



Original software publication

Hyperomet: An OpenSees interface for nonlinear analysis of unreinforced masonry buildings

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ABSTRACT

Seismic vulnerability assessment of historical unreinforced masonry (URM) buildings is crucial for the authorities due to the high susceptibility of historical URM buildings to earthquakes. Open system for earthquake engineering simulation (OpenSees) is a well-known, powerful, and versatile seismic analysis platform. In a lack of a free graphical user interface (GUI) for seismic analysis of URM buildings, Hyperomet was designed to bridge the gap between nonlinear analysis of URM buildings and OpenSees platform. The Hyperomet GUI includes an accurate enough macroelement representing the nonlinear behavior of URM components. The structures can be modeled based on the double-modified multiple vertical line element model (DM-MVLEM) and the Unified method (UM) using the GUI. Calculators for deriving the mechanical properties are provided to minimize the modeling time. Furthermore, the ability to perform various analysis types including incremental dynamic analysis (IDA) is facilitated.

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Code metadata

Current code version	V1.0
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-22-00103
Permanent link to reproducible capsule	None
Legal code license	EUPL-1.2
Code versioning system used	git
Software code languages, tools and services used	JavaScript, TypeScript, Node.js, React, Electron, and third-party libraries
Compilation requirements, operating environments and dependencies	Microsoft Windows
If available, link to developer documentation/manual	None
Support email for questions	Hyperomet@oslomet.no

1. Motivation and significance

Unreinforced masonry (URM) buildings compose a high portion of building typologies in high seismicity zones and historic areas [1]. Therefore seismic vulnerability assessment of URM structures is a crucial task for responsible authorities [2]. Developing an integrated resilience assessment platform utilizing a fast, adapted, and efficient multi-hazard risk assessment tool has recently gained acceptance for the sustainable reconstruction

of historic areas [3]. Moreover, simplified modeling approaches could be necessary tools for the seismic analysis of buildings for analysts or designers who lack specialized skills [4]. For this purpose, different simplified analytical methods have been proposed to assess the vulnerability of URM buildings at a large scale, see [1]. Nevertheless, by developing computer technology and emerging supercomputers, accurate and fast nonlinear modeling approaches should be utilized for the near real-time (n-RT) assessment or prediction of seismic risk with a lower level of uncertainty [4].

Open system for earthquake engineering simulation (OpenSees) is an open-source finite element framework used broadly for seismic analyses purposes [5]. Various graphical

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user interfaces (GUI) have been developed to facilitate using the OpenSees platform and automate the numerical modeling and analysis procedures [6–14]. Nevertheless, most of the mentioned GUIs are not free to use for researchers and industry, and there is still a need to develop an open-source GUI to automate the numerical modeling and analysis of URM buildings.

As one of the most common modeling approaches, the equivalent frame method (EFM) is used for seismic analysis of URM buildings with lower computational efforts and input data than the well-known continuum homogeneous method [15,16]. In the EFM, URM structural components are modeled via macroelements representing their nonlinear behavior [4].

The unified method (UM) is considered as one of the simplified EFMs for seismic analysis of URM buildings. In the UM approach, each perforated or unperforated URM wall is modeled with a single macroelement [17]. The macroelement consists of a nonlinear shear spring at the middle part that can be modeled using the twoNodeLink element in OpenSees and two twoNodeLink elements at two sides of the wall with an elastic behavior representing the axial stiffness.

However, the double-modified multiple vertical line element model (DM-MVLEM) was calibrated based on the experimental tests and is more accurate method than the UM. MVLEM is an available macroelement for the simulation of flexure-dominated reinforced concrete (RC) wall behavior [18,19]. MVLEM elements underwent modifications to simulate the pure axial-flexural behavior of a wall by neglecting the shear behavior [4]. Each DM-MVLEM comprises two modified MVLEM elements that are connected with a nonlinear shear spring using the zero-length element in OpenSees that represents the nonlinear shear behavior of the segment and more detail of the modeling procedure are presented in [4]. Each pier or spandrel can be modeled with a DM-MVLEM and connected with rigid elements to model a perforated URM wall [20]. MVLEM element comprises conventional FEM elements such as truss, beam-column, and spring element. The MVLEM macroelement that can be used for nonlinear analysis of RC walls was assembled using the basic elements and the macroelement is available in the OpenSees library. However, a unique macroelement for nonlinear analysis of URM building is not available in OpenSees library. The available MVLEM elements in OpenSees library can be utilized for modeling the URM pier elements; however the MVLEM elements cannot be modeled horizontally to simulate the URM spandrels based on DM-MVLEM.

