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Reliability-Based Standardization of Seismic Retrofitting Measures for Detached Houses

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Abstract

Detached houses are common structures located in both urban and rural environments. When judging the seismic performance of an existing detached house, to obtain consistent results from the structural analysis has been found to be challenging. This due to aspects such as: limited structural drawings, the type of and assumptions for the analysis, the variability/complexity in the structural layout and the expertise of the engineer. These, among others, may result in either insufficient or uneconomical solutions.

The repetition of similar measures applied to building typologies has been observed as the result of several evaluations performed by Royal HaskoningDHV for unreinforced masonry structures in the Groningen region of the Netherlands. This repetition is due to both, the expertise developed by engineers in applying certain retrofitting strategies and the typical reinforcement requirements for the evaluated building typology. Experienced engineers usually pre-known that structures will perform properly if a certain measure set is applied. Based on this observation, it seems a straightforward strategy to guarantee the effectiveness of the application of measures from the reliability point of view. This can be done by determining probability density functions for standardized retrofitting measures sets applied to building typologies and the use of target reliabilities. This hypothesis has been investigated throughout this document by means of the analysis of artificially simulated gable walls with and without a reinforcement measures located in the region of Groningen. The simulated gable wall part of the building follows typical architectural configurations of a small size detached houses.

Under the proposed probabilistic assessment approach, the necessity of measures is consequently defined from a detailed inspection of identified vulnerable structures and the seismic demand level at the location rather than from a deterministic structural analysis. This may bring advantages such as: standardization of measures, time reductions in the retrofitting process, and an improved retrofitting cost estimation based on a detailed initial inspection.

Keywords: Seismic Retrofitting Standardization; Reliability-Based Assessment; Groningen

1. Introduction

It has been observed for seismic evaluations of detached un-reinforced masonry houses for the region of Groningen in the Netherlands that consistency of deterministic evaluations in existing structures following typical normative methods is challenging. The inconsistency is linked to aspects such as the limited availability of structural drawings, the type of and assumptions for the analysis, the complexity due to the variability in the structural layouts of detached houses and the experience of the engineer. These, among others, may result in either insufficient or uneconomical solutions.

Probabilistic approaches developed from architectural typologies to characterize the seismic capacity of structures have been widely proposed in literature. They are commonly used for seismic risk studies and, more recently, as a screening technique to determine prioritization for seismic retrofitting [1]. A major advantage of these methods is that they are suitable to evaluate large amount of structures relatively fast.

In particular for the Groningen region, major challenges are to be addressed regarding the expected seismic performance of a large number of buildings. There, constructions have been designed without seismic guidelines and many are built up from un-reinforced masonry, “URM”. URM is a well-known high seismic vulnerable construction type [2]. In total, 85% of the building stock in the region is considered to be URM and the occupied building stock in the hazardous region is of about 150 000 buildings [3], where detailed assessments are possibly required for high importance structures and buildings located in the higher seismic hazardous areas. According to the National Coordinator Groningen “NCG”, about 23.5 thousand structures are located at higher earthquake hazardous area in Groningen [4]. This situation can trigger a safety concern and social unrest among the inhabitants affected, demanding a quick response from the Dutch responsible authorities.

Similar to most regulations, the Dutch NPR 9998:2018 [5] guideline mentions both linear and non-linear methods for seismic assessment of structures. Due to the structural complexity commonly found in non-seismic designed structures, the use of simple methods, such as the Linear Static “LS”, is rare because the structure will not meet the method requirements. This leaves the Modal Response Spectrum “MRS” analysis as the common assessment method for low rise detached houses. Other methods, such as Non-Linear Time History “NLTH” and non-linear pushover “NLPO” analyzes, have also been used since they provide economical retrofitting solutions, with drawbacks in terms of greater analysis costs, time and the necessity of higher engineering expertise. Nowadays, simplified NLPO procedures have been also proposed for the assessment of structures such as GSAT, the Groningen Seismic Assessment Tool [6].

1.1 Seismic activity in Groningen

Since the year 1986, seismic activity due to gas extraction activities has been recorded in the Groningen province in the North of the Netherlands, without raising major public attention up to the Huizinge earthquake, in 2012, when earthquakes became recognized as a potential safety risk [7]. Prior to the gas extraction activities, the region of Groningen has been considered as a very low seismicity area; in fact, located in the zone with the lowest expected seismic intensity for the country (about 0,01g according to [8]). The seismic hazard intensity to be used for the design and evaluation of structures has been a topic of debate since, different from usual tectonic earthquakes, it is dependent on gas production scenarios. The most recent production scenarios target to a cessation of production by 2030 [9]. Seismic design spectra for three different scenarios, according to the expected retrofitting measures construction execution period, can be found by means of a Webtool [10]. This webtool interface has been created to be used together with the recent 2018 Dutch seismic provision, the NPR 9998:2018. The seismic demand for the Groningen region described in the NPR has been determined from a PSHA procedure. A return period of 2475 to be used for a Near Collapse Limit State “NCLS” has been presented in the norm. Details about the probabilistic background for the determination of the reference ground motion are presented in [11].

