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SEISMIC ASSESSMENT OF COMPLEX ASSETS THROUGH NONLINEAR STATIC ANALYSES: THE FORTRESS IN SAN FELICE SUL PANARO HIT BY THE 2012 EARTHQUAKE IN ITALY

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Abstract. *This paper proposes a procedure for the seismic assessment of unreinforced masonry complex structures together with a first application to the case of fortresses. The proposal of such procedure arises from different reasons: firstly, Standards suggest procedures mainly addressed to ordinary structures; furthermore, even those Recommendations, which are more specifically addressed to monumental assets, state only general principles, without specifying operational targeted-procedure for their seismic assessment. The damage occurred after past earthquakes, and in particular the one hit the Emilia region in Italy, highlighted that fortresses are characterized by an aggregation of bodies with an own seismic behavior which, however, is strongly affected by their dynamic interaction due to the mutual boundary conditions. Hence, the adoption of a numerical three-dimensional model of the whole structure is necessary to take into account explicitly the effect of such interactions. The proposed procedure requires the execution of a modal analysis of the whole structure in order to define the modes involving the dynamic response of each units and their modal shapes. Then, fitting the modal shapes, proper load patterns are defined to pass to the execution of pushover analyses. In particular, one load pattern is applied for each unit but considering the whole numerical model. The pushover curve of each unit is then converted in the capacity curve to finalize the seismic assessment and verification. The proposed procedure is applied in the paper to the case-study of San Felice sul Panaro fortress, significantly hit by the Emilia earthquake, 2012 allowing the comparison between the occurred damage and the one simulated by the nonlinear static analyses and to validate the procedure. The potentialities of the proposed procedure seem relevant in order to provide a reliable seismic assessment also of other typology of complex structures.*

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1 INTRODUCTION

This paper deals with the seismic assessment and protection of complex monumental masonry assets. This kind of assets include a huge amount of structures, characterized by various specific seismic response. In particular, two main classes are relevant for the issues herein faced. The first class is formed by monumental palaces in historic centers (Figure 1a), characterized by aggregations of buildings joined to each other by means of connecting units which are often built with wooden floors and set up on arches or vaults: thus, the latter are characterized by lower weight and stiffness then the adjacent ones. The second class is instead formed by fortified constructions (fortresses or castles), which are usually formed by towers connected through defensive walls (Figure 1b). For both classes the assessment of global in-plane response is usually relevant, although the activation of local mechanisms is still possible as well. In particular, this paper refers to second class of complex architectonical assets focusing the attention to the seismic assessment of their in-plane global response through nonlinear static analyses. The vulnerability of fortresses was strongly highlighted by the Emilia earthquake, 2012 [1] being such typology very present in the area and pointing out the complexity in interpreting also their seismic behavior.


a.

b.

Figure 1: Examples of two monumental complex assets in Italy: Palazzo del Podestà in Mantua (a) and San Felice sul Panaro Fortress near Modena (b).

The seismic assessment of complex monumental structures poses several critical issues. The first problem deals with the definition of the best modeling choice to be adopted. The units to be modeled have to be limited in number for a reasonable computational effort, but at the same time, they have to be "sufficient" in order to guarantee a reliable assessment that is capable to catch the interaction effects, which can be relevant especially if the bodies are characterized by different stiffness and architectural features. The second problem is instead connected to the lack of tools and standardized procedures to perform the seismic analysis and verification of such complex structures. While Standards ([2]) are more oriented to ordinary buildings, Recommendations addressed to monumental assets (i.e. [3]) in general state a series of general principles and prescribe indications for possible methodologies of analysis, without however prescribing operational tools or indicating specific models and procedures. Therefore, it is necessary to provide reliable models and verification procedures able to quantify the structural safety level in order to pursue conservation aims.

In this context, this paper aims to overcome the lack of operational tools, by proposing a procedure for the seismic assessment of complex monumental masonry assets, using nonlinear static analyses. The required steps of the procedure are explained in §2. The procedure is then applied to a case-study, which is the San Felice sul Panaro Fortress. Since this asset was significantly hit by the Emilia earthquake 2012, the comparison between the occurred damage and the one predicted - in terms of ductility demand by the analyses- allowed to validate the procedure (§3). The procedure uses a three-dimensional detailed geometrical model of the entire structure, developed in the case of the San Felice sul Panaro Fortress starting from a laser-scan survey [4]. In this way, the dynamic interactions among the different units of the whole asset are explicitly taken into account, but with a bearable computational effort.

