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Dynamic analysis and seismic performance of reinforced concrete minarets

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Abstract

An unusually large number of minarets, which are slender tower structures, collapsed during the 1999 Kocaeli and Duzce, Turkey earthquakes with resulting damage to surrounding buildings and loss of life. The potential effects of the subsequently observed poor reinforcement detailing on the dynamic response is discussed. The probable cause of the extensive damage to reinforced concrete minarets is investigated by studying the observed failure modes and their seismic performance, and through the dynamic analysis of a representative minaret. The effects of spiral stairs, door openings, and balconies on the dynamic behavior are examined. The maximum dynamic internal force demands were compared with the calculated capacities. The locations of the maximum axial, shear, and flexural demands predicted from the finite element analysis of the minaret model were consistent with the earthquake damage observed at those critical locations.
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Keywords: Minaret; Reinforced concrete; Finite element analysis; Earthquake damage

1. Introduction

A minaret is a slender tower built next to a mosque. While most historical minarets were constructed using reinforced or unreinforced stone or brick masonry, the majority of minarets recently constructed in Turkey are reinforced concrete (RC) structures. As shown in Fig. 1, a typical minaret structure comprises a base or boot on top of its foundation, a tapered transition segment, a circular body or shaft with one or more balconies, and a spire at the top. The base or boot is usually square or polygonal, and is sometimes called the pulpit by architects. The minaret can be free standing or the boot may be attached to the mosque structure. The minaret contains interior spiral stairs running all the way up to the highest balcony level which are not externally visible. Historically the balconies are built so that someone could climb up the stairs and call for prayer. With the advent of loudspeakers, these balconies are not needed; however, one or more balconies are built in each minaret mainly for architectural reasons. Balconies create mass concentrations along the minaret's height and affect its dynamic structural response.

Currently, there are no structural code requirements or guidelines for the design of reinforced concrete minarets, or minarets in general, in Turkey. As a result, these slender structures have been built, for the most part, by experienced contractors and construction workers with no engineering knowledge. In most cases, each contractor constructs a typical minaret with the same structural and architectural features regardless of the local soil conditions or seismicity of the region.

Turkey is located in one of the most seismically active regions of the world. Fifty-seven destructive earthquakes have struck Turkey in the twentieth century, resulting in the destruction of infrastructure and more than 90 000 deaths. During these earthquakes, many minarets were damaged or have collapsed. Sezen et al. [14] documents and discusses vulnerabilities and damages to 64 masonry and RC minarets after the 1999 Kocaeli (M_w7.4) and Duzce (M_w7.2) earthquakes. As a result of these two earthquakes, the collapse of 115 minarets in the city of Duzce alone was

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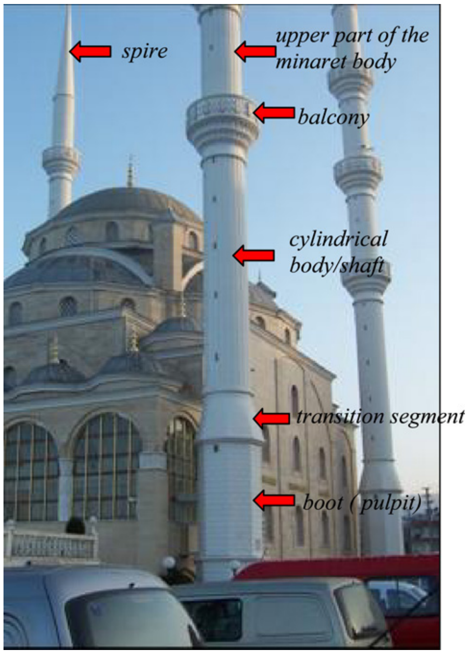

Fig. 1. Typical reinforced concrete minarets in Turkey.

reported [6]. Sezen et al. reports that approximately 70% of the RC and masonry minarets surveyed in Duzce sustained severe damage or collapsed. Even though the minarets are hardly ever occupied, they are located mostly in residential areas or shopping districts, and their collapse sometimes causes loss of life. It is extremely important to regulate the construction and design of these slender structures for safety reasons in anticipation of future earthquakes. This study attempts to identify the structural vulnerabilities of minarets based on their past seismic performance.

