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Harmonizing Computational Methods for the Seismic Assessment of Unreinforced Masonry Structures: The Dutch Case

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Abstract. Induced seismicity in Groningen, Netherlands, has necessitated the assessment of a building stock not originally designed for seismic hazards. With no prior national standards for seismic assessment, early evaluations relied on Eurocode EN 1998–3, which was not specifically suited for the region's shallow earthquakes and its unique building stock, mostly composed of low-rise unreinforced masonry (URM) buildings with cavity walls, slender piers, and large openings. Since 2015, the Dutch NPR 9998 guidelines have introduced various assessment methods, but inconsistencies in assessment outcomes remain a challenge. A full-scale URM house test at TU Delft, linked to a blind prediction contest, highlighted significant variability in key response parameters, such as base shear and displacement capacity.

This paper discusses three initiatives aimed at improving consistency in seismic assessment. First, cross-comparison exercises evaluated different nonlinear dynamic and static procedures on reference buildings. Second, a semi-probabilistic typology-based approach was developed for global seismic assessment, with a similar method under development for local out-of-plane URM wall assessments. Third, an experimental campaign on URM gable wall failures, combined with a blind prediction contest, seeks to enhance consistency in computational approaches for this under-researched typology. While progress has been made in improving the consistency of assessments, challenges remain, particularly in accounting for local failure mechanisms. The semi-probabilistic approach offers a promising path forward, but further refinements are needed for broader application beyond the Dutch context.

Keywords: Unreinforced masonry · Seismic assessment · Harmonization of computational methods · Cross comparison · Blind prediction · Typology-based assessment

1 Introduction

The seismic assessment of unreinforced masonry (URM) structures has been a focus of research in many countries, particularly in regions prone to natural earthquakes. In Groningen, however, the need for such assessments has emerged in recent years due to

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induced seismicity caused by decades of natural gas extraction, leading to ground subsidence and stress changes in the subsurface (Fig. 1) [1]. Unlike tectonic earthquakes, these induced events are typically shallow, generating higher ground accelerations compared to tectonic events of similar magnitude. Since the region's buildings were not originally designed for seismic loads, assessing their vulnerability has become a priority. The unique characteristics of Groningen's building stock, primarily URM structures with cavity walls and slender piers, present challenges for both seismic assessment and retrofitting.

Residential URM buildings in Groningen can be classified into four main categories: terraced houses, detached houses, semi-detached houses, and apartments [2]. Detached houses, prevalent before World War II, are low-rise (one or two stories) with timber diaphragms and loadbearing walls of solid clay brick masonry. These buildings typically have small openings and irregular plans. Terraced houses, a typical example of which is shown in Fig. 2, consist of multiple horizontally connected one- or two-story units. Their loadbearing structure includes slender piers and long transverse walls, with cavity walls where inner and outer leaves are tied with steel connectors. Various masonry types have been used, including calcium silicate (CS) masonry for inner leaves and clay brick for outer leaves. Most buildings feature concrete floors (either cast in-situ or prefabricated) and timber roofs. Semi-detached houses, consisting of two connected units, share characteristics with detached houses but have one common wall, influencing their seismic response. Apartments, usually in low- to mid-rise buildings, feature a mix of loadbearing masonry and reinforced concrete elements, with variations in wall configurations and floor systems.

Not being traditionally an earthquake-prone region, the Netherlands had no prior national standards for seismic assessment, and existing guidelines, such as Eurocode EN 1998–3 [3], were not well-suited to the specific characteristics of the shallow, low-magnitude yet high-acceleration earthquakes observed in Groningen, as well as of the region's built environment. To address these challenges, a newly developed national standard (NPR 9998) was introduced to provide specific assessment and retrofit guidelines tailored to Groningen's unique seismic hazard and structural typologies. The first released version (NPR 9998:2015 [4]) primarily included recommendations on Nonlinear Time History Analysis (NLTHA) but did not yet provide detailed guidelines for other advanced assessment methods. The focus in this initial version was on adapting the Eurocode EN 1998–3 principles to Groningen's induced seismicity, with NLRHA being the preferred method for assessing seismic performance. Later versions (NPR 9998:2018 [5], and 2020 [6]) expanded the framework by introducing simplified, linear, and nonlinear static procedures for the assessment of both the global building response and local failure mechanisms.