2 PROPOSAL OF A PROCEDURE FOR THE SEISMIC ASSESSMENT OF FORTRESSES THROUGH NONLINEAR STATIC ANALYSES

The seismic assessment of complex monumental assets can be developed by following two different approaches: (i) decomposing the whole asset into the different units (e.g. on the basis of historical and constructive features) and performing separate verifications; (ii) realizing a unique global model of the entire complex structures, performing the pushover analysis and, consequentially, make the verification through the capacity curve representative of the overall global seismic behavior. In principle both alternatives can be considered reliable and have to be chosen depending on the specific features of each monument, on their complexity that can make feasible only some alternatives and on the expected structural behavior. However, they both present pros and cons. Regarding the first choice, difficulties are mainly related to the need of defining a "border" for the asset and for each unit and consequentially the "equivalent" boundary conditions for each modeled body. Then, obviously, the analysis of the monument in aggregate decomposed in the different units is not able to consider the possible interaction effects between the different parts, except in an approximate and conventional way. On the other hand, the second choice implicitly considers these latter effects, but it is at the same time affected by difficulties connected to the computational effort determined by such a complex model. Traditional CAD-based modelling is an expensive and complex process, often carried out by the users with inevitable geometrical simplifications. On the contrary, more recent automatic advanced survey techniques (such as Terrestrial Laser Scanner – TLS) can generate three-dimensional detailed points clouds in a rapid way able to describe in details the most complex geometries, but then it is not easy to transform them into data usable for structural aims. For all these reasons, in general this unbearable computational effort forces to exclude too detailed models and to adopt alternative modeling strategies, such as procedures based on the equivalent frame or even more simplified models. Even both alternatives ((i) and (ii)) can be adopted, the second one is considered the most reliable for the fortresses which the paper focuses to. In fact, this kind of structures are characterized by an enormous complexity in terms of geometry, material properties, loads and boundary conditions. Hence, in most cases, the use of simplified structural scheme and conventional boundary condition is inadequate to model these features and a three-dimensional modelling is more appropriate to investigate the structural behavior.

Furthermore, a further critical issue deals with the procedure for analysis and verification, which is not manageable *a priori*. For this reason, at present, Standards and Recommendations ([2], [3]) do not suggest a well-established procedure for the assessment of such complex structures. In general, the nonlinear static analyses (NLSA) is the most widespread method to study the global response of existing ordinary buildings, but its application to complex assets is yet to be explored. NLSA is usually based on the application of a unique force distribution (for example proportional to masses or proportional to masses per height) or a combination of force distributions. However, performing a pushover analysis with a single load pattern on the whole model, risks to be conventional and inadequate to activate the nonlinear behavior of all the units in aggregate: in fact, when the most vulnerable part of the structure exhibits a nonlinear behavior, it implicates the others remain almost in the elastic field. Other strategies in the field of NLSA as the multimodal or adaptive approach have been mostly developed for other structural types (reinforced concrete and steel buildings) and their application to masonry is still under investigation even for ordinary buildings.

In order to face these problems, this paper proposes a procedure for the seismic assessment of complex structures together with a first application to the case of fortresses. In particular, the procedure requires the development of some steps, herein summarized:

1) realization of a numerical model of the entire aggregation of units aimed to explicitly capture the mutual interaction effects;
2) execution of a modal analysis in order to define the modes involving the dynamic response of each units and their modal shapes;
3) execution of a series of pushover analyses (one for each unit) by applying time by time the force distribution obtained from the modal shapes identified in 2). Each force distribution is defined by a function which varies in plan and height for the unit under examination;
4) conversion of the pushover curve of each unit in the capacity curve representative of the equivalent single degree of freedom system, in order to finalize the seismic verification.

