# DISIPAREA DE ENERGIE – UN INDICATOR AL DEGRADĂRILOR STRUCTURALE POTENȚIALE LA STRUCTURILE DIN ZIDĂRIE

# ENERGY DISSIPATION - AN INDICATOR OF POTENTIAL STRUCTURAL DAMAGES FOR MASONRY STRUCTURES

**NICOLAE DANIEL STOICA* , MIRCEA BARNAURE**

*Universitatea Tehnică de Construcții Bucureşti, Bd. Lacul Tei 122-124, 020396, Bucureşti, România*

***For existing buildings masonry, numerical simulation of the seismic behaviour is difficult, involving complex nonlinear models. Testing large-scale models on shaking tables involves important costs and time. Still, the main purpose of testing or simulations is often to identify structural vulnerabilities probable failure modes so that the correct strengthening solution can be chosen. A simplified method for the assessment of the potential structural degradation pattern for simple masonry buildings is proposed. This method is based on energy dissipation and can be easily implemented by practicing engineers. Four case studies are performed using linear numerical models. The results are compared with observations on buildings tested on shaking tables.***

***Pentru clădirile existente din zidărie, simularea numerică a comportării la acțiunea seismică este dificilă, implicând modele neliniare complexe. Testarea pe platforma seismică pe modele la scară mare implică timp şi costuri ridicate. De multe ori, scopul simulărilor este de a identifica vulnerabilitățile structurii şi modurile probabile de cedare astfel încât să se poată alege soluțiile corecte în vederea consolidării. Este propusă o metodă simplificată de stabilire a degradărilor structurale potențiale pentru clădiri din zidărie simplă, pe baza disipării de energie, care să poată fi uşor implementată de inginerii practicieni. Sunt realizate patru studii de caz, utilizând modele numerice liniare. Rezultatele sunt comparate cu observațiile din cadrul testelor pe platforma seismică pentru clădirile analizate.***

***Keywords:*** *d. Masonry, d. Construction, c. Mechanical properties, b. Fracture, b. Modelling*

## 1. Introduction

Although masonry as a building material has been used for thousands of years, its structural behaviour, in particular under seismic loading, is not yet sufficiently well known. For current design of new buildings, practicing engineers use the principles and the formulas indicated in the in-force national and European regulations [1, 2]. By design, it is ensured that, in case of a seismic event, the building is not damaged or if post-elastic deformations occur, they follow certain controlled failure mechanisms, while fragile failure patterns are avoided. As regulations also include formulas for determining the properties of the materials, the current design of buildings masonry can be achieved using linear numerical models.

For the analysis of existing buildings, numerical modelling is difficult, as the structural behaviour of masonry structures submitted to earthquake loads is influenced by many parameters [3]. The diversity of bricks and mortars used, the jointing details, the presence of reinforcement or confining elements lead to numerical modelling involving complicated tools [4] that are generally hard to implement by practicing engineers for current structural design.

For this reason, laboratory testing is often used, preferably using full-scale models. Costs are significant and the models cannot be no matter how large, but they depend on the height of the laboratories, the surface of the shaking table and the weight it can carry.

The main purpose of structural analysis is often to unravel the likely failure modes so that appropriate strengthening solutions can be chosen. A simplified method allowing a preliminary analysis with reduced modelling costs and time is very useful for practicing engineers.

The possibility of using, for existing unreinforced masonry buildings, simplified linear numerical models is analysed. The ETABS 2013 software is used. Four case studies are performed, on models of buildings previously tested on shaking tables. The degradation of the structures is assessed based on the amount of energy dissipated. The results are compared to observations during the tests on the shaking table.

## 2. Assessing structural degradations based on dissipated energy

In the last years, several solutions regarding the numerical modelling of the behaviour of

* Autor corespondent/*Corresponding author,*
E-mail: stoica@utcb.ro

masonry structures were proposed. A first class of models, generically named micro-models, rely on complex analysis using the finite element method (FEM). The first models of this type considered separately the bricks, the mortar and their interface [5]. Later, continuous models [6, 7] were developed based on damage models for the brick and mortar interface. These models, even in their recent optimised forms [8, 9] are difficult to implement and require high computational time.