Since 2014, an extensive and integrated experimental campaign has been conducted in multiple European laboratories, including EUCENTRE (Pavia, Italy), LNEC (Lisbon, Portugal), and TU Delft (Delft, the Netherlands) [7, 8], to gain knowledge on the seismic response of the Groningen URM building stock and provide benchmarks for the validation of numerical and analytical models. Additionally, part of the investigation focused on the initial crack propagation and light damage state due to the specificity of the Groningen hazard. This campaign includes both static and dynamic tests conducted

at different scales: from the material level [9, 10], to the component level [11–15], and the structural level [16–20].

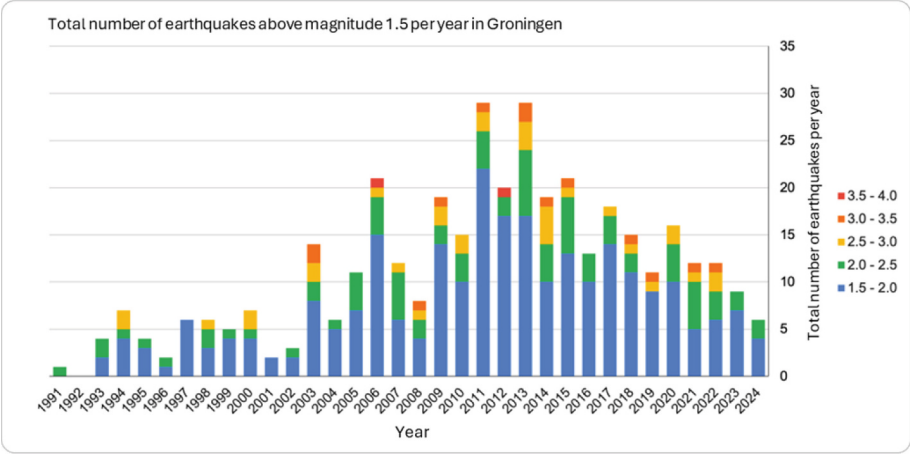


Fig. 1. Annual number of earthquakes in the Groningen gas field with a magnitude of 1.5 or higher from 1991 to 2024 (adapted from KNMI [1])



Fig. 2. Typical unreinforced masonry terraced house in the province of Groningen.

One of the quasi-static cyclic tests conducted on a full-scale structure [20] was selected for a blind-prediction contest open to engineering companies involved in the seismic assessment of the Groningen building stock. Nine engineering consultants participated in the contest, and a comparison between the predicted capacity curves and the envelope of the cyclic experimental curve is shown in Fig. 3. Participants used different modelling strategies, including finite element models (blue lines in Fig. 3), macro-element models (orange lines in Fig. 3), and an analytical-based approach (green line in Fig. 3), resulting in a high dispersion of results. While the mean of the nine predictions reasonably approximates the key response parameters, such as initial stiffness

(−18%), peak base shear (−8%), and ultimate displacement (−9%), high coefficients of variations, reaching 78% for the prediction of the initial stiffness in the negative loading direction, were observed [21].

The divergence in predictions highlighted a lack of consistency in professional assessments, partly due to the multiplicity of assessment procedures recommended in NPR 9998. This inconsistency underscored the need for greater alignment between assessment methodologies, improved calibration of modelling assumptions, and enhanced guidance for practitioners. To address these issues, multiple projects and cross-comparison exercises have been conducted over the years. This paper presents three initiatives aimed at improving consistency in the seismic assessment process. First, two cross-comparison exercises, involving different nonlinear dynamic and static procedures, are described in Sect. 2. Second, a semi-probabilistic typology-based approach developed for the global seismic assessment of buildings is outlined in Sect. 3. Third, a recent experimental campaign on the out-of-plane failure of URM gable walls, along with the related blind prediction contest, is briefly reported in Sect. 4. Final remarks are presented in Sect. 5.

