig. 2a-c). Prior to these comparative tests, the steel arms were loosened slightly by the mountmaker or conservator. The arms were not completely backed off of the statue to preclude overturning. It is anticipated that loosening the restraint would lower the stiffness of the combined system and reduce the system's natural frequencies.

Fig. 6a contains the overlaid FRF of *Colossi 111* in both the as-built condition and the loosened restraint condition. These FRF are obtained from the same, unmoved sensor near the top of the statue. As anticipated, a reduction of frequency associated with both modes is observed. This observation further emphasizes that these low-frequency modes are associated with the response of the entire statue-pedestal-restraint system. In comparison, the bending mode frequencies, as estimated via hand calculations and finite element analyses, are on the order of 40 Hz. According to this trend, one may anticipate that an increase in stiffness and system rigidity may be obtained by increased tightening of the system, as well. However, it should be recognized that nominal loosening will likely occur when the system is subjected to larger amplitude dynamic motions, such as occurring during an earthquake. In an effort to quantify the frequency shift, Fig. 6b plots the ratio of the frequencies of both statues in the loosened condition to that of the as-built configuration. While the loosened system frequencies are consistently lower than that of the as-built system, as anticipated, the reductions are consistently less than 5%, which highlights the role of other components, such as the pedestal, in the flexibility of the combined statue-pedestal-restraint system.

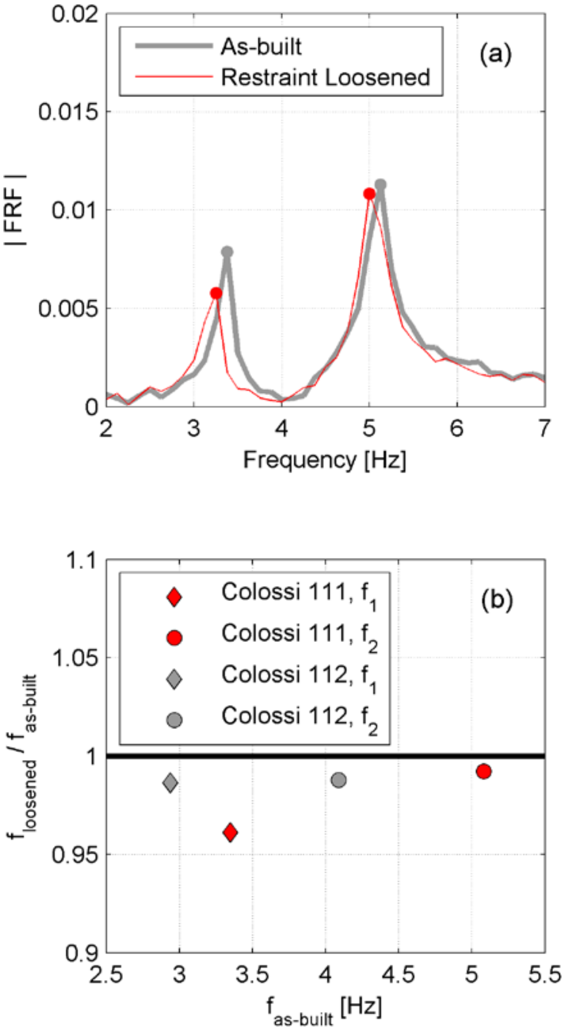


Fig. 6. (**a**) Frequency response function of *Colossi 111* in its as-built configuration overlaid with that of the restraint system loosened. (**b**) Ratio of the natural frequencies of the loosened system to that of the as-built system for *Colossi 111* and *Colossi 112*.

5.3 Comparison with Building Response

The tested statues are observed to be fairly flexible with complex restraint systems. Therefore, statue-specific time history analyses may be difficult to accurately conduct, given the assumptions needed for modeling at the connections. Furthermore, the studied statues are housed in a base-isolated structure and would be subject to a strongly filtered earthquake motion. As a result, a simplified comparison of the statue-restraint systems to anticipated average building response is presented. The structural designers responsible for the seismic retrofit and base isolation of the Asian Art Museum generated acceleration spectra for the individual floors and wings of the building [9]. The mean spectrum was generated using earthquakes scaled to a probability of exceedance of 2% in 50 years. The spectrum presented in Fig. 7 is for the critical gallery floor, which is subject to the largest dynamic amplification. The lowest natural frequency (first mode) of each statue-pedestal-restraint system is overlaid on this spectrum such that an approximation of any amplification due to the flexibility of the construction can be determined.

