Seismic analysis by macroelements of Fujian Hakka Tulous, Chinese circular earth constructions listed in the UNESCO World Heritage List

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Abstract

The overall seismic response of Hakka Tulous, massive traditional earth constructions located in the Fujian Province (China) and part of the UNESCO list of World Heritage buildings, is investigated. For this aim, non-linear static analysis (pushover) was used. Since Tulous are complex circular earth structures (about 50 m in diameter) stiffened by wooden frames along the whole inner perimeter of the circular earth wall, non-linear finite element models are hard to implement because convergence is difficult to achieve and very long computation time would be required given the large number of elements and degrees of freedom. For the above reasons, the equivalent frame approach is often used for masonry structures. Even if a few approximations are needed, non-linear static analysis of even very complex masonry structures can be successfully performed with fewer convergence problems and lower computational efforts. The seismic analysis of a representative circular Tulou is carried out. An extension to circular masonry structures of the analysis by macroelements through the equivalent frame method is hence studied. The results provides insight on the Tulou's failure modes and on its overall seismic response. Since this is the first study on the overall seismic response of these complex earth constructions, further research is needed to deepen our knowledge of their structural behaviour.

Keywords: Hakka Tulou; Fujian; earth; seismic analysis; macroelements; equivalent frame; pushover

1. Introduction

Hakka Tulous are well known Fujian traditional earth buildings that are part of the UNESCO World Heritage list. Even though they are a popular tourist destination, there is not much research on the structural aspects of these very peculiar and massive earth buildings. Recent years have seen a growing interest on earth constructions (including Tulous), with focus on historical, safety and comfort aspects. Interest in earthen materials has recently resumed due not only to the needs for the conservation and restoration of cultural heritage buildings, but also to the renewed attractiveness of earth as a low-energy and environmentally friendly material for use in ecological and sustainable architecture (Houben and Guillaud 1994; Minke 2007; Mattone 2001). The diffusion of earthen based solutions is justified by the earth's attractive characteristics and the associated building techniques, mainly its local availability, good thermal insulation and acoustic properties. Earthen constructions, which were widely diffused in the past, are still found throughout the world and more than one billion people live today in earth buildings because of the low cost of raw materials

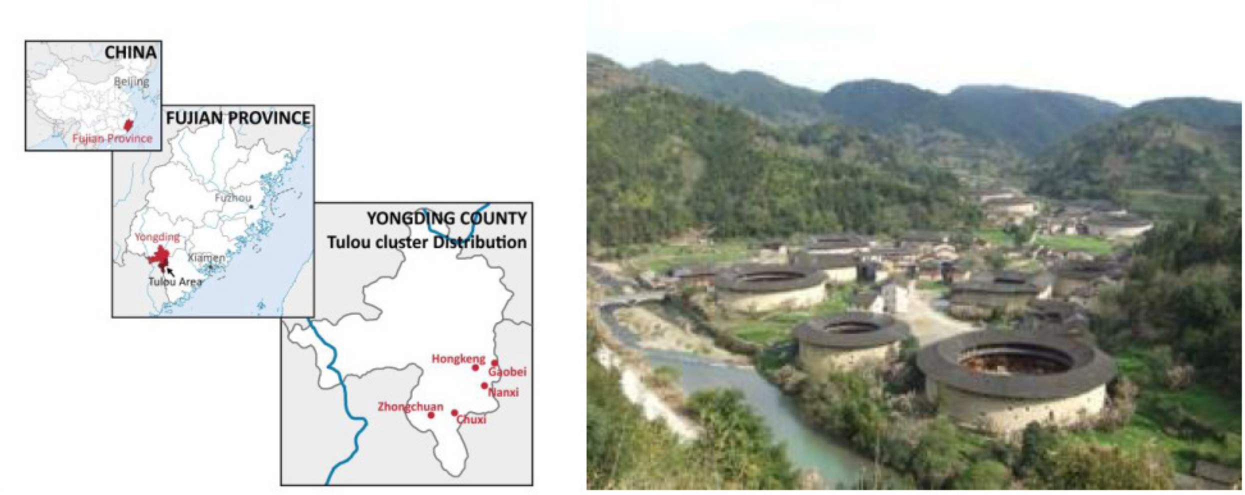


Figure 1. Map of Tulou distribution in Fujian Province (a) and aerial view of a Tulou cluster (b).

and of the simple technological and production process (Houben and Guillaud 1994). At the same, many of the areas with widespread earthen constructions also have a significant seismic hazard, and even if not very high, it can be critical for these buildings, as in the case of the Tulous of Fujian Province, the only Chinese Province where they are built (Figure 1a).

The oldest Tulous date back to seven centuries ago, while others were built as recently as last century. Originally, a Tulou was a collective fortress house of a clan of Hakka people (literally "guest people"). It consists of a circular rammed earthen wall about 2m thick, with only one door and very small window openings. The small window size and the high elevation of the lower window row were due to defensive reasons. The circular earth wall supports the radial beams of wooden frames that stiffen the circular wall along its whole perimeter. The wood frame supports the dwellings of the Hakka people. Besides circular Tulous, square Tulou were also built, because the square form allows to orient the Tulou according to the rules of feng-shui, a Chinese geomantic art (Figure 1b).

