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Seismic damage on merlons in masonry fortified buildings: A parametric analysis for overturning mechanism

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ABSTRACT

The observation of the damage occurred to ancient masonry buildings is the necessary first step to understand the seismic behavior of the elements that compose them. Looking at the recent seismic events in Italy, a severe damage could be noticed on a wide range of historical buildings, in some cases even for low values of peak ground acceleration. In particular, the present paper focuses on ancient fortified architectures, characterizing the historic city centers and landscapes, investigating the seismic vulnerability of its most typical element: the merlon.

The analysis of the observed damage on the fortified building typology, collected and catalogued in previous works, clearly points out that merlons are frequently damaged, particularly by out-of-plane mechanisms and even for low accelerations. Given the fact that these elements are particularly vulnerable and, at the same time, particularly meaningful from a historical and cultural point of view, the present work focuses specifically on the out-of-plane damage mechanisms suffered by these protruding elements, in order to better understand their behavior during earthquakes, to quantify their vulnerability and to provide simple instruments for their seismic protection.

Indeed, though the collapse of merlons is rather common, it has received little attention in the literature.

The present paper analyses both merlons on towers and on walls, in clay brick masonry or in stone masonry, and describes, through a parametric analysis, their behavior as the features change. A simple linear elastic model was adopted to identify the activation of the out of plane mechanisms, while the subsequent collapse was analyzed with a non-linear kinematic model. Moreover, appropriate filtering equations were chosen to modify the response spectrum at the ground, thus taking into consideration the seismic filtering effect exerted by the supporting wall or tower. The proposed procedure is discussed and validated by means of three different case studies: the San Felice sul Panaro Fortress (damaged in the Emilia 2012 earthquake), the Arquata del Tronto Fortress, and the Rancia Castle (both damaged in the 2016 Central Italy earthquake). By changing the parameters (geometries, materials, soil) between extreme but realistic values, the curves that relate the slenderness of the merlons to the PGA that leads to the activation of the mechanism (or collapse) are plotted. These graphs supply ranges of vulnerable conditions, representing a straightforward and reliable instrument, also for practitioners and public bodies in charge of heritage preservation, useful to define priority lists for interventions and to optimize the resources for the prevention of future damage.

1. Introduction

Recent seismic events in Italy have shown the significant vulnerability of historical fortified buildings, which are a typical architectural element of the landscapes and city centers skylines. Fortified architecture indicates a wide variety of buildings, generally characterized by the presence of defensive walls, towers, and other distinctive elements. It is common to identify this building typology by the presence of a specific type of protruding element called merlon.

Merlons are the solid standing part of battlements or crenellated parapets, typical of medieval architectures or fortifications. They have been used for centuries, not only for defensive purposes, but also as an ornament in order to show the alliance or the social status of the castellan. The decorative role of merlons became prominent only in more recent configurations; in fact, with the evolution of warfare, merlons started losing their defensive role since the 15th century and were

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employed for false decorative battlements to identify the strategic role of a building or family.

Through the collection and cataloguing of seismic damages on fortified architecture, Cattari, et al. [1] and Coïsson et al. [2] had already observed that merlons are particularly vulnerable elements. For this reason, the present work investigates specifically the damage mechanisms suffered by these protruding elements, in order to comprehend their behavior during earthquakes, to assess their vulnerability and to provide useful indications for interventions aimed at their seismic protection. This paper expands a preliminary study by Lenticchia et al. [3] on the seismic behavior of merlons, by extending the parametric analyses. The present work will start with the description of the role of merlons in fortified architecture and how it changed with the evolution of warfare, affecting their geometrical features and shapes. It will then give an overview of the observed seismic damage on these elements, by analyzing some relevant case studies. A procedure to study the overturning collapse mechanism of free-standing merlons is defined by means of up to date models and taking into account the dynamic filter effect of the underlying structure. The proposed procedure is discussed and validated by means of three case studies: the San Felice sul Panaro Fortress (Emilia 2012 earthquake), the Arquata del Tronto Fortress (2016 Central Italy earthquake), and the Rancia Castle (2016 Central Italy earthquake). The subsequent parametric analysis permits to observe how the geometry of merlons, and underlying structure, could influence their seismic vulnerability.

The findings of the present work represent an important contribution to the analysis and preservation of historical fortified buildings. They give new insights on the behavior of this architectural element and supply a straightforward tool that could be applied also at a territorial scale. This helps identifying the most vulnerable cases on which the strengthening interventions should concentrate.

1.1. Role of crenellation in fortified architectures

The crenellation of a wall or tower is a defensive technique employed since the ancient times, but it became a distinctive element of the fortified buildings only during the Middle Ages, when the process of castellation spread through the whole of Europe. Starting from the Carolingian Empire, in order to build a fortification, it was necessary to obtain a license of crenellation, a grant that gave permission for a building to be fortified [4]. The license to crenellate was employed as a way to control the construction of fortified buildings and prevent local lords from becoming too powerful. In medieval England, the license to crenellate was also a tool to demonstrate the lords' alliance to its monarch [5].