Hyperomet is designed, through an EU-sponsored Horizon 2020 project at Oslo Metropolitan University in Norway, to bridge the gap between the OpenSees users and analysts of URM buildings by addressing an efficient modeling approach in a more effectual process in terms of cost and time. In Hyperomet, modeling URM buildings using the UM and DM-MVLEM macroelements have been automated and eased. Furthermore, various analysis procedures, including incremental dynamic analysis (IDA) [21,22], are available to be used efficiently and in an automated way. Hyperomet can be utilized as a tool for probabilistic seismic analyses in which a high number of models are required to be developed, and iterative analyses are needed to be performed. The tool can be utilized for seismic vulnerability assessment of existing URM buildings by predicting their behavior subjected to different seismic records and hazard scenarios. Moreover, the GUI can be utilized as a simplified and fast tool for n-RT analysis of cultural heritage assets at a small scale and historic areas at a large scale.

2. Software description

Hyperomet is a GUI to produce the .tcl format file of the model and build .tcl format subroutine files for performing various types of analysis including pushover analysis and IDA. Therefore, Hyperomet provides fuel for the OpenSees as the engine for performing the nonlinear analyses.

2.1. Software architecture

The Hyperomet architecture for the modeling and analysis is illustrated in Fig. 1. The main steps for the modeling (4 steps) and analysis (2 steps) parts are highlighted and elaborated below. Due to high number of variables and complicated equations for defining the mechanical properties of the elements, various calculators are provided to reduce the human error. Note that Hyperomet is only available for 2D modeling in the current version. For the modeling phase and in step m1, the nodes will be defined by determining the coordinates in a 2D environment. It should be mentioned that for the UM approach, three coordinate geometry values in x-direction are required for modeling a wall. The middle nodes connect the twoNodeLink element for carrying the shear force, and two twoNodeLinks elements tolerate the axial loads at two sides of each wall. The rigid beams will also be modeled automatically to connect the twoNodeLink elements. Moreover, after defining the geometries of the nodes, the rigid length should be defined for the DM-MVLEM modeling approach. The numbering of the nodes and modeling of rigid elements are automatically created in the software.

In step m2, material properties are defined; the user defines an alias for each material and fills the corresponding properties' blanks. In order to facilitate the calculation of the material properties of the elements, the provided calculators can be utilized. These calculators can be utilized for defining the maximum shear strength and initial in-plane stiffness of the URM components and other features of the trilinear backbone can be derived based on these two main values as elaborated in [4]. For the UM, calculators are provided to derive the maximum shear (lateral) strength of the URM wall based on [17]. Moreover, the complicated process of calculating the initial in-plane stiffness of perforated URM walls using the equivalent height method (EHM) is eased [23,24]. The geometry of each pier and the elastic material properties are the input for calculating the initial in-plane stiffness of each URM pier section based on the deep beam theory. Afterward the initial in-plane stiffness of the whole perforated wall will be calculated based on the stiffnesses of all structural components using the parallel and series spring rules. More detail about the procedure of the EHM can be found in [23]. For the DM-MVLEM, the calculators can derive the elastic stiffness of the nonlinear shear spring and the maximum shear strength of piers and spandrels based on the deep beam theory. Note that for calculating the maximum shear strength of the piers and spandrels, different values for different damage patterns will be calculated, but the minimum value should be selected and assigned to the corresponding material [4]. The lateral nonlinear shear spring at the middle of the DM-MVLEM would simulate the shear behavior of the URM components. The maximum lateral strength of piers due to the rocking failure mode can be calculated but should be neglected for the definition of the hysteretic material for the zero-length elements of the pier elements.

