Seismic vulnerability assessment for historical masonry aggregates

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Abstract – **In this contribute, the authors propose a comprehensive limit analysis approach based on consolidated and innovative techniques for the exact identification of local mechanisms in masonry aggregates. On a three-dimensional (3D) model of the whole aggregate both pre-assigned mechanisms (CINE) and adaptive meshes (NURBS) are used. The computation of the horizontal load multiplier is carried out through the application of the Principle of Virtual Powers with a classic upper bound point of view. The analysis results show that, compared with the simple overturning collapse mechanism, the other collapse mechanisms are only activated under specific stress conditions. Some typical walls are selected to have an insight into the possibilities and limitations of the procedure proposed.**

I. INTRODUCTION

Unreinforced historical masonry aggregates represent a large portion of the building stock around the world, especially in Italian historical city centers and as so, prove to be an essential component of cultural heritage. In masonry aggregates, buildings are not isolated but aggregated in clusters that may date back to the Middle Age: they are the result of progressive building transformation and urban developments which were characterized by the addition of structural units to existing ones, floor elevations and also plan extensions. Masonry aggregates can thus be seen as assemblies of several structural units that are independent from the viewpoint of the intended use but that are structurally connected to each other. They are large and complex structures involving several adjacent structural units with different heights, number of storeys and inter-storey heights, erected in continuity one to each other, making rather difficult to distinguish the independent units and to identify a global behavior of the whole construction [1][2].

Originally conceived to withstand only vertical (gravity) loads without any seismic design criterion, they are generally highly sensitive to seismic actions, as recent seismic events have showed. This vulnerability can be explained by different factors. First, construction details aimed at providing a satisfactory global response to horizontal loads are typically absent. Then, the irregularities in the masonry textures (multi-leaf walls, facings separated by an inner core) combined with the degradation of materials over time (formation and development of cracks, degradation of mortar which leaves empty joints) make these structures unsuited to withstand horizontal loads. Furthermore, the most common typology of floors in historical aggregates is constituted by traditional wooden slabs supported by wooden beams, themselves simply supported by perimeter masonry walls. The stiffness of such floors is usually considered negligible. The presence of deformable floors, with absence of adequate connection with the masonry walls, promotes the activation of partial failure mechanisms, with the collapse of portions of most vulnerable structural units due to out-of-plane overturning. Irregular plan configuration, topographic and stratigraphic conditions in the foundation soil can also be responsible for additional sensitivity to seismic excitations.

To reduce vulnerability, retrofitting or protection interventions can be carried out to better resist the seismic demand. These interventions require a sufficient knowledge concerning the seismic site response, the definition of the seismic load and the geometrical and mechanical characteristics of existing buildings.

From an assessment point of view, the seismic vulnerability evaluation is at the same time an open issue and a difficult task mainly for two main reasons. First, one can notice a lack of adequate tools able to consider the complexity of the problem in terms of geometry, material non-linearities, local strength criteria, proper evaluation of the floors and roof stiffness. Second, the identification of the different units and the characterization of the connections between them are fundamental tasks to understand properly the overall structural behavior: a thorough knowledge is therefore desirable but is rarely achieved.

Indeed, in most of the cases there is a limited knowledge about crucial features that play a key-role in the evaluation of potential mechanisms, such as the evolution of the geometry with different construction phases, the geometry of the neighboring units, the state

and quality of connection between the various units, the previous interventions carried out, or the presence of local strengthening devices (e.g. tie-rods, chains, concrete ring beams).

Typically, geometrical data, information about the inner core of structural elements, historical data (construction sequence, changes in the constitutive structural elements) are not easily available or missing. Moreover, the existing damage and the behaviour of the connections between masonry elements and with timber elements are generally unknown. The characterization of the mechanical properties of the constitutive materials (blocks and mortar) is difficult and expensive and does not necessarily provide reliable information due to the large variability of the mechanical properties accounted for by the workmanship and the use of natural materials.

This limited knowledge leads the engineer to assume some hypotheses concerning materials and structural details. In addition, even though some information is provided concerning the methods to be employed, current guidelines available do not provide reliable methodology and detailed procedures for the seismic assessment of such typology of structures. The development and use of specific tools to deal with masonry aggregates is therefore an open challenge that is discussed in the present paper.

After modelling the masonry buildings in 3D and applying suitable loading and constraint conditions, an Autolisp implementation of the C.I.N.E code (based on pre-assigned failure mechanisms) and an adaptive mesh with NURBS Matlab Upper Bound FE code are used to estimate the horizontal load multiplier and the associated horizontal acceleration for different potential local mechanisms in an aggregate case-study. Comparing results allows to determine the validity of the 3D model, the applied loads and above all the method implemented. It also aims to estimate the accuracy of such method and the applicability of the assumed hypotheses with respect to more sophisticated approaches.