1.2 Current assessment and expected measures

Structures are currently evaluated by means of a structural model analyzed by an engineering software or webtools such as GSAT. In modelling, to be able to perform reliable assessments usually the evaluator requires to include certain constrains such as fixed at the top of walls, providing already a retrofitting measure related more to suitability for a stable software analysis and/or the assessment method rather than the necessity of the measure itself. It is also the case, that the assessments' quality relies greatly on a proper inspection of the structure and realistic structural drawings, which are in many occasions not available.

Within the participation of Royal HaskoningDHV in the VIIA-Groningen project (VIIA is a joint venture between Royal HaskoningDHV and Visser & Smit Bouw), several URM buildings had been assessed mostly by means of MRS and NLTHA methods. Some relevant observations toward standardization of measures and advantages of non-linear methods can be observed by analyzing the assessment database. Fig.1 shows a comparison between 59 buildings analyzed with both methods. There, the total cost of all measures, in Euros to November 2018, are associated to a so-called reference base shear, which corresponds to the value of the total mass multiplied by the reference seismic acceleration. From Fig.1, it is observed that there is a clear tendency to achieve economical advantages from the use of NLTHA. This highlights well the fact that usually methods of higher sophistication lead to cheaper solutions, though their use may be difficult to be justified for relatively low-cost houses (so the typical detached house). Nevertheless, it is important to observe that not necessarily the differences came only from advantageous use of non-linear material properties in NLTHA, but they are also related to conservatism linked to uncertainties in URM structural assesment by means of MRSA.

For some specific cases, like clay URM buildings constructed before 1945, the average ratio between MRS and NLTHA results increases to a factor of about four times the cost as shown in Fig.2. Fig.2 reflects the comparison for clay brick URM built previous to and after 1945. There, MRS method seems to be more suitable for post-1945 URM buildings which usually present rigid concrete floors, lower wall thickness and less structural modifications during their life span. When separating the applied strengthening measures in Fig.2 according to the Groningen Retrofitting Measures Catalogue, GMC [12], it is evident that the most substantial impact between MRS and NLTHA is related to measures to improve out-of-plane, OOP, and in-plane, IP, behavior. There, measures related to L5 and L6 are indicators of structural lateral capacity insufficiency. Regarding the similarities in between methods in Fig.2, a comparable average cost of measures is provided to improve connectivity between walls and floor/roof, and also applied to improve behavior of floors and roofs. Both measures related to connections and floors promote the joint behavior of structural elements; hence, enhancing structural redundancy of the system which comes out into a better global behavior of the structure. The use of L3 and L5 measures is proposed as the method to improve the behavior of gable wall in this study.

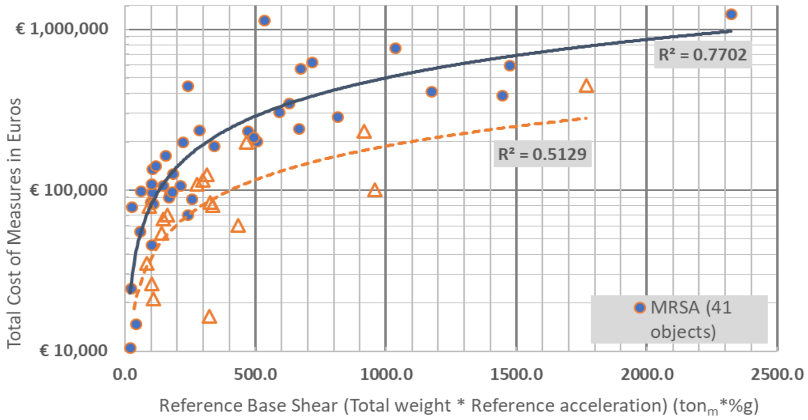


Fig. 1 – Relation between seismic retrofitting estimated cost and the reference base shear for URM in Groningen (not including costs of the structural analysis and for PGA between 0,14g and 0,36g)