For Step m3, the mass of each node should be assigned. For this purpose, the user can see the model, choose a specific node, and assign a mass. Note that for DM-MVLEM, a very small value should be assigned to the mass of the middle point of the element due to possible numerical instability for the MVLEM.

Now the elements should be assigned in step m4. For the UM modeling approach, the user chooses the elements in the GUI

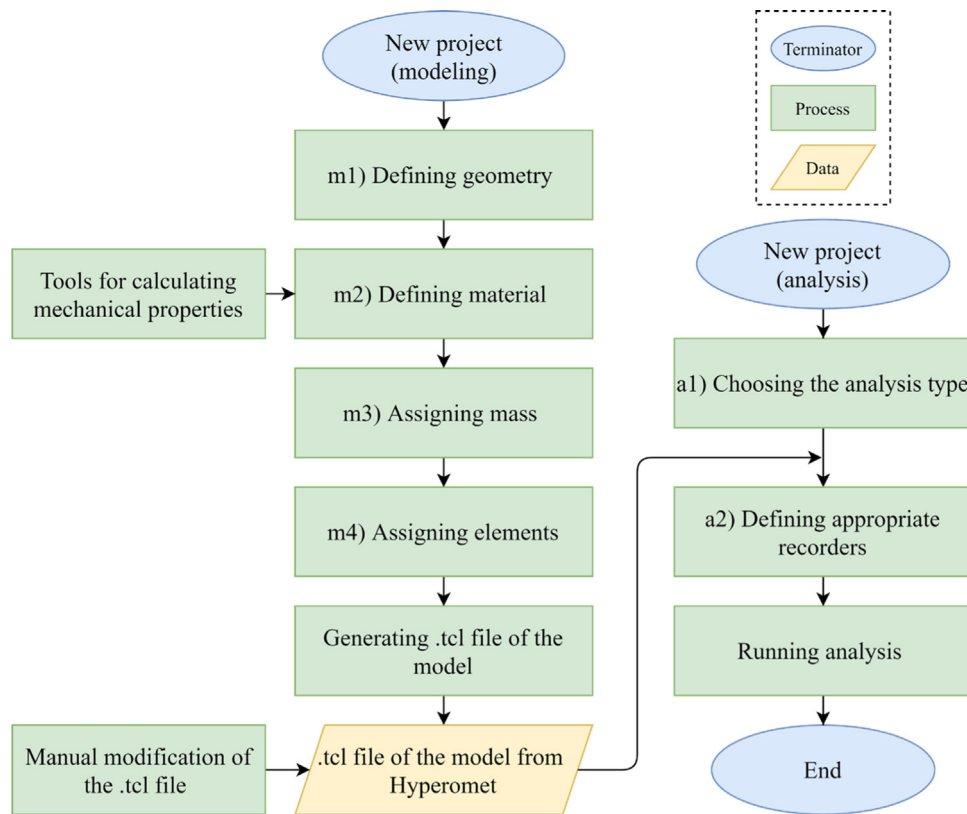


Fig. 1. Software architecture and the main six steps of the Hyperomet.

