ABSTRACT: Three models are applied to a given structure in order to determine the best one to simulate the real response of the structure under a specific seismic action and its failure mode. In order to model the material, a macro model approach has been used because of the great number of elements forming the structure and its geometric complexity. The models analyzed in this paper are: an elastic linear model, a Drucker-Prager's type elastic-plastic model and an elastic linear model until cracking of material happens using Willam-Warncke's criterion. A seismic action synthetically generated and increased until chimney's failure was applied to the structure in accordance with the present regulations about seismic-proof constructions in the city of Valencia. Results of the three models analyzed are shown in this paper and a comparative analysis has been performed to determine the suitability of each model depending on the results expected and the available calculation capabilities.

1 INTRODUCTION

Industrial brickwork chimneys from latest XIX century and earliest XX century are very typical in Valencia City (Spain) and shape a characteristic landscape.

These constructed elements are protected by laws as cultural heritage so it's interesting to know their seismic response in case of an earthquake happens.

The models analyzed in this paper are: an elastic linear model, an elastic-plastic Drucker-Prager's type model and an elastic linear model until cracking of material happens using Willam-Warncke's criterion.

The main goals of this paper are to compare three different ways to do a seismic calculation with masonry using these three different failure criteria presented, to conclude important aspects to take into account when performing this kind of calculation and to know the suitability of each model depending on the results looked for and the available calculation capabilities.

None of these three simulation models provides the degradation in stiffness of the masonry caused by successive plastic deformations resulting from cyclic behavior, neither material's fatigue.

However, this paper shows the cracking process in masonry due to a seismic action and its progress in time considering that loads applied to the structure do not cause crushing or plastic deformation in the masonry due to excessive compression, and that cracking is the governing phenomenon.

2 METHODOLOGY

The process followed to do these calculations is:

1. Establish the structure model: this phase deals with the geometric definition of the structure, determining the height, base section, thicknesses, etc. When all dimensions are established, we proceed to the discretization of the continuum through the finite element method in order to reduce the degrees of freedom into a discrete number. After this, contour conditions and initial values are fixed so the model is ready to receive the seismic action.
2. Generate artificial accelerograms compatible with the seismic spectrum proposed in the current Spanish rules for the city of Valencia, Ministerio de Fomento (2002): the lack of real records of earthquakes for the city of Valencia to use in the calculations leads to apply energy spectrums for the seismic action or to generate accelerograms synthetically in order to account for the earthquake motion. This last approach has been used in this paper.

3. Set up failure criteria: with the model defined and the seismic action established, a failure criteria is needed to collect the inelastic behaviour of masonry during the loading process. Three different cases have been studied.

4. Do calculations and obtain results: when all the previous aspects are considered, calculations can be performed with a finite element program and results must be carefully analyzed in order to get valuable conclusions from the big amount of output data stored.

5. Conclusions: conclusions are outlined and presented in the last point of this paper.

3 STRUCTURE

The structure under study is an industrial chimney made of masonry of the type which was common in the industrial revolution by the end of the 19th century and the beginning of the 20th century. It is a 30 m high brickwork chimney without reinforcements, as shown in Figure 1.

This chimney is sited in an area of the city which is now in expansion and that was, in the end of the nineteenth century, an industrial area with many factories dedicated to the paper manufacture.

The urban development has "consumed" most of the old factories, but many of the chimneys have stayed as witnesses of those past times.

Valencia Town Hall has protected these structural elements as a cultural heritage and many of them can be watched walking across the city. Different protection levels depending on the type of chimney and its location can be found.

The structure can be clearly divided in three parts, Pallarés et al (2001):

1. Base: It is the bottom part of the chimney and its task is to distribute the stresses to the foundation until they reach an acceptable value. Sometimes it is not necessary and does not exist. The shapes can be very mixed: square, hexahedron, octagonal, ...

2. Shaft: It is the chimney strictly speaking, and their tasks were to lead the smoke at a great height to avoid environmental harm and to create the necessary draught to facilitate the combustion. It is a prismatic tube with different sections: circle, square, hexagon, and octagon. They were varied in height with different colours, prismatic or helicoidal shapes.