The geometries of the crenellations could vary enormously (shape and dimensions of the merlons, width of the crenels between two merlons), but their purpose was always the same: the crenel allowed defenders to shoot arrows and throw down missiles, while the merlons offered shelter from assailants' shootings (Fig. 1).

The geometrical features of merlons depend on the period of construction, the geographical location and, most important, warfare evolution (Fig. 1b). Indeed, during the Roman Empire, the defensive line was mostly represented by its legions [7]: *castra* were a temporary shelter for Roman legions, and, in ancient warfare, fighting battles in open battlefield was preferred to starting a siege. Siege warfare became common in the Middle Ages, when fortified cities, fortresses and strongholds were adopted to maintain control on a certain area. Crenellations soon became an indispensable defensive element and merlons were designed as thin elements, more tall than wide, and could be made in wood or, later, in masonry. Usually, they were wide enough to shelter a couple of men, and they could be provided with loopholes of various dimensions and shapes, for shooting arrows. This configuration lasted until the appearance of gunpowder artillery [8,9]. When the employment of artillery in war became frequent, fortified buildings erected in previous periods turned out to be vulnerable to this new type of attack. In fact, originally the main strength in fortified constructions was due to their height, while this then became a weakness since cannonballs could easily damage slender elements. With the introduction of gunpowder weaponry, the shape of defensive walls and merlons changed abruptly: walls became less regular in plan, increased in thickness, and lowered in height; correspondingly, merlons started to assume a stockier shape and their thickness increased (Fig. 1b).

Merlons were used until the artillery made them useless or even unsafe for defenders. However, they started to be employed as a decorative element. Fake merlons and battlements were largely used in the Neo-Gothic Style of the 19th century. Various geometrical decorations were already used in the Middle Ages, to indicate alliance to a particular faction. A well-known appearance was the one adopted by the Guelf and the Ghibelline factions: the former used a rectangular shape, while the latter adopted a merlon that ended with a swallow-tailed form (Fig. 2). In the Middle-East regions, instead, merlons were usually rounded, shaped with steps tapered at the end, or even triangular (Fig. 2).

2. Observed seismic damage

A thorough analysis of the damage observed in several Italian earthquakes was carried out in order to focus modelling activities on the most significant seismic effects on merlons. It is not trivial to define general rules because the reported effects depend on one side on the frequency content of each earthquake and on the other side on the different features of the fortifications that can vary a lot depending on the period of castellation, availability of resources and materials, soil morphology, and on local architectural styles and technical skills [10,11]. Nevertheless, the analysis carried out in [2] on 73 damaged castles pointed out that the damage mechanisms observed on merlons can be classified in two typologies: in-plane shear failure (mechanism 4a, following the definition in [2]) and out-of-plane overturning (mechanism 4b). These damage mechanisms are shown in Fig. 4.

Usually, the overturning mechanism is more frequent in case of freestanding merlons. The overturning mechanism is very dangerous, not only for the structural integrity of the damaged buildings, but also for public safety. For these reasons, after the activation of the mechanism, preventive removal of the merlons is frequently preferred (Fig. 3a). Alternatively, temporary reinforcements are inserted (Fig. 3b).

For this type of damage many examples can be found, for instance:

– In the 2016 Central Italy earthquakes: the Castles of Arquata del Tronto (Fig. 4), whose damage was investigated in [12], the Rancia's Castle in Tolentino, as well as the fortified walls of the town of Tolentino, all of them built in brick masonry, and the fortified town of Visso [13], built in stone masonry.
– In the 2012 Emilia earthquake: the Castles of Giovannina (in San Giovanni in Persiceto) (Fig. 4), Pio (in Carpi), and Galeazza, the fortresses of Finale Emilia and Reggiolo, the Gonzaga Ducal palace (in Revere), all in brick masonry;
– In the Espolón tower of the Lorca castle hit by the Lorca earthquake in 2011 [14].
– In the 1980 Irpinia earthquake: the Castle of Monte (in Montella), built in stone masonry;
– In 10 out of 14 stone masonry castles hit by the Friuli earthquake and analyzed in [2].

Overturning was documented also in the case of a roof structure rested on merlons. An example is the castle of Zoppola, built in brick masonry, which was hit by the 1976 Friuli earthquake: unfortunately, information that we collected is not sufficiently detailed to explain this behavior. The same behavior was observed in the fortress of San Felice sul Panaro, hit by the 2012 Emilia earthquake, where the overturning mechanism of some merlons of a walkway over a defensive wall was