and then chooses the predefined material in step m2 and the corresponding direction. Afterward, the twoNodeLink elements will automatically be defined and assigned. However, for the DM-MVLEM approach, this procedure is different, and three sub-steps are presented. The zero-length elements in the middle of DM-MVLEM elements are assigned, and DM-MVLEM elements will be assigned to simulate the piers and spandrel elements. For assigning the zero-length elements to connect the two modified MVLEM elements, the nodes will be selected, and the suitable material will be assigned in three directions. Afterward, the DM-MVLEM elements are assigned by selecting the pier element, defining the fiber numbers, and assigning the corresponding material properties that were defined in step m2. For modeling piers, the user can define a specific location and assign the DM-MVLEM elements in the Hyperomet GUI which facilitate the modeling procedure and decrease human errors. As mentioned, the MVLEM elements cannot be used to model spandrel elements and cannot be placed in a horizontal direction. Therefore, the MVLEM elements should be modeled manually and modified to produce the DM_MVLEM element. In the case of modeling spandrel elements based on the DM-MVLEM and using the OpenSees framework by writing the scripts, the nodes should be defined manually for modeling the MVLEM elements, and rigid link elements should be encoded to connect the nodes. Furthermore, the twoNodeLink elements should be modeled to produce the modified MVLEM. However, the whole procedure for modeling the modified MVLEM elements and connecting them with zero-length at the middle has been automated. The asymmetry of spandrel elements is taken into account. This procedure works by defining the number of truss elements for the upper and lower parts of the elements. Furthermore, the related material will be assigned to the truss and twoNodeLink elements. Then the model is ready to be generated. The produced .tcl format file should be checked and modified if needed.

The .tcl format models should be selected as input for the analysis sections, and relevant .tcl format subroutine files will be produced based on the user's input. The generated subroutine files will be automatically called inside each model file. Therefore, the selected analysis will be carried out by opening the .tcl file of the model. No input is needed for performing the modal analysis, and the first six natural periods of the structure will be concluded. For gravity analysis, the nodes and the gravity load should be defined. The load pattern is defined by determining the displacement values for pushover analysis, and suitable recorders can be selected to derive the pushover curve. Time history analysis can be done by mentioning the name of the seismic record file which must be available in the model folder and other details related to the seismic record characteristics, such as the number of data points in each record, time steps, and response spectrum time history. Note that the record will be multiplied by the gravity of earth (g) automatically in the subroutine file, and the scale factor defined by the user is another influential factor. Several features are provided to ease the IDA as the most demanding analysis type. The inputs for performing the IDA are divided into 1- limit state values 2- start and increment acceleration 3- number of analyses and records 4- damping properties 5- recorders 6- node-height pairs. In the case of URM, a very little value can be considered for the collapse slope ratio; it is considered 20% for steel frame structures based on [25]. For the damping section, the nodes with mass should be listed to be assigned with the mass-proportional term of the Rayleigh damping [26]. The stiffness-proportional term will be automatically applied to the model. The recorders are helping to evaluate the roof displacement and the base shear of the structure in every step, and in the last part, one node for each floor should be selected, and the corresponding height should be mentioned to let the GUI calculate the inter-story drift in each step and compare with the limit state.

The hunt & fill algorithm [22] is employed for performing the IDA to decrease the analysis duration. Three phases should be

```

if {($tetaMax > $tetaLimit) || ($slpRato < $slpRato_limit)}
#checking the collapse criteria
{
    set clpseFlag YES
    puts $clpseFlag
    set saClpse $sa
    set clpseRsln [expr ($saClpse-$saStble)/$saStble]
    if {$clpseRsln < 0.025} {set goFill YES}
    set sa [expr $saStble + ($saClpse-$saStble)/3.]
#Phase 2: increase step for Sa for bracketing collapse
} else {
    if {$clpseFlag == NO } {set nLastStble $nn}
    set nPrevStep $nn
    set saStble $sa
    if {$clpseFlag == YES} {
        set clpseRsln [expr ($saClpse-$saStble)/$saStble]
        if {$clpseRsln < 0.025 } {set goFill YES}
        set sa [expr $saStble + ($saClpse-$saStble)/3.] ;
# Phase 2: increase step for Sa for bracketing collapse
    } else { set sa [expr $sa + $nn*0.05] } ;
#Phase 1: start increasing Sa to reach the collapse
}
if {$goFill == YES} {
    set sa [ expr ( $saArray($nLastStble) + $saArray([expr
nLastStble-1]) )/2. ] ;
#Phase 3: filling gaps before collapse
    set nLastStble [expr $nLastStble-1]
    if {$nLastStble < 1} {set continue N0}
}
set nn [expr $nn +1]

```

Listing 1: Three main steps of the hunt & fill algorithm and the collapse criteria in the IDA subroutine file.

considered: 1- increasing the intensity to reach the collapse, 2- finding the accurate intensity that the structure reaches collapse (improving the capacity resolution) 3- going back and filling the gaps of the first step. The steps in the subroutine file are presented in the Listing 1 to clarify the code.

