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A fast, NLTHA-based assessment method for out-of-plane capacity of URM walls: the Wandenaanpak framework for the Groningen building stock

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Keywords: Nonlinear time-history analysis; Out-of-plane response; Portfolio seismic assessment; Retrofit solutions; Single-degree-of-freedom models; Unreinforced masonry; Webtool implementation.

Induced seismicity in the Groningen gas field has raised concerns regarding the structural safety of the local building stock, which is predominantly composed of unreinforced masonry (URM). Assessments performed according to the current Dutch guidelines (NPR 9998) have often shown insufficient out-of-plane (OOP) capacity in URM walls, which frequently governs the seismic safety check. Annex H of NPR 9998 provides a three-tier approach for OOP assessment, with increasing levels of complexity and accuracy. The first two tiers are based on nonlinear kinematic analyses (NLKA) and allow for rapid evaluation, while the third tier prescribes nonlinear time-history analyses (NLTHA) of the entire building, which provide a more detailed representation of wall response but are computationally demanding and impractical for portfolio-level screening, especially only when the local OOP capacity of walls is of concern. To circumvent this, the Wandenaanpak project developed a method that is fast, and easy to apply without being overly conservative. The method is implemented in a web-based tool that provides engineers with precomputed results for a wide range of building and wall configurations, both unstrengthened and retrofitted.

The Wandenaanpak methodology follows a structured workflow that combines the evaluation of seismic demand at building level with the assessment of the OOP response of individual masonry walls, as schematically illustrated in Figure 1. In a first step, the seismic demand acting on a wall is derived by accounting for the dynamic response of the building in the direction orthogonal to the wall under assessment. This is achieved through a simplified, linear elastic, building single-degree-of-freedom (B-SDOF) model, defined by the fundamental period of the building, the number of storeys, and the assumed damping ratio. The B-SDOF model is excited using a set of 22 ground motion records, consisting of 11 records in each horizontal direction, consistent with the seismic hazard defined in NPR 9998 for the Groningen gas field. The resulting floor accelerations are then used to define the input motion acting on the wall, taking into account the position of the wall within the building and the stiffness of the floor diaphragms above and below it.

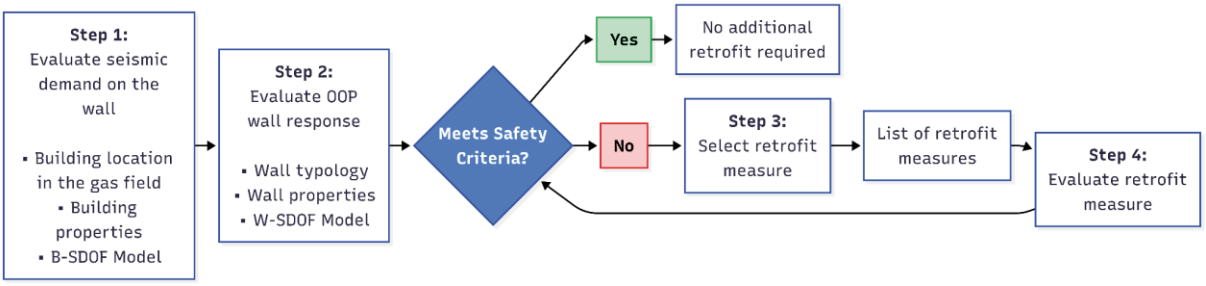


Figure 1: Schematic overview of the Wandenaanpak assessment framework for out-of-plane seismic assessment and retrofit of unreinforced masonry walls

The dynamic OOP response of masonry walls is evaluated using non-linear wall single-degree-of-freedom (W-SDOF) models specifically developed for rectangular one-way bending walls and rectangular cantilever walls, which are currently included in the methodology. The W-SDOF models are formulated to reproduce the rocking behaviour of cracked masonry walls and are based on rigid-body kinematics. The models also account for the interaction between the leaves of cavity walls, considering alternative modelling assumptions depending on the effectiveness of wall ties. Wall behaviour is represented through bi-linear or tri-linear force–displacement

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relationships defined as a function of wall geometry, axial load, boundary conditions, and load eccentricities, and calibrated against available experimental evidence. The nonlinear equations of motion are solved through time-history analysis, and wall response is evaluated in terms of OOP displacements at a control point. The W-SDOF formulation has been calibrated and validated against available full-scale dynamic shake-table tests performed on URM buildings and components representative of the Groningen masonry typologies and boundary conditions.

For each combination of building and wall parameters, such as building period and number of storeys, wall geometry, axial load, boundary conditions, and wall position within the structure, a set of NLTHAs is performed using the seismic input motions derived from the building-level analysis. The wall response is evaluated by monitoring the OOP displacement of a control point representative of the governing rocking mechanism. Wall safety is assessed by comparing the average of the maximum displacements obtained from the analyses with a dynamic instability displacement threshold. This threshold is defined as a fraction of the static instability displacement prescribed in Annex H of NPR 9998, in accordance with the indirect near-collapse verification approach described in Annex F of the guideline. Within the Wandenaanpak framework, collapse is not simulated explicitly; instead, the adopted displacement-based criterion provides an indirect and code-consistent indication of wall failure that is suitable for systematic application.

For wall configurations that do not satisfy the safety criterion in their as-built condition, the assessment can be extended to strengthened configurations following the same workflow illustrated in Figure 1. The methodology includes the assessment of strengthening solutions commonly adopted in the Groningen context, such as the provision of top connections for cantilever walls, timber strong-backs, and carbon-fiber reinforced polymer (CFRP) and fabric-reinforced cementitious matrix (FRCM) systems. Each retrofit solution is represented through an adapted W-SDOF model, in which the contribution of the strengthening system is incorporated based on experimental evidence and derived analytical formulations. The effectiveness of the selected retrofit measure is verified using the same displacement-based safety criterion adopted for unstrengthened walls, without modifying the instability displacement threshold, resulting in a conservative and consistent assessment. If the selected measure is not sufficient, the procedure can be repeated by considering alternative retrofit layouts.

All NLTHAs required by the methodology are performed a priori and stored in a database that is accessed through the Wandenaanpak web-based tool. The database covers a wide range of combinations of building properties, wall geometries, boundary conditions, hazard levels, and retrofit configurations, resulting in billions of NLTHAs. By relying on these precomputed NLTHA results, the web-based tool allows engineers to rapidly retrieve assessment outcomes for specific wall and building configurations, identify walls that do not meet the safety criteria, and evaluate the effectiveness of retrofit measures without performing additional nonlinear simulations. The database is intentionally built on discrete combinations of input parameters, and interpolation between results is avoided due to the highly nonlinear nature of the problem; in practice, conservative selections among the available configurations are adopted.

Verification studies conducted within the Wandenaanpak project indicate that nonlinear kinematic analyses according to Annex H of NPR 9998 tend to provide conservative estimates of OOP wall vulnerability for many configurations, particularly for one-way bending walls, while also highlighting specific cases in which simplified kinematic approaches may lead to unconservative outcomes. Within this context, the Wandenaanpak framework provides a practical and robust tool for the systematic assessment and retrofit verification of URM walls under induced seismicity, while ongoing research is extending the methodology to include unreinforced and retrofitted masonry gable walls, whose OOP behaviour is currently under investigation through combined experimental and numerical studies.

By relying on a predefined set of modelling assumptions and precomputed nonlinear dynamic analyses, the Wandenaanpak framework promotes transparency and reproducibility in the OOP assessment of URM walls, limiting the influence of user-dependent modelling choices. This makes the approach particularly suited for systematic application at portfolio level, where consistency across assessments is essential for the prioritization and verification of retrofit interventions.