II. METHODOLOGY

A. Description of the method

For both approaches, the theoretical base of the method is the kinematic theorem of limit analysis applied to no-tension or quasi no-tension materials: a kinematically admissible load multiplier, i.e. for which the power associated to external forces is equal to the power associated to plastic dissipation, in a failure mechanism obeying compatibility, is an upper bound of the true collapse load multiplier. In the framework of a kinematic analysis, the modelling of the structure in rigid macro-blocks allows to easily transform the structure into a kinematic chain or a problem in few variables when a mechanism is activated.

Both approaches start from a 3D CAD model of the masonry construction. In the first procedure with pre-assigned failure mechanisms (C.I.N.E. with Autolisp implementation), within the modeling environment, the structure can be directly subdivided into a group of macro-blocks supposed to be involved in the mechanism. The seismic action is modelled by a horizontal acceleration converted into a horizontal load multiplier α: in this way, the inertia effects are represented by horizontal loads associated to the masses of the involved elements (walls and applied weights). Masonry is represented as a no-tension material (rigid blocks, tensile strength supposed null, compression and shear ultimate strength infinite [3]), the internal plastic dissipation is thus automatically equal to zero. Depending on the typology of mechanism assessed, a virtual displacement (or better velocity) field is applied. The Principle of Virtual Powers can be then applied, allowing to compute the horizontal load multiplier $\alpha0$ from the equality between external (deriving from horizontal and vertical forces) and internal work (set equal to zero).

Many mechanisms have been implemented in the aforementioned procedure, including overturning mechanisms (facade, walls with diagonal wedges, orthogonal walls with bi-diagonal wedges, corner), vertical flexure (one, or two levels), horizontal flexure (with and without confinement) and breakthrough of the gable wall. For some of the mechanisms, some adjustment of the initial shapes of the macro-blocks can be required to obtain a good estimation of the minimum kinematic multiplier.

The second approach is an adaptive upper bound where masonry behaves as a quasi no-tension material; few infinitely resistant NURBS elements are used to mesh portions of the aggregate and the actual activating failure mechanism is reproduced progressively adjusting the shape of the NURBS elements by means of consolidated meta-heuristic approaches. For the sake of conciseness and due to the theoretical complexity of the model, the interested reader is referred to Ref. [4] for further details.

B. Presentation of the C.I.N.E. spreadsheet by ReLUIS

The Italian Excel spreadsheet C.I.N.E version 1.0.4 [5], freely available since 2009 on the ReLUIS website, is the result of a collaboration between various university research laboratories, the National Research Council (CRN-ITC) and the Marche and Molise regions. It is an Excel tool for the seismic verification of local failure mechanisms under out-of-plane loads in existing masonry buildings. The theoretical basis is the linear kinematic analysis, as recommended by the Italian guidelines for the preservation of cultural heritage [6], where the failure mechanisms active are a-priori assumed.

The Excel sheet is made up of tabs corresponding to the different mechanisms to be tested, each tab being divided into three distinct parts:

-A first part must be filled in by the user, it details the

geometry of the structural element analysed and the loads applied to the macroblocks.

-A second part includes the calculation steps and the final result of the evaluation of the horizontal load multiplier.

-A third part is dedicated to the calculation of the seismic parameters according to the Italian standard NTC 2008 [157], the seismic data being entered by the user, to obtain the demand in terms of accelerations.

The mechanisms evaluated by the calculation sheet include simple overturning, composed overturning with diagonal or bi-diagonal wedges, corner overturning, vertical flexure on one to three levels, horizontal flexure with and without lateral confinement, gable breakthrough.

The C.I.N.E. application requires the user to perform several calculations and measurements beforehand: weight of the macroblocks, position of the macroblocks' centers of gravity, vertical and horizontal distances of the load's application point in relation to the cylindrical hinge, sum of the loads applied to a single macroblock. These manual calculations can be tedious if the actual geometry of the structure is considered, which generally leads to simplifications. Furthermore, the geometry of the structure must be sufficiently simplified to be processed by the calculation sheet: constant wall thickness, application of tie-rod actions at floor level, flanges of openings located at the same height, limited number of floors, limits in the loading possibilities. To supersede such problems, the authors automatized the same approach in an Autolisp-CAD application, to facilitate the implementation of the input data by the user.