3. Crown: It is the upper part of the chimney with an aesthetic task.

These chimneys were built by rings of equal height with special bricks and the section could be constant or variable in height depending on the construction of each ring. It was common for the external faces a 2%-3% slope.

Figure 2 shows the shape of the bricks that were used for the construction.

The main dimensions of the chimney are shown in the next figure, obtained through an extensive search in old references as Álvarez (1904), Gouilly

![Figure 1. Industrial brickwork chimney studied in the present work.](image1)

![Figure 2. Bricks used for the construction. They could be hollow bricks or not depending on the strength needed.](image2)
(1876), Mazzocchi (1965) and compares with the real chimneys located in Valencia City.

Furthermore, design rules used in the past have been applied to get the thicknesses of the walls and compared them with the real ones measured in the chimney. In addition to the previous check, loads as wind or self weight have been applied in a static analysis to verify stresses were in accordance with that recommended in the design procedures. Examples of these design rules are:

1. Stresses transmitted to foundation lower than 250e3 N/m².
2. Stresses in masonry lower than 1000e3 N/m².
3. Some thicknesses in crown recommended (0.15–0.20 m).

With all these considerations, the chimney shown in figure 1 is idealized as this shown in Figure 3.

As shown in point 2 Methodology, now we proceed to the discretization of the continuum through the finite element method. The discretization of the structure has been made through 3D solid elements with plastic and cracking capabilities depending on the failure criteria used.

Figure 4 shows the finite element used in the discretization (an 8 node brick with 3 degrees of freedom per node).

Figure 5 shows the finite element model used for this chimney. The degree of refinement in the

![Figure 3. Longitudinal section.](image)

![Figure 4. Solid element used in the discretization process.](image)

![Figure 5. Discretization using 3D solid elements. Isometric view.](image)
discretization process is chosen depending on the computational capabilities and accuracy looked for. The model shown achieves a reasonable accuracy level for the purposes of the study. Calculations have been made with a commercial software (see reference ANSYS) through a non-linear calculation except for the linear elastic model.

4 SEISMIC ACTION

In order to define the seismic action, due to the lack of real accelerograms occurred in Valencia, artificial generation has been performed. The methodology can be consulted in Gasparini & Vanmarcke (1976). Base line, velocity and frequency corrections have been made.

The initial accelerogram was proportionality increased until total failure of the structure, thus allowing understanding the failure process. This increased accelerogram was applied to the base of the structure in order to simulate an earthquake through a large mass approach.

Several accelerograms have been applied to the structure in order to know the sensibility and the seismic behavior despite results will be shown only for one accelerogram. Here, Figure 6 shows the response spectrum for Valencia city from the Spanish rule while Figures 7 and 8 show two artificial accelerograms generated.

5 CHARACTERISTIC VALUES

A macro-structural approach has been made in order to model the whole structure because of the great number of elements forming part of the chimney. The main values for the bricks, mortar and contact surface between them are supposed to be constant until failure or plastic criteria are reached. For masonry, the values used have been:

- Uniaxial compressive strength: $f_c = 637,500 \text{ N/m}^2$
- Uniaxial tensile strength: $f_t = 196,200 \text{ N/m}^2$
- Elasticity modulus: $E = 5.886 \times 10^9 \text{ N/m}^2$
- Poisson ratio: $\nu = 0.2$
- Density: $\rho = 1600 \text{ kg/m}^3$

Due to the lack of laboratory tests, these values have been chosen based on references as Gouilly (1876), Mazzocchi (1965) from the beginning and the middle of the 20th century, when these chimneys were built. These references provide information about masonry strengths used for these chimneys. These values have been changed in order to take into account the seismic action, mainly the elasticity modulus, reducing it accordingly to papers found in the scientific literature for similar dynamic calculations.

6 CRACKING AND PLASTIC CRITERIA

Plastic and cracking criteria used have been the well-known Drucker-Prager and Willam-Warncke criteria used for geo-materials.

For the elastic model without cracking or plastic criteria, conclusions are directly outlined in Conclusions due to its simplicity.

