Seismic analysis of Fujian Hakka Tulous

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ABSTRACT: The overall earthquake response of Hakka Tulous, traditional earth constructions of the Fujian Province (China) and listed among the UNESCO World Heritage buildings, is investigated. Non-linear static analysis (pushover) with the equivalent frame approach is used. Although some rough approximations are assumed, this approach is well suited to model complex masonry structures, like Tulous. In fact, non-linear analysis implemented by finite elements or by discrete elements would involve complex models hard to converge and needing long computational time. After carrying out seismic analysis of a Tulou prototype, its failure modes and overall seismic response were evaluated. The Tulou has shown to have good earthquake resistance with respect to the maximum seismic action that can be expected in the Fujian Province.

KEY WORDS: Hakka Tulou; Fujian; earth; earthquake analysis; macroelements; equivalent frame.

1 Introduction

Hakka Tulous are house-fortresses situated in the Fujian Province of China and inhabited by Hakka clan people. For their heritage and architectural value, are inscribed in the UNESCO World Heritage list.

A Tulou consists of a circular or square perimetral earth wall internally stiffened by 3D wooden frames supporting wooden floors, subdivided by partition walls delimiting the

Figure 1. Hakka Tulou in the Fujian Province.

Hakka people dwellings.

They are large-sized earth constructions, with a unique large entrance and small windows mainly located at high elevation in the earth wall (Figure 1**Error! Reference source not found.**).

Notwithstanding their relevance, few studies are available in the scientific literature on their structural behaviour. In particular, there are only few studies on their seismic response, although in some areas of the Fujian Province, where the Tulous are traditionally built, the seismic hazard is not negligible (Briseghella et al., 2017, 2019b; Liang, Stanislawski, & Hota, 2011).

Despite the few studies available on Tulous, earth constructions are increasingly studied both because all over the world there are many monuments and historical buildings made of earth, and because of their sustainability, thermal comfort performance and energy efficiency (Houben & Guillaud, 1994).

Regarding the recent studies on the behaviour of the earthen material and of earth structural elements, significant work have been carried out on the fracture behaviour of earth considered as a quasi-brittle material (Aymerich, Fenu, Francesconi, & Meloni, 2016; Aymerich, Fenu, & Meloni, 2012), as well as on its influence on the structural response of adobe bricks and panels (Blondet & Vargas, 1978; Parisi, Asprone, Fenu, & Prota, 2015; Vargas & Ottazzi, 1981; Varum et al., 2007).

With reference to the seismic response of earth constructions (Varum et al., 2014), the damages caused by earthquakes have been studied by many authors (Blondet, Vargas, & Tarque, 2008; Webster & Tolles, 2000). The influence of brittleness and low tensile strength on the seismic vulnerability of the adobe structures has been investigated by Blondet et al. (Blondet, Vargas, Velásquez, & Tarque, 2006). Their vulnerability was observed in recent earthquakes, as in Peru (1970, 1996, 2001 and 2007), El Salvador (2001), Iran (2003), Pakistan (2005) and China (2008 and 2009) (Varum et al., 2014).

The seismic response of earthen structures has been experimentally investigated through shaking table tests on reduced masonry section walls (Antunes, Lima, Varum, & André, 2012; Figueiredo, Varum, Costa, Silveira, & Oliveira, 2013; Tareco, Grangeia, Varum, & Matias, 2009) and on scale models of entire buildings (Webster & Tolles, 2000). Unfortunately, shaking table tests are expensive and need long time especially for constructing the model. For all these reasons, shaking table tests are not the first choice to investigate the seismic response of masonry structures including earth constructions, even if they can provide reliable and qualitatively valid results.

The numerical modelling techniques are instead a more advantageous and less expensive way of studying earth buildings. The main methods of numerical analysis to model masonry structures are the Finite Element Modelling (FEM), the Distinct Element Modelling (DEM), and the analysis by macroelements with the Equivalent Frame Method (EFM). Unfortunately, nonlinear analysis with FEM and DEM of complex masonry structures usually lead to encounter convergence problems hard to solve, as well as to high computational costs (Briseghella et al., 2019a).