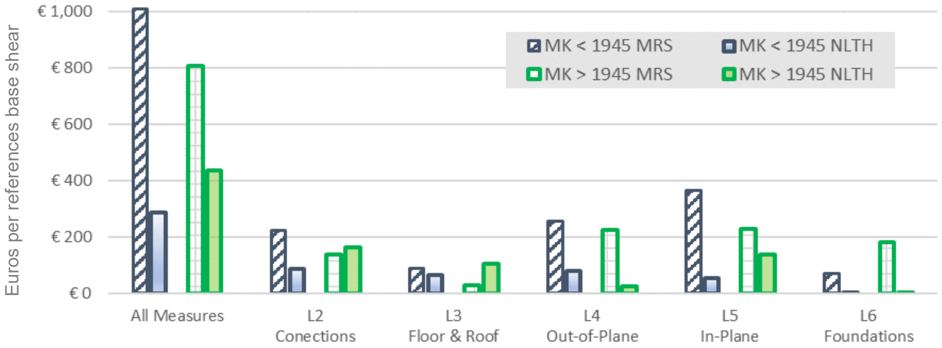


Fig. 2 – Estimate normalized cost of retrofitting measures for pre-1945 clay masonry (MK) and post-1945 clay masonry by means of MRSA and NLTHA methods

1.3 Towards standardization of measures in Groningen, the "GMC"

At the beginning of the seismic assessment and retrofitting of structures activities in Groningen, the involved parties followed the typical assessment processes which faced various downsides. Difficulties were identified for the experience gaining and to investigate the seismic behavior of the traditional Dutch building under earthquake load, where the parties struggled with the same questions and with their outcomes not documented nor collected on a shared platform. Following this engineering procedure is a labor-intensive process, where the assessing and retrofitting of every at-risk building individually would take decades. Also, it was identified that the results of the assessments and proposed retrofit designs varied strongly among the various operating firms, even for similar buildings located at the same street. These differences enlarged the social unrest among the inhabitants. Finally, the constructability of the proposed measures was not always in relation with the capabilities of the building contractor. Because of this, difficult to implement measures from design could have caused much additional work.

In response to these difficulties, the Groningen Measures Catalogue, "GMC", has been developed. The GMC is an online platform that enables co-creation and exchange of knowledge and experience across companies. The measures are described upon various aspects such as the structural objective, structural effect, material specifications, health & safety, impact on aesthetics, costs, etc. The development of the retrofit measures is performed in conjunction with various engineering firms, the construction industry, universities and the local authorities. Over 50 parties are currently working with the online GMC. When a measure is applied, the experiences of the contractor and construction workers is fed back to the catalogue, enabling a self-improving process aiming for a better characterization of the measures based on practical experience. The development of the GMC and the uncertainties related to a likely inadequate structural model in terms of the building characteristics and assumptions related to deterministic approaches for seismic assessment and retrofitting, triggered the idea that a probabilistic process may also be suitable for a fast and reliable seismic assessment procedure of structures in Groningen.

2. Assessment for existing building typologies

Advantages of analyzing a structure from a probabilistic point of view includes a more suitable treatment of assumptions/variables by means of probability density functions (avoiding Boolean assumptions), the possibility to analyze the sensibility/influence of assumptions, the possibility to assess building populations by typology rather than an individual structure, and finally it can easily incorporate the influence of a variating seismic demand. This last aspect is convenient for the Groningen region since the seismic hazard is linked to the gas production rate, which can vary according to the energy policies of the country. For deterministic approaches, full recalculation of the suitability of measures previously proposed for a new seismic demand will usually be necessary.

Typological based approaches are useful to address buildings aspects from a typological point of view facilitating assessment elements such as:

- Identification of typical expected structural weaknesses.
- Decision making from a population point of view.
- Standardization and specialization in the application of measures (in collaboration with the industry).
- Facilitating the possibility to incorporate the effect of other upgrades (such as the energy efficiency measures).
- Being used as a guideline for research necessities, aiming first to those studies based on the expected impact.
- Structural safety assessment of existing and retrofitted structures based on the code required reliability.

The downsides of typological approaches to address structural safety are related to the failure to identify structural weaknesses, a misinterpretation of the structural typology family by the evaluator, and the possible the use of measures that may not be necessary. Most of these issues, it’s relevant to mention, are also presented in deterministic evaluations.

2.1 Influence of a retrofitting intervention

One of the main aims of this paper is to present observations about the influence of retrofitting measures sets in terms of their impact to reduce the probability of failure for structures. This can be easily observed in terms of the limit state equation formulation. There, the resistant probability density function component of a retrofitted building system is expected to improve its behavior; usually for both the increment of the strength capacity of the structure and a reduction in the expected behavior uncertainty (Fig.3). This change reflects on the calculation of the probability of failure for the house. This new condition of the structure may be enough to meet the safety requirement in function of the specified reliability targets described in codes. The variation of the probability of failure of a building part in a detached house will be investigated from section 3.