3 APPLICATION OF THE PROPOSED PROCEDURE TO THE CASE STUDY OF SAN FELICE SUL PANARO FORTRESS

In this chapter, the procedure proposed in §2 is applied to the case-study of San Felice sul Panaro Fortress ([5], [6], [7]), a medieval historical building dating back to the 14th-15th century and located near the city of Modena in San Felice sul Panaro (Italy). This case-study reflects the aforementioned features to be a monument that behaves as an aggregation of bodies (towers, perimeter walls and recently added buildings) which are independent dynamically and with own features, but each other interacting at the same time, as deduced from the knowledge path and interpretation of the exhibited seismic response.

This fortress represents a typical example of Emilian fortified medieval architecture, composed by a very massive main structure, characterized by a compact quadrilateral plan with an inner yard and five towers: four of them are localized at the corners, while the other one is placed on the north fortress façade (Figure 1b, Figure 2a). The fortress was seriously damaged by the Emilia earthquake of May 2012 [1], which induced the collapse of the four minor towers' roofs (Figure 2b), shear cracks of different relevance on the main body of the Mastio (Figure 2c) and of the other towers and extensive collapse in the north tower (Figure 2d), also promoted by some heavy interventions recently realized [1]. Furthermore, significant damage was concentrated also in the battlements and in the masonry corbels that support the upper parts.

a. b. c. d.

Figure 2: Schematic floor plan (a) and examples of collapse mechanisms exhibited by the fortress: collapse of a minor tower's roof (b), damage pattern in the Mastio (c) and collapse in the north tower (d).

The proposed procedure can take benefit from a very detailed Finite Element (FE) numerical model (see Figure 5). This latter was developed starting from the data acquired from a laser scanner survey and by means of a non-standard mesh generation procedure called CLOUD2FEM, conceived and set up by part of the authors in ([4], [8]). Such an original procedure semi-automatically transforms 3D points cloud of complex geometries in 3D FE models, keeping low the user-time demand with respect to traditional CAD-based routines.

As far as the constitutive law for masonry is concerned, an isotropic damage-plasticity model implemented within the Abaqus software package [9] has been adopted. The model's mechanical parameters were assumed with respect to the recommendations prescribed by the Italian Code in case of URM existing buildings ([10]).

Even if the procedure has been already applied to all the bodies which constitute the San Felice sul Panaro Fortress (Figure 3), the paragraphs below present only the results obtained for the Mastio (unit n. 4 in Figure 3).

1. North (N) tower
2. North-West (N-W-) tower
3. South-West (S-W) tower
4. Mastio
5. North-Est (N-E) tower
6. West body
7. Wall-walk
8. Construction named "Casa Matta"
9. East wall
10. Entry body

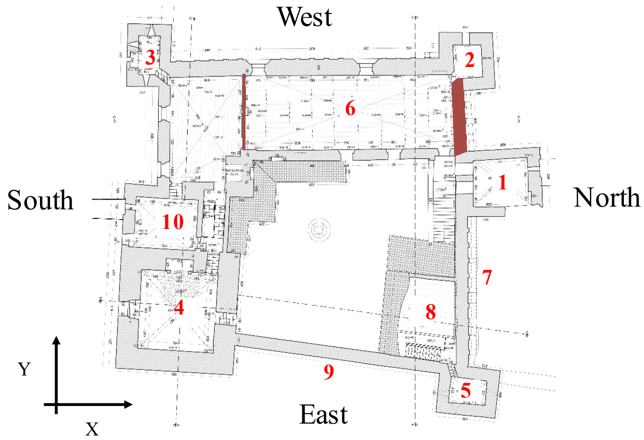

Figure 3: Identification of the main bodies in the San Felice sul Panaro Fortress.

3.1 Definition of the adopted forces' distribution

Once realized the detailed three-dimensional model of the whole structure, the procedure requires to perform a modal analysis to define the modes involving the dynamic response of each units and their modal shapes. Then, for each unit, only the modes involving its dynamic response have been considered and, for each mode, the so obtained modal shapes have been fitted with exponential functions (polynomial and linear), varying in plan and height. These functions define the load pattern to be applied to each unit on the pushover analyses. The analyses were executed on the model of the entire structure, hence taking into account explicitly the interactions among the different bodies.