None of these three simulation models provides or takes into account the stiffness degradation of the masonry caused by successive plastic deformations or
non linear response resulting from cyclic behaviour, neither the material's fatigue; however, the purpose of this paper is to understand the cracking process in the material considering that loads applied to the material do not cause crushing or plastic deformation in the masonry due to excessive compression, and that cracking is the main phenomenon that governs the process.

Both criteria (Drucker-Prager and Willam-Warncke) are usually used in masonry and concrete structures to conclude the end of the elastic behaviour and the beginning of the non linear range.

Their capability to reproduce seismic behaviour will be shown.

- Drucker-Prager
  This plastic criterion states the beginning of plastic strains if:

\[
\beta I_1 + \sqrt{J_2} - \sigma_y = 0
\]  

where \( \beta \) = parameter related with the internal friction angle; \( I_1 \) = first stress invariant; \( \sigma_y \) = parameter related with cohesion and \( J_2 \) = deviatoric stress invariant.

Both parameters are fitted in order to obtain the \( f_i \) and \( f_e \) strengths fixed in (1).

- Willam-Warncke
  This cracking criterion states initial crack if an equation as:

\[
f(\sigma_m, \tau_m, \theta) = \sqrt{3 \frac{\tau_m}{\rho(\sigma_m, \tau_m)}} - 1 = 0
\]  

is satisfied, where \( \sigma_m \) = average normal stress; \( \tau_m \) = average shear stress; \( \theta \) = angle of similarity. For more information see reference Chen & Saleeb (1982).

Parameters to define the failure surface are those given in (1).

7 RESULTS

The calculations have been done with a Pentium-IV, 2.8 GHz, 1 GB RAM and 60 hours needed to complete the seismic action.

Next figures present different times during the earthquake motion in which stresses, plastic deformations and cracks are plotted.

- Drucker-Prager
  Figures 9 and 10 show normal stresses and plastic deformations stated by Drucker-Prager criterion in a particular time of the analysis.

  Figures 11 and 12 show, in the same way, normal stresses and plastic deformations when plastic strains have progressed.
Figure 12. Plastic deformations on chimney's base. Frontal view.

Figure 13. Normal stresses (vertical axis) along the chimney. Frontal view.

Figure 14. Stress at chimney's base after cracking. Isometric view. Base zoom.

Figure 15. Cracking plot at chimney's base. Isometric view. Cracks appearing on the right side of the base for the accelerogram shown in figure 7.

Figure 16. Cracking plot at chimney's base. Frontal view.

Figure 17. Cracking plot at chimney's base. Frontal view. Cracks appearing on both sides of the base.
• Willam-Warncke

Figures 13 and 14 show normal stresses in the chimney for a particular time of the analysis when cracking has happened.

Figures 15 and 16 show the cracks appeared in the base of the chimney due to the stress distribution shown before for the particular time stated by the Willam-Warncke criterion.

Figure 17 shows how cracking progresses in depth and extends to both sides of the base due to the cyclic load.

8 CONCLUSIONS

Comparing the results obtained for the three calculations made, the main conclusions for this presented work are, Pallarés (2003):

1. Elastic linear analysis does not capture failure but indicates qualitatively possible failure modes, finishing the entire motion to which the chimney is undergone.
2. Failure becomes from cracking mode and not crushing mode in the masonry for this structure.
3. Drucker-Prager and Willam-Warncke criteria lead to a non finished seismic motion when convergence can not be achieved, opposed to a linear elastic analysis.
4. Drucker-Prager criterion is suitable to represent the first crack. After that, failure mode could be wrong because of the tensile strength still remains after this criterion is reached.
5. Drucker-Prager criterion is less computer time consuming than Willam-Warncke criterion and gives a good understanding of the seismic behavior being aware of the previous conclusion.

6. Willam-Warncke is the most suitable of the three criteria to represent and to know the failure mode because it takes into account the cracking phenomenon and the lost of resistance after cracks happen.
7. Willam-Warncke allows the knowledge of crack progression during the earthquake motion if a time analysis is made.
8. After the study of different accelerograms, the chimney studied presents a failure mode by toppling over the base due to the cracks appeared.

REFERENCES

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