Journal of Cultural Heritage 20 (2016) 641–648

Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en

Original article

Experimental modal analysis and seismic mitigation of statue-pedestal systems

Christine E. Wittich *, Tara C. Hutchinson

Department of Structural Engineering, University of California, San Diego, 9500 Gilman Dr. MC0085, La Jolla, CA 92093, USA

ARTICLE INFO

Article history:
Received 3 September 2015
Accepted 3 February 2016
Available online 2 March 2016

Keywords:
System identification
Museum contents
Statue
Experimental modal analysis
Seismic isolation
Cultural heritage

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 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.

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

* Corresponding author. Tel.: +1 (858)-866-8327.
E-mail addresses: cwittich@ucsd.edu (C.E. Wittich), tara@ucsd.edu (T.C. Hutchinson).

http://dx.doi.org/10.1016/j.culher.2016.02.001

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 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

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

Statue	Date	Origin	Material	Restraint description	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