Note that the values assigned for each phase can be changed based on the model type. For instance, the bracket criterion (BC) for the sufficient resolution of the collapse point in step 2 is calculated based on:

$$BC = \frac{S_{a,i} - S_{a,j}}{S_{a,j}} \quad (1)$$

where $S_{a,i}$ and $S_{a,j}$ are the values $S_{(T,5\%)}$ of the current and previous step of the analysis, respectively. The default limit state value is 0.025, which can be changed manually.

Although adaptive time-step, adaptive convergence criteria and adaptive solution algorithms are the routine of every finite element software, these features are not available in the OpenSees framework. In this light various convergence tolerances are considered for different levels of the analysis. If the analysis is not converged, the algorithms are tried to decrease the tolerance step by step to reach the convergence. Furthermore, different types of solution algorithms available in OpenSees that efficiently analyze the model are provided in the subroutine files that are changed automatically until convergence is reached.

2.2. Software functionalities

The main sections of the software are modeling, analysis, and results and all the functionalities of the GUI are highlighted in

Fig. 2. Note that the modeling section comprises assigning mass to the nodes, defining material, and assigning elements for the UM and DM-MVLEM.

In the final section, which is the result tab, the user can post-process the IDA results to derive the IDA curves. The $S_{(T,5\%)}$ values and the maximum inter-story drifts and other results for each step of IDA of a record will be recorded in the text format files. However, for developing the IDA curves the $S_{(T,5\%)}$ and the corresponding maximum inter-story should be selected and the $S_{(T,5\%)}$ values are required to be sorted from the smallest to the largest. These processes can be automatically performed on the IDA results to develop the IDA curves.

3. Illustrative examples

A full-scale URM wall was tested at the University of Pavia by applying prescribed displacement to the first and second floors with a ratio of 0.65. The details of the case study are presented in [27]. The assigned material properties are based on [27], while the modeling steps of the wall using DM-MVLEM are illustrated in Fig. 3. Pushover analysis was performed when the gravity loads were applied to the system. Fig. 4(a) depicts the pushover curve derived from the numerical modeling versus the backbone curve of the experimental test result. The results show a good match between numerical and experimental test results regarding roof displacement and base shear. Furthermore, IDA was carried out by applying 44 seismic records of FEMA using the Hyperomet GUI, and the IDA curves are plotted in Fig. 4(b) after post-processing the results. More illustrative examples and details are presented in: <https://www.youtube.com/playlist?list=PLmph2U5TqH1x0zeqYDtsJb9f-QXzuxBg2>

