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Fragility functions for unreinforced masonry walls made from hollow clay units

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ABSTRACT

A relatively large database of masonry specimens tested in laboratories across Europe was established and used for the estimation of fragility functions for unreinforced masonry walls built from hollow clay units, which are the most common type of masonry units for the construction of new buildings in Europe. The proposed fragility functions can be used to predict minor, moderate, and near collapse damage states for structural walls with expected predominantly shear or flexural behaviour. The results indicate that in addition to failure mode, the h/l ratio, the normalized compressive load, and the boundary conditions have a significant impact on fragility functions. However, due to small sample size, it was not possible to explicitly incorporate their effect in fragility functions. It is shown that the near collapse damage state of the investigated type of masonry wall is most likely attained at drifts of 0.4% or 0.7%, respectively, in the case of shear or flexural behaviour. Useful additional information is provided by the total dispersions of the structural component drifts corresponding to a designated damage state, these dispersions being large regardless of the damage state. In the case of the near collapse damage state, it was estimated that they amounted to 0.57 and 0.47, respectively, depending upon whether the structural components behaved in a predominantly shear or a predominantly flexural manner. It is also shown how the proposed fragility functions can be used to predict the probability of occurrence of a certain damage state, which can be used for loss estimation of masonry buildings.

1. Introduction

Engineers and researchers can evaluate the damage and vulnerability of masonry structures on the scale of cities, individual buildings, the individual components of a particular building, and, even, on the micro scale of mortar beds or bricks/blocks, depending on the purpose of the study, the level of knowledge about the investigated building, and the complexity of the models to be used. A combination of damage surveys and simplified methods of analysis is usually chosen for the estimation of the vulnerability of a particular class of masonry buildings, where the fragility function expresses the proportion of buildings that are likely to experience a certain damage state ([1–4]). The vulnerability of masonry buildings is often assessed at the level of an individual building ([5–8]). However, data about seismic fragility at the level of the structural and non-structural components of buildings are needed for the seismic risk assessments and loss estimations.

The fragility functions of the structural and non-structural components of a building can be based on empirical information by observing the behaviour of actual buildings which have experienced different levels of intensity and earthquake damage. However, in most cases the drifts are not monitored during real events, which means that fragility functions cannot be expressed in terms of engineering demand parameters. Consequently, empirically-based fragility functions usually cannot be applied to numerical models which simulate the seismic response of a structure in terms of engineering demand parameters. Therefore, the results of cyclic tests are often used as the basis for the estimation of fragility functions for multiple damage states of structural and non-structural components. Such an approach was applied in this paper, where the fragility functions of masonry walls built from hollow clay masonry were derived. Masonry walls of these types are considered structural components, but here they are simply termed as components, unless otherwise specified.

There have been previous attempts to consolidate experimental data about the seismic behaviour of masonry walls, and the resulting fragility functions are summarized in the Table 10. Augenti et al. ([9]) collected data about the results obtained in a total of 658 tests performed on masonry specimens in an online masonry database (MADA). Rota et al. ([10] performed cyclic tests on tuff masonry with shear behaviour in order to develop fragility func-

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tions which were then used in the numerical analysis of tuff masonry elements which failed in shear. In the case of flexural failure, the drift capacity for tuff masonry according to Eurocode 1998-3 ([11]) was assumed. Abo-El-Ezz et al. ([7]) provided a literature review about the behaviour of stone masonry walls, as well as corresponding fragility functions for multiple damage states, without, however, differentiating between shear and flexural failure.

Salmanpour et al. ([12]) investigated the deformation capacity of a total of 24 unreinforced masonry specimens which failed in shear, and 22 specimens which failed in flexure. Mean drift capacities of 1.21% (COV = 0.58) and 0.40% (COV = 0.49) for the specimens showing flexural and shear behaviour, respectively, were determined. Ruiz-Garcia and Negrete ([13]) developed fragility functions for confined masonry walls in Latin-America made from hand-made clay bricks, industrialized clay bricks and concrete blocks, based on the experimental results of tests performed on 118 confined masonry specimens. They provided fragility functions for numerous subgroups of specimens. Murcia-Delso and Benson-Shing ([14]) derived fragility functions for reinforced masonry walls showing shear or flexural behaviour, which were used for the preparation of a background document for FEMA P-58 ([15]).

