A masonry catalogue for the Groningen region

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A MASONRY CATALOGUE FOR THE GRONINGEN REGION

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ABSTRACT

Human induced seismicity has become an uprising problem in the Groningen region of The Netherlands, in which the vast majority of buildings are non-seismically engineered unreinforced masonry houses. In order to accurately assess the seismic vulnerability of these buildings, a characterization of the constitutive masonry is required. In 2015, as a part of a larger project, a campaign on the material characterization of existing buildings was performed, including laboratory and in-situ testing of the masonry walls. The campaign constitutes the germ for the creation of a regional material properties database.

16 buildings were tested in total, comprising residential structures and schools, dating from the early '20s to 2005. The constitutive walls included both clay and calcium silicate brick masonry of various qualities and conditions. The in-situ testing included non-destructive tests such as rebound hammer and sonic tests, and semi-destructive test, i.e. flat jack and shove test. Samples were carefully taken to the laboratory, where the destructive campaign took place, including compressive, flexural, shear and bond wrench tests.

Despite of the limited number of sampled buildings, the campaign provided a better insight of the researched material. The available data suggests that the use of sub-typologies (e.g. depending of the masonry quality or condition) could reduce the dispersion on the results. A first attempt of correlation between in-situ and laboratory tests is proposed, which could benefit from further calibration.

In this paper, the material characterization campaign is described, and the main outcomes are discussed.

Keywords: Unreinforced masonry; Material characterization; Lab testing; In-situ testing; Catalogue

1. INTRODUCTION

Human induced seismicity has become an uprising problem in the Groningen region of The Netherlands, in which the vast majority of buildings are non-seismically engineered unreinforced masonry (URM) houses. In order to accurately assess the vulnerability of these buildings to the new loads, a characterization of the constitutive masonry properties is required. In 2015, as a part of a larger project, a campaign on the material characterization of existing masonry buildings was performed. It included both laboratory and in-situ testing of the masonry present in the walls of several building typologies. Properties for the characterization of the masonry in compression, bending and shear were investigated.

This work is a collaborative effort between Arup, TU Delft (laboratory testing), EUCENTRE (mainly in-situ testing) and TU Eindhoven (laboratory testing, subcontracted by TU Delft).

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1.1 Objectives of masonry testing

The main objective of material testing within this project is to provide a set of masonry properties to be used as input for numerical models, used both as a reference for the development of fragility curves and for the upgrading of specific buildings. Assumptions based on international and local practice for material properties due to lack of experimental data are increasing the uncertainties of the predictions. Material testing will allow for a better prediction of the behavior and capacity of URM buildings typical of the building stock.

When taking into account the large picture, the following secondary (long-term) objectives can be set:

- Provide a larger set of properties to be used in building implementation, i.e. expanding the database that will be created for the main objective above.
- Provide calibration of (simple) in-situ tests which will be used for large scale implementation.

Once an extended masonry database is in place, the results of the tests performed on a specific building can be checked against it as a validation. If the results are significantly not in line with the values in the database, an explanation will be required or the tests may be repeated.
The existence of this extended database will also reduce the number of required tests per building, decreasing the total implementation costs. But in order to achieve this, the correlation between different properties needs to be researched, and the values in the database need to be reliable.
When in-situ testing is included in the studies, these individual testing campaigns can be further reduced and become non, or very little, destructive. In order to achieve this, and since both in-situ testing of masonry are recent techniques in the Netherlands, the correlation between them and laboratory testing is needed.
The addition of the secondary or longer term objectives translates in a larger amount of tests per building compared with the minimum tests required for the fulfilment of the short term aim, but also in an increased benefits/costs ratio. That is, if each building to be implemented is treated as a separated object without taking into account the big picture, a reduced number of tests could be specified in its testing campaign. Nevertheless, that number will not decrease for the following building to be implemented. When taking each object as an opportunity of gaining knowledge in a much general way, the masonry database gets populated, the knowledge on correlation between properties is enhanced and the less destructive methods are calibrated. This was the philosophy behind this testing campaign.
As will be explained in the following chapters, this work stands on the findings of a shorter campaign performed on 2012-13, and is intended to be a mid-term campaign, aimed not to fulfil the general goal of an extended database as indicated above, but to provide the next step in the ladder, populating the catalogue and providing insight on future phases (see Arup 2015 for more information).