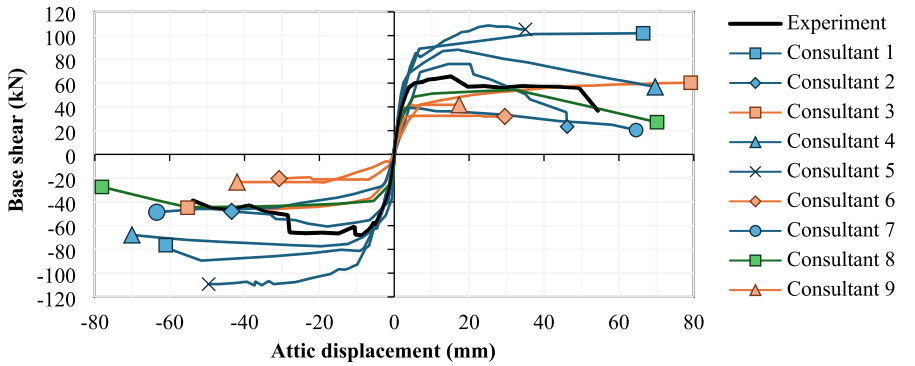


Fig. 3. Comparison of predicted capacity curves from nine consultants with the experimental envelope for the blind-prediction contest of the full-scale structure tested at TU Delft [21]

2 Cross-Comparison Between Numerical Assessment Methods Recommended by the Dutch Standard NPR 9998

Annex G of NPR9998:2018 [5] introduces the possibility of assessing the global response of URM buildings via nonlinear pushover (NLPO) analyses. The standard allows for alternative calculation methods, including simplified hand-calculation mechanism-based approaches, such as the Simplified Lateral Mechanism Analysis (SLaMA) [22], pseudo-nonlinear analyses using iterative elastic analysis, and full nonlinear finite element modelling, which accounts for material and geometric nonlinearities. These methods differ in complexity and expected accuracy, both of which increase from the hand-calculation approach to full nonlinear finite element modelling. Additionally, the assessment must be supplemented by the evaluation of local failure mechanisms, including the out-of-plane (OOP) collapse of individual walls. This is comprehensively addressed in Annex H of

NPR9998:2020 [6], which provides analytical calculations, namely the nonlinear kinematic analysis (NLKA) of one-way spanning walls and the method of virtual work for two-way spanning walls. However, there remain concerns regarding the consistency of assessment outcomes across different permitted methods, as well as their comparability with assessments based on nonlinear time history analyses (NLTHA). Furthermore, the guidelines detail two distinct alternative assessment procedures for NLTHA: one based on an explicit check of the near collapse (NC) limit state, defined as a volume loss in the analysis model, and the other based on an indirect check of the NC limit state via deformation criteria. This adds additional complexity and potential uncertainty to the assessment process.

Within this framework, a task group comprising both researchers and professionals investigated the consistency of the assessment process when applied to four representative buildings: one detached house and three terraced houses [23]. The investigation primarily focused on the global building response, comparing assessments conducted using NLTHA and NLPO analyses. In total, nine alternative analysis procedures were compared. Four procedures employed NLTHA, using three different software packages: two based on a continuum modelling approach (Software A and B) and one using a macro-element modelling approach (Software C). For Software A, both explicit and indirect assessment procedures were applied. The same software packages, along with an additional macro-element based software (Software D) and mechanism-based calculations (SLaMA), were used for NLPO-based assessments. Additionally, the local OOP failure of individual walls was assessed by means of NLKA, and the deformability of the diaphragms was evaluated to verify their ability to ensure the box-like behaviour of the structure. For all four buildings and nine assessment procedures, the minimum Peak Ground Acceleration (PGA) value corresponding to non-compliance with the standards' requirements was computed. This value was derived by considering the elastic response spectrum at the building's actual location, followed by scaling the spectral acceleration parameters for NLPO analyses, or by running incremental dynamic analyses for NLTHA. The results of the predicted values of PGA at near collapse, normalized by the PGA of the site where each building is located, are plotted in Fig. 4. This can be interpreted as a capacity over demand ratio. Since a complete assessment requires evaluating both global building performance and local failure mechanisms, the PGA value computed from local failure checks caps the capacity derived from NLPO, as indicated by the horizontal red lines in Fig. 4. It should be noted that not all analyses were conducted for all four buildings.

