Chapter 4
Seismic Vulnerability of Arches, Vaults and Domes in Historical Buildings

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ABSTRACT

Arches, vaults and domes are common features in the cultures of old civilizations. They were usually made of sun-dried bricks, fired bricks or stones with different types of mortar. The majority of these components are vulnerable to seismic effects. Furthermore, the thrust actions transmitted by arches, vaults and domes to walls and piers usually cause damage to the supporting walls or piers. The present chapter discusses the structural behaviour and performance of these elements in past earthquakes and reviews the numerical models used for the seismic assessment of these elements. Furthermore, different damage assessment approaches are reviewed and suggestions are made on further research.

INTRODUCTION

The term "historical buildings" refers to any type of construction that stands witness of past civilizations in that it conveys tractable information about technology, aesthetics, and way of life, customs, religious practices, art, defense and forms of government in former times (Pantazopoulou, 2013). Due to the many environmental causes; aging, earthquakes, traffic vibrations, wind and temperature loads, air pollution, and soil settlements, the structural elements of these buildings have been found vulnerable to cracking and dangerous failure mechanisms (Pantazopoulou, 2013). Of the many possible threats to the survival of historical buildings, earthquake stands as the principal threat due to the limited earthquake resistance capacity of these buildings (Asteris, 2008).

Domes and vaults were the favored choice for large-space monumental coverings for centuries (Kuban, 1987). For such structures, the construction materials should retain their strength as they subjected to different environmental conditions. Masonry, strong in compression, has been an ideal material to fit with these structural shapes. Timber has been rarely used in such historical monumental structures.

According to historical records, many arches, vaults and domes were subjected to severe earthquakes in the past without sustaining large dam-

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ages. The many historical monuments around the world that remained safe during many centuries are living examples of this fact. Furthermore, in recent years, many arches, vaults and domes had survived the effects of earthquakes with little or no damages. The Pantheon, the dome of St Peter's Cathedral, the aqueduct Pont du Gard, Nîmes, France, and the Segovia Aqueduct, Spain are few examples of the such monuments. Another more recent example of the behavior of such buildings has been demonstrated in the 1999 Kocaeli Earthquake. Most of the main compounds of mosques, having single dome with multiple semi-spherical domes, were generally intact or suffered very slight damage (JSCE, 1999; Dogangun & Sezen, 2012). Therefore, it can be concluded that each of these monuments had an inherent lateral strength that was sufficient to resist moderate sized earthquakes with an acceptable degree of damage (Palacios, 2004).

As a result of the many factors explained above, a gradual deterioration of materials or the load carrying structural system is expected to occur during the life time of the structure (Garavaglia, Anzani, & Binda, 2006; Dogangun & Sezen, 2012). Thus, it is essential to evaluate the capacity of existing structural members and assessing their retrofitting need (Dogangun & Sezen, 2012). From engineering point of view, a probabilistic measure of the damage to the building resulting from a given ground motion need to be specified. Thus, the vulnerability of an element in a historical building is defined as the probability that the said element will sustain a specified degree of structural damage given a certain level of ground motion severity (Palacios, 2004).

In general, there are two main types of vulnerability methods. The probabilistic approach (also called observed vulnerability) is, mainly, used when a group of buildings are studied and it is based on statistic of past earthquake damage. On the other hand the deterministic approach (also called predicted vulnerability) can be used in dealing with single structural units and it refers to the assessment of expected performance of buildings based on calculation and design specifications (Palacios, 2004). Studies of vulnerability of masonry structures are usually conducted within an empirical framework, based on past observation and historic damage data. However empirical approaches have limitation in terms of regional applicability and comparison among different typological and geographical context (D'Ayala & Kishali, 2012).

BACKGROUND

Many historical masonry buildings are located in regions of high seismicity. Many of these buildings have very complex geometry that consists of the combination of curved one-dimensional elements (arches), two-dimensional elements (vaults), and three-dimensional elements (domes). Moreover, the thrust action transmitted by arches, vaults and domes to walls and piers usually cause damage to the supporting walls or piers. If the thrust is too high, it might cause out of plumb, overturning and deformation of the supporting structure. Thus, the presence of these elements in buildings can increase still further their vulnerability.

In ancient times, the only applicable construction method was the "rule of thumb" based on the experience and tradition of the builders. Masons had no means of calculating the amount of buttressing required by any particular design, and seem to have discovered the margins of safety through observation and experience. Before the formulation of the principles of the strength of materials, the theory of elasticity, and limit analysis, the design of vaulted structures had been essentially based on geometrical and proportional construction rules acquired by centuries of experience (Huerta, 2012). The first ''scientific" graphical attempts for the study of the equilibrium of masonry domes go back to the early 18th century. As it was clear from the beginning, the cracking occurs on curved masonry elements in presence

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