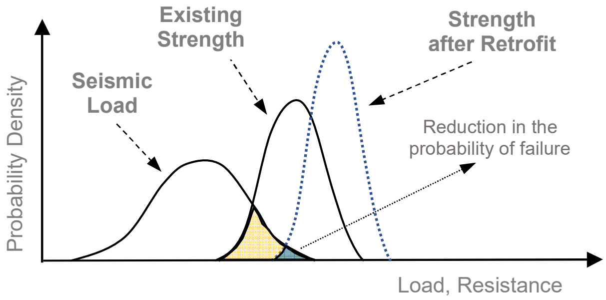


Fig. 3 – *Schematic influence of strengthening measures for the system resistance probability density function*

3. Modelling and evaluating a URM detached house part

URM detached houses is a common housing typology in the Netherlands. Different from relatively regular layouts typologies such as terraced houses, they may present variable structural configurations since these structures were in many occasions tailored-made to the owners’ requirements. This may include the addition of extra areas to the original during the life span of the structure. From a building stock point of view, this will result in a greater variability of the expected seismic performance of this building typology.

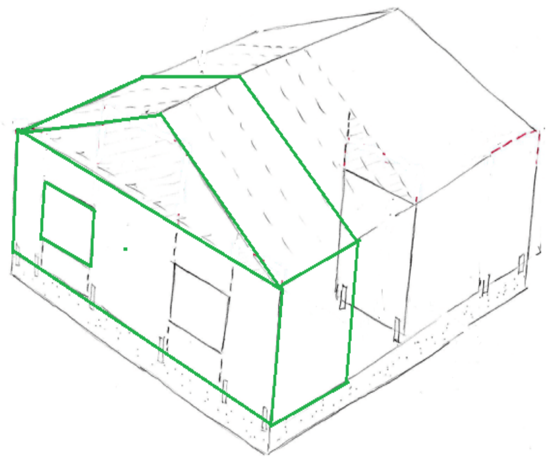
As an initial step for the analysis of detached houses, the in-plane capacity of a part of a typical Dutch un-reinforced masonry gable wall in a one-story building has been investigated in this study. The expected variability of the characteristics of gable walls for small area URM detached houses according to experience is explained in section 3.1. The purpose of limiting the analysis in this study to one wall is to better understand the behavior of a section of the structure before introducing greater complexities, in particular for

URM with flexible floors, were the seismic evaluation of the structure may be even conducted by decoupling the structure in several parts, as is done with methods such as SLaMA [13].

3.1 Architectural characteristic of a URM detached house gable wall

A gable wall has been selected in this study as a building part. A reason to select this particular element for testing is the triangular variation of the overburden load on the wall piers, which is expected to contribute to a wider possibility of realistic overburden load cases than a uniform overburden load. Other aspects considered are that walls are modelled with at least one opening (so at least 2 piers) and the possibility to include or not windows in the upper gable. Further details for the simulated building part are presented in Table 1. The low seismic intensity range presented in the table is linked to the area of interest in the probability of failure distribution; hence, a greater number of intensities are evaluated at that range. The wall tested consists of Dutch clay masonry, with a thickness of 10 cm. In the context of this study, the initial characteristics presented in Table 1 are based on experience, common sense and on the data collected for the analysis of 60 one story houses in the area of Groningen.

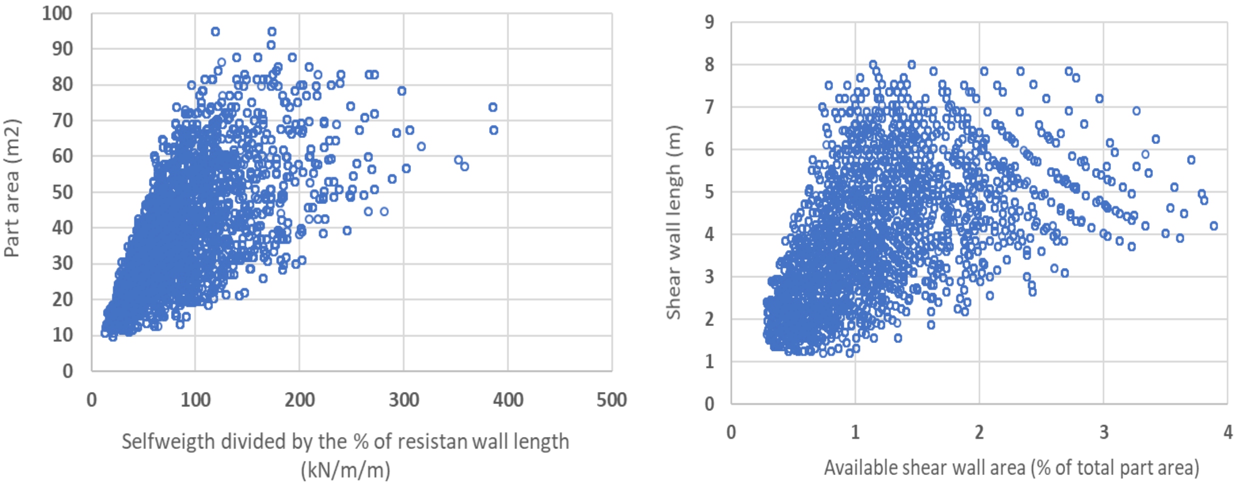
Table 1 – Summary of the building part simulation characteristics for a gable wall