The results indicate that simpler and faster NLPO approaches generally produce more conservative assessments compared to more advanced dynamic methods such as NLTHA, with differences remaining within a reasonable range, particularly for the regular Buildings A and B. However, this trend applies only to global NLPO calculations: when the OOP checks supplements the NLPO assessment, a sudden reduction of the predicted building capacity is observed, resulting in predicting much higher building vulnerability compared to NLTHA-based assessment.

The cross-comparison exercise highlighted additional aspects pertaining to the seismic assessment. Such process requires multiple modelling choices that impact the predictions, with variations observed across NLPO and NLTH methods. NLPO approaches,

require supplementary checks for local out-of-plane mechanisms, connection resistance, and diaphragm stiffness. Specifically, macro-element-based NLPO methods assume predefined retrofits, such as strengthening of the connections, to ensure result validity. Despite efforts to align modelling assumptions, subjectivity remains, as engineering choices vary across analysts and consulting firms. Further discrepancies arise from modelling choices, particularly in NLTHA conducted with continuum finite element models, which require defining several material properties, constitutive models, and numerical schemes. Interpretation of the near-collapse criteria also varies, affecting assessment consistency. These findings highlight the need for clearer methodological guidelines, standardized NPR interpretations, and further validation efforts to enhance seismic assessment consistency and reliability.

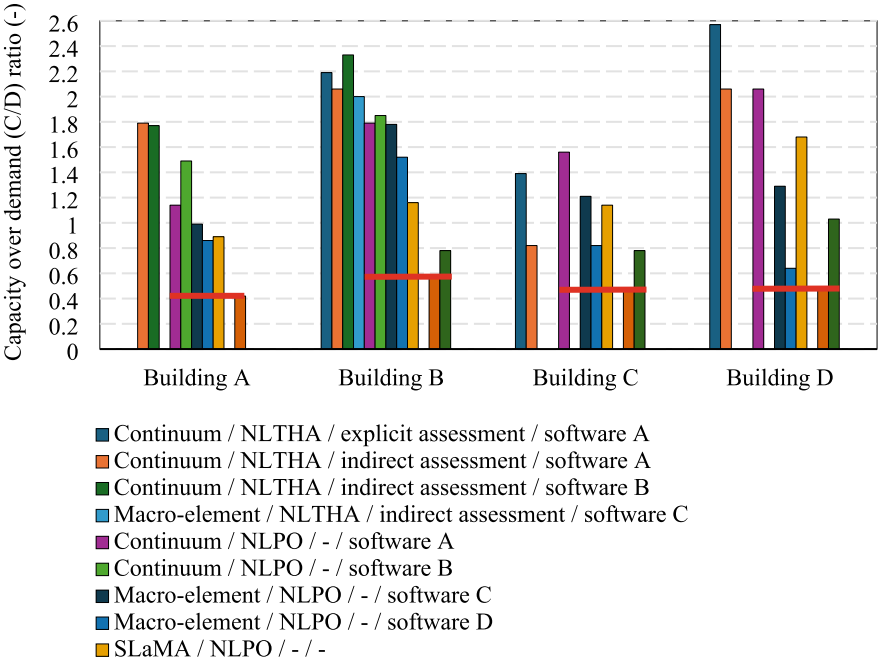


Fig. 4. Comparison between the capacity over demand ratios computed at near collapse for four reference buildings and nine assessment procedures.

Building B was also considered for a more detailed investigation of the selected assessment methodology for an NLPO analysis [24]. While NPR9998:2020 [6] recommends the use of the Capacity Spectrum Method (CSM) [25], the European standard EN 1998–1 [26] includes an informative annex where the target displacement (i.e., the expected maximum displacement of a structure under a specific seismic demand) is computed based on the N2 method [ref]. Additionally, recent research [28] has proposed a modification to the N2 method, the so-called Modified N2 (or MN2) method, specifically developed for short-period structures, and hence is more suited for low-rise URM buildings. The PGA value corresponding to the negative modal pushover capacity of the

building is computed using these three methods, showing large differences, with the N2 method predicting nearly twice the value computed using CSM, as shown in Fig. 5. When compared to the PGA value at near collapse predicted via NLTH analyses (0.33 g), both the MN2 and the CSM provide reasonable estimates, while the original N2 is largely unconservative (+66%), demonstrating its limitations for short-period buildings, in line with the findings of the research presented in Marino et al. [29], Guerrini et al. [30] and Giusto et al. [31].