A second class of models, named macro-models are focused on the overall structural behaviour, for which a detailed description of the interaction between the bricks and the mortar is not required. The simplest macro models [10] simulate masonry by means of a pier and beam system, but the precision of the results can be low in the absence of laboratory tests that enable calibration of the numerical model. Other models [11,12] consider that the material is continuous and homogenous and describe failure using smeared crack criteria, similar to those used for reinforced concrete modelling. These models often wrongly estimate the extension and intensity of damages, which are, usually, in the case of masonry buildings, single wide cracks [13].

For practicing engineers, more familiarised with calculations using linear models, a simpler method that allows identifying the behaviour tendencies of the structure is needed. Part of the seismic energy induced in the structure is transformed into elastic strain energy, while another part is dissipated by post-elastic deformations. Considering that the material has a certain capacity of energy storage, the induced quantities that exceed this value must be dissipated by post elastic deformations, which can be ductile or fragile. It is assumed that the elements that show, in the linear elastic model, the higher energy concentrations will correspond to the areas where failure first occurs. Energy dissipation thus becomes an indicator of the potential structural damages.

Starting from the idea of sequentially linear analysis [14] an iterative method is proposed that allows simulating a profoundly nonlinear behaviour by a series of linear analysis. The method is based on the hypothesis that a relationship exists between the energy induced in the unit of volume of the material and fracture. For the seismic load used for service limit state verifications [1, 2], the induced energy for the various parts of the structure is identified. The values are normalized, such as the largest one has a value of 100. The chosen failure criterion is a value of the normalised energy higher than a given value. The damaged elements are eliminated from the numerical model and the algorithm is repeated until full collapse of the building. This method allows a qualitative assessment of the structural failure mechanisms and of the highly vulnerable elements [15].

## 3. Case studies

In order to check the influence of the modelling parameters on the results, four numerical simulations were done for a structure previously tested on shaking table. ETABS 2013 software was used. The software determines, for a loading pattern, the energy per unit volume associated with each element in the structure.

The failure mode of the full scale model is shown in Figure 1. It is to be noted that the rupture occurs mainly in the ground floor walls at the doors and windows level. Cracks develop diagonally. Breaking occurs in both plans for the corner areas.

The strength characteristics for the materials (concrete, masonry and mortar) were determined in laboratory tests [16]. The geometry of the model tested on shaking table is described in [17 - 19]. For the linear numerical models, the deformability characteristics of the materials were chosen based on the strength characteristics using the formulas from the European Standards for the design of concrete [19] and masonry [20] design. The deformability parameters of materials were then adjusted so that the dynamic characteristics of numerical model correspond to those observed on the model tested on the shaking table (Figure 2).

The analysed parameters are the following: the value of the normalized energy considered as a failure criterion, the size of the finite elements and the influence of defining the areas with a low failure potential as perfectly rigid.

Fig. 1 - *Collapse mechanisms observed on full-scale test / Mecanismul de colaps pentru modelul la scară reală.*

