



An automation approach to the seismic assessment and strengthening of unreinforced masonry buildings

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ABSTRACT

Large scale seismic assessments in areas of dense unreinforced masonry buildings (URM) is a significant challenge for structural engineers. URM buildings respond to earthquake excitation with a variety of mechanisms as they transition from elastic to nonlinear response. This behaviour is notoriously difficult to assess and often requires nonlinear structural modelling which is generally complex and time-consuming.

Recent developments from Europe have demonstrated a need for large scale URM building seismic assessments with confidence in the accuracy of the results. The aim of these assessments is to determine if existing buildings have sufficient earthquake resistance in relation to life-safety, and to provide necessary strengthening measures.

The time and complexity of constructing individual URM building models has led to the development of an automation procedure by Holmes Consulting in conjunction with European partners. The procedure automates nonlinear URM building seismic assessments. This paper summarises this automation procedure. Utilising the ETABS API (application programming interface) and Python, input and output Excel workbooks have been developed to enable the user to create 3D macro element models, perform nonlinear pushover, and process URM building assessments against acceptance criteria without manually constructing the model. This produces accurate results and enables precise strengthening measures and cost estimates to be obtained.

1 INTRODUCTION

Large scale seismic assessments in areas of dense unreinforced masonry buildings is a significant challenge for structural engineers. URM buildings respond to earthquake excitation with a variety of mechanisms as they transition from elastic to nonlinear response. This behaviour is notoriously difficult to assess and often requires nonlinear structural modelling which is generally complex and time-consuming.

Finite Element Analysis (FEA) using Micro and Macro modelling software packages have been used to model URM buildings. Micro modelling (full three-dimensional FEA modelling) offers the most versatility, but it also presents the most challenge in terms of model parameter calibration and computational resources. Macro-models are relatively simple to use, require less input data and are suitable for studying the behaviour of the entire masonry structures as it reduces computation time and provides acceptable URM performance (Oliver et al, 2018).

Recent developments from Europe have demonstrated a need for large scale URM building seismic assessments with confidence in the accuracy of the results. The time and complexity of constructing individual URM models has led to the development of an automation procedure to perform URM building seismic assessments by Holmes Consulting in conjunction with European partners.

2 AUTOMATION PROCEDURE OVERVIEW

Automation using the ETABS API, Python, and Excel workbooks have been developed to enable the user to create 3D macro element models, perform Nonlinear Pushover (NLPO), and perform assessments against acceptance criteria all without the need for a graphical user interface (GUI).

The automation process is based on the following modules (Figure 1):

- User interface: an input Excel workbook for preparing model geometry, material, and loading data
- Python: a programme language to interface with the input workbook, extract data, and push model data to ETABS through the ETABS API
- ETABS: an analysis program to construct and analyse a nonlinear URM building model
- Post-processing: ETABS results are extracted vis Python, assessment calculation completed, and processed results (considering code acceptance criteria) passed to Excel workbook.