1.2 Previous works

The testing campaigns performed so far provided initial information aimed at exploring the masonry present in the Groningen area building stock and at gaining knowledge on what could be actually achieved.
As such, a reduced number of properties (three) was researched, and the data gathered was clearly insufficient to fulfil the objectives above. However, a first analysis of the gathered data showed interesting trends worth further and deeper investigation, which justifies the continuation of the material characterization activities on new and representative buildings.

2. CAMPAIGN PREPARATION PHASE

2.1 Working methodology

The approach followed for the completion of the aforementioned mid-term objectives was:

a. First, an analysis of the used finite element (FE) and constitutive modelling techniques has been performed by Arup and TU Delft, and the required material properties are identified;
b. Laboratory tests are designed by TU Delft in order to produce the required properties and to define a correlation among them;
c. A laboratory calibration campaign for in-situ testing is designed by EUCENTRE;
d. Partners for the testing of the objects are identified: TU Delft and TU Eindhoven are identified for laboratory testing, the Italian firm P&P was identified for in-situ testing – previous calibration at EUCENTRE, and several local contractors are identified for support tasks;
e. Masonry categories are identified based on year of construction and brick material and a minimum number of representative testing objects per category is set;
f. Information about the selected buildings is gathered. The addresses and availability is provided by Nederlandse Aardolie Maatschappij BV (NAM), and Arup performs the required inspection of the buildings (see Figure 1);

Figure 1. Inspection of wall for material determination

g. Testing proposals are produced by Arup for each testing object based on the outcomes of the inspections, with input from TU Delft regarding testing locations, and issued to the in-situ testing firm;
h. The houses are prepared for testing by the local contractor: the relevant walls are stripped out, the samples for lab testing are cut, prepared and transported to the laboratory, and, when needed, repairs are made;
i. In-situ testing and reporting take place;
j. Lab testing and reporting take place;
k. The database will be populated during the process; the final results are analysed and conclusions on correlations and final values are reported.

2.2 A-priori categorization of masonry walls and building selection

In order to subdivide the masonry buildings present in the area, a first categorization can be made based on the material of the brick units. The main materials that can be observed are clay and calcium silicate (CaSi).
A second differentiation was made based on the construction period, including milestones in the production methodologies. Two time periods were considered for the CaSi unites: before 1985, when smaller blocks and mortar were used; and from 1986 to the present, when larger, glued units are mostly employed. Regarding clay units, two time periods were considered: pre-war period (until 1945) and post-war period. Clay bricks are also present in modern masonry, but mainly in façade outer leaves, and is thus not represented in the categories. According to Arup's Exposure database (Arup 2017), the following percentages of the building stock apply: almost 20% of the buildings present pre 1985 CaSi bricks, while a 13% presents newer CaSi block or elements masonry. Regarding clay brick masonry, pre-1945 buildings constitute almost 25% of the building stock, and post-1945 buildings 12% of the stock.
In order to obtain meaningful results, it was decided that a minimum of four buildings per masonry category should be tested. Following the philosophy of maximizing the usefulness of the performed tests, the new test buildings were chosen among those which will be used in more than one sector of the project (see Figure 2). In particular buildings which will be upgraded and buildings to be demolished.

Figure 2. One of the tested buildings, typical terraced house of the Groningen region

Once the houses have been inspected and prepared for testing (see following section), it was observed that several of them did not present the expected wall materials. This variability is inherent of the construction technology, and cannot be easily avoided without an early inspection of the testing buildings. As a result, some categories lacked a large enough number of buildings.
The amount of test samples per masonry typology was limited (especially for CaSi post-1985), as extracting specimens from the walls was not always possible, and some of the specimens became damaged during transportation. The final count was 5 calcium silicate buildings and 10 clay ones (the 16^{th} building presented unexpected concrete bricks).