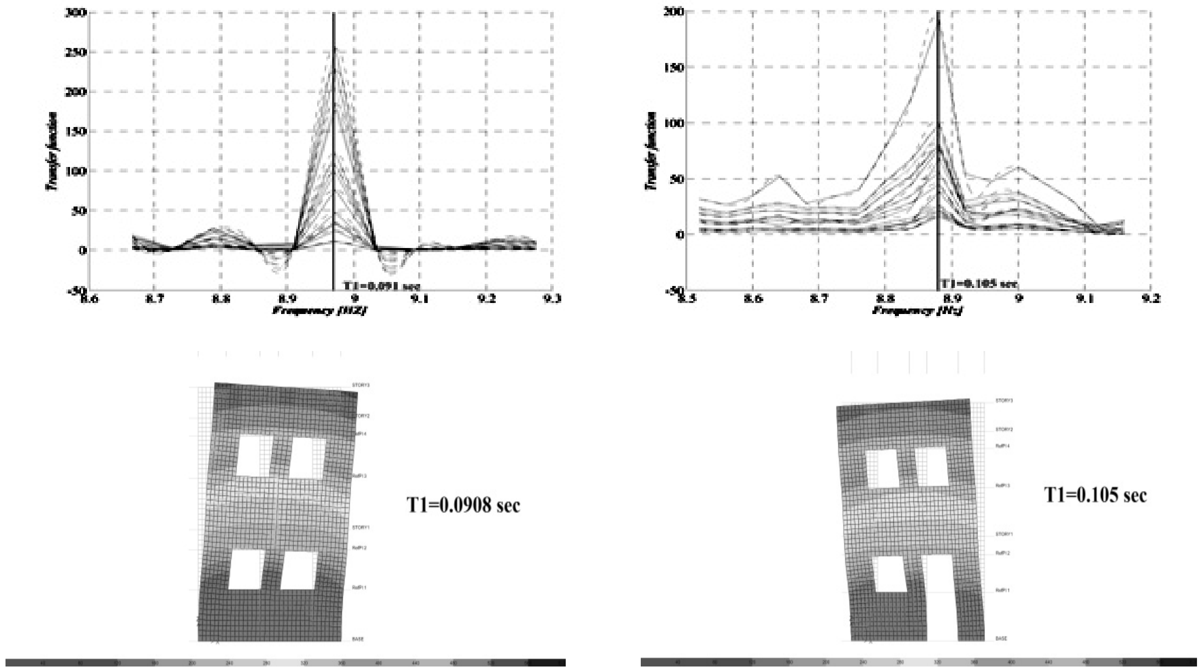
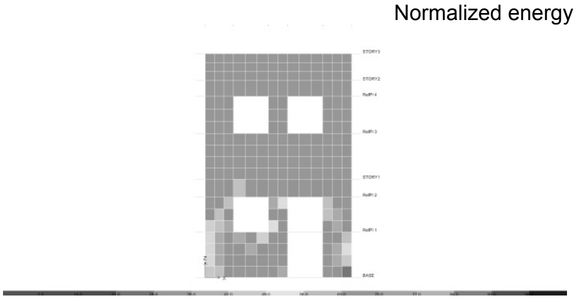


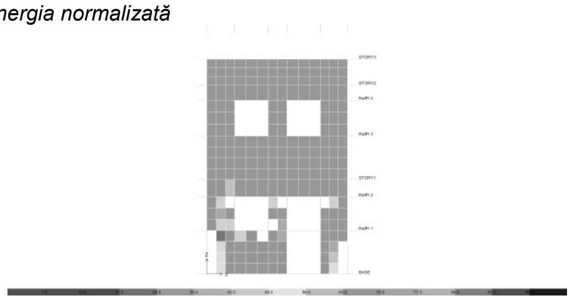

Fig. 2 - Transfer functions for full-scale model [16] and fundamental period in the main directions for the numerical model / *Funcții de transfer pentru modelul testat pe platforma seismică [16] şi perioadele proprii ale modelului numeric .*

**Table 1**

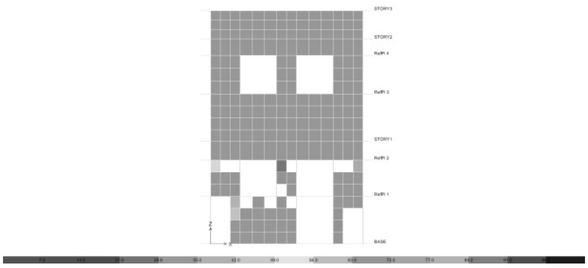
Normalized energy / *Energia normalizată*