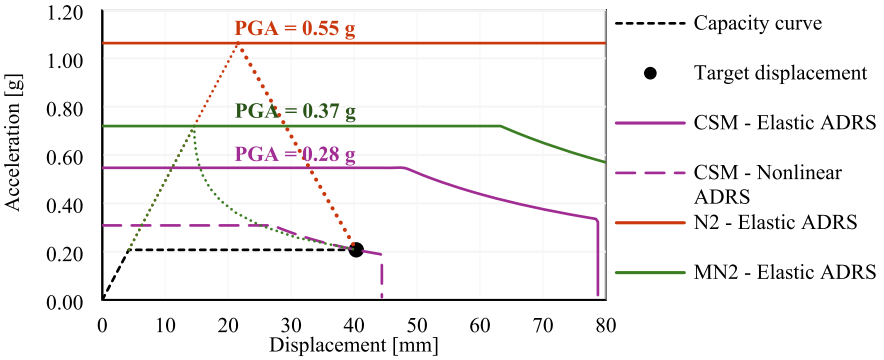


Fig. 5. Assessment of the NLPO negative modal pushover of Building B for different assessment methods.

An additional study [32, 33] focused on the comparison between the NLPO assessment using the Simple Lateral Mechanism Analysis (SLaMA) method and nonlinear finite element analyses (NLFEA). Specifically, key parameters such as base shear and displacement at near collapse (NC) were consistently compared for 94 variations of terraced and detached buildings, and 1356 2D walls with openings with geometries corresponding to those of the building facades. The ratio between the computed parameters is illustrated in Fig. 6, in terms of cumulative distribution functions (CDFs) of the SLaMA/NLFEA ratio for terraced and detached houses. While SLaMA reliably identifies the global failure mechanisms, it systematically underestimates the peak base shear, with values often less than half of those computed from NLFEA. The discrepancy increases with structural complexity, from walls to entire buildings. For displacement at near collapse, SLaMA predictions align well with NLFEA for ductile failures, while slight over-predictions occur in brittle cases; however, the sample size for brittle failures is too small to draw firm conclusions.

Overall, SLaMA provides conservative base shear estimates and reasonable displacement predictions in most cases, making it a useful screening tool for seismic assessment. However, for buildings failing the SLaMA-based check, more advanced numerical analysis is recommended to proceed with a more refined assessment, in line with the recommendations provided in NPR9998:2020 [6].