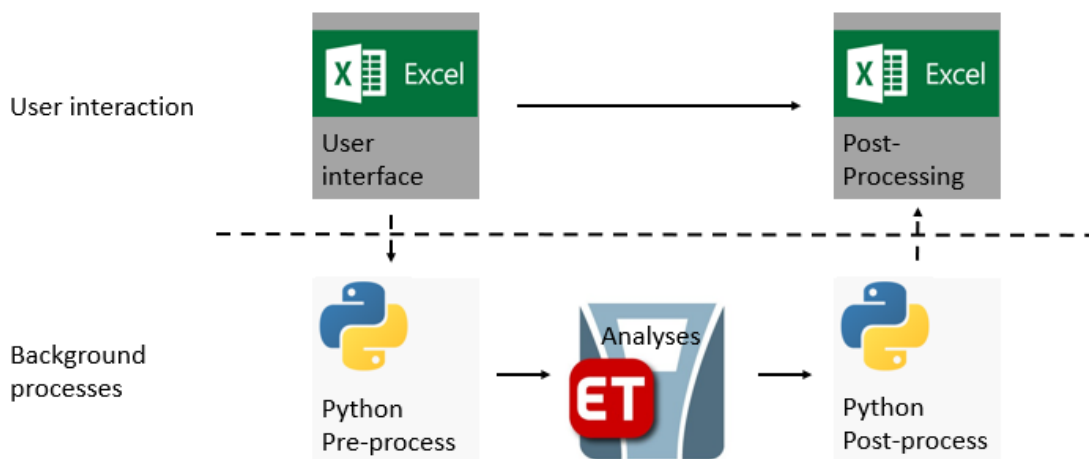


Figure 1: An overview of the automation procedure pathway

3 USER INTERFACE

An Excel workbook has been developed to enable the user to construct a URM model by data entry. The user defines components such as geometry, materials, and loadings. However, the workbook is setup in a way that minimises the amount of input that the user needs to provide. The Python scripting procedure interprets the input data and converts it into an ETABS18 model. This method provides a standard approach for model inputs and supports efficient model reviews.

After the input data is defined, a Python script automates the re-modelling of the building structure into sub-assemblies of piers, spandrels, panel zones and nonlinear link elements. The user can view the re-modelling before processing in ETABS with the aid of a graphics viewer (Figure 2). The viewer is used to replace the graphical user interface of ETABS by providing all the viewing functionality that is needed to accurately construct and verify the model.

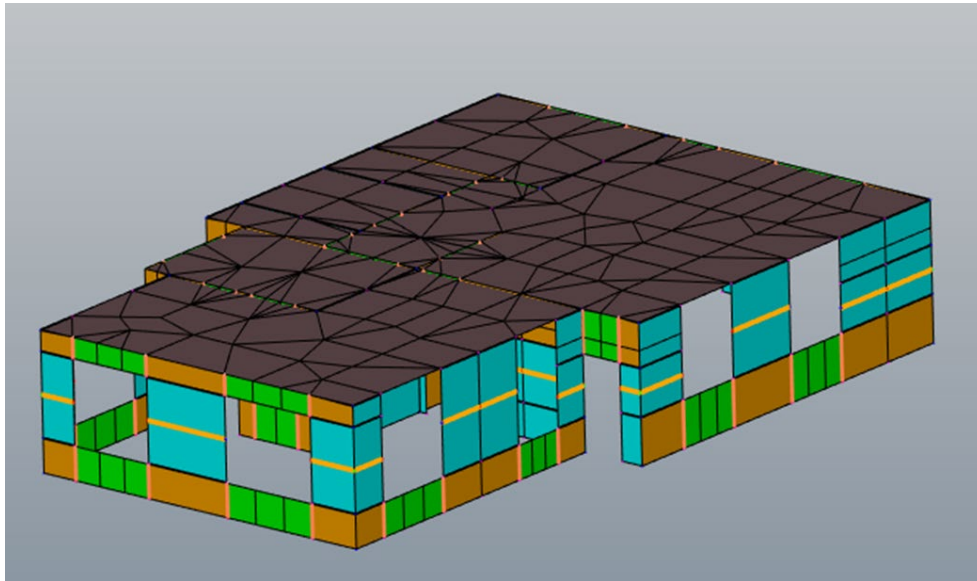


Figure 2: Meshing of walls into piers and spandrels shown in the graphics viewer

4 ETABS MODELLING

The modelling procedure implemented is specific to a macro-modelling approach for masonry buildings using ETABS. All plasticity is concentrated at the nonlinear link elements with flexure or shear backbone relationships. Building standards and guidelines such as ASCE 41-13 (ASCE, 2014), EN 1998-3 (CEN, 2005) and NZSEE Guidelines (NZSEE, 2017) provide standardised backbone curves which can be used.