3 MODELLING AND REQUIRED MATERIAL PROPERTIES

3.1 Requirements for risk assessment studies

In risk assessment studies, sophisticated nonlinear FE models are used as reference for the definition of fragility functions. For this study, a statistical description of the input parameters is needed. This means that, for each parameter, a *mean value* and a *coefficient of variation* need to be provided. Material properties are one of the inputs to these models and, as such, they are a source of uncertainty in the final results. In order to obtain meaningful results, as stated in the previous section, a minimum of 4 buildings per category are needed. The more samples are available, the less uncertainty will be present in the process.

3.2 Requirements for structural upgrading

According to EUROCODE 8 Part 3 (EC-8), for the calculation of the capacities of structural elements, mean value properties of the existing materials shall be used as directly obtained from *in-situ* tests and from additional sources of information, appropriately divided by the confidence factors, accounting for the level of knowledge (LK) attained.
There are three possible levels of knowledge: *Limited*, *Normal* and *Full* knowledge level. The factors determining the appropriate knowledge level are geometry, details and materials (e.g. mechanical properties).
The knowledge level achieved determines the allowable method of analysis, as well as the values to be adopted for the confidence factors. These two points will be further explained in the following sections.

3.2.1 Allowable method of analysis

According to EUROCODE 8, each determined method of analysis requires a specific minimum level of knowledge. Different types of analysis are used, with several purposes, in this project:

i. Linear elastic methods, like hand calculations using the static equivalent lateral force method or response spectrum analysis, require a *limited level of knowledge*, for which limited in-situ testing is needed.
ii. Nonlinear methods, such as static push over or time history analysis, require at least a *Normal Level of Knowledge*, for which extended in-situ testing is required.

3.2.2 Decrease in the confidence factor value

As stated in the previous section, each method of analysis requires a minimum level of knowledge, but a higher level could also be obtained in order to diminish the *knowledge factor* (known as *confidence factor* on NEN-EN 1998-3). The values for the knowledge factors recommended by the EC-8 are 1.2 for *Limited*, 1.1 for *Normal* and 1.0 for *Full Level of knowledge*. This means that going from limited to full knowledge could produce an "improvement" of 20% in the materials' design parameters.
In terms of materials, Full Knowledge implies the use of comprehensive in-situ testing.
The classification of the levels of testing depends on the percentage of structural elements that have to be checked, as well as on the number of material samples per floor that have to be taken for testing.

Table 1. Recommended minimum requirements for different levels of testing according to EC-8

Level of testing	Material samples per element per floor
Limited	1
Extended	2
Comprehensive	3

3.3 Required URM properties

For nonlinear modelling and analysis of masonry structures in LS-DYNA and DIANA, used both in risk assessment and structural upgrading, the masonry will be primarily modelled using 2D shells with smeared crack/crush material models. In risk assessment, also TREMURI, using 2D macro-elements is employed. The masonry material properties required as input to the modelling methodologies can be classified under five main groups: mortar, brick, compression, shear and bond properties, and can be found in Table 2. Focus was primarily made on the strength and stiffness properties. From a limited number of displacement-controlled tests also toughness properties like fracture energy for compression, tension and shear were extracted, and transferred into a summary table of properties included in the Dutch code (NEN/NPR, 2017).
In nonlinear FE model analysis the use of *mean values* (i.e. expected, average values) for the above

listed properties is prescribed. In nonlinear analysis, the local failures and subsequent redistributions can be altered by the use of factored properties (design values) as inputs, resulting in artificial and unrealistic failure modes. The safety factor, if needed, will thus be applied at the end, on the basis of a limited set of systematic variation studies whereby also additional analyses with *characteristic values* are carried out.
This implies that there is a need for both *mean values* (highest priority) and *characteristic values* of the material parameters. Hence, and in order to have statistically representative data, a minimum of 5 samples need to be tested per case, and *standard deviations* and subsequently *coefficients of variation* (c.o.v.) will be derived.