Figure 4 presents, for example, the load pattern applied to the Mastio (unit n. 4 in Figure 3). In particular, this figure illustrates:

a. the modal shape in plan obtained from the modal analysis performed on the whole structure (the selected modes are the ones involving the dynamic response of the examined unit);
b. the maximum and minimum modal displacements of the nodes in each section of the examined body;
c. the function fitted from the modal shapes and assumed for the forces' distribution in the nonlinear pushover analyses;
d. a three-dimensional picture of the distribution.

As it is possible to see, the load pattern applied to the Mastio varies only in height, while it remains constant in section. More complex load patterns have been defined for other towers of the fortress.

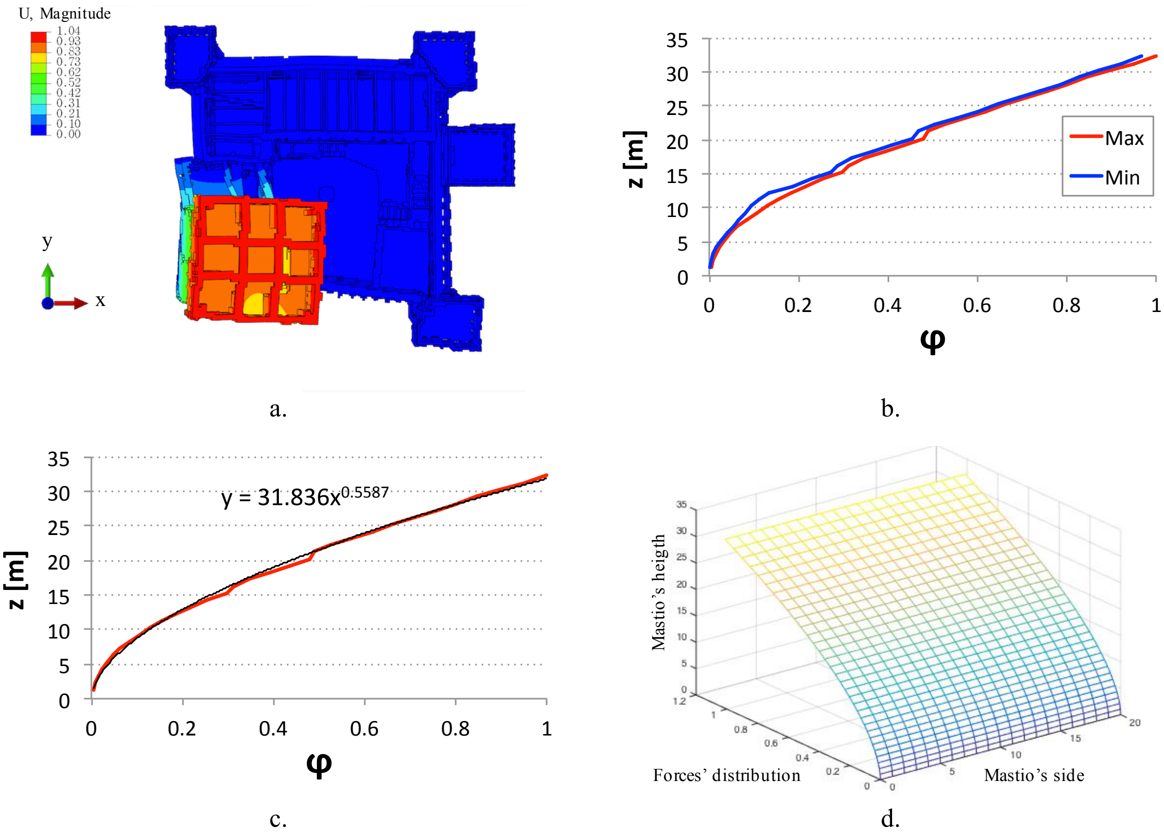

Figure 4: Forces' distribution assumed for the Mastio.

3.2 Nonlinear static analyses' results

Once evaluated the load pattern as explained in §3.1, in order to verify the procedure's reliability, firstly the procedure has been applied to the Mastio comparing the achieved results with those obtained applying a unique forces' distribution on the whole fortress. In particular, the results were compared in terms of damage pattern (Figure 5), pushover curves (Figure 6a) and capacity curves (Figure 6b). As one can see, the results almost correspond.