The Fujian Province Tulous have experienced several earthquakes over their life, and their present use testifies to their structural soundness. However, the seismic behaviour of these earth constructions is yet to be thoroughly investigated. Understanding their behaviour appears to be a worthwhile effort given their intrinsic cultural heritage value, the fact that the buildings host both living and commercial quarters and the seismic hazard of the buildings' site. Though these Tulous are very peculiar to the Fujian Province, many of their mechanical characteristics are similar to those of other earth structures found around the world, and more specifically in seismic prone areas. Since the actual knowledge of the seismic behaviour of earth constructions is still limited, the research in this field appears to be necessary, both to protect the lives of people living in earth constructions, and to preserve the important cultural heritage buildings (such as the Tulous) located in seismic areas. Thus, the results of previous research on the seismic resistance of earth constructions are reviewed first.

Blondet et al. (Marcial Blondet et al. 2006) note that adobe buildings often present high seismic vulnerability due to the low tensile strength of the earthen material and to its brittle behaviour (unless reinforced with straw fibres), which constitute an undesirable combination of mechanical properties. A proof of this vulnerability is provided by the enormous human, social and economic losses recorded when earthquakes occurred in regions with a number of earth-constructions, as documented in El Salvador (2001), Iran (2003), Perú (1970, 1996,2001 and 2007), Pakistan (2005), and China (2008 and 2009) (Varum et al. 2014).

Over the last decades, research in various fields of earth construction has allowed to expand the knowledge on their behaviour, particularly under earthquake loading (Varum et al. 2014). The analysis of earthquake damage in existing buildings is one of the starting points in understanding the seismic behaviour of earth constructions, as shown by several authors (Dowling 2004; Marcial Blondet, J., and Tarque N. 2008; Webster and Leroy Tolles 2000).

In the study of earth structures, it is important to start from the materials' mechanical characterization including the impact behaviour of the earthen material (Aymerich et al. 2016). If adobe brick construction is of interest, the first step is to look at the bricks' characteristics (Doat et al. 1991; Millogo, Hajjaji, and Ouedraogo 2008; Pui Ling 2005; Crocker 2003; Ghavami, Toledo Filho, and Barbosa 1999; Yetgin, Çavdar, and Çavdar 2008; Aymerich, Fenu, and Meloni 2012; Parisi et al. 2015; Mattone 2001) and then to study the response of adobe panels (Bei and Papayianni 2003; M Blondet and Vargas 1978; Vargas and Ottazzi 1981; Varum et al. 2007).

Another important research area is the earthquake response of earth constructions through experimental tests on physical models, both at the real scale and at smaller scales. The first contribution in this field was provided by the Getty Seismic Adobe Project (GSAP) (Tolles and Krawinkler 1990; Tolles et al. 2000). Other tests dealt with the seismic response of housing structures (Marcial Blondet et al. 2006) and of masonry double T-section walls (Marcial Blondet et al. 2005; Figueiredo et al. 2013; Tareco et al. 2009; Antunes et al. 2012).

As for the modelling issues involved in assessing the seismic behaviour of earth structures, relatively few studies have been published, probably due to the brittle behaviour of this type of unreinforced masonry material and the related numerical convergence issues. So far, earth constructions have been studied mostly through experimental tests, while numerical studies are still limited. Undoubtedly, it is fundamental to study these structures extending the numerical modelling techniques available today for the seismic analysis of masonry structures.

It is only in recent decades that scientific research has focused on the numerical modelling of masonry buildings and of masonry members. This originated from the need to have effective tools for predicting their static and dynamic behaviour of masonry structures, particularly to reduce their seismic vulnerability. Three categories of numerical modelling can be identified for static and seismic analysis of masonry buildings, mainly: non-linear finite elements, macro-elements and distinct elements.

Finite element analyses on earth constructions have been used in two recent studies. The first deals with the problem of modelling the seismic behaviour of earth constructions with the masonry walls reinforced by steel or wood frames (Bettini 2010). The second compares the results of two possible strategies of masonry finite element modelling, one based on discrete mechanics, the other on continuum mechanics (Nicola Tarque 2011; Nicola Tarque et al. 2013; N Tarque et al. 2014).

Macro-element methods have been used to model masonry buildings with good accuracy and low computational cost. Among these methods, the RAN method was initially developed by Raithel and Augenti (Raithel and Augenti 1984) and later improved by Augenti (Augenti 2004), Parisi (Parisi 2010) and Augenti and Parisi (Parisi and Augenti 2013b). The macro-element modelling, and more specifically the Equivalent Frame method (EFM), has proved to be very efficient in modelling masonry structures and very effective to predict their seismic response, particularly when used for nonlinear static analyses, that represent a reasonable compromise in terms of computational effort and convergence stability between linear and full nonlinear dynamic analyses (Marques and Lourenço 2011; Galasco et al. 2004).

In the EFM, the walls of a masonry structure are modeled as frames with rigid nodes connected by deformable vertical and horizontal members (piers and lintels, respectively), thus allowing to analyse the masonry structure as a frame structure. Among the codes using the Equivalent Frame Method, SAM and TREMURI softwares have significant diffusion (G. Magenes and Fontana 1998; Guido Magenes 2000; Penna et al. 2004; Lagomarsino et al. 2013; Galasco et al. 2004).