Table 2. Masonry properties required for modelling and respective lab test

(number of samples)	Symbol	Property	Brick and mortar tests	Compression test	Shear tests (triplet)	Bond test
Mortar (9)	f_c	Mortar compressive strength	EN 1015-11:1999			
	f_t	Mortar tensile strength				
Brick (12)	$f_{mu,c}$	Bricks compressive strength	EN 772-1 NEN 6790			
	E_{mu}	Bricks Young's modulus				
	$f_{mu,t}$	Bricks tensile strength				
Compression* (6)	E_m	Masonry Young's modulus		EN 1052-1:1998		
	f'_m	Masonry compressive strength				
	$G_{(m)}$	Masonry shear modulus				
	v	Masonry Poisson's ratio				
Shear (9)	f_{v0}	Mortar joints shear strength (cohesion)			EN 1052-3:2002	
	μ	Mortar joints friction coefficients				
Bond (6)	f_w	Mortar joints bond strength				EN 1052-5:2002

* When enough samples were available, compression tests have also been performed in horizontal direction, i.e. loading parallel to the bed joints.

4. LABORATORY TESTING

Laboratory testing was performed at both TU Delft and TU Eindhoven. The properties that were researched, according to the lab testing campaign designed by TU Delft, can be observed in Table 2 and included compression and bending tests on bricks and mortar, compression tests on masonry, shear tests on masonry (see Figure 3) and bond wrench tests. The codes followed for each test type, and the dimensions of the required specimens can be seen in Table 2 (Delft 2015).

Figure 3. Laboratory shear test on calcium silicate masonry

As a consequence of the limited number of tested samples (see Section 2.3), no statistical distribution for the mechanical parameters could be derived and only the average value, the coefficient of variation and the minimum and maximum value measured during the campaign were proposed as results. The mechanical parameters were considered as uniformly distributed between the provided minimum and maximum value. An example of the results can be seen in Table 3, in specific the compression strength of clay brick masonry.

Table 3. Results for solid clay bricks masonry samples

Building	**Year of construction**	**Masonry quality**	**Mean compression strength [MPa]**	**Mean Young's modulus [MPa]**	**Ratio**
A	> 45	Good	10.6	4980	469
B	> 45	Poor	14.1	6779	480
C	< 45	Good	11.3	8222	727
D	> 45	Poor	15.4	9797	636
E	> 45	Good	15.4	4332	281
F	< 45	Good	12.1	4613	381
G	< 45	Good	12.6	3864	306
H	< 45	Poor	4.0	3568	892
I	< 45	Poor	3.9	1690	433
J	> 45	Good	20.7	7888	380
Average (c.o.v)	**ALL**		**12.0 (43%)**	**5573**	**463**
	< 45	All	8.8 (45%)	4391	500
		Poor	4.0 (13%)	2629	665
		Good	13.4 (1%)	6166	461
	> 45	All	15.2 (21%)	6755	443
		Poor	13.6 (13%)	8266	607
		Good	20.7 (-)	7888	380

As can be seen in the table, the suggested division upon year of construction is validated by the results. In line with this, the available data suggests the possibility of identifying sub-typologies (e.g. based on masonry quality) which could potentially present lower variability, and helps in better representing the studied material. However, this would imply a larger number of testing specimens.

5. IN-SITU TESTING

As explained in the previous sections, each building was subjected to both laboratory and in-situ testing. The in-situ testing campaign has been designed in order to accommodate the differences in both geometry (specially thickness of the walls) and overburden of the tested walls. In specific, the most important changes are performed on the application and analysis of the shove test (Bonura et al., 2018).

While the laboratory tests are in general more accurate and complete, the in-situ campaign is typically cheaper, faster and much less disruptive. Furthermore, testing in-situ adds the unknowns of a not completely controlled environment, but eliminates the non negligible effects of the samples cutting and transportation, and allows the testing of very poor quality masonry which would be impossible to be brought to the laboratory.

Figure 4. Single flat jack test (left), shove test (right)

The in-situ campaign is divided in semi-destructive test, i.e. single and double flat jack and shove test, and non-destructive tests, including rebound hammer test, penetrometric test on mortar and sonic test. A complete list can be seen in Table 4 below, together with the main property obtained and the possible correlations with other properties.