III. DESCRIPTION OF THE CASE STUY: "YUNGAY'S HISTORIC URBAN CENTER" AGGREGATE IN SANTIAGO, CHILE

C. Research background

As one of the most representative historical areas in Santiago, Chile, the Yungai's historic urban center has a long history and has considerable historical research value. The area was originally composed of a large amount of farmland and was named "Quinta de los Portales", and it was in January 1839 that Chile established the "Yungay". The term "Yungay" was taken from the federal war between Chile and the Peruvian-Bolivian Confederation, with the president intending to commemorate the victory of the battle of Yungay. Nearly 40 years after 1836, engineers Jacinto Cueto and Juan de la Cruz Sotomayor used a checkerboard planning to align the plan structure of the city, making the urban architectural planning take shape (Fig. 1).

This paper selects one part of a building in Yungay historic urban center as a case-study (according to Fig. 1, its name is M36), the building is made with Unreinforced Brick Masonry, and the architectural style is classicism. It is a combination of traditional masonry building and new building (Fig. 2); the present investigation focuses on the traditional masonry part (Fig. 3). The building contains a unique element, called "Ochavo", which is the corner of the building giving rise to a sort of monumental facade with doors that serve as the main entrance to the building. This architectural configuration is also common in other South American colonial urban centers. With the research of past earthquake, the structure Ochavo was particularly vulnerable to seismic action, because of the poor connection between transverse walls. Considering this reason, it is worth investigating the seismic vulnerability of such portion [7].
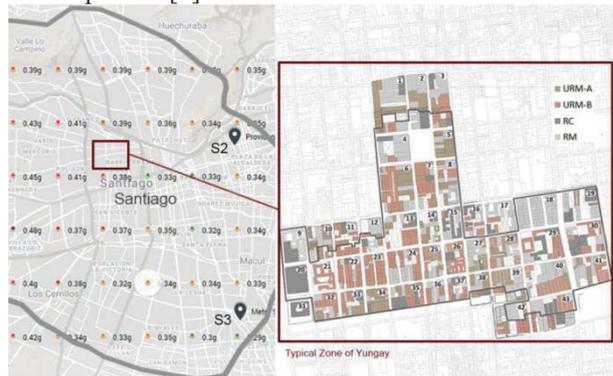

Fig. 1. Yungay historic urban center [7].

D. Modelling of the aggregate

The aggregate is modelled using the aforemention AutoCAD tool, each wall being represented with a 3D solid to correctly reproduce the complex geometry of the masonry aggregate, especially concerning the varying thickness of walls, the different types of openings and the geometrical irregularities (Fig. 2 and Fig. 3). The partition into macroblocks corresponds to the walls defined by the subdivision into structural units and the distinction between perimeter walls and internal walls. The subdivision into structural units and the notation adopted for each wall is reported in Fig. 4 (with a letter indicating the structural unit and a number indicating the position).
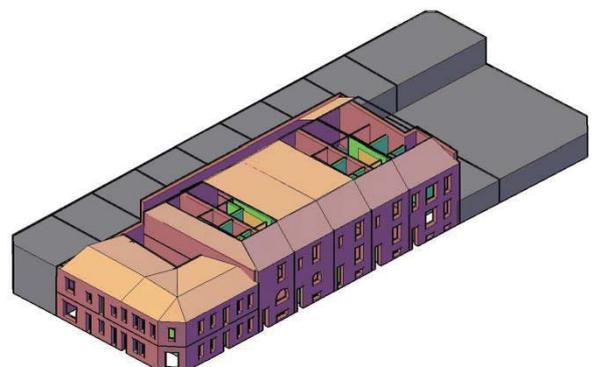

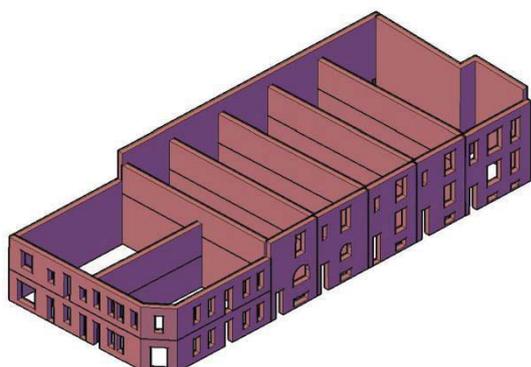Fig. 2. 3D model of aggregate M36 on AutoCAD (South-East view).
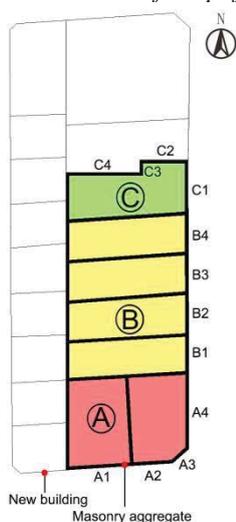
Fig. 3. South-East view of simplified model.