FEMA P-58 ([15]) presents a possible loss estimation methodology, in which a large database of fragility functions for various structural and non-structural components was developed. It includes fragility functions for reinforced masonry walls of various dimensions with shear or flexural behaviour, but these functions cannot be applied to the types of masonry which are commonly used in Europe (e.g. unreinforced masonry walls made from hollow clay units). FEMA P-58 ([15]) also recommends methods for the derivation of fragility functions. Method A, which was also used for the derivation of fragility functions proposed in this paper, is considered the most reliable since it is based on a sufficiently large quantity of experimentally obtained data. However, if data from test specimens are not available, the behaviour of walls can be modelled numerically, and the fragility functions can be estimated from the simulated levels of demand at which a particular damage state occurs (Method D). Fragility functions can also be derived on the basis of expert opinions (Method E).

In this paper, a survey of available data about the results of cyclic loading tests performed on masonry wall specimens was first conducted, and a database of cyclic tests was established regardless of the masonry type. The minor, moderate, and near collapse damage states are then defined, and the corresponding drifts are obtained from the database. The methodology which can be used for the derivation of fragility functions derivation is then described, and applied to unreinforced hollow clay masonry wall specimens showing predominantly shear or predominantly flexural behaviour for all three damage states. The probability of the occurrence of each damage state is calculated, and the drifts from the database are compared to the ultimate drifts for structural masonry walls which are presented in Eurocode 1998-3 ([11]).

2. The established database about the results of experiments performed on masonry walls

In order to determine the probability of exceeding a certain damage state in numerical models, it is necessary to collect data about the drifts occurring in typical masonry walls, and damage levels corresponding to these drifts. For this purpose, the results from multiple experiments performed on structural masonry walls at different European laboratories and research centres were assembled. During the ESECMaSE project (Enhanced Safety and Efficient Construction of Masonry Structures in Europe) 61 static cyclic tests were performed at the University of Kassel ([16]), the Technical University of Munich ([17]), and the EUCENTRE research centre, which is located in Pavia ([18]) with the aim of analysing the influence of different boundary conditions on the shear strength and deformation capacity of masonry walls. One of the findings of this project was that the influence of the optimization of the masonry units on the load bearing capacity of the walls was rather low, although the deformation capacity of walls made from optimized clay units was higher than of walls made from conventional units. Another large experimental campaign on masonry walls was performed after co-operation between ZAG, the Slovenian National Building and Civil Engineering Institute, and Wienerberger ([19,20]), where the goal was to improve the thermal properties of the masonry units and to develop a new, faster and cheaper technology for the construction of masonry walls. As a result of such optimization, hollow masonry units with reduced thicknesses of their shells and webs were produced, and 46 masonry walls built from these units were tested using various combinations of the input parameters (i.e. the geometry, head and bed joints, compressive loads). The Slovenian National Building and Civil Engineering Institute ([21]) provided another set of experimental results. It included 9 masonry walls made from hollow clay bricks with unfilled tongue and groove head joints and thin layer bed joints. These specimens were tested as cantilevers at three levels of compressive load in order to validate a new system with dry vertical joints, which could potentially be included in Eurocode 1996-1 ([22]). The final set of 11 specimens, which was included in the database, was provided by Technical University of Dortmund ([23]). Static cyclic tests were performed in order to verify the recommended q factor in Eurocode 1996-1 ([22]) for the masonry walls made of hollow clay and calcium silicate units.

Altogether, the database contains a total of 127 entries. Walls built from hollow clay units represent the majority of the database (87 specimens), followed by calcium silicate units (27 specimens), and lightweight aerated concrete units (13 specimens). Note that only a subset of 58 specimens was appropriate for the determination of fragility function for structural masonry walls made from hollow clay units. However, the metadata presented in the text which follows are the same for all the different types of masonry walls, and make it possible to estimate the level of damage to each of the test specimens, together with the corresponding drifts, for all 127 entries in the database.

Each specimen in the database is described by multiple parameters, which are divided into six sections: general information, units and mortar, geometry and material characteristics of the wall, information on the test set-up, the experimental results, and the calculated values of the investigated parameters.

2.1. Data about the test specimens and the experimental set-ups

The first section of the database includes general information about the source from which the data were obtained, and about the institution/laboratory which performed the tests. It also includes the original laboratory designation of the masonry test specimen, as well as about the type of masonry wall, the reinforcement and confinement. Some general information about two example test specimens from the database is provided in Table 1; these two specimens were included in the derivation of the fragility functions. The first example corresponds to shear behaviour of the wall, whereas the second corresponds to flexural behaviour.

The second section in the database (Table 2) consists of information about the masonry units, including data about the unit dimensions, type, class, and measured compressive strength of the unit f_b. Most of the specimens were made from hollow clay units from Group 2 ([22]), with between 25 and 55% of vertical holes. Information about the mortar is then given: the type of head