Building part schema of the simulated portion	Parameter	Min	Max	Distribution type
	Story height	2.6 m	3.2 m	Triangular (mode = 2.8 m)
	Story length	6 m	10 m	Uniform
	Spanning in the other direction	0,5 (story length)	2 (story length)	Triangular (mode = 1)
	Doors	0	1	Uniform
	Piers	2	5	Uniform (dependent of the wall geometry)
	Windows on gable	0 (no windows)	60 % of gable area	Uniform
	Roof slope	40 deg.	50 deg.	Uniform
	Resistant wall length	20 %	80 %	Uniform
	Seismic intensity range	Min median 0.07	Max median 0.3	Median value for Lognormal (σ = 0.3)

3.2 Review of simulated parameters

Several aspects have been checked for verification of the resultant modelled walls. According to the specific characteristics from Table 1, aspects that can be mentioned are, for instance, that average overburden loads at the attic floor level on the walls which varies between 0.4 kN/m (minimum for a gable with openings) to a maximum of 4.5 kN/m.

Fig.4 shows 2 examples of aspects that had been controlled. Also, in Fig.8a the number of walls modelled per available shear wall area is shown. In total 24400 walls have been synthetically generated. Many present small amounts of available shear wall area, typical for the somehow large building part areas and the 10 cm thickness of the walls. Other aspect of control is a realistic estimation of the seismic weight, which is found to be accurate in terms of the building part area observed in Fig.4a. Other building simulated characteristics and the applied seismic intensity are presented on Fig.7 and Fig.8 of section 4.



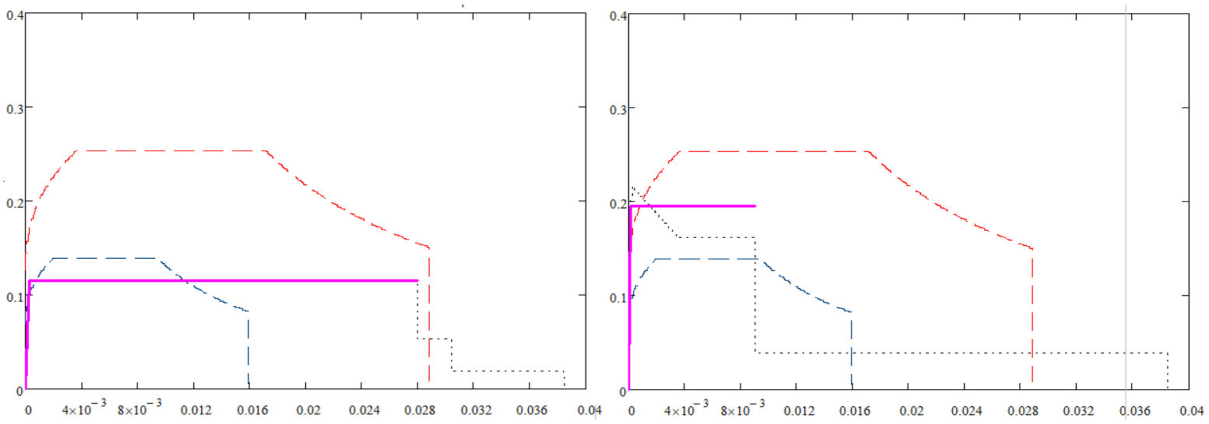
a) *b)*

Fig. 4 – Variation of modelled walls in terms of a) the total wall area to the total seismic weight of the part divided by the percentage of the resistant wall length, and b) the shear wall length related to the total available shear area in percentage of the total part area

3.3 Non-linear pushover analysis according to the NPR 9998:2018

For determining the seismic capacity of the gable walls, a non-linear pushover procedure according to the recent NPR 9998:2018 requirements is followed. For walls were a weak spandrel mechanism was observed (following the procedure proposed in [13]), a strong spandrel condition is provided for the retrofitted version of the walls, which is an effect of applying L3 or/and L5 measures on spandrels. The effect of measures is that the change in the boundary conditions for piers will increase the spectral seismic strength capacity and may change the failure mechanism as observed in Fig.5b when compared with Fig.5a.