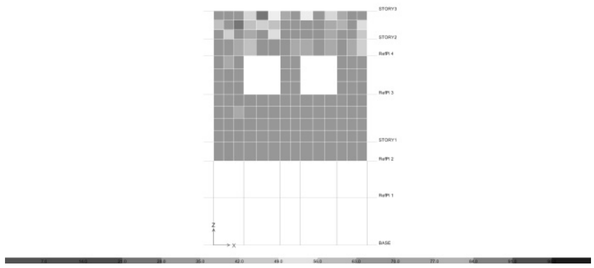
Energy for step 1 / *Energie în pasul 1*



Energy for step 2 / *Energie în pasul 2*



Energy for step 3 / *Energie în pasul 3*



Energy for step 4 / *Energie în pasul 4*

### *3.1. Case study 1*

In the first case study the failure pattern for the wall with the door and window opening is analysed. The same material characteristics are considered for all the areas of the wall. A previous research considered as a failure criterion a normalized energy value greater than 50 [15]. The failure criterion considered in the present study is a value of the normalized energy higher than 70.

After each loading step, the elements that exceed this threshold are removed and then the charging of the structure is resumed. The geometry of the model considered for the successive charging steps and the normalized energy values computed for each step are shown in Table 1. The energy values are normalized, the maximum value is 100 (blue), and the minimum value is 0 (pink).

### 3.2. Case study 2

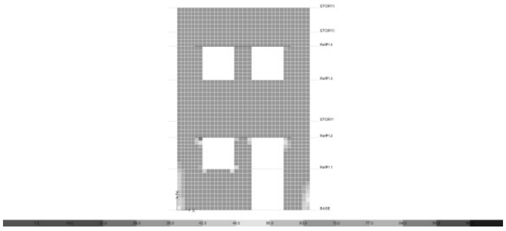
In the second case study, the influence of the size of the finite elements on the results is analysed. The model has 4 times more finite elements than for the previous case study. The considered failure criterion is a value of the normalized energy higher than 70. The values of the normalized energy computed for the successive charging steps are shown in Table 2.

### 3.3. Case study 3

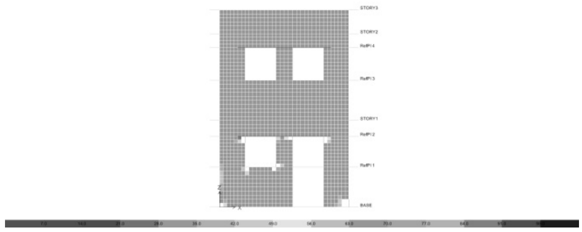
For the third case study, it was taken into account the fact that certain areas of the masonry walls are rarely damaged during earthquakes and, therefore, their deformations can be considered negligible [10]. In this regard, these elements were introduced into the model as infinitely rigid (blue areas in the model geometry in Table 3). The considered geometry of the model and the energy values computed for each loading step are shown in Table 3.

**Table 2**

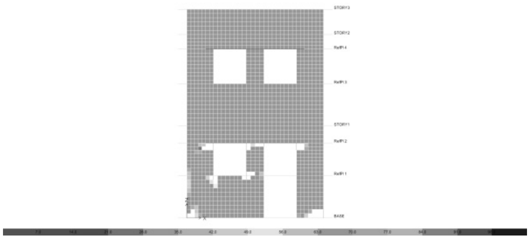
Normalized energy for the fine mesh model / *Energia normalizată pentru modelul cu discretizare mai fină*