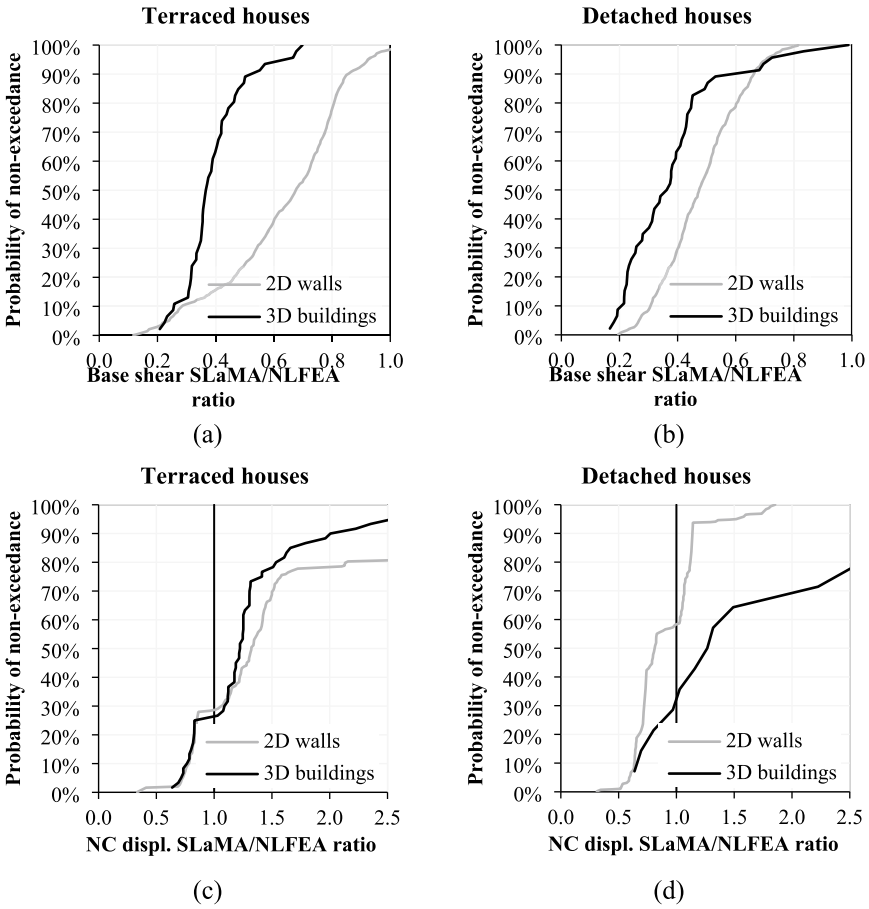


Fig. 6. Cumulative distribution functions (CDFs) of the SLaMA/NLFEA ratio for terraced and detached houses and 2D walls, for both the base shear (a, b) and the NC displacement (c, d).

3 A Typology-Based Assessment of the URM Building Stock in Groningen (NL)

To reduce the variability of assessment outcomes related to the use of different methodologies, a typology-based approach was developed by TNO in collaboration with TU Delft to assess the seismic vulnerability of buildings in the Groningen province [34]. By classifying buildings into typologies based on shared structural characteristics, this approach enables large-scale evaluations without requiring individual structural modeling. While thirty typologies have been proposed for all buildings in the region [35], including concrete, timber, and steel structural systems, the typology-based approach has proven particularly effective for URM buildings, given their large presence in the area. Within this approach, masonry buildings are categorized into thirteen typologies based on key seismic parameters, including building type (terraced or detached houses, apartment buildings), number of stories, facade composition (described in terms of opening

percentage), presence of cavity walls, and floor and roof construction types. These characteristics determine how a building responds to seismic loads, influencing its stiffness, failure mechanisms, strength, and ductility.

For each typology, the outcomes of advanced finite element analyses of reference buildings and significant structural variations were used to establish seismic resistance levels for the median typology building [36] and quantify building-to-building variability (as an example, the procedure adopted for typology '*Metselwerk 1*' (Masonry 1) is described in [37]), leading to the development of fragility curves that estimate the probability of failure under different ground motions. This approach eliminates the need for new calculations; users only need to inspect buildings and classify them into one of the predefined typologies. By cross-referencing the building's location and typology using distribution maps, the assessment process becomes extremely fast, enhancing consistency and efficiency. Overall, the typology approach provides a cost-effective and scalable solution for managing seismic risks across a large building stock and has been applied in Groningen since mid-2021. Additionally, by identifying common vulnerabilities in masonry structures, it supports targeted reinforcement strategies, helping accelerate the strengthening of buildings that do not comply with safety standards (Fig. 7).

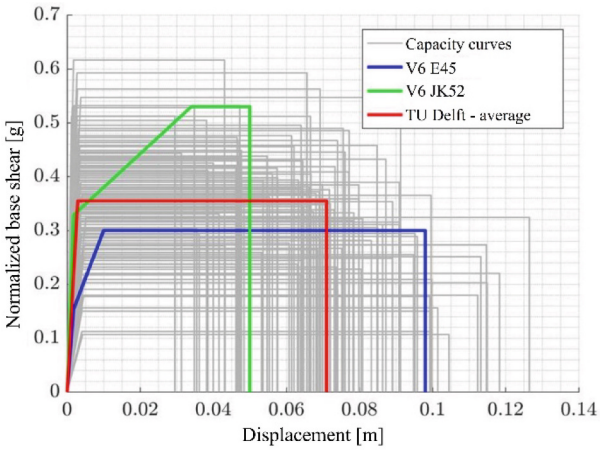


Fig. 7. Calculations in support to the definition of building-to-building variability for the building typology '*Metselwerk 1*' (Masonry 1) (adapted from [37])