Referring to the overlaid lines in Fig. 7, the primary gallery statues (i.e. *Bodhisattva*, *Attendant*, *Rama*) are sufficiently stiff such that very little amplification at low levels of acceleration is likely to occur. This implies that the acceleration of the museum floor that the statue is subject to would not be amplified by the vibration of the installed statue-pedestal-restraint system. This amplification (or lack thereof) is presented on the right axis of Fig. 7, which indicates the ratio of the pseudo-spectral acceleration at a given frequency to that at a frequency of zero (rigid). As such, the natural frequencies of the *Colossi*

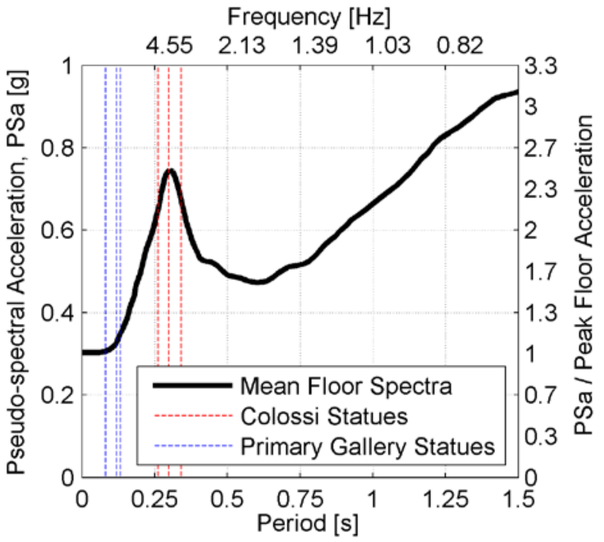


Fig. 7. Design floor response spectrum (digitized from: Tuholski and Rodler [9]) overlaid with the first modes of the *Colossi* statues and the primary gallery statues (5% damped).

statues are observed to lie within a region of amplification. Due to the flexibility of the system, the *Colossi* statues would be subject to nearly 250% the acceleration of the museum floor. To this end, an alternative method for seismic mitigation is required to avoid potentially large amplitude displacement and acceleration demands.

6. Seismic Isolation

Seismic isolation, or colloquially termed base isolation, is an effective means of protecting structures from the damaging effects of earthquakes. In the present case, the historical building has been seismically retrofitted with lead-rubber bearing isolators placed between its foundation and the superstructure. Isolation of this type elongates the building's period (reduces the natural frequency). As a result, it is typically recommended to rigidly fix building contents to the floors as the contents are likely much stiffer, i.e. have frequencies much greater than that of the isolated building. However, certain contents, such as the *Colossi* statues in their installed condition, have natural frequencies that may result in amplification of seismic forces while on display. To overcome this, isolation at the statue-pedestal level can protect the statues from the floor level excitations anticipated during an earthquake.

Isolation systems are typically designed to elongate the period of the statue-pedestal system away from that of the building. Typical structural isolation (i.e. rubber bearings) is not applicable given the lightweight construction of the statues [11]. Alternative isolation systems targeted at smaller structures include friction-pendulum systems [12] and rolling systems [13]. However, these systems are still designed to shift the period of the statue-pedestal system requiring a statue-specific, and sometimes complex, design that is difficult to implement in a base-isolated building. An alternative system, which aims only to reduce the amplitude of seismic forces, is the flat sliding plate system. This system incorporates a low-friction interface beneath the pedestal; and, when subject to horizontal forces greater than its coefficient of friction, the system slides and the larger forces are not transferred to the statue. This system, therefore, also has the potential for large displacements during and after an earthquake, which typically limits its application. However, in this case, the sliding plate isolation system was selected, as the area around the statues was free of obstacles and the intent was to reduce the potential for large earthquake forces with limited frequency modification of the system.