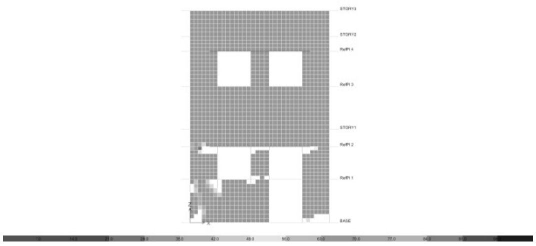
Energy for step 1*/ Energie în pasul 1*



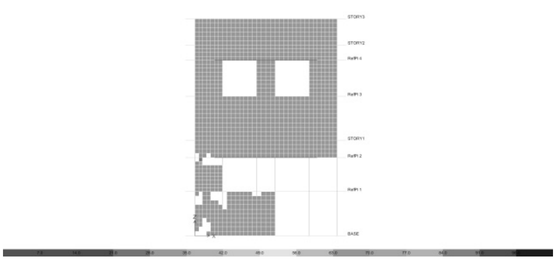
Energy for step 2 / Energie în pasul 2



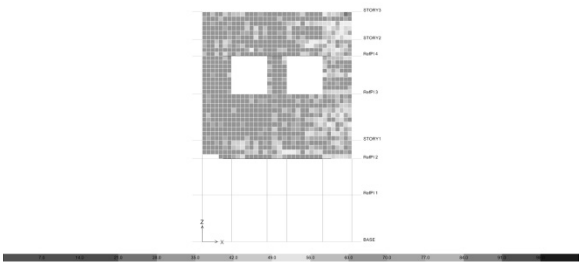
Energy for step 3 / *Energie în pasul 3*



Energy for step 4 / *Energie în pasul 4*



Energy for step 5 / *Energie în pasul 5*



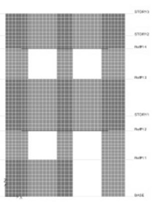
Energy for step 6 / *Energie în pasul 6*

**Tabelul 3**

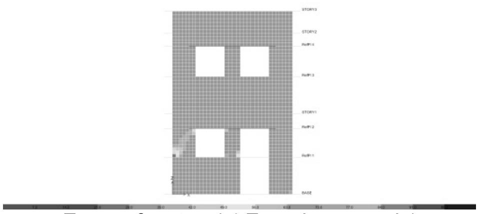
Figures with models and energy for the simplified model with rigid nodes
*Figuri pentru modelul de calcul şi energia în cazul utilizării modelului simplificat, cu noduri rigide*

Numerical Model / *Model numeric*

Energy [%] / *Energie [%]*



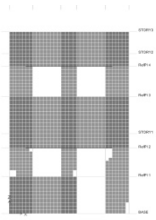
Initial model (step 1) / *Model de bază (pas 1)*



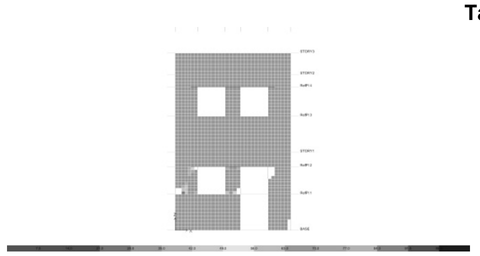
Energy for step 1 / *Energie în pasul 1*

Table 3 continues on next page

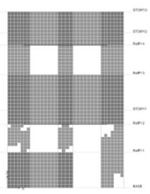
**Table 3**



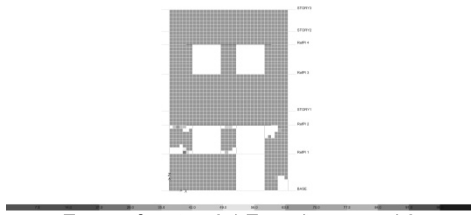
Model - step 2 / *Model - pas 2*



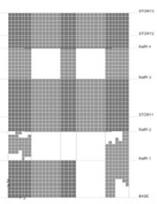
Energy for step 2 / *Energie în pasul 2*



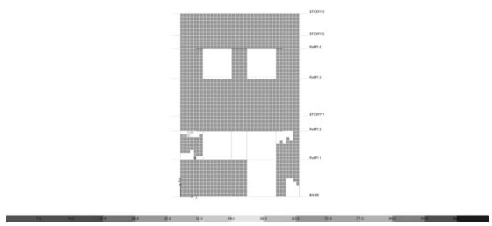
Model - step 3 / *Model - pas 3*



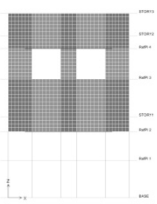
Energy for step 3 / *Energie în pasul 3*