On the contrary, the analysis by macroelements with the EFM well apply in nonlinear analysis

of complex masonry structures because, despite some approximations in defining the macroelement geometry and its structural response, the equivalent frame approach allows to obtain reliable results.
As a matter of fact, schematization of the wall with openings as a frame where piers and spandrels are deformable linear elements connected by indeformable rigid nodes, allows to facilitate convergence and reduce the computational costs.
Among the different codes using the macro-element approach, considerable diffusion have RAN (Augenti, 2004; Augenti & Parisi, 2010; Raithel & Augenti, 1984), SAM (Magenes, 2000; Magenes & Fontana, 1998) and TREMURI (Lagomarsino, Penna, Galasco, & Cattari, 2013) codes. In particular, in this study TREMURI code has been used to carry out non-linear static analysis (pushover) of a Tulou prototype with the EFM.
Regarding numerical modelling of earth constructions, a first study in this field was made by Tarque (Tarque, 2011), who tested the validity of different modelling strategies using the results obtained by FEM.
The EFM was first applied to earth structures as part of a research project funded by the Region of Sardinia (Asprone, Parisi, Prota, Fenu, & Colasanti, 2016), an Italian region where earth constructions are still built and where there is an important heritage of traditional ones, too. The validity of the use of the EFM in earth buildings was first assessed through comparing the results obtained from simple earth buildings and similar tuff buildings. Moreover, the validity of the macro-element approach in modelling earth structures was also evaluated through comparing the results obtained by shaking table tests with those obtained by numerical models using the EFM. The results of shaking table tests funded within the Getty Seismic Adobe Project (GSAP) (Gavrilovic et al., 1996; Tolles, Kimbro, Webster, & Ginell, 2000) and carried out with increased acceleration values on small scale models of adobe constructions were compared with those obtained from nonlinear static analysis (pushover) performed by macroelements on real scale prototypes.
Based on these validation tests, in this article the macroelement approach with the EFM has been applied to the prototype of a Hakka Tulou. Their typical cylindrical wall has been discretized and shaped as a 24-sided polygonal wall.
The geometry of the Tulou prototype as well as the mechanical properties of the earthen material have been extracted from some studies on Huanji Tulou available in the scientific literature (Liang et al., 2013, 2011). This research has provided a first significant contribution to the study of the seismic response of Tulous.

2 Building technology and structure of a Fujian Hakka TulouAbout Author and abstract

Tulous are distributed in small villages in the mountainous area of west-south of the Fujian Province (China) (Figure 2) (Zhang, Luo, & Liao, 2011). They are circular buildings made of a cylindrical earth wall about 2m thick at its base whose typical diameter and height are 50

Figure 2. Bird’s eye view of a Tulou cluster.

and 20 m, respectively. For defensive reasons, a single door guarantees the access to the internal courtyard. For the same reason, Tulous have only two or three rows of small windows starting at up to 10 m elevation. Inside the Tulou, the floors hosting the Hakka People dwellings are supported by wooden frames whose radial beams are in turn supported by the circular earth wall at one end and by wooden columns at the opposite end. The wooden floor system is likely to be only partially rigid, because rafters and wooden planks are not firmly connected one to the other. Similar considerations can be done for the two-pitch roof, supported by an A-frame truss system.

Few information is available on the mechanical properties of the materials and on the structural features of the construction elements. About the Tulou geometry, in this study we refer to a Tulou prototype whose dimensions are obtained from a FEM model of the Huanji Tulou (Liang et al., 2013, 2011), differing from it just for having regularized the window opening spacing, that in Huanji Tulou is not uniform.

2.1 Equivalent frame approach

The Tulou prototype has been modelled by macroelements through the EFM using TREMURI code.

Despite some rough approximations, this method has proved to be particularly suited to model masonry constructions (Braga & Dolce, 1982; Marques & Lourenço, 2014), and successfully applied to earth constructions, too (Asprone et al., 2016).

In accordance with dynamic test data and post-earthquake survey of damages caused by the seismic action, in the EFM method each wall is modelled as an equivalent frame where deformable piers and spandrels correspond, respectively, to columns and beams, connected by non-deformable rigid nodes.

The spandrel length corresponds to the opening width. The dimension of the nodes defines the pier length and depends on the opening size and position. Membrane elements are used to model stiff or partially-stiff floors, depending on the membrane stiffness. Stiffness and geometry of walls and diaphragms highly affect the box-behaviour and structural efficiency of the masonry construction (Lagomarsino et al., 2013). Each macroelement (piers and spandrels) is divided into three parts: a central one, almost coinciding with the whole masonry panel, where shear deformations are addressed with nonlinear contribution of the frictional force opposing to the sliding mechanisms, and two thin end ones, where the axial and bending deformations are instead addressed and where the inelastic contributions are obtained from the unilateral perfectly elastic contact condition (Brencich, Gambarotta, & Lagomarsino, 1998).