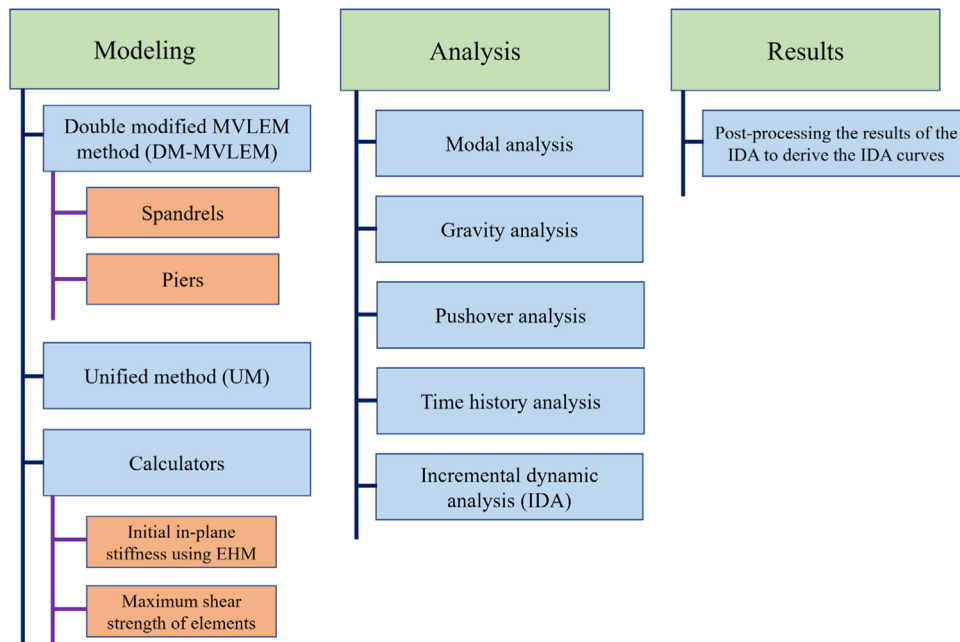


Fig. 2. Hyperomet functionalities that are divided into three main sections: modeling, analysis, and the results.

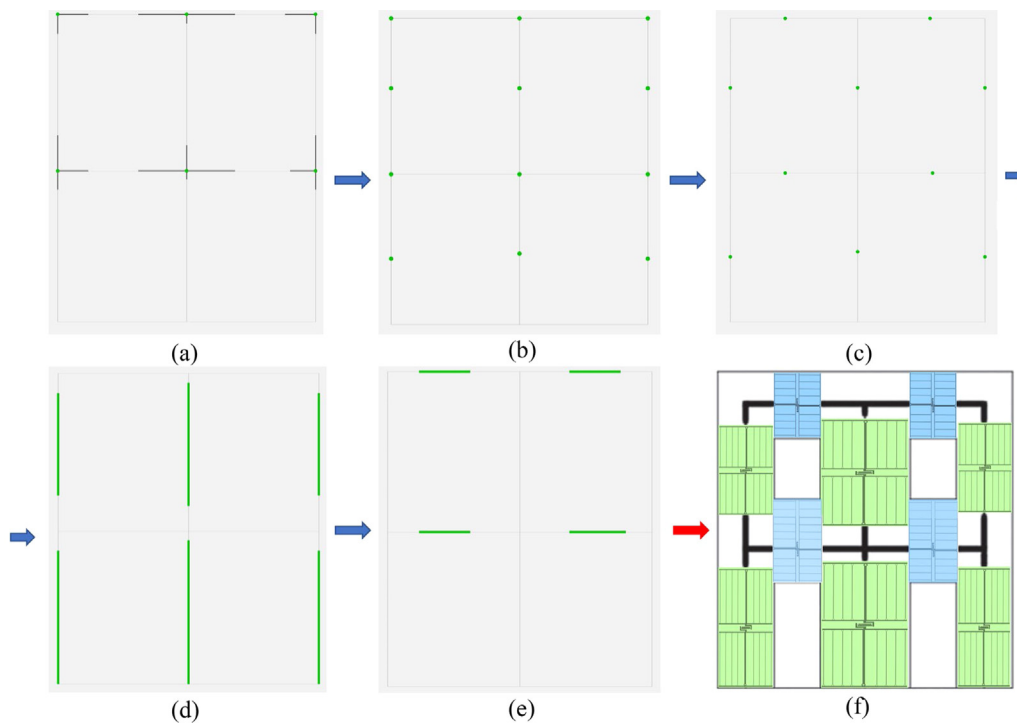


Fig. 3. The modeling procedure includes (a) defining the rigid elements (b) assigning mass (c) assigning zero-length elements, assigning DM-MVLEM elements to (d) pier and (e) spandrel elements, and (f) the final model of Pavia door wall using the DM-MVLEM.

4. Impact

Since no predefined macroelement is available in OpenSees library, developing DM-MVLEM and facilitating the modeling procedure is essential for researchers and analysts who use this powerful and versatile platform for nonlinear analysis purposes. On that account, the GUI can be utilized as a fast and efficient tool for performing time-consuming probabilistic analysis with a high number of variables, performing IDA, n-RT analysis, and seismic analysis at a large scale.