6.1. System Description

The installed isolation system beneath the *Colossi* statues consisted of an assembly of low profile, low-friction sliding plates. This system is fitted to the width of the pedestal, less than a couple of millimeters in height, and is virtually invisible to patrons of the museum. Furthermore, this type of system is relatively simple for installation, as it does not require modification of the statue, the pedestal, or any restraints above the base. A schematic of this system as well as a close-up image beneath *Colossi 111* are shown in Fig. 8. In addition to these pragmatic attributes of the system, a low-friction interface seismic isolation system is conceptually simple and easy to convey to the non-engineering members of the museum community. When subject to lateral loading, the acceleration transferred to the statue-pedestal-restraint system will be a fraction of that which would be achieved for a non-isolated system. This fraction is the coefficient of friction, which in the case of the *Colossi* statue isolation assembly is 2%.

6.2. Experimental Verification

Prior to installation, the sliding plate system was tested on a uniaxial shake table with a representative pedestal and stiff statue-like structure. This experimental setup is shown in Fig. 8c juxtaposed with the installed system in Fig. 8b. The pedestal rested atop the same sliding plate isolation system that was installed beneath the *Colossi*, however it was characterized by an approximate coefficient of friction of 15%. While other sliding isolation systems have been tested in the past, the installed system consisting of unattached corrugated and coated steel plates had not previously been tested under earthquake motions. It is also noted that the culturally significant nature of the real Colossi statues precluded their transportation and use during shake table testing; therefore, the stiff, statue-like structure was designed to capture the mass and geometry of the statues. In addition, it was further restrained to a pedestal, yielding a system that is dynamically similar to the *Colossi*.

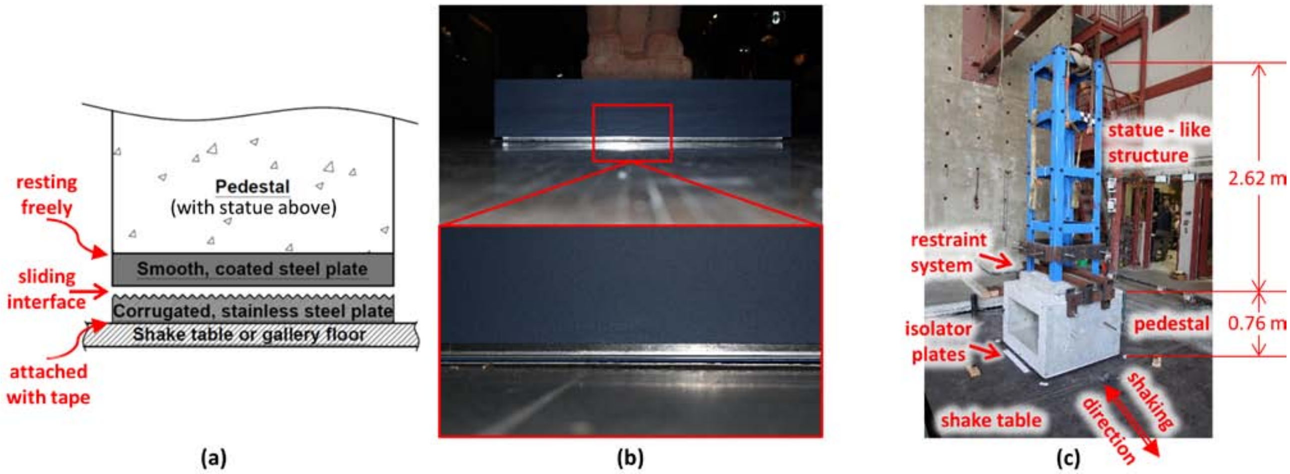


Fig. 8. (**a**) Schematic of the low-friction sliding plate isolation system. (**b**) Photograph of the installed isolation system beneath *Colossi 111*. (**c**) Experimental setup for shake table testing of the isolation system beneath a restrained statue-pedestal system.