Sardinia, an Italian island in the Mediterranean Sea, has a large cultural heritage of earth buildings. The Sardinia Region has recently funded a research on the seismic behaviour of earth buildings (Asprone et al. 2016). The earth structures were first modelled using the Equivalent Frame Method, starting from very simple adobe buildings with different wall openings, and different horizontal diaphragms (floors and roofs). Non-linear static analyses of these simple buildings were carried out for different acceleration values using TREMURI, and their dynamic behaviour was compared with that of similar masonry buildings made of tuff bricks. Since tuff is a material with low strength and high deformability, it can be considered similar to adobe. The comparison between the seismic behaviour of adobe and tuff buildings was useful to fine tune the modelling of adobe constructions (Colasanti 2016). More complex adobe buildings were also modelled showing that, since the adobe strength is low, their seismic resistance is mainly due to the high deformations of the earthen material, especially if reinforced with straw fibres.

The applicability of the EFM to the analysis of earthen structures was also assessed by comparing experimental and numerical results. The results of shake table tests carried out by Gavrilovic et al (Gavrilovic et al. 1996; Tolles et al. 2000) on a large scale physical model of an adobe construction (1:2 scale) were compared with those obtained using the EFM approach. The shaking table tests were carried out in the laboratory of the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, in Skopje, Republic of Macedonia. The numerical model was developed using TREMURI. The aim was to assess the effectiveness of the macroelement modelling to predict the seismic performance of adobe masonry buildings by means of nonlinear static analysis procedures. The results showed that the EFM was able to capture the main characteristics of the dynamic response observed in the shaking table tests (Asprone, D., Parisi, F., Prota, A., Fenu, L., & Colasanti 2016).

The advantages of the EFM is quite clear: it provides the nonlinear capacity of a masonry structure with relatively low computational cost, with a relatively good accuracy in predicting both strength and ductility.

This paper presents the study on the nonlinear modelling and seismic response assessment of a typical round Fujian Tulou. The data needed for the Tulou numerical model were gathered from the available literature (Zhang, Luo, and Liao 2011; Liang et al. 2013; Stanislawski 2011; Liang, Stanislawski, and Hota 2011). The EFM implemented in TREMURI was used to generate the building model and run the nonlinear pushover analyses (Briseghella et al. 2017).

The circular wall of the Tulou was approximated through vertical extrusion of a 24 side polyline. Each side corresponds to a plane wall perforated by a vertical row of window openings. Each one of these walls was modelled as an equivalent frame, and was connected with the neighboring walls at an angle depending on the number of sides of the polyline. The overall assembly of masonry walls, wooden frames (used to stiffen the circular wall along its whole perimeter) and flexible floor diaphragms supported by the circular wall and by the wooden frames, was finally analysed through the EFM. An extension to circular masonry structures of the analysis by macroelements through the EFM is proposed.

This paper proposes a preliminary study on the seismic analysis by macroelements of circular masonry buildings using the EFM. A comparison with the results of experimental tests and other types of numerical analysis, such as by finite elements with appropriate constitutive laws, is needed in future research.

2. Description of the Hakka Tulou prototype

The Hakka Tulous are increasingly studied from both a cultural and an architectural viewpoint. However, very few technical studies on the mechanical and structural characteristics of the Tulous are available in the published literature. The mechanical properties of the earthen material of a few Tulous have been investigated (Zhang, Luo, and Liao 2011; Liang et al. 2013), as well as the thermal response of Huanji Tulou (Stanislawski 2011; Liang, Stanislawski, and Hota 2011) (Figure 2).

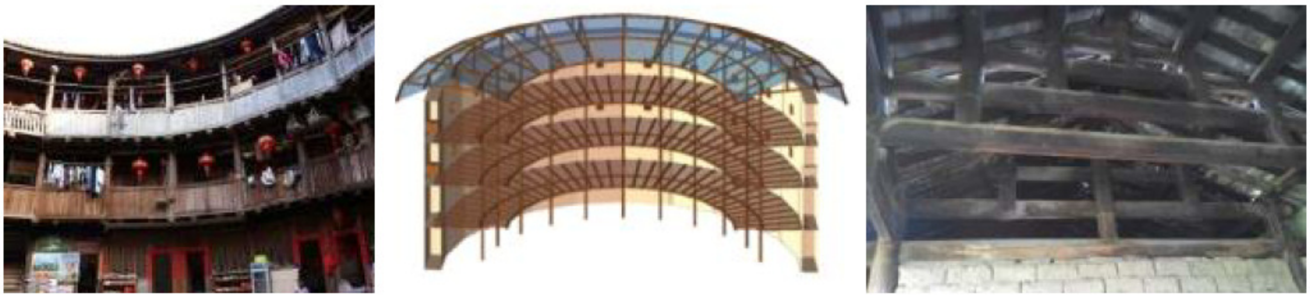
The authors are not aware of any full survey of the Fujian Tulous. Nonetheless, since the aim of this study is to provide a first evaluation of the seismic response of a typical round Tulou, the prototype of a round Tulou was developed starting from information available in the published literature (Zhang, Luo, and Liao 2011; Liang et al. 2013; Stanislawski 2011; Liang, Stanislawski, and Hota 2011)

Figure 2. Huanji Tulou.

A round Tulou typically consists of a circular wall with a single access opening and few very small window openings. The elevation of the lower window row is quite high. Since no full survey of a Tulou is at the moment available, constant window spacing was assigned, even if this is clearly an approximation.