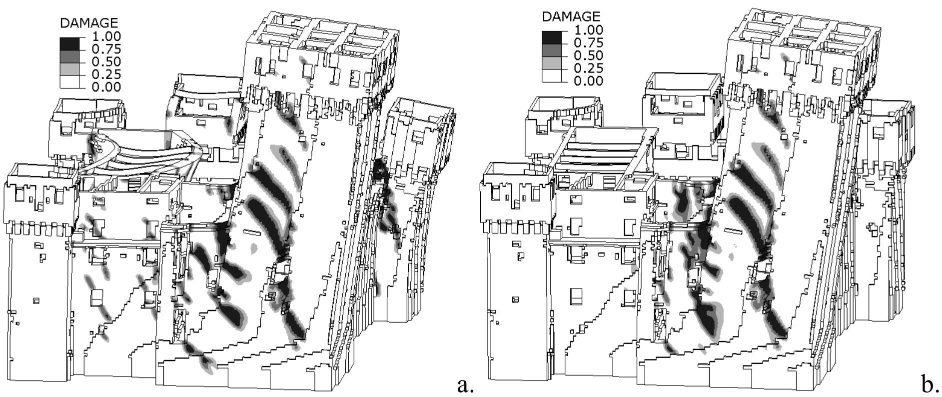

Figure 5: Comparison in terms of damage pattern obtained applying the forces' distribution simultaneously to the whole fortress (a) and only to the Mastio (b).

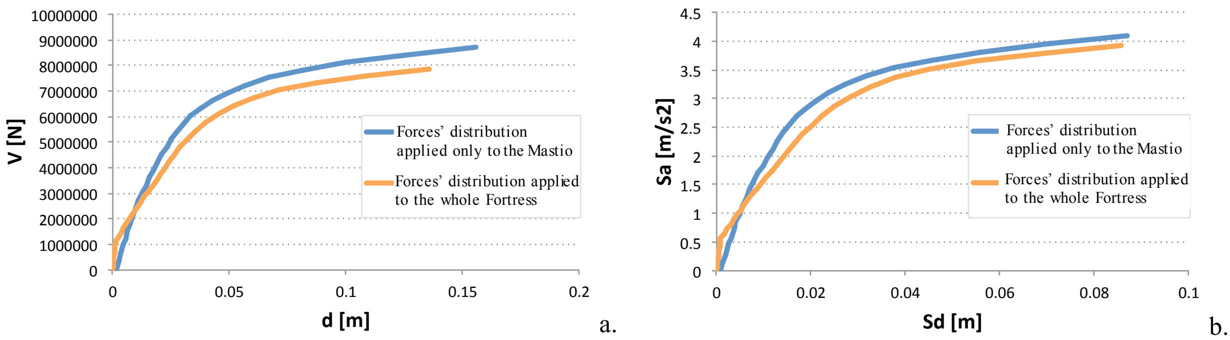

Figure 6: Comparison in terms of pushover curves (a) and capacity curves (b) obtained applying the forces' distribution simultaneously to the whole fortress (graphs in orange) and only to the Mastio (graphs in blue).

Nonlinear static analyses were then developed in both the directions +/- X e +/- Y, as indicated in Figure 3. From the results, these data were extracted:

- the global shear at the base of the whole fortress, expressed as function of the average displacement at the top level of each unit. Hence, since the applied load pattern aims to activate the inertial forces of the examined unit, the major contribution was due to the base shear of the body pushed through the load pattern, but at the same time it was possible to explicitly consider the interactions with the other bodies;
- the displacements associated to the different nodes placed at increasing levels of each unit for negligible values of the horizontal force, thus representative of an elastic phase of the response. These values allowed calculating the participation coefficient and the participation mass necessary to transform the pushover curves into the capacity curves of the equivalent Single Degree of Freedom (S-DOF) system.