A representative comparison is included in Fig. 9 for the response of the isolated and non-isolated systems subject to a motion from the 1999 Duzce earthquake recorded at Bolu station in Turkey, though the system was tested to a number of additional recorded motions (e.g. 1985 Valparaiso at USFM; 1989 Loma Prieta at Gavilan College; 1994 Northridge at UCLA). The motions used, including the Duzce motion as shown in Fig. 9, were selected due to the presence of long-period pulse content, which was anticipated to excite the response of both the pedestal and the statue-like specimen. The acceleration of the isolated and non-isolated pedestals is provided in Fig. 9 as both a time history and in the pseudo-spectral acceleration format. A significant reduction of amplitude for the isolated specimen is observed in both plots. However, the limited frequency modification is quite evident in the pseudo-spectral acceleration plot, which also includes that of the shake table (input). Moreover, in this plot, there is little modification to the general shape of the acceleration across most of the significant period range including the range of the statues' natural periods (less than 0.3 seconds). Specifically, for this example, the acceleration is reduced by nearly 50% in the range of the *Colossi* frequencies. It should be noted that this percentage might vary according to the amplitude of the input motion, as the sliding isolators will yield at accelerations in excess of the coefficient of friction. These and other test results support the use of a sliding isolation strategy for reducing the acceleration

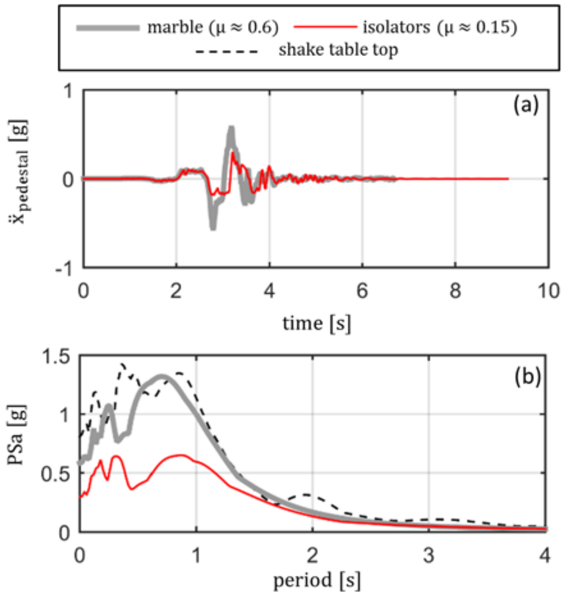


Fig. 9. Experimental results for the isolated system overlaid with that atop a typical marble interface: (**a**) acceleration time history of the pedestal, and (**b**) pseudo-spectral acceleration measured at the top of the pedestal and top of the shake table assuming 5% damping (motion from the 1999 Duzce Earthquake recorded at Bolu station in Turkey, see [14] for additional information).

demands to statue systems. It should be noted that this experimental test was part of a much larger campaign studying the seismic response of tall, slender, eccentric structures in various configurations; and, additional details, results, and analyses regarding this experimental campaign can be found in Wittich and Hutchinson [14, 15].

7. Conclusions

The seismic response of cultural heritage statues is an important area needing further research, particularly given their irreplaceable nature and significant damage from recent earthquakes. Analyses of statues typically treat the boundaries as either completely free (freestanding or unattached) or as completely rigidly attached to the ground or floor. However, the assumption of total rigidity may not be adequate as drilling or modification to the statue is rarely, if ever, permitted. In an effort to quantify the dynamic characteristics of typical as-built statue systems, experimental modal analysis was conducted for six statues at the Asian Art Museum in San Francisco, California (USA). The measured natural frequencies ranged from 14 Hz (near-rigid) to 3 Hz (flexible). These low frequency modes characterize how rigidly the as-built statue-pedestal-restraint system is attached, as the first bending mode of the fixed-base statues would be significantly larger. The stiffest system consisted of simply embedding the base of the statue into a well-fitted pedestal. This system requires no modification, drilling, or epoxying of the statue; however, it does entail obstructing the view of a portion of the statue. Lateral restraint just below the mid-height of the statue was the most flexible horizontal restraint system tested. A comparison of these measured frequencies with the anticipated building response during earthquakes indicated a potential for significant excitation of the statues restrained in this manner. For these most vulnerable statues, a simple non-intrusive seismic isolation system was installed. The proposed isolation system consisted of a low-friction interface beneath the statue's pedestal, which was shown to markedly reduce the seismic accelerations transferred to the statue while having little frequency modification.

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