A wood structure inside the Tulou earth ring supports the living and commercial quarters of the Tulou (Figure 3). Wooden frames are used, with radial beams simply supported by wooden columns at one end and the round earth wall at the other. The wood radial beams cantilever out from the inner columns toward the Tulou centre (Figure 3a-b).

Since the Fujian Province is subjected to typhoons, both wood and earth must be protected from the heavy rains. The Tulou is covered by a circular gable roof that significantly cantilevers out externally and internally from, respectively, the earth wall and the wood frames (Figure 3b-c). Finally, the A-shaped wood frame



(a) (b) (c)

Figure 3. Tulou inner wood rings: vertical pillars (a), model geometry (b), and wood truss (c)

supporting the circular gable roof has a very peculiar element arrangement that is typical of traditional Chinese architecture (Figure 3c).

The reference structure herein assumed is the Huanji Tulou (Figure 2), that has been studied in the last decade by other researchers because it survived a strong earthquake in 1918 that caused a large crack that developed for many meters without compromising the Tulou's stability. The large extension of this crack led other authors to investigate the thermal dilatancy of the Tulou by FE analysis (Stanislawski 2011; Liang, Stanislawski, and Hota 2011).

The numerical model used in this FE study does not perfectly reflect the window opening distribution visible in Figure 2, that do not appear to be always vertically aligned. This is the reason why for the present study it was decided to assume a prototype Tulou. While the wall thickness and major openings are correctly modelled, all small upper windows are considered equally spaced and vertically aligned. A thorough description of the Tulou geometry, including the wooden frames placed inside the outer earth ring, is presented hereafter. The wood structure mostly carries gravity loads, but a more detailed description of the model is provided later in the paper.

3. Hakka Tulou structural model

The structural behaviour of an earth construction, and more specifically of a Tulou, can be numerically investigated using three types of structural model, namely a full 3D finite element model, a discrete element model and a macro-element model. Non-linear Finite Element (FE) analysis applies well to earth structures with high plastic deformations. Assuming that the high cohesion given by suction to the unsaturated earth material can be considered as a sort of "cementification" among the earth grains, the non-linear behaviour of the earth material can be accurately modelled by the Concrete Damage Plasticity (CDP) model. However, although the micro-mechanical approach can accurately model the static and the seismic response of masonry buildings by capturing how the masonry walls crack, these models are quite complex to run because of the inherent brittleness of the earth walls that lead so serious convergence problems that make even the analyses of single walls/panels quite difficult to run. Hence, non-linear FEs are currently difficult to use for the analysis of large structures. Similar problems also occur with discrete elements.

Though the EFM introduces some crude approximation in the modelling of structures, where walls and lintels are approximated by single line elements, this is currently the only reliable method for analysing full structures with both nonlinear static and dynamic analyses. It is effective in simulating the different roles of piers, lintels and nodes, particularly under horizontal loads, even though details on the stress and force distributions in the walls are lost when compared with a more detailed FE analysis. The static and seismic behaviour of multi-floor masonry buildings with openings can be suitably modelled with sufficiently good adherence to the real structural response and low computational times. This method achieves convergence with fewer difficulties when compared with shell or solid element FE meshes, and with a considerable gain in the total number of degrees of freedom. Rigid nodes are used to connect piers and lintels. The node size depends on the length of the macro-elements, which in turn depends on the openings' size.

The EFM approach concentrates deformations in piers and lintels only, while all deformations in the connecting wall areas (the rigid nodes) are neglected. The idealization of the masonry wall in an equivalent frame model starts from the identification of piers and spandrels. Their geometry (and therefore of the rigid nodes connecting them) is almost trivial in walls with regular opening distributions (that is with all the openings of each floor with same dimensions and with the openings of different floors vertically aligned and with same width). In irregularly perforated walls the identification of the rigid nodes is more complicated.

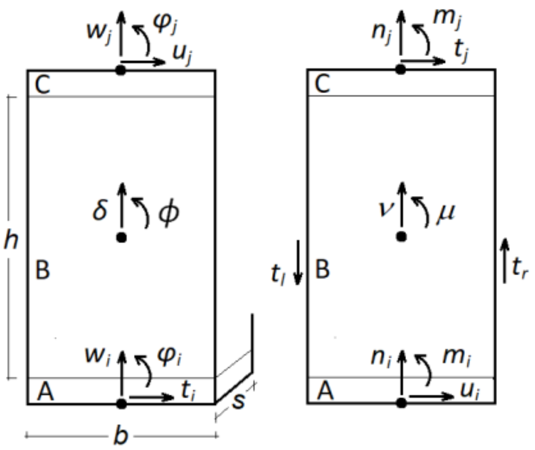


Figure 4. Macroelement kinematic and static variables

The criteria to identify them typically derive from experimental results achieved by testing irregularly perforated walls and by post-earthquake damage surveys. Methods to define the macroelements' geometry are reported in (Dolce 1989; Braga and Dolce 1982; Raithel and Augenti 1984; Augenti 2004; Parisi and Augenti 2013a). In TREMURI the geometry of the wall deformable elements (piers and lintels) with regular opening distribution is obtained following simplified rules. The spandrel and the inner pier length are assumed equal to the opening width and height, respectively, while the height of the lateral piers is computed as the average of the heights of the interstorey and of the opening, thus allowing the corner cracks to develop in the lateral piers without intersecting the wall lateral nodes. Piers and spandrels are modelled as line elements made of two zero-length end hinges (that account for the bending deformations only) connected by a central element (that accounts for the shear deformation only). In other words, the single macroelement is made of three sub-elements connected in series (Figure 4Figure 4). Nonlinear constitutive laws are assigned to the three sub-elements. These laws can also describe progressive damage under cyclic loading. The macroelements are connected to the rigid zones to form a global 3D model of the masonry structure (Brencich, Gambarotta, and Lagomarsino 1998; Galasco et al. 2004; Lagomarsino et al. 2013; Penna et al. 2004).