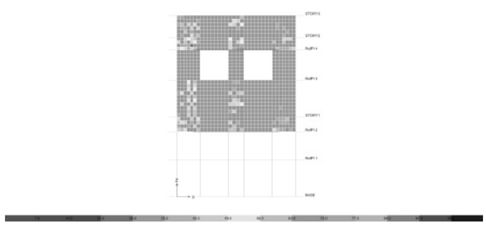
Model - step 4 / *Model - pas 4*



Energy for step 4 / *Energie în pasul 4*



Model - step 5 / *Model - pas 5*



Energy for step 5 / *Energie în pasul 5*

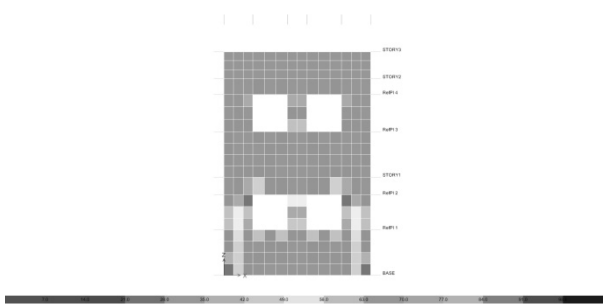
### *3.4. Case study 4*

In the fourth case study the failure pattern for the wall with window openings is analysed. The same material characteristics are considered for all the areas of the wall.

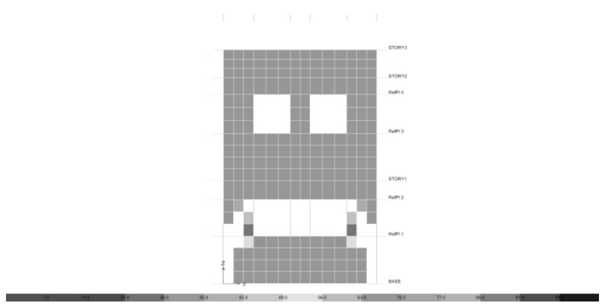
The failure criterion is a value of the normalized energy higher than 70. The normalized energy values computed for each step are shown in Table 4 and 5.

**Table 4**

Normalized energy for the wall with window openings / *Energia normalizată pentru modelul cu goluri de ferestre*



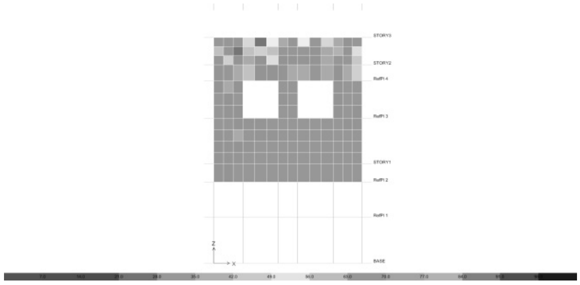
Energy for step 1 / *Energie în pasul 1*



Energy for step 2 / *Energie în pasul 2*

Table 4 continues on next page

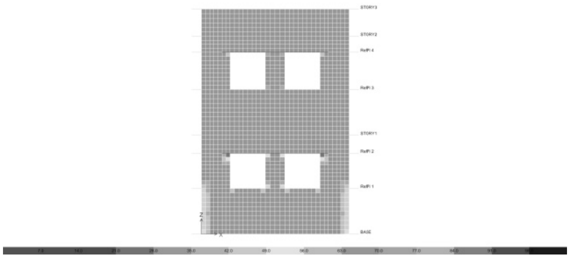
**Table 4**



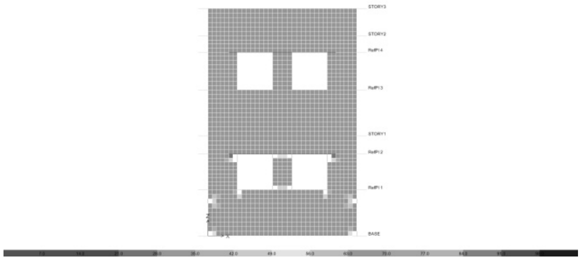
Energy for step 3 / *Energie în pasul 3*

