Approaches for the improvement of the seismic performance of masonry constructions

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Abstract: - In the paper one presents some approaches for improving the resistance of masonry constructions to dynamic events through the adoption of composite reinforcements. Design approaches may be vary very significantly depending on the geometry and the expected failure modes of the structural system, in order to best fit the specific need of the structure under analysis. In the paper some design issues and criteria are presented according to some different typologies and geometries of the masonry structures, able to strengthen the structural system and to increase the seismic resistance of the construction, tailored on its shape and overall behavior.

Key-Words: - Masonry, geometry, typology, composite materials, reinforcements, design

1 Introduction

Approaches to the study of masonry constructions require the understanding and treatment of the non-linearity related to the structure geometry and material, that is unable to resist tensile stresses and should be handled by non-linear analytical models such as the No-Tension (NT) model (for bibliography by the authors one may refer to [1]-[10] and to [11]-[20] in case of reinforcements). Such preliminary analytical treatment is mandatory when forecasts are aimed at the protection of monumental and historical building, and at the set up of preservation strategies based on
the adoption of composite reinforcements or of
dynamic control systems [21]-[27].

In the following two geometries are referred to,
the masonry vaults and tower chimneys, presenting
some criteria and layouts for their reinforcement
through fiber-reinforced composite provisions.

2 A design criterion for composite
reinforcement in masonry vaults

2.1 Premise

When dealing with masonry constructions, the most
common geometry is represented by vaulted
structures.

The theoretical treatment of this typology is not
trivial, and, of course, it requires the equilibrium
with the applied loads and the admissibility of the
material at any point of the structure.

Actually one may somehow invert the problem
and perform the analysis by selecting families of
load shapes equilibrated by sets of admissible
solutions, outlining a strategy that allows to identify
the areas of the vault to be reinforced with fiber-
reinforced composite provisions.

2.2 Set up of the problem

Equilibrium of a No-Tension vault with plant X, and
upper and lower profiles respectively \( z = z_1(x,y) \)
and \( z = z_2(x,y) \) \( [z_1(x,y) \leq z_2(x,y)] \), subject to a vertical
load \( p_j(x,y) \geq 0 \ \forall (x,y) \in X \) per unit area, can be
obtained by solving the following system

\[
\begin{align*}
\mathbf{H}_z(x,y) &= [z_{,xx}(x,y)z_{,yy}(x,y) - 2z_{,xy}(x,y)]^2 = \\
&= \frac{\overline{p}_j(x,y)}{Q} \geq 0 \quad (1)
\end{align*}
\]

where \( z = z(x,y) \) denotes any surface included in
between the intrados and extrados surfaces, \( H_z(x,y) \)
denotes the Hessian determinant of the \( z \)-function
and \( Q \) represents any positive real parameter i.e. the
boundary thrust (dimensionally, a force); the
variables preceded by a comma denote in Eq. (1)
derivation with respect to these variables.

The first two rows in Eqs (1) express the
condition for the convexity of the function \( z(x,y) \),
and hence of the membrane force surface.

After introducing the problem in Eq. (1), the
shape of the membrane function may be selected in
order to comply with the given geometry and load
shape.

At this stage the membrane function should be
partially defined leaving unknown its coefficients,
whose identification should follow the imposition of
boundary conditions.

For a sail vault, by selecting a symmetric shape

\[
z(x,y) = K + \frac{A}{2} x^2 + \frac{B}{12} x^4 + \frac{C}{2} y^2 + \frac{D}{12} y^4 \quad (2)
\]

with 5 unknown constants \( K, A, B, C, D \), these may
be shown to be related to the load polynomial
coefficients \( p_o, p_x, p_y \) and \( p_{xy} \) by the following
equations through equilibrium

\[
\begin{align*}
\frac{A}{2} &= p_o \\
\frac{B}{12} &= p_x \\
\frac{C}{2} &= p_y \\
\frac{D}{12} &= p_{xy}
\end{align*}
\]

which represent four equations in five unknowns.

The NT admissibility conditions should be
checked by considering the values of the function
\( z(x,y) \).

2.3 Design strategy

Different criteria may be selected for designing the
composite reinforcement and arranging its layout,
depending on the tasks to be achieved and on the
expected failure modes for the structure under
dynamic action.