To implement the macroelement constitutive laws, eight kinematic variables $[u_i, w_i, \varphi_i, u_j, w_j, \varphi_j, \delta, \phi]$ correlated to eight static variables $[n_i, t_i, m_i, n_j, t_j, m_j, \nu, \mu]$ are defined (Figure 4). The external forces are the macroelement self-weight and the forces t_r and t_l, applied at the connections between the shear walls.

The constitutive equations are obtained considering on the one hand a unilateral linear elastic response concentrated in the bottom and top layers A and C, respectively, and on the other hand the coupled damage and frictional shear sliding, typical of masonry, modelled as concentrated in the central panel B, thus decoupling the axial and bending response from the shear behaviour (Figure 4).

For the upper and lower layers A and C, the constitutive equations link the kinematic variables w_i, φ_i (w_j, φ_j) to the corresponding static quantities n_i, m_i (n_j, m_j). The inelastic contributions are obtained from the unilateral perfectly elastic contact condition. Linear and decoupled equations are thus obtained up to the limit for which the section becomes partially compressed.

A uniform shear strain distribution $\gamma=[(u_i+u_j)/h]+\varphi$ in the central portion B is considered to model the shear response of the macroelement. The constitutive equations for shear are obtained by adding the linear elastic contribution to the nonlinear contribution of the frictional force opposing to the sliding mechanisms as well as of the damage causing an increase of the shear strain γ.

The expression of the overall constitutive model of the macroelement is therefore defined as $\mathbf{q}=\mathbf{K}\boldsymbol{\alpha}+\mathbf{q}^{*}+\mathbf{q}^{\circ}$, where $\mathbf{q}$ is the vector of the static variables, $\boldsymbol{\alpha}$ is that of the kinematic variables, $\mathbf{K}$ is the elastic matrix, $\mathbf{q}^{*}$ is a vector collecting the inelastic contribution and $\mathbf{q}^{\circ}$ is that of the external forces.

In typical masonry buildings, the model is made of (mostly) orthogonal walls made in turn of macroelements and rigid nodes.

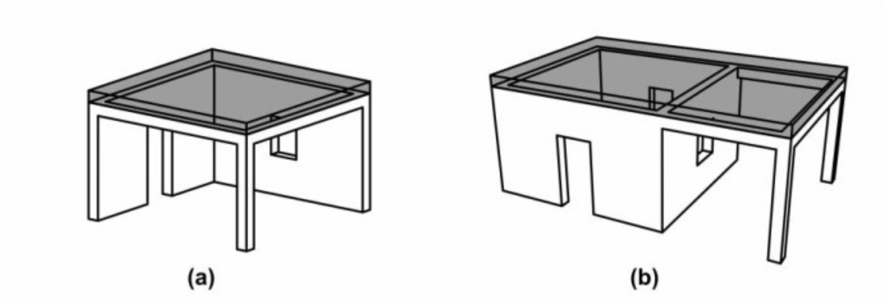


Figure 5.Masonry structures stiffened by concrete frames

When dealing with new structures where a stiff floor slab well connected to the vertical walls is built, the EF approach describes the box behaviour of the masonry construction, with horizontal diaphragms (floors, roofs or vaults) that distribute the gravity loads to the walls. The walls resist the horizontal seismic forces primarily in their plane direction. The walls' out-of-plane behaviour is typically neglected.

To achieve a box-like behaviour the key point is to ensure that the slab is very stiff in its plane and the slab itself is well connected to the vertical walls, including the use of special connection ties and ring beams. In this framework, the walls absorb all horizontal actions in their plane, up to failure. The walls' in-plane failure can typically happen in three modes: flexural failure (more ductile with considerable energy dissipation), shear failure and mixed failure. Several studies on the capacity of the EFM to describe the actual behaviour of masonry buildings have shown good accuracy with respect to both experimental tests (Parisi 2010; Marques and Lourenço 2011; Marques and Lourenço 2014) and post-earthquake damage surveys (Braga, Dolce, and Liberatore 1982; Braga and Dolce 1982; Penna et al. 2004; Parisi 2010; Marques and Lourenço 2014). In general two adjacent walls (and therefore two corresponding plane equivalent frames) can be at any angle to each other, as long as the walls behaves as belonging to a box, and their in-plane response is provided. It can be noted that the masonry structure can provide its in-plane response to the horizontal loadings even if made of only two adjacent walls at any angle to each other, whose piers at the opposite sides with respect to the adjacent ones are suitably connected through one or more frames (Figure 5a).Moreover, the box masonry structure can be stiffened by frames connected to the walls (Figure 5b). The case of the Fujian Tulous is similar, though the wood structure built inside the outer wall is mainly intended to carry gravity load (Figure 6) as the timber simply connected elements are much more flexible than the massive earth walls. The application of the EFM to older masonry structures with possible deformable floors and poor

Figure 6. Inner view of the wood structures of a square tulou

floor-wall connections is still possible, provided the model can accurately describe the in plane flexibility of the floor. In some cases, the out-of-plane behaviour may also be important, as discussed later in this paper.