The 3D frame is obtained through connecting the nodes of the lateral piers of the 2D equivalent frames (Lagomarsino et al., 2013).

The Equivalent Frame Model of the circular Tulou (Figure 3**Error! Reference source not found.**), has been obtained by approximating the cylindrical wall to a 24-side polygonal wall. Having assumed constant horizontal spacing and vertical alignment of the window openings, in each wall side there are two small windows, one for each of the two upper levels.

Wooden floors and roof sections stiffness have

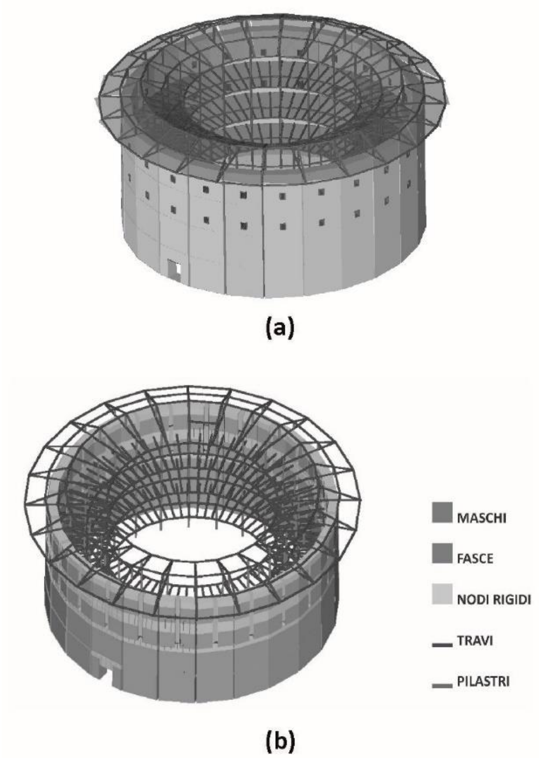

Figure 3. Tulou numerical model: 3D view (a); detail of the Equivalent Frame (b).

been modelled with diaphragms of appropriate rigidity accounting for their orthotropic behaviour, too. Figure 3b shows the Equivalent Frame implemented to analyse the Tulou through the EFM.

The mechanical characteristics of the Tulou construction materials (earth and wood) have been assumed by literature-based data (Liang et al., 2013). In particular, the earth mechanical properties used to model the Tulou prototype herein considered are shown in Table I.

Table I. Mechanical properties of earth material

f_c [MPa]	f_{v0} [MPa]	E [MPa]	w [kN/m^3]
1.00	0.10	1000	12

3 Seismic analysis of a Tulou prototype modelled through the EFM

With reference to performance-based earthquake engineering concepts (Lagomarsino et al., 2013; Liu, Zordan, Zhang, & Briseghella, 2015) in the last decades the nonlinear static analyses (pushover) have shown to be the most reliable analysis method for seismic assessment.

To analyse Tulou seismic response, pushover analysis implemented in TREMURI has been herein performed with mass-proportional horizontal forces plotted as a function of the consequent displacements of a suitably chosen control node. The displacement demand obtained from the ADRS spectrum at the Life Safety Limit State (475 years return period) has been then compared with the capacity displacement obtained from the capacity curve of the structure, thus evaluating the Tulou safety under the seismic risk of the Fujian Province. The peak ground acceleration (PGA) ag = 0.16g, as well as F0 = 2.45 and TC* = 0.32 were assumed to draw the ADRS spectrum referred to the Tulou site. Since the Tulous are probably constructed on a rocky subsoil in the mountain area of the Fujian Province, in this first study on the Tulou seismic response, the stratigraphic and topographic amplification is not considered.