**Table 5**

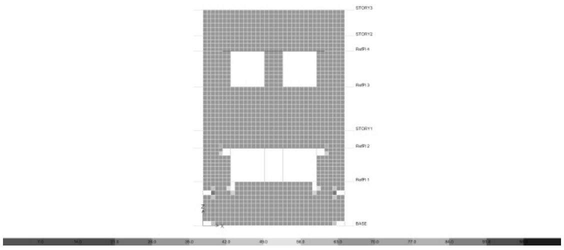
Normalized energy for the fine mesh model of the wall with window openings
*Energia normalizată pentru modelul cu discretizare mai fină a peretelui cu goluri de ferestre*



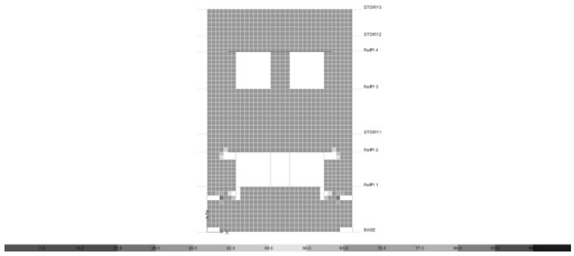
Energy for step 1 / *Energie în pasul 1*



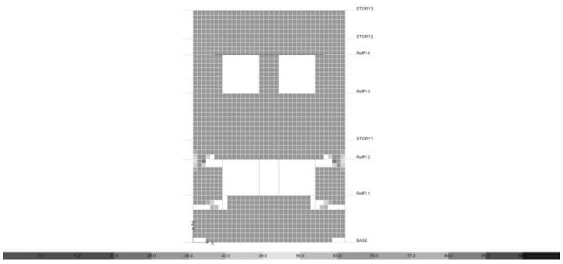
Energy for step 2 / *Energie în pasul 2*



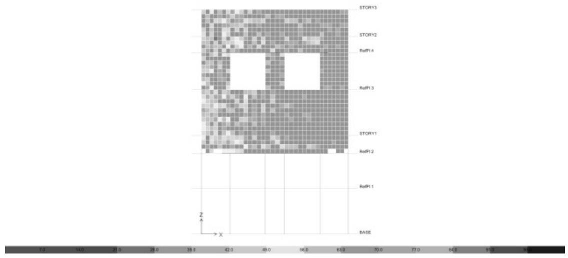
Energy for step 3 */ Energie în pasul 3*



Energy for step 4 */ Energie în pasul 4*



Energy for step 5 / *Energie în pasul 5*



Energy for step 6 */ Energie în pasul 6*

## 4. Conclusions

The likely structural failure pattern of an unreinforced masonry structure under seismic loads was estimated based on the dissipated energy. Linear numerical models were used. The simulated failure patterns were compared with observations on the building tested on the shaking table. The influence of certain modelling parameters on the results was analysed.

The results indicate a good applicability of the proposed iterative method. The method is based on the assumption that the areas of the structure with the highest values of energy, under a certain combination of loads, are the areas with the highest probability for failure.

If a normalised energy level equal to 70 - rather than 50 - is considered as the failure criterion threshold, then better qualitative estimates of the structural behaviour are obtained.

A model with a finer finite element mesh allows a better identification of the failure patterns. At the same time, using 4 times more finite elements increased the number of loading steps from 4 to 6 for the wall with door opening, respectively from 3 to 6 for the wall with window openings.

Considering in the simplified model that the areas with a low probability for failure are infinitely rigid lead to results similar to those obtained on the complete model.

This simple method is based on linear models that closely resemble those employed in designing new masonry structures. If such an approach is followed by practicing structural engineers, they can obtain a qualitative estimate of the likely structural failure modes of unreinforced masonry buildings. In essence, solutions aimed at dealing with the structural retrofit may be selected even without having to resort to complex numerical models or to perform shake table earthquake simulations.

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Liceul Mihai Viteazul (vezi pag. 301)

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