The model of the Fujian Tulou prototype of the present study (Figure 7), even though geometrically simple turns out to be rather complex because it is a large round earth construction (the round Tulou radii can reach more than 50 meters). The geometry in itself is quite different from that of a typical rectangular masonry building. Furthermore, in the traditional Tulou (either rectangular or circular) a wood frame is attached to the inside of the structure and supports the living and commercial quarters of the Tulou. The defensive nature of these structures appears clear: the outer thick wall with few very small openings is intended to defend from outside attacks while people are safely hosted by the inside wood frame that holds their living spaces. Horizontal radial beams span from the inside of the wall to a ring of inner wood pillars. The wood floor system consists of wood planks and rafters. A complex wood gable system completes the wood structures. The roof protects the earth wall, the wood and the Tulou inhabitants from the rain. Water is indeed the main threat to earth structure.

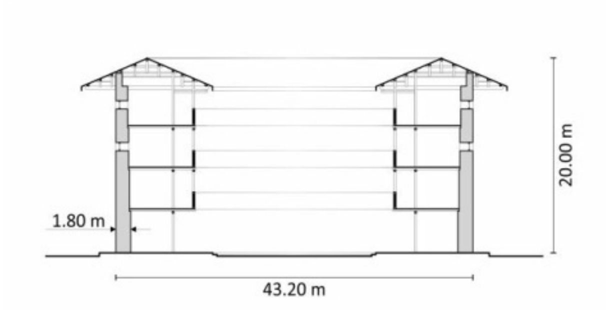


Figure 7. Section of the Fujian Tulou prototype.

The overall behaviour of the round Tulou is clearly not box-like, mostly for two reasons: the floors are rather flexible in their plane and the masonry lateral resisting system is a ring. The floor diaphragm constraint cannot be realistically applied.

The geometry of the earth wall and of the elements of the wooden frames were obtained from the work by Stanislawski (Stanislawski 2011) who modelled the walls with shell elements plus linear elements for the wood beams and columns. The analysis was linear elastic. As for the mechanical properties of the earth wall, there is limited data available from material tests carried out at Xiamen University (Liang et al. 2013; Stanislawski 2011; Liang, Stanislawski, and Hota 2011) . The mechanical properties of the earth material implemented in the model are those of Table I and were elaborated starting from the above mentioned material tests.

f_c	**f_{v0}**	**E**	**w**
[MPa]	[MPa]	[MPa]	[kN/m^3]
1.00	0.10	1000	16

Table I. Mechanical properties of the earthen material

One of the key aspects of the proposed model is the EF mesh for the earth ring. Though the ring is not a frame, it is approximated as a series of 24 vertical walls whose horizontal section is a round polyline. Each wall is modelled as a series of vertical elements if no openings (windows) are present, otherwise the wall is modelled as a frame. The distance between the elements is important. An initial study was carried out to select a realistic number of sides. It was eventually decided to use 24 sides (Figure 8), since fewer sides would not accurately represent the round geometry of the building. This is a non-standard application of the EFM,

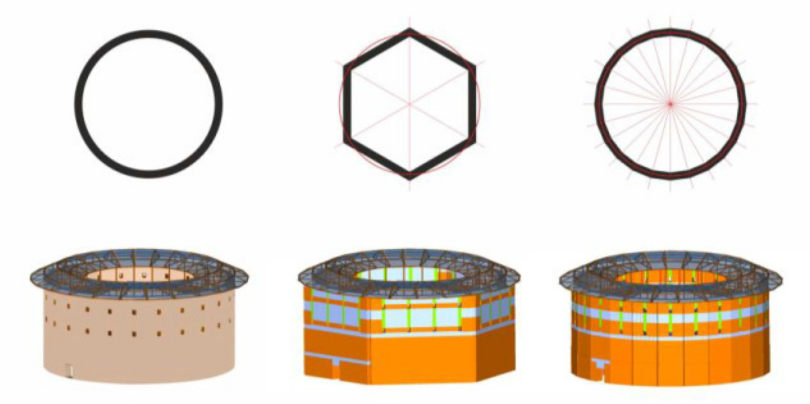


Figure 8. Modelling of the round earth wall with different number of sides (each side is modelled as an equivalent frame).

but it permits the analysis of the ring approximated as a series of walls connected at an angle to each other (Lagomarsino et al. 2013).

Figure 9 shows the equivalent frame generated in each plane wall when approximating the circular wall through extruding a 6-sided and a 24-sided polygon. While in the latter case the smaller width of each plane wall allows to obtain an equivalent frame with lateral piers only. in the former case an equivalent frame with both lateral and central piers can be generated. Following what said in section 3 about the equivalent frame generation, in both cases the height of the lateral piers was computed as the average of the interstorey and of the opening heights. The height of the central piers of the model obtained through extruding the 6-sided polygon instead coincides with the window height.