The MVLEM is a predefined macroelement available in the OpenSees library. The DM-MVLEM consists of two modified MVLEMs. DM-MVLEM cannot be modeled in OpenSees by connecting two modified MVLEMs horizontally, and modified MVLEMs should be modeled in detail using rigid beam-columns and truss elements. To tackle this limitation, the modeling procedure is eased for the spandrels by just defining the geometries and the properties of truss elements in the Hyperomet GUI.

Furthermore, various calculators for deriving the initial in-plane stiffness of masonry walls with openings using the EHM, maximum shear strength of masonry piers and spandrels etc.,

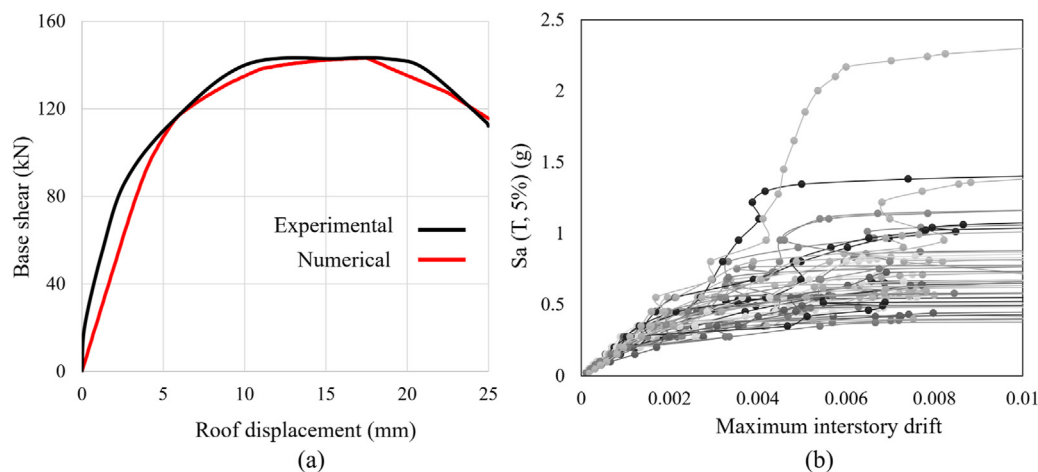


Fig. 4. (a) Pushover curve versus backbone curve of the test result, and (b) IDA curves of the Pavia door wall.

were provided to decrease uncertainty related to the modeling of the URM structures.

In Hyperomet, performing IDA is eased by defining the seismic records and appropriate recorders, and a post-processor is embedded to derive the IDA curves. Furthermore, IDA is automatized since the seismic records are changed and applied, intensities are increased, solution algorithms are changed, and convergence tolerances are changed automatically.

Hyperomet can be used by the authorities to improve the resiliency of the historic areas hosting a large number of URM buildings to predict the economic impact of future earthquakes and to define risk mitigation plans. It will also facilitate future research studies on the vulnerability of URM buildings in OpenSees, including reliability analysis, stochastic analysis, soil–structure interaction analysis etc., that are demanding and time-consuming by employing existing commercial finite element software packages.

5. Conclusions

The main aim of Hyperomet was to allow OpenSees users to perform various types of nonlinear analysis for vulnerability assessment of URM buildings. The UM and DM-MVLEM approaches, and many types of analysis were provided in the GUI to facilitate and automatize the assessment procedure. The main features include but are not limited to 1- providing calculators for defining the maximum shear strength of elements, 2- providing calculators to derive the initial in-plane stiffness of perforated URM walls using the EHM, 3- modeling spandrel elements using DM-MVLEM, and 4- automatization of IDA and using the hunt & fill algorithm. The users and authorities can benefit from the open-source Hyperomet GUI to perform computational demanding nonlinear analyses to improve the resiliency of historic areas comprising a large number of URM buildings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code can be downloaded via the share link in the article

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