Nonlinear pushover calculations were conducted for the 24400 walls by means of a Mathcad function that produces random gable walls and evaluates compliance of the wall simulated. In other to run several times the Mathcad function, a C+ routine has been coded to call the Mathcad function. Compliance or non-compliance to near collapse limit state according to the NPR annex G equations is recorded for each simulated wall and seismic action. The capacities have been computed for the mean material properties according to the values presented for pre-1945 clay masonry according to annex F of the NPR.



a) *b)*

Fig. 5 – Variation of pushover equivalent bilinear curves for a) non-retrofitted (with weak spandrel mechanism), and b) retrofitted wall parts (strong spandrel condition provided to the original weak condition)

4. Assessment of results

From the non-linear pushover analysis conducted for the so called reinforced and unreinforced conditions several aspects were observed. As commented before, the reinforced condition in this case is attained by the effect of improvement of the boundary conditions that may be attained by the application of reinforcement. Walls that already present a strong spandrel condition will not change the capacity. The effect in the variation of boundary conditions for the NPR equations can be observed in Fig.6 in terms of the resisting gable wall to the total building part area. This ratio has been suggested in the Table 9.3 of the Eurocode 8 part 1 for design of structures according to simple rules [14]. Fig.6 shows that with the increasing wall resistant area there is, as expected, an increment of the median of both retrofit and no retrofit conditions and also a reduction of the standard deviation (in the figure log-normal PDFs for two wall resistant rages, 0.5±0.1 and 1.0±0.1%, are presented). From Fig.6, it can be observed that for this tested building part, the expected improvement of the behavior according to Fig.3 with the application of a measure is not always effective, in this case, for walls with resistant wall ratios below 0.5%.

The variation of the probability of non-compliance of the NPR evaluation according to the non-linear push over analysis technique is presented in Fig.7. The capacity of the gable walls has been calculated according to the mean values of the material properties given in annex F and to the strength and displacement capacity equations presented in the annex G of the NPR for the near collapse limit state. A lognormal function has been fitted to the data, adjusted to the low seismic intensity tail of the probability density function since it's the region of interest for this study. In Fig.7a, a detail of the seismic intensities is also presented to show that emphasis to the low seismic intensities had been performed. The number of simulations for the Monte Carlo process has been determined in function of the observed frustration of the probability of non-compliance values for the lower seismic intensities. It should be observed here that the number of simulations should be adapted to provide enough scenarios according to the reliability philosophy of the local seismic code.

In Fig.7b, a significant shift between the non-retrofitted and retrofitted cases can be observed. The median values are 0,255g and 0.29g respectively. The standard deviation is lower for the retrofitted case with a value of 0.335 meanwhile the non-retrofitted case presents a value of 0.365. The results presented in Fig.7b differ from those typically observed when constructing fragility curves since it's evaluated if the structure is compliant or not; hence, compliance conditions includes all damage limit states below the near collapse limit state. This approach is suitable for existing or the retrofitting of existing structures with one performance goal to comply with.

Similarly to Fig.7b, probabilities for non-compliance to the NPR have been derived in terms of spectral displacements. Here the results present medians of 36 mm with a standard variation of 0.32 for the retrofitted case and 32 mm with a standard variation of 0.36 for the non-retrofitted case. Fig.7b result in terms of the spectral acceleration is preferred here rather than the spectral displacements because its currently more straightforward to be linked to typical seismic normative definitions in terms of acceleration intensities.

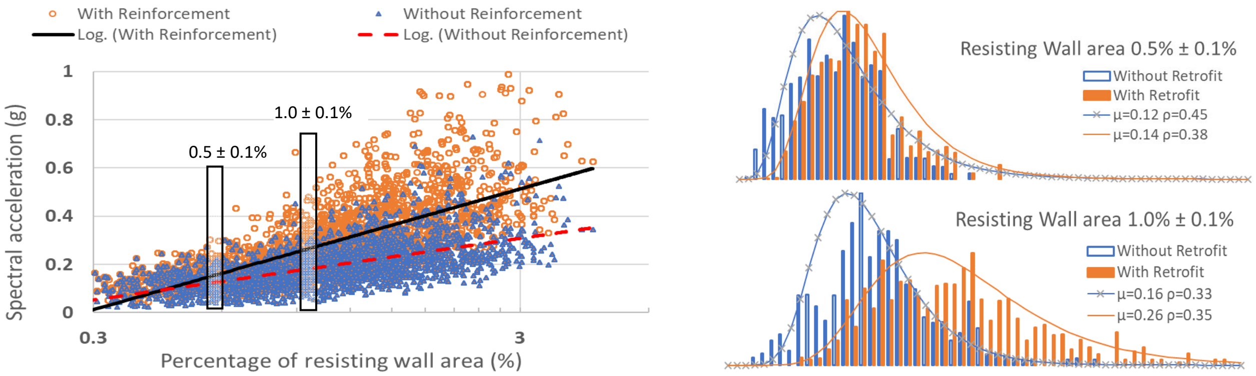
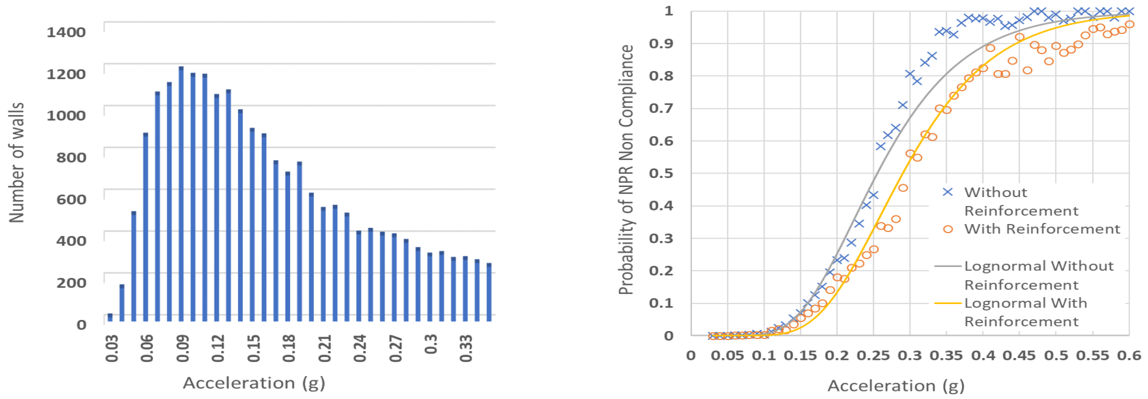