4.1 Unreinforced masonry piers and spandrels

URM piers and spandrels are modelled as a combination of shell-thick elements, multi-linear plastic links, and gap link elements. These nonlinear links are used to model the in-plane strength mechanisms.

A wall rocking mechanism is modelled by nonlinear gap link elements. The gap link elements, located at the pier ends, are compression only and allow uplift to occur when the rocking force exceeds the gravity force. Shear and diagonal tension mechanisms are modelled using multi-linear plastic links. A multi-linear plastic link is located at the mid-point of the wall or end of a spandrel and contains the force-displacement data associated with the mechanism. The link allows the shell elements to displace laterally when the force exceeds yield strength.

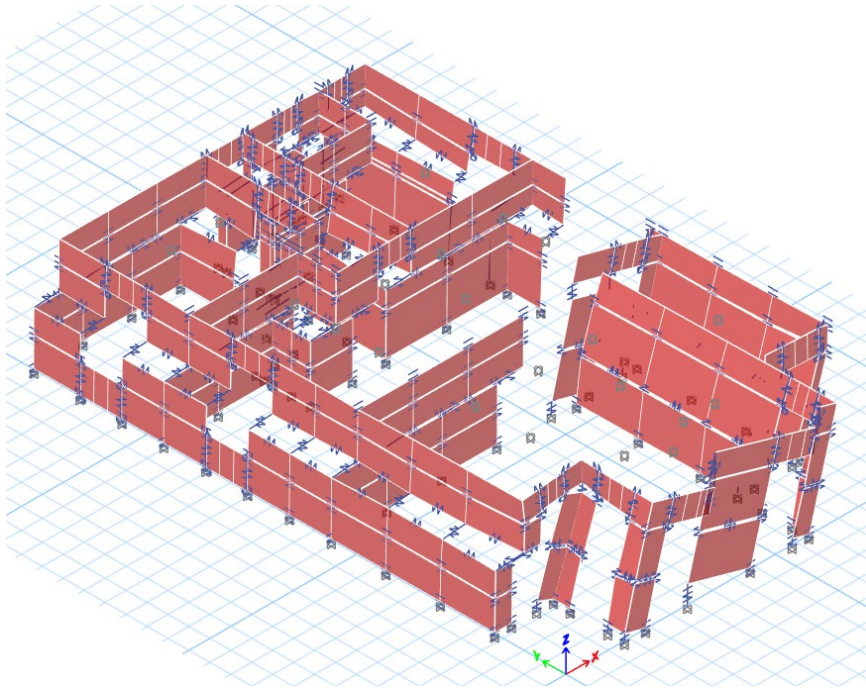


Figure 3: ETABS model showing mechanisms forming in the piers and spandrels

The force-displacement relationship is a function of the wall geometry, material properties, and gravity loads which is contained in the Excel workbook. A Python script processes the workbook data and completes a moment-curvature analysis on each pier and spandrel section to determine the governing mechanism. The resulting force-displacement backbone is then transferred into the multi-linear plastic link within the model. This process removes manual computation of deriving backbone data, but spot validation checks are still required.

The effects of wall flanges are considered in the backbone analysis - if wall and flange are assessed as integral. Compression flanges are considered to increase the compression area. Tension flanges, increasing wall hold-down based on the area of wall forming from a likely crack pattern (Moon et al 2006). Consequently, the presence of flanges improves the shear and flexure capacity of the primary wall in both directions.