4 Blind-Prediction Contest of Out-Of-Plane Failure of URM Gable Walls

As indicated above, large differences remain in the assessment of local out-of-plane (OOP) failure mechanisms of individual URM walls when methods of varying complexity. Additionally, while extensive experimental research has been conducted to investigate the seismic response of one-way [11] and two-way spanning walls [12–15], limited research has focused on the response of the gable walls, particularly on their interaction

with the roof structure [38]. For this reason, the ERIES-SUPREME experimental campaign was recently conducted to investigate the seismic OOP response of URM gable walls connected to different roof systems, with a particular focus on the Groningen case [39]. As part of this initiative, a blind prediction exercise was organized to assess the predictive capabilities of numerical models. The contest focused on two of the three tested specimens, those with a stiff and a flexible roof system, while the intermediate semi-flexible roof configuration was excluded. The collapse of the gable wall during the experiment for the configuration with a stiff roof system is shown in Fig. 8. The primary objectives of this exercise were to benchmark state-of-the-art modelling techniques, identify key challenges in capturing gable failure mechanisms, and highlight areas for improvement.

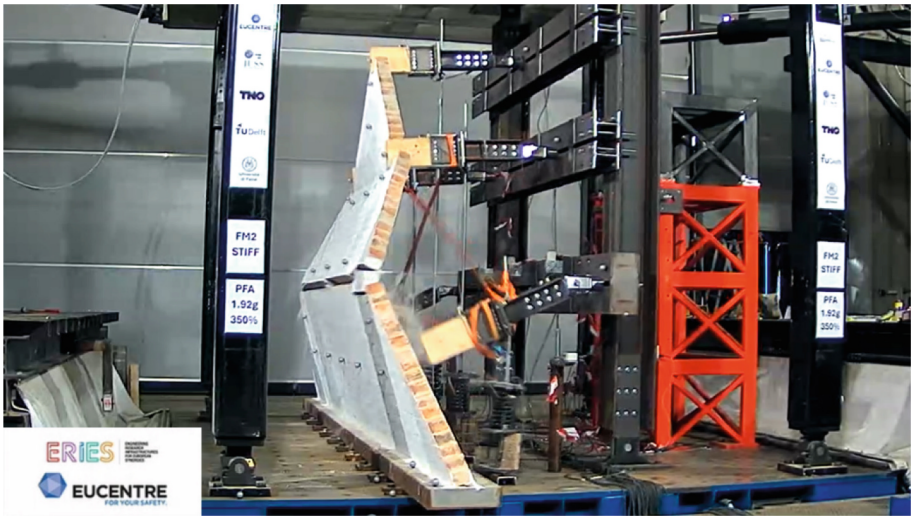


Fig. 8. Frame showing the collapse mechanism of the gable wall subjected to motions transferred by a stiff roof system.

Participants were required to predict two primary response parameters: peak base acceleration (i.e., the acceleration applied at the base of the gable wall, which corresponds approximately 1.5 times the ground acceleration [40]), and failure mechanism, including crack formation and progression. Eight teams participated in the competition, employing different numerical approaches, including the finite element method (FEM), both with block-based and continuum elements, the discrete element method (DEM), and the applied element method (AEM). All teams performed incremental dynamic analyses, enabling a direct comparison between the predicted and experimental peak base accelerations, as shown in Fig. 9.

The results indicate that 15 out of 16 predictions underestimated the capacity of the gable wall. Consequently, the mean predicted capacity was lower than the experimental results, although good alignment was observed for the flexible roof system (−11%). This trend is consistent with previous blind prediction contests related to the out-of-plane

response of URM structures [41]. Compared to earlier exercises (e.g., [41–43]), the coefficient of variation was relatively low at 43% for both the rigid and flexible roof cases, suggesting a reduction in the spread of predictions. While some models achieved high accuracy in predicting peak force capacity, capturing crack initiation and progression patterns proved more challenging, particularly for the flexible roof configuration. Submissions incorporating sensitivity analyses tended to obtain more accurate predictions, highlighting the importance of multi-faceted modelling approaches. Additionally, there was a general trend where models that performed well for one configuration also provided good predictions for the other. However, exceptions to this pattern were observed, suggesting that certain modelling approaches may be more sensitive to specific boundary conditions.