In addition to widespread earthquake damage and collapses, some reported failures of minarets due to wind loading indicate that most of these tower structures are vulnerable to lateral loads. A large number of research studies investigating the seismic response of historical masonry minarets and towers are available [3,7,11,15–17]. However, there are only a few studies investigating the lateral response of RC minarets [8,14]. Dogangun et al. [4,5] investigate the architectural and structural properties of these slender structures. The description of each minaret segment and the associated observed damage are presented below.

2. Observed damage and implications

The type and distribution of damage in a structure varies greatly depending on many factors, including the detailing and properties of the structure and its components, soil properties, and the magnitude of the earthquake. The effect of local soil conditions on the seismic response of RC minarets is investigated by Acar et al. [1]. Observations from recent earthquakes suggest that the damage in the minarets is usually concentrated in a few specific locations. These observed local damage concentrations and vulnerabilities of minarets are presented here.

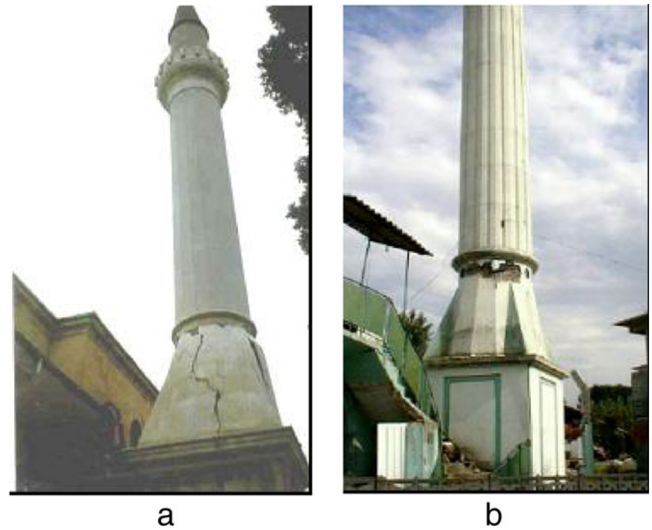

Fig. 2. Damage to the transition segment (photos by (a) Firat [8] and (b) Scawthorn [13]).

The relatively stiff boot or base of the minaret normally suffers no damage. The stiffness and strength of the minaret are reduced over the height of the tapered transition segment with a larger square or polygonal shape near its bottom and circular shape near the top. In a few cases, damage over the transition segment was observed. Fig. 2 shows two such cases where the concrete cracking or spalling was either spread over the segment or concentrated near the top just below the cylindrical body.

Horizontal circumferential cracks and concrete spalling near the bottom of the minaret cylinder or body were the most common types of damage, leading to the collapse of RC minarets (Fig. 3). There are two main reasons for this type of failure. First, the cross section size becomes smaller, which results in reduced lateral and flexural strength. Second, as shown in Fig. 3 in most cases at that location all longitudinal steel bars were lap spliced, creating a discontinuity. Prior to 1999, smooth reinforcing bars were commonly used in Turkey because they are less expensive, more readily available than ribbed bars, and easier to bend and cut on site compared with ribbed bars. Considering that the anchorage length required for the smooth longitudinal bars is significantly larger than that of deformed bars, it is most likely that the lap spliced longitudinal bars failed before the full flexural strength could be developed. However, many other minaret collapses, e.g., top two pictures in Fig. 3, suggest that failure may have occurred simply because of insufficient flexural strength near the bottom of the cylinder.

The minaret shown in Fig. 4 survived after the August 17, 1999 Kocaeli earthquake with some apparent distress causing light cracks and concrete spalling near the cylinder base. After nearly three months, during the November 12 Duzce event, the minaret collapsed at the section near the bottom of the cylinder where the smooth longitudinal reinforcing bars had been spliced. The lap splice length was approximately 800 mm (Fig. 4b). The ends of the longitudinal bars had 180° hooks (Fig. 4c). It appears that the combination of smooth bars with 180° end hooks, and the existence of short lap splices,

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