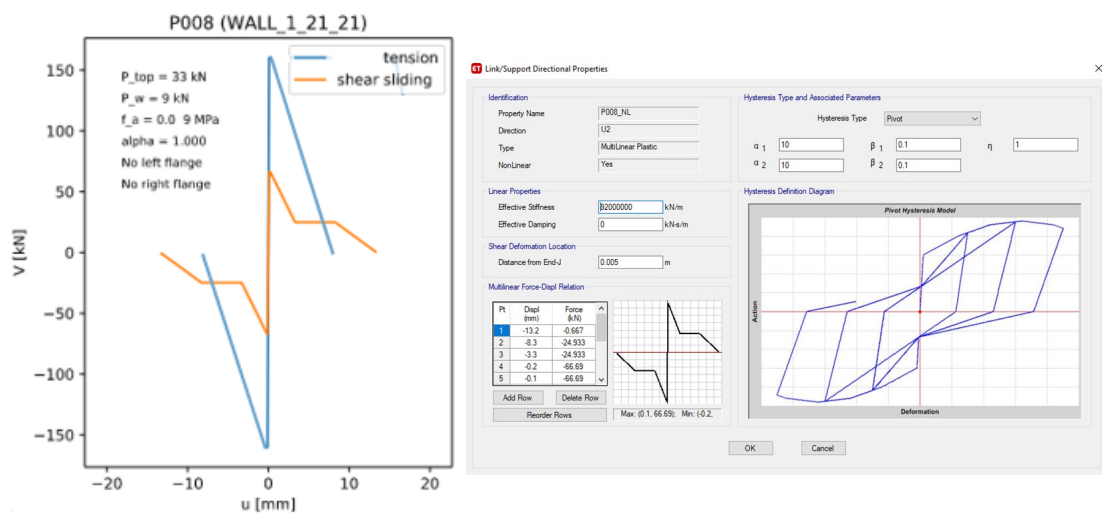


Figure 4: Backbone plots calculated pre-model construction. Governing shear sliding mechanism transferred into ETABS multi-linear plastic link

4.2 Diaphragms

The user can specify rigid and flexible diaphragms to assess the global and individual wall line responses from within the Excel workbook. Both diaphragms are modelled as membrane elements and remain elastic in the analysis. However, flexible diaphragms are modelled with a representative in-plane stiffness and pushover induced diaphragm displacements are extracted for assessment purposes (Figure 5).

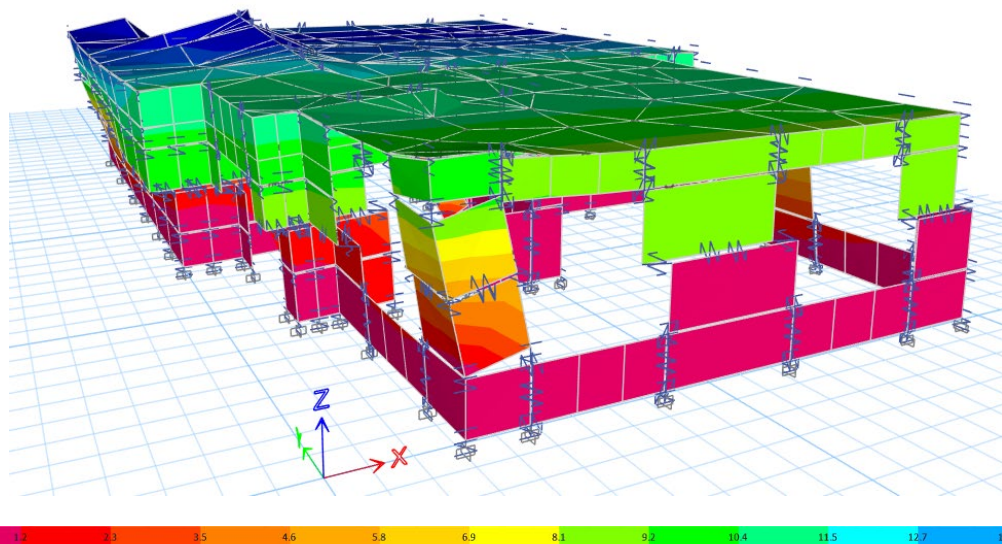


Figure 5: ETABS model showing contoured displacements in millimeters

4.3 Nonlinear push over analysis

A NLPO analysis is used to determine the inelastic response of the URM building model. As masonry is highly nonlinear, the analysis is displacement controlled to capture the full extent of the force-displacement response. Target displacements are user defined in the Excel workbook and are chosen appropriately to reduce model run times.