Starting from these data, the pushover curves (V-d) of each body have been obtained. Then, these curves were converted into the corresponding capacity curve (V*-d*), following the general principles of [11], adopted by [2] as well, and based on the evaluation of the participation coefficient Γ and the mass M* of each body (see Eq. (1), where ϕ_i is the i^{th} component of the eigenvector representative of the first modal shape and m_i is the correspondent nodal mass). Hence, the capacity curve was obtained by dividing the displacement d by Γ ($d^*=d/\Gamma$) and the base shear by the product ΓM* ($V^*=V/(\Gamma M^*)$), where Γ and M* are the bodies to verify each time.

$$\Gamma = \frac{\sum m_i \phi_i}{\sum m_i \phi_i^2} = \frac{M^*}{\sum m_i \phi_{x,i}^2} \qquad (1)$$

4 VALIDATION OF THE PROPOSED PROCEDURE

Once evaluated the capacity curve for each body, it was possible to validate the procedure by considering the actual seismic action that hit the monument on the 29th May 2012. Then the comparison between the actual occurred damage pattern and the corresponding ductility demand μ_{PP_actual}, evaluated from the analysis (Figure 7), was adopted to the aim of validation. In fact, the ductility demand μ_{PP_actual} represents an estimation of the ductility reached by the different bodies during the 2012 earthquake: it is expected that the bodies with higher values of μ_{PP_actual} would correspond to the most damaged ones while the ones with lower (values closest to the unit) μ_{PP_actual} would be the most intact.

Table 1 presents a summary of the results obtained for the Mastio, in terms of:

- Data which briefly describes the capacity of the equivalent Single Degree of Freedom (S-DOF) system in terms of equivalent bi-linear curve [11], that are:
  - period which defines the initial elastic branch of the bi-linear curve (T*);
  - value of the bi-linear curve's maximum spectral acceleration (S_{ay});
  - value of the system's ductility μ_u, evaluated as the ratio between the displacement capacity d_u and the displacement d_y. In particular, d_u has been assumed in correspondence of the maximum displacement obtained during the analyses, while d_y the displacement associated to the end of the initial elastic branch of the equivalent bi-linear curve.
- Data necessary to highlight the validation of the numerical model and of the verification procedure, that are:
  - The safety margin I_{SPP_actual} expressed as the ratio between the ultimate displacement d_u and the expected seismic demand; this latter was evaluated by applying the Capacity Spectrum Method [12] based on the use of overdamped reduced spectra. In particular, the expected seismic demand was expressed by the displacement obtained comparing the capacity curve with the response spectrum generated from the actual records of May 2012 ($d_{PP\_max\_actual}$);
  - The ductility demand calculated as $\mu_{PP\_actual} = d_{PP\_max\_actual}/d_y$. The correspondence between the so obtained ductility level and the damage pattern actually occurred after the earthquake implicitly means that the numerical model and the procedure of verification and analysis can be considered reliable. It is worth noting that the values are higher than 1 as the structural response was entered in the nonlinear field; hence, in this case, one has to expect a more significant and spread damage.

From Table 1, it is possible to see that the obtained results are promising confirming the potential reliability of the procedure. In fact, it is clear that, from the numerical analyses, a significant damage interested the Mastio (which reaches a ductility level in the most punitive direction equal to 1.593). The comparison with the actual damage occurred after the 2012 earthquake highlighted a good correspondence with the one numerically simulated.

			Bi-linear capacity curve			**Validation (with actual response spectrum)**	
Body	**N**	**Dir.**	**T* [s]**	**S_{ay} [m/s^2]**	**μ_u [-]**	**Is_{PP_actual} [-]**	**μ_{PP_actual} [-]**
Mastio	4	W	0.44	5.060	2.871	1.888	1.521
		S	0.53	3.761	3.228	2.088	1.546
		E	0.55	3.507	3.124	1.961	1.593
		N	0.48	4.383	3.281	2.182	1.504

Table 1: Results of the validation of the proposed procedure, applied to the Mastio.

Figure 7 shows the obtained results for the Mastio and for the analyses in the West direction. In particular, the following is represented:

a. a comparison between the capacity curve (in green) and the overdamped response spectrum obtained from the May 2012 actual records (the value of the maximum displacement induced in the system is represented in the figure by the dotted blue line);
b. a picture of the damage pattern occurred after the Emilia earthquake;
c. some pictures of the damage pattern obtained from the developed analyses.