Fig. 4. Independent structural units and plan view for the nomenclature of walls.

IV. RESULTS OF YUNGAY AGGREGATES

A. Analysis of simple overturning mechanisms with poor connection conditions

The results obtained for the simple overturning mechanisms on the different perimeter walls are presented in Table 1, with the horizontal load multiplier corresponding to the activation of the mechanism and the involved levels of the studied wall. The number associated with the walls for the partial failure mechanisms indicates the level at which the failure hinge is located: the subscript "0" indicates the overturning of the whole wall, the subscripts "1" indicate that the collapse takes place respectively from the first floor.

Table 1. Aggregate "Yungay" M36, horizontal load multiplier for simple overturning mechanisms obtained with C.I.N.E application.

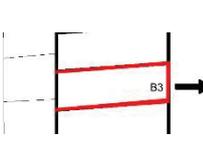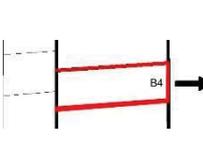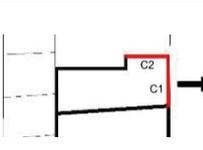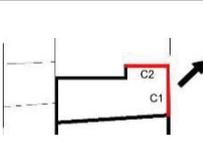| Wall Reference	C.I.N.E application	
	$a_0[/]$	$a_0^*[g]$
A1-0	0.068	0.596
A1-1	0.133	1.046
A2-0	0.068	0.603
A2-1	0.125	0.991
A3-0	0.061	0.517
A3-1	0.128	1.001
A4-0	0.065	0.575
A4-1	0.122	0.951
B1-0	0.043	0.368
B1-1	0.117	0.912
B2-0	0.054	0.464
B2-1	0.137	1.066
B3-0	0.052	0.445
B3-1	0.125	0.968
B4-0	0.052	0.445
B4-1	0.125	0.968
C1-0	0.052	0.456
C1-1	0.122	0.933

### B. Analysis of simple overturning mechanisms with good connection conditions

Then the hypothesis of good connection between walls of the same structural unit is considered to evaluate composed overturning mechanisms. The hypothesis of disconnection between walls is maintained at the boundaries between the different structural units. Depending on the direction of the ground acceleration, different participating walls are considered and the failure crack patterns forming the mechanism corresponding to the lowest value of the horizontal load multiplier are sought. For walls belonging to the same structural unit, different orientations of the ground acceleration are successively assumed, and the failure hinge is positioned on the wall perpendicular to the ground acceleration. Overturning can imply either one or two additional walls, depending on the geometry of the structural unit. Corner overturning mechanisms are also tested for some units, assuming a diagonal direction of ground acceleration. The nomenclature referring to walls is composed of the reference number of the wall (according to Fig. 4).

The results in Table 2 show the influence of the choice of the failure mechanism: different shapes are assumed to minimize and better approximate the collapse multiplier. Despite the horizontal load multipliers for composed overturning are quite low, they are still greater than those in simple overturning.

Table 2. Aggregate "Yungay" M36, composed overturning mechanisms, corner overturning mechanisms and resulting loading multiplier and acceleration obtained with C.I.N.E application.

Schematic	No.	a_0	$a_0^*[g]$
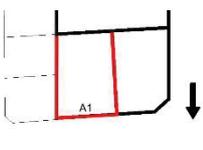
Schematic	No.			
	A1-0	0.155	0.115	
	A1-1	0.231	0.172	
	A2-0	0.135	0.124	
	A2-1	0.170	0.157	
	A3-0	0.287	0.213	
	A3-1	0.308	0.224	
	A4-0	0.276	0.293	
	A4-1	0.321	0.300	
	B1-0	0.156	0.119	
	B1-1	0.232	0.181	
	B2-0	0.155	0.121	
	B2-1	0.254	0.190	
	B3-0	0.158	0.123	
	B3-1	0.257	0.218	
	B4-0	0.158	0.123	
	B4-1	0.257	0.218	
		0.244	0.271	0.293
		0.299	0.341	0.357
		0.283	0.210	0.301
		0.323	0.297	0.357
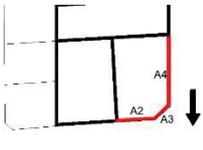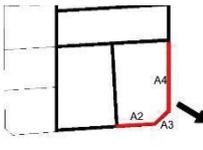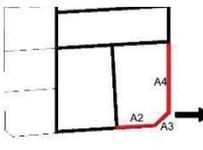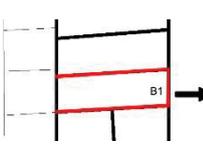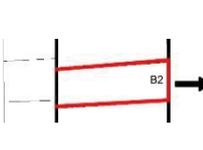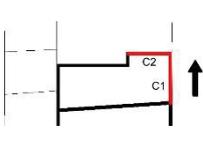
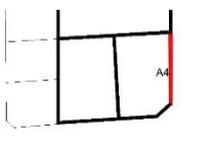| Schematic			
	0.145	0.139	0.155
	0.182	0.162	0.183