The lateral loads are applied at floor and roof levels in small increments, with top floor displacements recorded at every time step. The magnitude of load and subsequent displacement profile is a function of the pushover load pattern applied in the model. Uniform, triangular, and modal load patterns can be defined in any orthogonal direction with or without eccentricities from the workbook.

The completed analysis determines the failure mechanism of each pier and spandrel. The model displays mechanisms either by sliding or rocking (Figure 3). The force-displacement response of the building and each URM element can be viewed (Figure 6) which forms part of manual validation checks. However, a Python script automates the transfer of the force-displacement data into the post-processing Excel workbook for assessment.

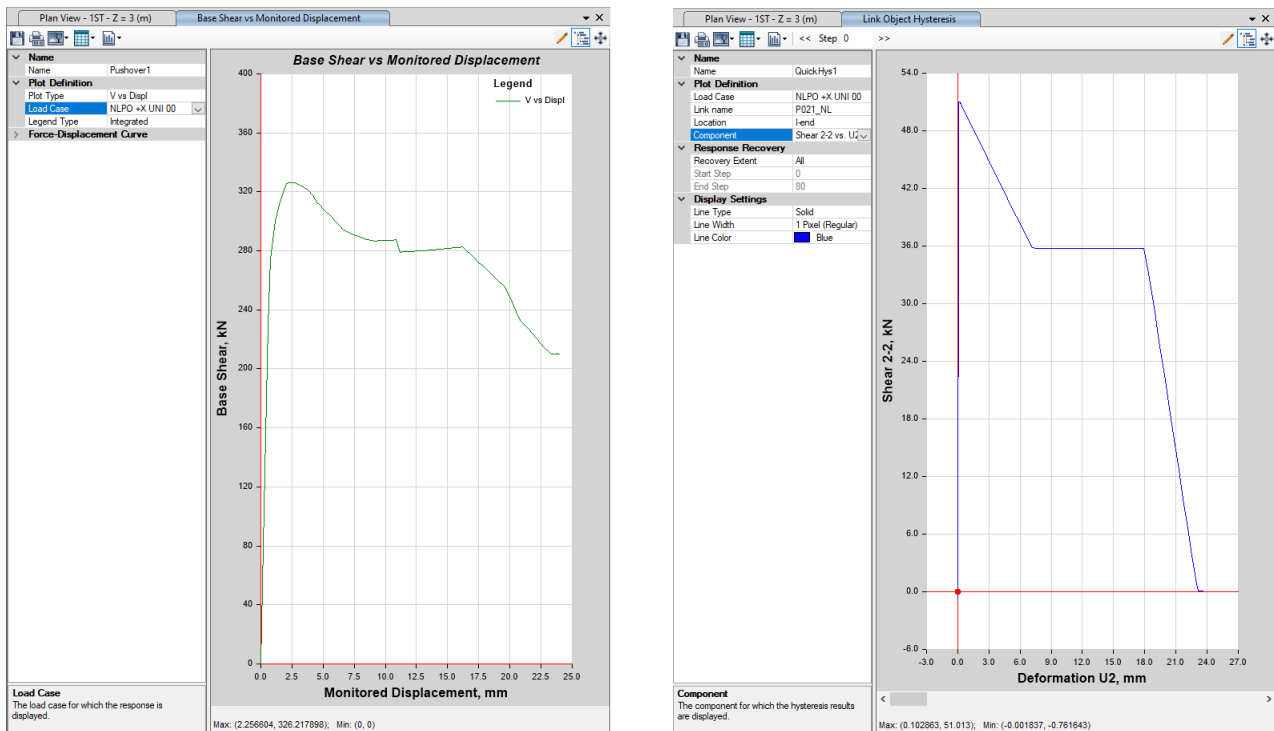


Figure 6: Global force-displacement curve and nonlinear pier link showing a bed-joint sliding mechanisms