The capacity curves obtained assuming earthquake direction and control node reported in the legend are shown in Figure 4**Error! Reference source not found.**. Unfortunately, while the most appropriate position of the control node should coincide with the centre of mass of the structure, this is not allowed by Tulou geometry. In fact, its centre of mass is

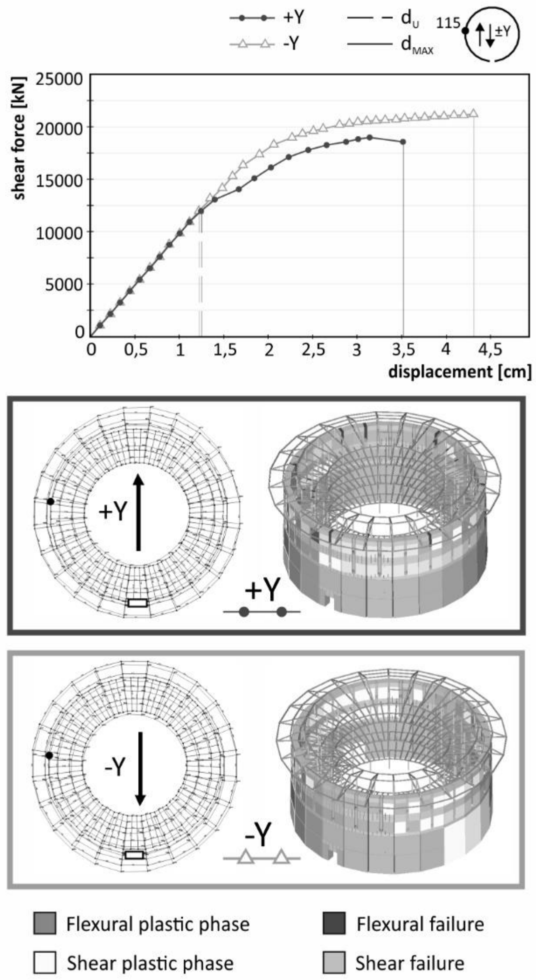

Figure 4. Nonlinear static analysis of the Tulou numerical model for Y loading direction of the seismic action.

practically coincident with the centre of the Tulou court, where no node can be assumed as a control node because in the centre of the court there is no Tulou structure.

The two capacity curves shown in Figure 4, are obtained for same direction but opposite orientation of the seismic action (±Y). The ultimate displacement corresponds to the Tulou displacement capacity, where failure is attained for a loss of shear load bearing capacity at the base of at least 20% of the maximum shear resistance recorded during the pushover analysis. The displacement demand obtained from the ADRS response spectrum is also indicated. Since the displacement demand results far lower than the capacity displacement, then the Tulou structure is shown to well resist to the Fujian seismic action without losing its stability.

The Tulou seismic response is better described in the damage sequence of Figure 5 where, for increasing displacement values of the control node, the increasing damage in the Tulou wall is mapped as described in the following:.

-The 1-st point (Figure 5b) corresponds to flexural yielding in the wall over the Tulou entrance and parallel to the loading direction. Yielding of some spandrels also occurs in the upper level. In Tremuri, yielding of a macroelement is shown to occur when it reaches its flexural capacity but with still a residual ductility reserve before failure.

-At the 2-nd point (Figure 5c), shear yielding of the other macroelements above the opening occurs. Moreover, both the lateral piers of the Tulou entrance yields in flexural-compression. Also in this case, failure is not yet attained because both in flexure and in shear some residual ductility is still available.

-At the 3-rd point (Figure 5d) many piers almost parallel to the loading direction yield in shear at the first level, but still without any reduction of the overall loading capacity in shear of the Tulou structure. The yielded piers are those close to the Tulou entrance together with the corresponding ones at the Tulou opposite side.