Table 4. In-situ testing campaign and related properties

	Main property	**Derived properties**
Single flat jack test	Compressive stress in the masonry	
Double flat jack test	Masonry vertical Young's modulus	Compressive strength masonry can be derived
Shove test	Mortar joints shear strength for bed joint (cohesion) and friction angle	
Rebound hammer test	Masonry homogeneity	Compressive strength brick can be derived through correlation with other tests
Penetrometric test on mortar	Qualitative strength mortar	Compressive strength mortar can be derived
Ultrasonic test	Masonry homogeneity	Compressive strength and stiffness of masonry can be derived

6. PROPOSED CORRELATIONS

In order to reduce the number of tests (and tests types) to be performed on each new upgraded building, it is of paramount relevance to underpin correlations among the studied properties. In this way, one could derive several properties from the results of fewer (or less intrusive) tests.
With this aim, the following possible correlations were studied:

Young's modulus & Compressive strength, based on the results of the compressive strength tests, performed in displacement control. The factor E/f_m (in terms of average, mean values) amounts to approx. 460 (see Table 3) for clay masonry and 700 calcium silicate masonry. These values are lower than the prescriptions in codes, where a factor between 700 and 1000 is typically suggested. As can be seen in Table 3, this ratio is variable, and could depend on the quality of the masonry, being higher for lower qualities. Please note that the use of these ratios involve some subtleties that will be addressed further in future research. First, EUROCODE 6 (EC-6) expresses the ratio as mean Young's modulus divided by characteristic compressive strength, rather than mean compressive strength. That ratio for Dutch masonry is recommended as 700. Secondly, the average ratio for all masonry types can also be found by regression on all results for all tests (buildings A to J), rather than averaging the ratios found per building, which may alter the correlation factor to some extent.
Compressive properties of masonry in orthogonal directions: by performing the compressive strength tests with the direction of loading parallel to the bed joints (see Figure 5), the relation between strength and stiffness values for orthotropic directions was investigated. A trend was observed, indicating the influence of the direction of loading on the values of compressive strength and Young's modulus. This effect can be explained by the type of failure observed: brittle splitting in the vertical direction, versus delamination at bed joints, at a lower load but less brittle, in the horizontal direction. Again, given the sample size, only trends and qualitative conclusions, and not a quantitative ratio could be identified at his stage.

Figure 5. Horizontal compressive test on masonry

Compressive properties of masonry from lab testing & results from in-situ double flat jack test. Given the low overburden present in the tested walls, the in-situ test provides information of the initial stage of the compression curve exclusively. Thus, the results can be compared with the lab ones only for the linear part. When this is done, a trend is observed, and, although a relation cannot be specifically established at this stage, the results suggest that further calibration could provide full correlation of the results. This could allow for the use of in-situ test only in future phases. Also because of the low overburden, the double flat-jack test cannot be executed up to the failure of the masonry, and as such, the evaluation of the compressive strength would rely on the correlation between stiffness and strength described above.
Shear properties as obtained in the lab & results of in-situ shove test. This correlation proved to be the most difficult to obtain, due to both the complexity of lab testing set up and in-situ test interpretation. More extensive information can be found at Bonura et al., 2018.

7. CONCLUSIONS

The works described in this paper allowed for the collection of a limited set of Groningen existing masonry properties to be used as input and mean of validation for sophisticated analytical models, through both laboratory and in-situ testing. The campaign is not meant to be final, but an initial step in a larger study. The knowledge obtained by the lab tests along with general knowledge about Dutch masonry from other sources and knowledge from previous characterisations in a Dutch study in the '90s (CUR 1994) has been transferred into a guiding table of mean properties for four types of masonries in the Dutch code (NEN/NPR 2017), which will be updated at intervals upon new findings and data.

The proposed masonry categories proved to be a good initial differentiation of the material, however the available data suggests the possibility of identifying sub-typologies (e.g. subdividing by construction quality) which could potentially present lower variability in the measured properties, with the drawback of a larger number of testing specimens needed.

Both lab and in-situ testing have pros and cons in the characterization of the material, and at the moment of writing, both methods are still prescribed. The correlation between laboratory and in-situ results has been investigated, showing promising results, which could benefit from further calibration.

Several correlations between material properties such as Young's modulus & Compressive strength, have been proposed. Given the sample size, only trends and qualitative conclusions, and not a quantitative ratio could be identified at his stage. The results would benefit of further testing, including a larger number of specimens, and dedicated sub-categories. The variability in the properties values is due to a variation of the masonry material between buildings and it is related also to the intrinsic variability of masonry material. This variability diminished when appropriated sub-typologies were employed.

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