Mastio - West direction

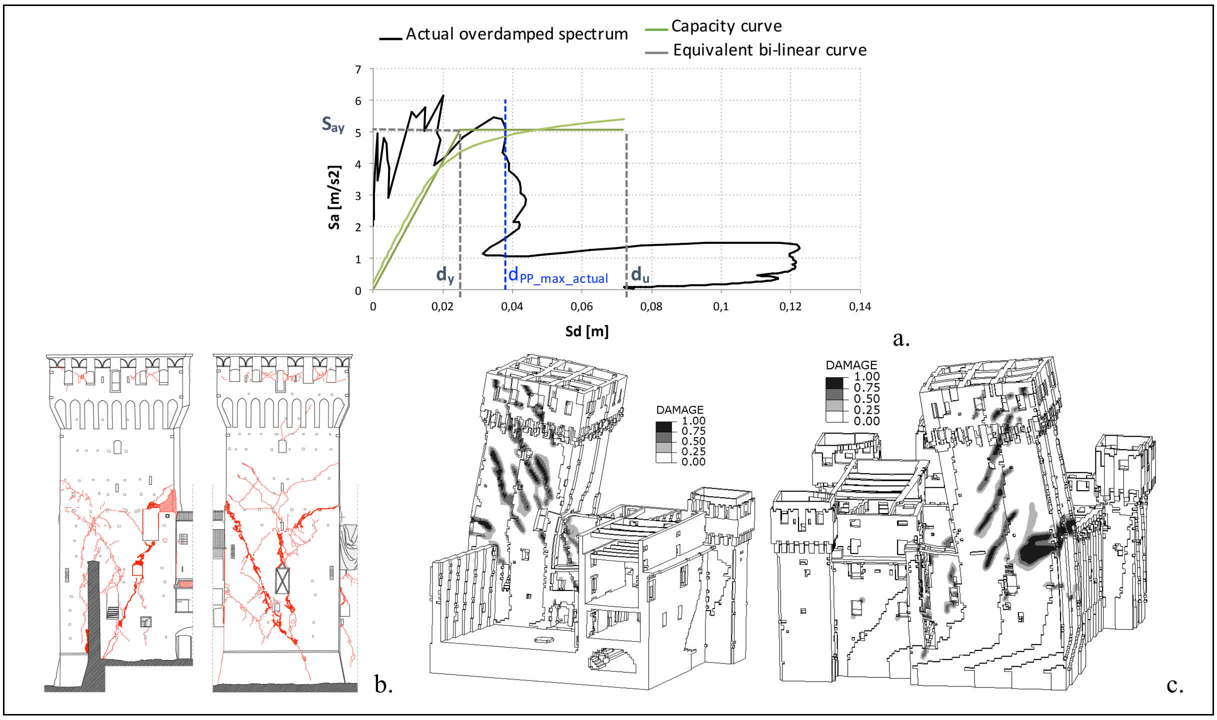

Figure 7: Results of the nonlinear static analyses for the Mastio in the West direction.

5 CONCLUSIONS

The seismic assessment of ancient complex masonry monuments is a very difficult task, not manageable *a priori* through well-defined procedures of analysis and verification. As a first attempt to provide operative tools, the paper proposes a procedure for the seismic assessment of URM complex structures together with a first application to the case of fortresses.

The procedure requires: a numerical model of the entire aggregation of units, in order to explicitly consider the interaction effects among these latter; the execution of a modal analysis to define the modes involving the dynamic response of each units and their modal shapes; the execution of a series of pushover analyses (one for each unit) by applying time by time the load pattern fitted according to the identified modal shapes; the conversion of the pushover curve of each unit into the corresponding equivalent single degree of freedom system, in order to perform the seismic verification.

The procedure has been then applied to a case-study, represented by the San Felice sul Panaro Fortress, significantly hit by the Emilian earthquake 2012. Although in the paper only the results of the Mastio have been illustrated, it has been already applied to the other Fortress' bodies, showing again good results in terms of comparison between the damage actually occurred after the Emilia earthquake 2012 and the one predicted. Such result confirms the potential of the proposed procedure even for other kinds of complex monumental structure.

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