5 POST-PROCESSING

5.1 In-plane Assessment

A post-processing Excel workbook has been developed to enable the user to import and process the ETABS output files. The workbook has been setup so that the user can select the processing options appropriate for the building geometry, construction, and assessment methodology required (i.e. wall-line, global, or both). The Python script imports the ETABS results into specific workbook sheets displaying the performance of the spandrels and piers, and the performance assessments of the wall-lines and/or global behaviour. This allows both the behaviour of components and the building performance to be reviewed efficiently.

The seismic hazard spectrum is imported from the Excel input workbook (Figure 7). This is subsequently converted into an acceleration-displacement response spectra (ADRS) allowing the capacity of the building (global or wall line elements) to be assessed against the demand. This is completed through the Capacity Spectrum Method (CSM).

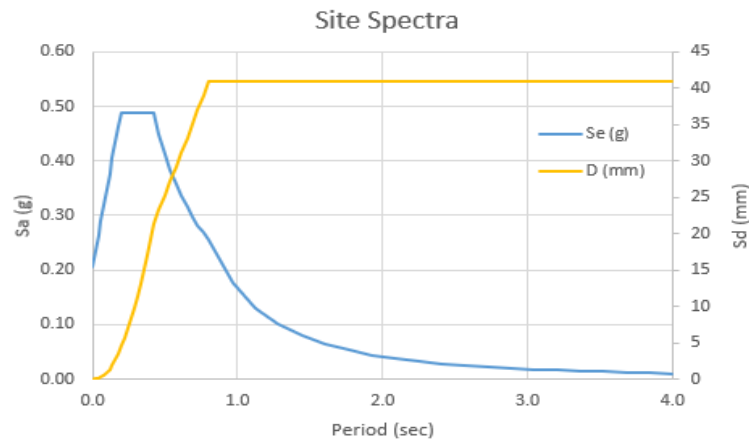


Figure 7: Site Response Spectrum showing acceleration and displacement plot against period

Review of the imported results is undertaken in stages, initially focusing on the behaviour of the pier elements. The reported results include the pier ID, associated wall-line number, load case, pier mechanism (rocking or shear sliding), and the allowable drifts and displacements for the pier geometry and mechanism.

The pier results are compiled into wall-lines and assessed using the CSM to identify wall-lines that have insufficient strength or deformation capacity. The results summary (partial) and ADRS plots for wall-line assessments are illustrated in Figure 8. The results summary reports the results by wall-line for flexible diaphragms or global for rigid diaphragms. For each wall-line (or global) capacity curve, the force-displacement capacity curve (extracted from ETABS) is bi-linearised, CSM is employed to determine effective ductility/damping and the performance point (intersection of capacity curve and ADRS spectra). Once the performance point is known, the corresponding analysis step of the NLPO analysis is therefore known and corresponding results can be extracted and reported.

Load Pattern			Bilinearisation				Spectral Reduction Factor					Performance Point
Wall Line ID	Direction	Load Pattern	$S_{i,ik}$ g	$U_{i,ik}$ m	$U_{i,ik,eff}$ m	T_1 sec	β_1	$\beta_{2,3}$	β_4	$\beta_{5,6}$	η_1	Result
11	+X	UNI	0.115	0.0006	0.0036	0.149	5.0%	15.0%	0.0%	20.0%	0.56	Pass
12	+X	UNI	0.660	0.0004	0.0041	0.047	5.0%	0.0%	0.0%	5.0%	1.00	Pass
14	+X	UNI	0.460	0.0004	0.0060	0.062	5.0%	1.0%	0.0%	8.0%	0.94	Pass

Figure 8: Wall Line Assessment Sheet results summary (partial)

Representative results from three wall-lines are presented in Figure 9. The backbone for Wall-line 11 intersects the damped spectra in the constant displacement portion of the ADRS plot. The rocking mechanism associated with wall-line 11 is sufficiently ductile that the required deformation for the wall-line is achievable. The deformation requirements for wall-line 12 are significantly reduced as they exceed the elastic demand and intersect the damped spectra in the constant acceleration portion of the spectra respectively.