C. Analysis of flexural mechanisms

Vertical and horizontal flexure mechanisms are simulated for the walls A1 and A3, which are the most slender walls in the aggregate. Vertical flexure is observed when connections between floors and walls are well ensured, a situation which prevents tilting of the wall. It is promoted by poor connections with orthogonal walls and a good connection degree at the head of the wall. Different positions of the fracture lines are tested to get a better approximation of the minimum value of the load multiplier, considering the distribution and position of openings, which can play as weak spots in the structure.

The results are shown in Table 3. For vertical flexural mechanisms of walls A1 and A4, results show that the horizontal load multiplier is higher for ground levels: this is due to the fact that the wall thickness is higher for the base level than for the upper levels. Stockier levels are characterized by higher horizontal load multipliers whereas slender levels exhibit lower horizontal load multipliers.

Table 3. Aggregate "Yungay" M36, vertical mechanisms and horizontal flexure mechanisms for walls A1 and A4, with resulting loading multiplier obtained from C.I.N.E application.
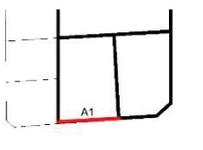
Schematic	No.	a_0
	A1-0	0.473
	A1-1	0.612
	HF-A4	0.657
	A4-0	0.497
	A4-1	0.779
	HF-A4	0.437

D. Analysis of a typical wall with NURBS UB adaptive FE code

In NURBS analysis, it is considered a constant-in-height horizontal acceleration proportional to masses (G2 distribution). It can be seen from Fig. 5 that the failure

327

mechanism after optimization is a combination of diagonal cracks for walls A3 and A2, A4. The damage mainly extends to the roof along the openings and the pattern is rather complex. This part is the more unstable one of the whole building. It can be seen from Fig. 6 that under the action of horizontal loads, wall C1 cracks along the door and window openings and almost completely overturns.
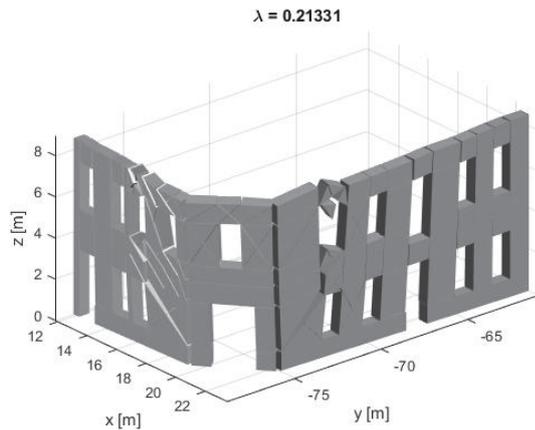

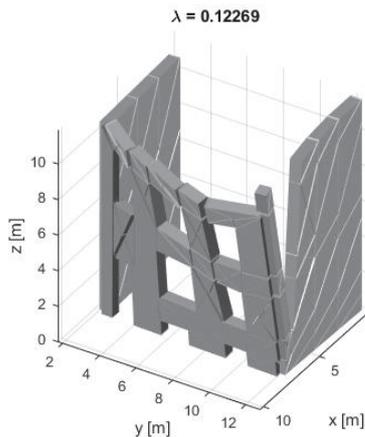*Fig. 5. NURBS matlab analysis of corner (A1, A2, A3).*

Fig. 6. NURBS matlab analysis of wall C1.

V. CONCLUSION

This paper mainly analyzes a masonry aggregate in Santiago, Chile through an Autolisp implementation of the C.I.N.E. approach and adaptive NURBS UB limit analysis. The analysis results show that, compared with the simple overturning collapse mechanism, the other collapse mechanisms are only activated under specific stress conditions and specific geometric and mechanical constraints between contiguous walls.

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