Overall, the blind prediction exercise provided valuable insights into the capabilities and limitations of existing numerical modelling techniques for URM gables subjected to seismic loading. These findings contribute to ongoing research efforts aimed at improving predictive models for URM gables under seismic loading, ultimately informing future seismic assessment methodologies and risk mitigation strategies.

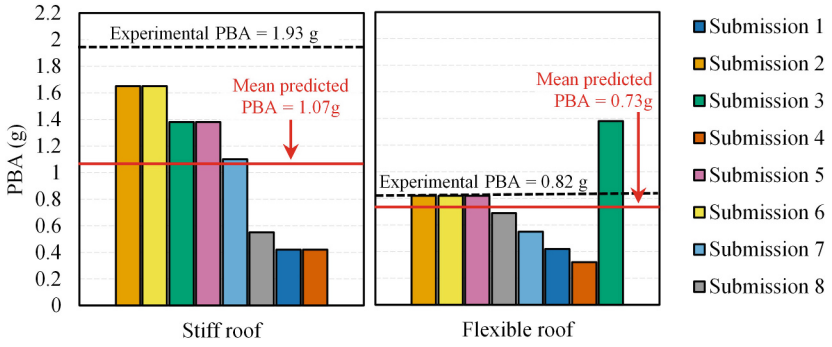


Fig. 9. Comparison between the experimental and numerically predicted Peak Base Acceleration (PBA) at collapse for both the configurations with stiff and flexible roof.

5 Conclusions

This paper presents an overview of initiatives aimed at enhancing consistency in seismic assessment in the Dutch context. It includes a cross-comparison of different nonlinear dynamic and static procedures, a semi-probabilistic typology-based approach for evaluating global seismic vulnerability, and an experimental campaign on the out-of-plane failure of URM gable walls, complemented by a blind prediction contest. The main findings are as follows:

- When the global building response is assessed, NLPO-based assessments provide consistently more conservative estimates compared to more time-consuming NLTHA, while maintaining the differences within a reasonable range in the case of regular buildings. However, specific attention must be given to the selection of the assessment method, as the N2 method [27] recommended in EN 1998–1 provides largely unconservative predictions. A modified version of the method proposed by Guerrini

et al. [28] or the Capacity Spectrum Method [25] appear to be more suitable for the Dutch case.
- Subjectivity remains a challenge, particularly for advanced numerical methods such as NLTHA, as engineering choices vary across analysts and consulting firms.
- NLPO capacity curves obtained via simple mechanism-based procedures generally show significantly smaller peak capacities, but comparable near collapse displacements to those obtained through more advanced FEM simulations when the recommendations of the Dutch guidelines NPR9998 are followed.
- Large differences exist in the assessment of local failure of URM walls in the out-of-plane (OOP) direction between simplified analytical and advanced numerical calculations, with the former strongly underpredicting the wall performance. The results of a blind prediction contest related to the OOP of gable walls show that even advanced NLTHA tends to underestimate ultimate wall capacity. However, improved accuracy and greater consistency in numerical predictions compared to earlier blind prediction contests have been observed.
- A typology-based approach streamlines seismic vulnerability assessment by eliminating the need for individual structural modelling, making large-scale evaluations faster and more consistent. However, it shows limited adaptability to nonstandard structures and cannot capture inter-building interactions. For these reasons, its applicability may be limited in contexts with more heterogeneous structures than in the Groningen area and in dense urban settings, where the inter-building interactions play a significant role.

Ongoing work focuses on reducing the variability of assessment outcomes for the local OOP failure of individual walls, following a typological approach. Future work should aim to extend the applicability of this approach to contexts other beyond the Dutch case.

Acknowledgements. This work summarizes the outcomes of multiple projects, made possible through the collaboration of numerous colleagues. While their individual names are too many to list here, their contributions are fully recognized. References to the relevant projects and their authors can be found in the reference list. I sincerely acknowledge all colleagues for their fundamental contributions.

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