Similarly, the ADRS plot for Global (rigid diaphragm) assessment is illustrated in Figure 10. The information presented in the global assessment ADRS figure has the capacity of all contributing walls (in each direction) compared to the global demand. Additional checks are required to ensure any eccentricity between the centre-of-stiffness and centre-of-mass are within allowable limits or further assessments are required to determine the effects of eccentric masses in the +/- X/Y directions.

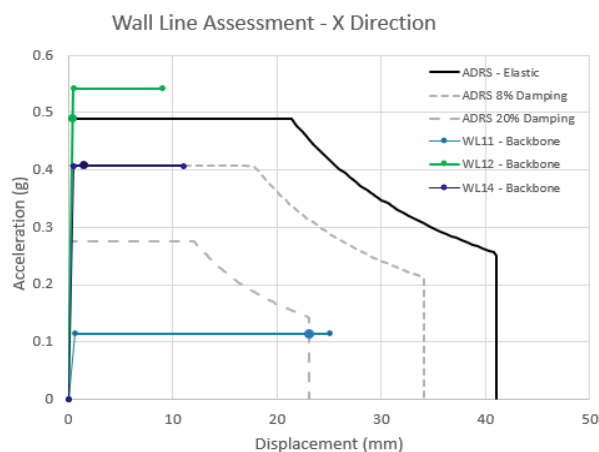


Figure 9: ADRS Plot – Wall-line Assessment

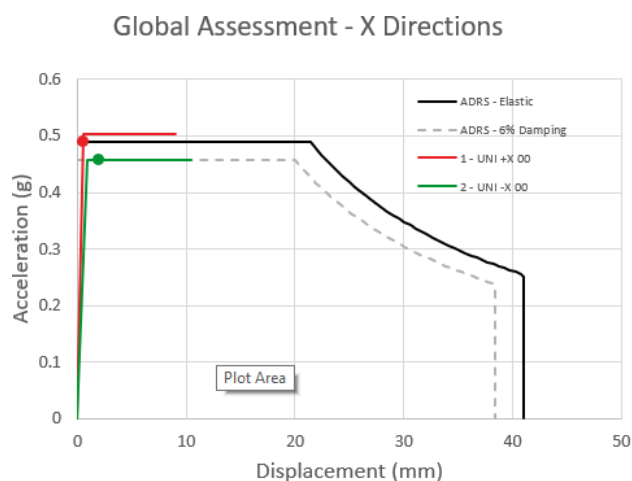


Figure 10: ADRS Plot – Global Assessment

5.2 Out-of-plane assessment

Out-of-plane (OOP) assessments are based on the nonlinear kinematic analysis (NZSEE, 2017) and are performed by separate Excel workbook. This analysis is further developed to incorporate the influence of diaphragm and perpendicular wall-line effective period, which are extracted from the ETABS NLPO analysis. As demonstrated by Galanakis (Galanakis, 2019), the non-linear response (represented by its effective period) of the perpendicular primary structure can have a significant influence on the OOP response of the wall being assessed. As the displacement demands are amplified, the second-order effects will also be affected potentially leading to earlier stability issues.

Additional checks utilising two-way spanning are also undertaken, however that is not the focus of this paper.

5.3 Diaphragm assessment

Flexible diaphragm displacements can be extracted directly from the ETABS model for assessment or diaphragms can be assessed by a separate Excel workbook. The ETABS pushover provides diaphragm and side wall displacements. These values are used to assess wall-instability and building drifts limitations (NZSEE, 2017). Rigid diaphragms are typically assessed on the basis the masonry wall becomes ductile whereas the floor plate remains elastic – otherwise a special study or strengthening assumptions may be required.