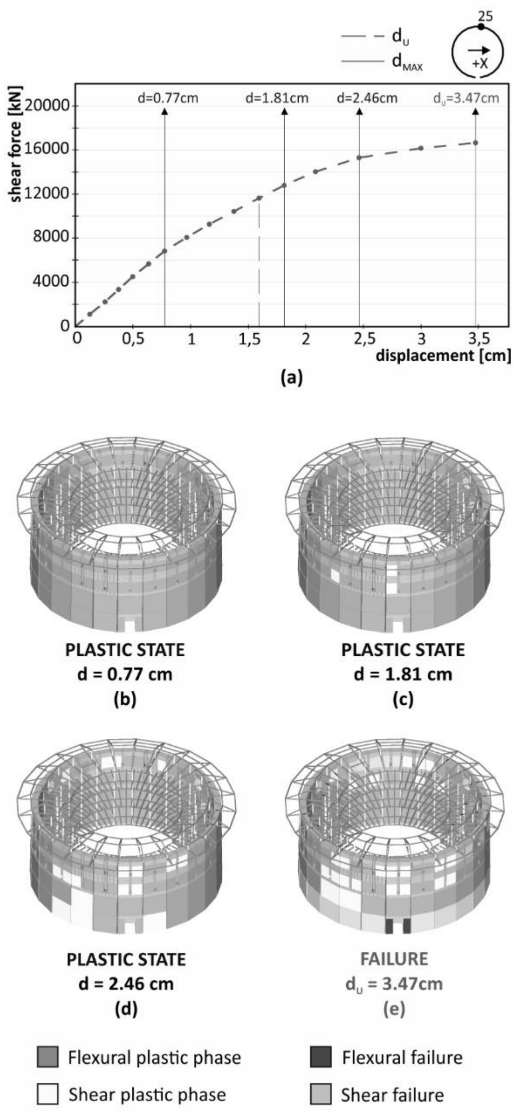

Figure 5. Capacity curve (a) and sequence damage at different displacement levels: 0.77cm (b);1.81cm (c); 2.46cm (d); 3.47cm (e).

-Finally, at the 4-th point (Figure 5e), shear failure occurs in the already yielded piers of the first level close to the Tulou entrance, as well as in the corresponding piers at the Tulou opposite side. Also other piers parallel to the loading direction but located at higher level fail in shear. Failure of all these piers cause a sudden drop, higher than 20%, of the shear overall load-bearing capacity of the Tulou structure, meaning that the capacity displacement is attained.

Finally, sensitivity analysis to the elastic modulus has been carried out (Figure 6). In fact there are some uncertainties on the actual value of the earth elastic modulus. It was then considered as a parameter varying between 150 and 1000 MPa, thus allowing to obtain a parametric representation of the capacity curves, that is shown in Figure 6 for control node 25 and +X direction of the loading action. Figure 6 shows that the capacity curves are only slightly affected by the elastic modulus value when it ranges between 650 and 1000 MPa. Only very low values of the elastic modulus (close to 150 MPa) affect the shape of the capacity curve, with an elasto-rigid response of the Tulou structure.

Therefore, an elastic modulus of 1000MPa has been assumed in the pushover analyses herein reported.

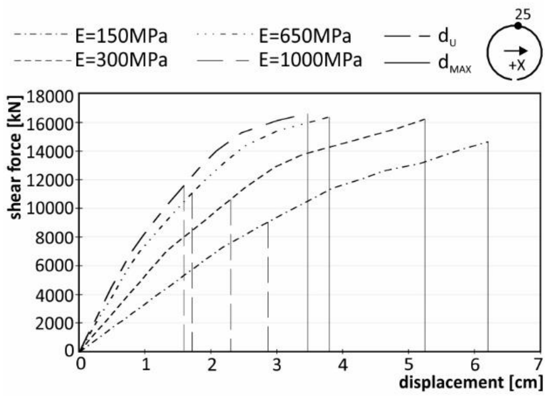

Figure 6. Sensitivity analyses to the elastic modulus.

4 Conclusions

Few studies are available in the literature on the structural behaviour of Fujian Tulous, massive earth house-fortresses of the Fujian Province (China).

The study presented in this paper represents the first investigation on the seismic response of Tulous using nonlinear static analysis and is one of the first studies on their structural behaviour.

The Tulou seismic response has been investigated by macroelements through the EFM, that has proved to be very efficient in modelling the structural behaviour of complex masonry constructions.

The model of a Tulou prototype has been implemented in TREMURI code using the data available in the literature. Even if the EFM is typically applied to masonry structures made of plane walls, in this study its use has been extended to curved walls. For this aim, the Tulou circular wall has been approximated with plane walls extruded from a 24-side polygon.

Linear elements have been used to model the wooden structure, with flexible wooden floors and roof pitches modelled with diaphragms of appropriate stiffness.

From the analysis by macro-elements carried out on the prototype of the Fujian Tulou, it has been proved that the equivalent frame approach can well simulate the in-plane response of the Tulou and lead to reliable results.

Pushover analysis has allowed to show that the Tulous have good earthquake resistance compared to the maximum Fujian seismic action. This favorable response is mostly due to the circular form of the earth wall, that avoids out-of-plane local mechanisms and channels the horizontal forces in in-plane internal forces.

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