Fig. 6 – Variation of the spectral acceleration plateau values for bilinear PO analysis



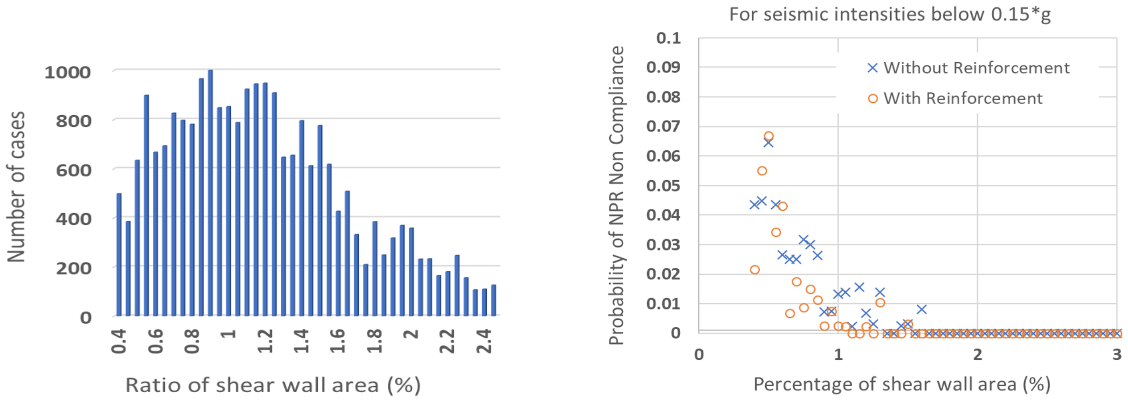
a) *b)*

Fig. 7 – a) Number of simulated gable walls in function of the seismic intensity, and b) variation of the probability of non-compliance of the NPR 9998:2018 for walls with and without retrofit measures

4.1 Comparison with other simplified assessment procedures and target reliability

Simplified rules for the design of URM structures are drawn in section 9 of the Part 1 of the Eurocode 8. There, this approach is limited to low seismicity areas and various structuration rules, including a table were a minimum amount of resistant shear wall area in terms of the total area is specified. The method is valid for structures were shear walls are the main lateral resistant elements of the structure. This amount of resistant shear wall area has been used in this study to present results such as those of Fig.6. Probabilities of non-compliance can be calculated as well in function of this shear wall ratio as observed in Fig.8b. For Fig.8b, the seismic intensities had been limited to 0.15g since this is the upper limit of intensity observed in table 9.3 of the Eurocode 8 (with ‘k’ equal to 1) [14].

By inspecting Fig.8b, a non-compliance trend is clear toward lower available shear wall area ratios. This is consequent with the increasing shear area requirements from table 9.3 of the Eurocode 8. Also from this figure, it has been observed that after a ratio of about 1.6%, there are no more failing cases. This is can be just observed as a tendency because, as it can be deduced from Fig.8a, not that many walls had been simulated with high shear wall area ratios. This is related to architectural parameters and the number of simulations. Judging from Fig.8b, the requested amount of walls equal to 3.5% of the total building are may be too conservative if applied for design of Dutch URM clay masonry houses. This should be investigated further.