6 ASSESSMENT RESULTS AND STRENGTHENING

The post-processing stage provides an accurate report of the structural components that are non-compliant in accordance with building code requirements. Where non-conformity occurs, the provision of a strengthening concept scheme is typically required.

Walls identified as non-compliant, due to limited ductility by a shear mechanism, can be strengthened to achieve a rocking mechanism. However, the increased displacement demand lengthens the effective period of the wall line. Therefore, the critical effective period between diaphragm and strengthened wall-line is determined as part of the OOP wall assessment. If the diaphragm effective period leads to OOP wall failure, diaphragm strengthening could be considered more economical compared to OOP wall reinforcing.

After the structural failures have been identified, a concept strengthening scheme is developed. Strengthening measures can be selected using a catalogue of engineered reinforcing details (Figure 11a). The measures can be implemented into a Revit model (Figure 11b) to provide both precise drawings and cost estimates.

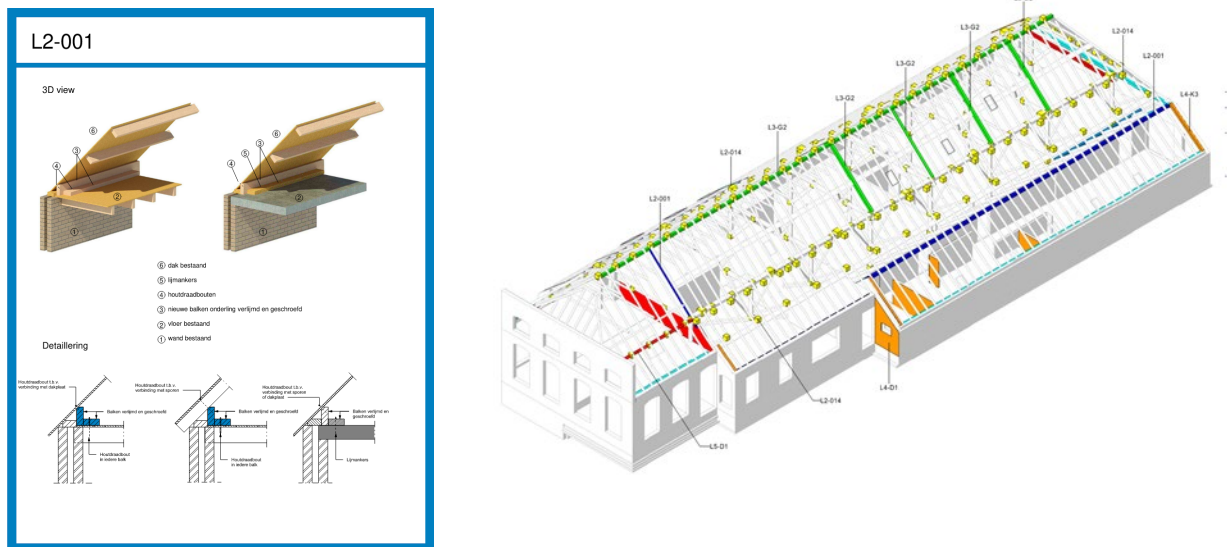


Figure 11: (a) catalogue strengthening measure example (b) Revit model with strengthening measures

7 CONCLUSION

Areas of high density URM buildings that require detailed seismic assessments has led to the successful development of an automation procedure. Automation using ETABS API, Python, and Excel workbooks have allowed the user to construct, analyse, and assess URM buildings without constructing the model using the GUI. This leads to global conformality from both a modelling and review point of view as well as drastically reducing the modelling time for complex nonlinear macro models. The procedure assesses the performance of buildings against local and global building code requirements. Thus, precise strengthening measures and cost estimates obtained.

8 REFERENCES

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