One possible design criterion following the
overall strategy consists of considering the
minimum thrust transmitted by the structure onto
the abutments.

Different levels of reduction of the thrust may be
chosen and achieved, allowing to finally identify the
area of the vault to be reinforced according to the
procedure.

In this case one should specialize the problem to
the case when the membrane surface is tangent to
the extrados vault profile at its keystone.
3 The reinforcement of masonry chimneys

3.1 Premise

A specific category in the class of masonry typologies is represented by industrial chimneys, which are towered constructions often recognized a monumental and historical value.

Masonry chimney architectures are quite diffused in European countries, witnessing the XIX century industrial revolution.

Since accidental loads as earthquakes were not usually considered when designing these structures, they are often damaged and subject to restoration interventions for their preservation against future dynamic events.

The assessment of their seismic vulnerability for checking the structural integrity thus represents a fundamental issue to be addressed, as well as the design of reinforcements for their refurbishment and protection.

In the following investigations are presented relevant to a masonry chimney in Valencia, with the final layout of a fiber-reinforced composite provision.

3.2 A case study

Results are reported relevant to the investigations conducted on the industrial masonry chimney represented in Fig.3.

The development of dynamic tests executed using four seismic accelerometers located at different heights of the chimney and with different orientations, allowed to get the structural identification of the tower, with its natural frequencies and structural damping.

Following the experimental tests, a numerical model has been calibrated adjusting the numerical frequencies in such a way to match those experimentally obtained.

The updated numerical model has then been used in a seismic analysis in order to know the seismic response of the chimney when it is acted on by different earthquakes.

At the second stage the refurbishment intervention is designed based on the adoption of some FRP strips.
In this phase, the usefulness of using vertical strips of FRP in the strengthening to meet the requirements of safety, serviceability and durability for the different earthquake load is studied, so strips of FRP are introduced in the calculations to obtain the reinforced level achieved regarding seismic vulnerability.

3.3 Experimental/Numerical tests

The chimney is vertical and 36 m high made in masonry, without any visible crack. The masonry is made of bricks and lime mortar.

Since no experimental tests were done for the material characterization, usual values [30] for the main mechanic parameters were used to obtain a numerical model:
- uniaxial compressive strength: $f_c = 637,500$ N/m$^2$
- uniaxial tensile strength: $f_t = 196,200$ N/m$^2$
- elastic modulus: $E = 5.886 \times 10^9$ N/m$^2$
- Poisson coefficient $\nu = 0.2$
- density: $\gamma = 1600$ kg/m$^3$

Thereafter accelerations recorded on site due to ambient vibrations through accelerometers at different heights, were employed in order to get the characterization of the chimney.

Artificial accelerograms compatible with the Spanish Seismic Standard (NCSE 2002) were then generated [31] and introduced in the numerical 3D model, reproducing the actual geometry of the chimney, with homogeneous material and failure surface according to [32].

Cracks were then obtained for one of the accelerograms scaled up to a peak ground acceleration of 0.06g, basically located at the bottom of the chimney and at approximately half height of the tower, allowing to select the reinforcement provision.

3.4 FRP composite strengthening

With reference to the above reported results from experimental/numerical investigation, some fiber reinforced provisions were considered for improving the strength of the chimney.

Fig. 4 shows the layout of the strips up to a height of 20 m and 45° rotational symmetry angle, with the cracks displayed for the same seismic load previously considered on the unreinforced structure, that appear translated to the point where the strengthening ends.

4 Conclusion

Modeling masonry structures is a difficult task that requires a deep understanding on the behavior involved.

In the paper two typologies are addressed, one referred to vaulted structures and the other one relevant to chimneys. Selection of the refurbishment provision to be realized with fiber reinforced composites is considered.
The approach proposed for vaulted structures shows that some easy application of the theoretical set up developed by the authors may be performed, also with the specific objective of identifying the regions of the vault to be reinforced with the introduction of FRP provisions.

As regards chimneys, after setting up a technique for calibrating a numerical model using experimental results, for a dynamic analysis of a masonry chimney, investigations are developed leading to a FRP layout.

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