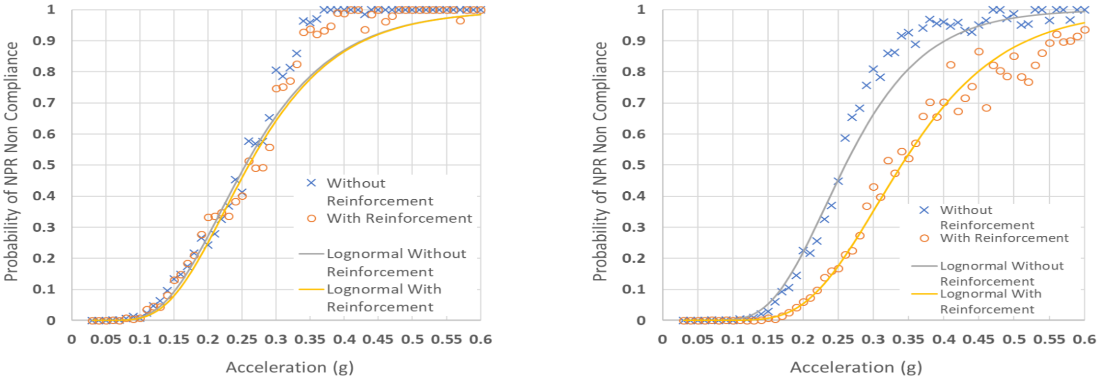


a) *b)*

Fig. 8 – a) Building part simulated cases in function of the number of resistant walls are per total building part area, and b) probability of non-compliance of the NPR for walls with and without retrofit measures

According to the Dutch NPR 9998:2018 philosophy, the target reliability is between 0.8 and 1.2 times 10-5 [11]. The same document mentions that: “for a structure (with mean properties) loaded by the design seismic load (*return period of 2475 years for the structural elements* [5]), the acceptance criteria should be defined in the model to calculate the resistance such that the structure has a 5% probability of global collapse” [11]. Considering, as an initial reference for this study, that this probability is valid for architectural varying wall populations, acceleration limits for expected sufficient performance can be attained. For Fig.7b, this will correspond to about 0.14g and 0.17g of the NPR seismic load for the non-retrofitted and the retrofitted cases respectively. Here it can be noticed that the effectiveness of the application of measures may not have a major impact for all wall simulations.

In Fig.9, the impact of the measures has been divided for shear wall ratios below 1% and above 1%. This provides a interesting overview about the impact in terms of the applied measures, where for low ratio of shear wall area there is almost no impact related to the measures and consequently other solutions should be provided for these architectural conditions. On the other hand, for ratios above the 1%, the effectiveness of the measures is evident, passing for 0.14g to 0.2g.



a) *b)*

Fig. 9 – Probability of non-NPR compliance for a) building parts only with resistant walls to total area ratio below 1%, and b) building parts only with resistant walls to total area ratio above 1%

4.2 Analysis of non-compliant structures characteristics

The analysis of structures that failed the NPR compliance can be used to identity house characteristics that can be related to structural weaknesses or weak structural configurations. For example, it was observed in section 4.1 that the amount of resistant wall area in terms of the total area is a relevant parameter to identify weak structural configurations and even to evaluate the effectiveness of the introduction of measures.

To identify potential structural weaknesses causing non-compliance is, on the other hand, helpful to detect houses that may be not suitable to be addressed by simplified methods and required deeper deterministic analysis. This is an additional aspect that can be considered towards the reliable used of this kind of approaches. Structural weaknesses may be related to rules such as those used for the simplified design of URM commented in the Eurocode 8.

Conclusions

A strategy for the seismic assessment and the effect of retrofitting in existing structures has been presented. This approach, has been proposed for detached houses in response to several situations observed for seismic assessment of this houses in Groningen such as: a gas production dependent seismic demand, difficulties observed for deterministic modelling of detached houses, difficulty to justify non-linear methods to be used for relatively low-cost structures, the availability of standardized retrofitting measures tool (“GMC”), and finally the large amount of structures that require to addressed in the region in a short period of time.

After conducting simulations for a building part consisting of a gable wall, the various observations presented in section 4 suggested the viability of the strategy, especially when calibrated to be used for certain building conditions, such as cases when the ration of resistant wall area to the total building part area is bigger than 1%. Some of the results have been compared with statements provided for simplified design of URM structures commented in the Eurocode 8.

Research on the topic presented here is suitable to demonstrate trends but a rigorous theoretical background is currently still under development. To assess whole structures for detached houses with flexible floors will probably reduce capacity of the structure since the structure is expected to fail at the weakest wall line of assessment [13] and, on the other hand, the application of measures (such as a stiffer floor) will probably increase the capacity since redistribution of load between walls will be possible and if torsion is not relevant. Another relevant aspect is that the probability of failure in the out-of-plane mode of walls is still to be included together with the in-plane failure mechanism.

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