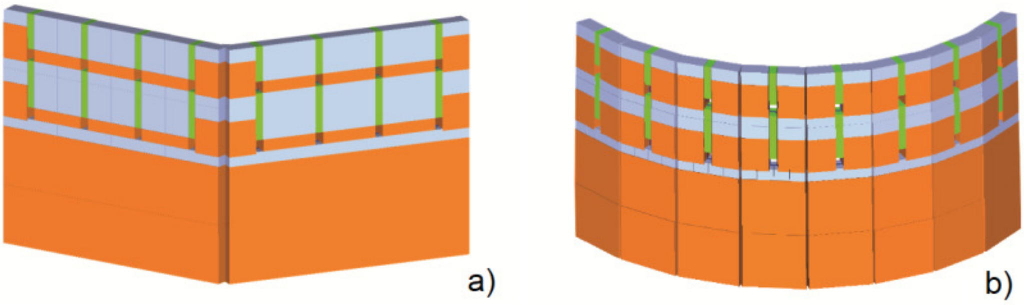


Figure 9. Geometry of piers, spandrels and rigid nodes of the equivalent frame generated in the plane walls obtained through extruding a 6-sided (a) and a 24-sided (b) polygon.

The thickness of the circular wall at its base is 1.8m. It thins along the wall height (see Figure 7). The wall mass is 6769 ton. The mass of the wood structure is subdivided as follows: columns and beams have a 34.3 ton mass, wood elements of the gable roof 16.6 ton, diaphragms of floors and roof 281 ton and 180 ton, respectively. The floors' service load considered for the seismic load combination is $0.3 \cdot 2000$ N/m^2.

Linear elements are used to model the wooden frames. A 18cm x 18 cm cross section is assumed (A = 300 cm^2) following Stanislawski (Stanislawski 2011). The cantilevering radial beams are supported by the columns (before cantilevering inward), as well as by the circular earth wall. Transverse beams connecting the columns and the inner end of the radial beams are used. The beams have the same cross-sectional area of the columns. Figure 10 shows a Tulou slice with one of the 24 plane walls approximating the circular earth wall, as well as a detailed view of the wooden structure stiffening it.

Radial beams and columns are assumed to be hinged to, the circular wall and the column base, respectively. For the sake of simplicity, continuity was assumed at the connections between wood elements (beam-to-column and beam-to-beam). This is a crude assumption that will be updated after a careful survey of the Tulous. After a preliminary study of the influence of different connection types it appears that the capacity

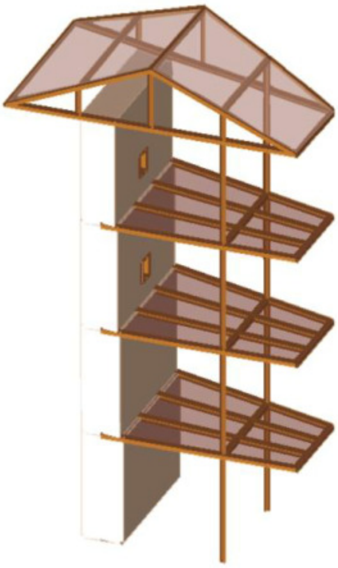


Figure 10. Tulou slice with a detailed view of the wooden structure.

curves of the Tulou structure are only slightly affected by the release of the rotational D.O.F between beams and columns.

The floors are modelled through membrane elements as orthotropic partially stiff diaphragms, whose stiffness is defined by the elastic moduli in two orthogonal directions, the related shear modulus and Poisson's ratio. The elastic modulus of the rafter wood is used in the stiffer direction, while stiffness is considered practically zero in the other direction, due to the very low rigidity of the boards of the wooden plank. The shear modulus depends on the diaphragms' stiffness (i.e. the rigidity of planks boars, wooden planks, concrete slabs), as well as on the type of their connection with the floor rafters, as described in Brignola et al (Brignola, Podestà, and Pampanin 2008). Similar considerations can be drawn regarding the gable roof. It is only partially stiff, and its rigidity depends on the rigidity of the wooden truss, as well as on the low stiffness of the diaphragms between two close trusses, whose stiffness, similarly to the floors, is mainly governed by the rafters.

4. Seismic analysis of Hakka Tulous using EFM.

In the last years nonlinear static analyses (pushover) have become more and more popular for the seismic assessment of existing structures (Lagomarsino et al. 2013; Liu et al. 2015). In this paper pushover analyses of the Multi-Degree-of-Freedom (MDOF) system were carried out with displacement control at a Single-Degree-of-Freedom (SDOF) by opportunely defining the stiffness matrix and maintaining the assigned force distribution in TREMURI. A preliminary linear finite element modal analysis yielded a first flexural vibration mode with 2.2 Hz frequency. Considering the structure complexity and its irregularity in the radial direction, and given the absence of an effective floor diaphragm, it is difficult to identify the first translational mode with a large mass participation factor in any loading direction. It was thus decided to use mass proportional loads for the pushover analyses.

