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Seismic fragility functions of industrial precast building classes

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ABSTRACT

The seismic vulnerability of twelve industrial precast building classes has been investigated by conducting nonlinear dynamic analyses on sample buildings from these building classes and taking into account selected seismic events. The results of the study can be used for seismic risk and loss estimation of precast building stock by considering the collapse of buildings and several other damage states, which were defined on the basis of the physical damage occurring to the vertical panels, horizontal panels, or masonry infills. The use of fragility functions derived on the basis of spectral acceleration corresponding to the so-called optimal period of the building class is suggested. Fragility functions are also presented for the peak ground acceleration, which is an intensity measure, independent of the building class. This means that all these fragility functions can be used to discuss how the variation of structural configurations, code levels, and the type of non-structural components and their fastenings affect the overall seismic response of industrial precast building classes, at a given level of the seismic intensity measure. It can be concluded that the vulnerability of non-structural elements is the largest in the case of precast buildings with horizontal panels, followed by those with masonry infills and vertical panels. It was also observed that non-structural components have an impact on the structural collapse, both in terms of reducing the median and increasing the dispersion of the collapse fragility functions. It was also observed that a higher seismic design force may worsen the seismic performance of a precast building if the connections are not adequately designed.

1. Introduction

The seismic fragility of Italian industrial precast buildings became evident to society as a whole when earthquakes struck L'Aquila in 2009 and the Emilia-Romagna region in 2012. Many precast buildings, which had been built in the last decades, partly or totally collapsed (e.g., [1,2]). The reasons for the poor behaviour of such buildings were at least twofold. Firstly, the design seismic forces were insufficient since most of the Emilia-Romagna region was classified as a seismic zone, for the first time, only in 2003 (e.g., [3]). Secondly, and probably more importantly, the seismic response of precast buildings was not well understood at the time of construction of these buildings. In fact, in recent years this research topic has been frequently addressed (e.g., [4–6]), which implies that there are still many unanswered questions. In addition to the structural damage, the recent seismic events in Italy once again revealed the vulnerability of non-structural components. Even if only limited damage occurs to the load-bearing structure of a building, the collapse of non-structural components often led to the interruption of the manufacturing process and huge indirect losses. According to Magliulo et al. [2], the indirect losses due to the earthquakes in the Emilia Romagna region were estimated to about 5 billion euros, whereas the direct losses amounted to about 1 billion euros.

In this paper, single-storey precast buildings, which are most often used by industry, are investigated. The load-bearing structures of such buildings usually consist of cantilever columns, which are fixed at the bottom by socket foundations and connected at the top by a roof, which is essentially an assembly of precast elements (beams, girders, TT slabs, or hollow core slabs) and does not act as a rigid diaphragm [2,3,6,7]. The frictional connections between the columns and beams may consist only of neoprene pads, which are inserted between the elements. However, in recently built structures, additional steel elements have been used (e.g. dowels), which increase the strength of the connections. In Italy, this is mainly true after the adoption of the new code in 2008. Horizontal and vertical precast panels and masonry infill walls are used for the façades of these buildings. These elements are considered to be non-structural.

The seismic vulnerability of various classes of buildings is often estimated by performing a seismic fragility analysis (e.g., [8,9]).

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The results of such analyses consist of fragility functions, which represent the expected ratio of buildings within a given class for which the damage is equal to or exceeds the designated level of damage given the level of seismic intensity. However, studies which have addressed the seismic fragility of precast buildings are quite limited. Senel and Kayhan [10] investigated the fragility of typical Turkish precast buildings, whereas Bolognini et al. [11] and Casotto et al. [6] calculated fragility functions for different classes of Italian precast buildings. In these studies, the effect of non-structural components was not taken into account for the estimation of the fragility functions. Korkmaz and Karahan [12] determined fragility functions for precast buildings in Turkey taking into account the presence of masonry infills. However, only in-plane failure of the infills was taken into account.

In this paper the vulnerability of existing, single-storey industrial precast buildings, typical for Italy, is firstly addressed with an emphasis on the provision of a description of the most common failure mechanisms which were observed in the field after the earthquakes or during experiments. Then investigated building classes, their basic characteristics, and corresponding models of the various structural and non-structural components, are presented. The load-bearing structures of each building class were simulated by means of a sample of the load-bearing structures of 100 buildings. The approach is the same as that proposed by Casotto et al. [6]. The most common types of non-structural components (vertical panels, horizontal panels, and masonry infills) were also considered in the definition of the building classes and the corresponding sample of buildings. The fragility functions of twelve classes of Italian precast buildings were then calculated using the slightly modified methodology as proposed in [6]. The results are presented for two types of intensity measures and for five different damage states, which were defined on the basis of the observed physical damage of non-structural and/or structural components.

2. The vulnerability of single-storey industrial precast buildings

2.1. The vulnerability of their load-bearing structures

Under the effect of an earthquake, single-storey industrial precast buildings behave as an assembly of cantilever columns connected to a roof system. Their performance mainly depends on the rotational capacity of the columns, and on the shear capacity of the beam-to-column connections. This was confirmed after the recent earthquakes in Italy [1–3,13], where plastic hinges which occurred at the bases of columns and the failure of beam-to-column connections (Fig. 1a) were the most common sources of structural damage. Other types of failure, such as the shear failure of columns due to interaction with the masonry infills [2,3,13], the unseating of roof elements [1,13], and loss of verticality due to rotation of foundation elements [2] were also observed.

Recently, extensive studies aimed at investigating the capacity of precast elements were performed. Very slender columns, which are usually used in precast structures, were experimentally tested by Fischinger et al. [14], who observed very large drifts (up to 8%) during cyclic tests and concluded that the cyclic response of columns may be well predicted by the lumped plasticity model using the Ibarra hysteretic rules [15], calibrated by Haselton [16]. However, it was also found that, in the case of smaller drifts, Takeda rules [17] with the moment–rotation envelope curve based on idealised curvatures would yield adequate results. A greater focus was placed on the beam-to-column connections, which may be divided into those involving mechanical components, such as dowels (i.e. dowel connections) and those relying only on friction between a beam and a column (i.e. friction-only connections). The behaviour of the dowel connections has been addressed in several studies (e.g., [4,18–22]). Two types of failure were observed. Local failure, which typically occurs if the distance of the dowel from the edge of the column or the beam is large enough (e.g. about six diameters of the dowel), is associated with crushing of the concrete and yielding of the dowel. If, however, the dowel is closer to the edge, then spalling of the entire concrete edge, denoted as a global failure, is more probable. It was shown that in this case load-carrying capacity depended on the stirrups being placed around the dowels [4], which was often neglected in commonly used design guidelines [23]. In order to assess the load-bearing capacity of friction-only connections, Magliulo et al. [24] investigated the friction coefficient between a concrete beam and a neoprene pad, which is normally placed on the top of a column. It was observed through experimental tests that the friction coefficient is inversely proportional to the stresses acting normally on the neoprene pad, and varies between the values of 0.1 and 0.5.

2.2. The vulnerability of precast panels

The strength of reinforced concrete panels is superior to that of their fastenings. As a result panels are dislocated when the fastenings fail at the top of the panels, where they are connected to the structure. There are several types of fastenings, which can be divided into pinned and sliding types, both of which have recently been experimentally tested [25]. It was shown that so-called sliding fastenings have a greater deformation capacity.

After the L'Aquila and Emilia earthquakes [1–3,13] both pinned and sliding fastenings were found to be inadequate to withstand

(a) (b)

Fig. 1. (a) Collapse of a precast RC building, and (b) collapse of precast vertical panels due to the earthquakes in the Emilia Romagna region.