The seismic performance at the Life Safety Limit State was evaluated by comparing the (capacity) pushover curves with the ADRS spectrum (demand). The linear response spectrum for the given Limit State corresponds to a 475 year return period. Seismic hazard studies on the Fujian area indicate a peak ground acceleration a_g=0.16 g. The shape of the response spectrum was obtained following Eurocode 8. Since no other data is available about the elastic spectrum in the Fujian Province, the values of the spectrum amplification factor F_0 and of the highest period T_C^* of the spectrum plateau (apart from any effect due to subsoil and topographic amplification) were selected following Eurocode 8 values, that is F_0=2.45 and T_C^*=0.32 sec. Even though there is uncertainty about these values for the Fujian Province, the assumed values and shape are considered acceptable for a first study of the Tulou seismic response. No data are available about the influence of the subsoil. Since Fujian Tulous are in a mountain area, a rock subsoil was assumed, with no subsoil amplification. This point needs to be further explored for future studies.

Separate pushover curves were carried out in two orthogonal directions, labelled X and Y here. The Y direction is orthogonal to the Tulou main entrance. Two different control degrees of freedom were taken for the two separate directions. The control displacements are indicated in the relevant pushover curves. The selection of the control degree of freedom is not trivial in a building with the centre of mass far from all the structural elements, as in the case of the Tulou, whose centre of mass is in the centre of the Tulou court. Figure 11 and Figure 12 show the location and direction of the two degrees of freedom. Given the flexibility of the diaphragm and the change of shape of the earth ring during the pushover, different degrees of freedom were originally compared. Since there is no node in the center of the ring, which in this case basically corresponds with the centre of mass, it was decided that the best location was along the walls parallel to the load direction. The displacements of ring points located along the pushing direction suffer from the additional displacements due to the loss of shape of the earth ring, an aspect further discussed later in the paper. The only issue with the selected control degrees of freedom (Figure 11 and Figure 12) deals with possible torsion of the ring. However, since the ring is torsionally very rigid and basically symmetric with respect to the loads, torsion is not an issue.

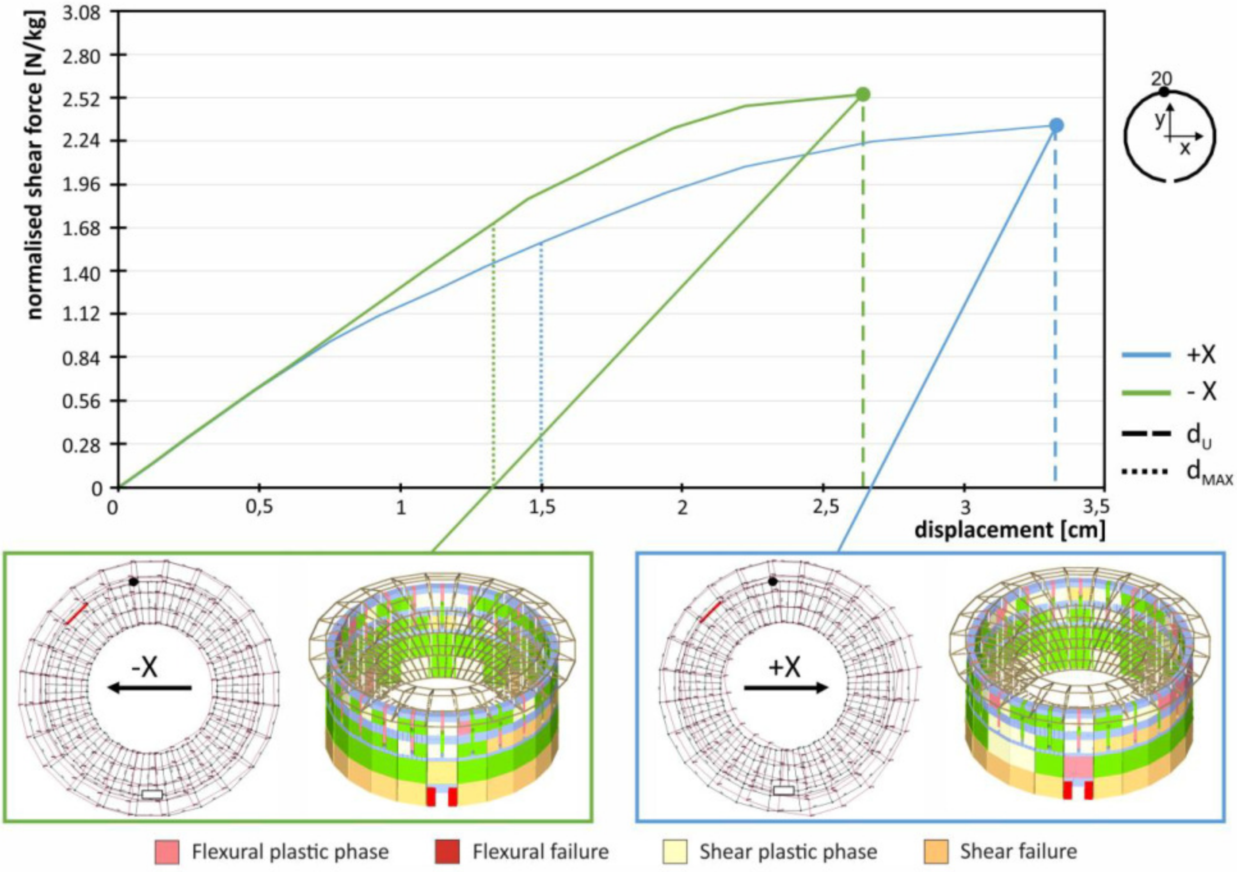


Figure 11. Pushover curves in the X direction

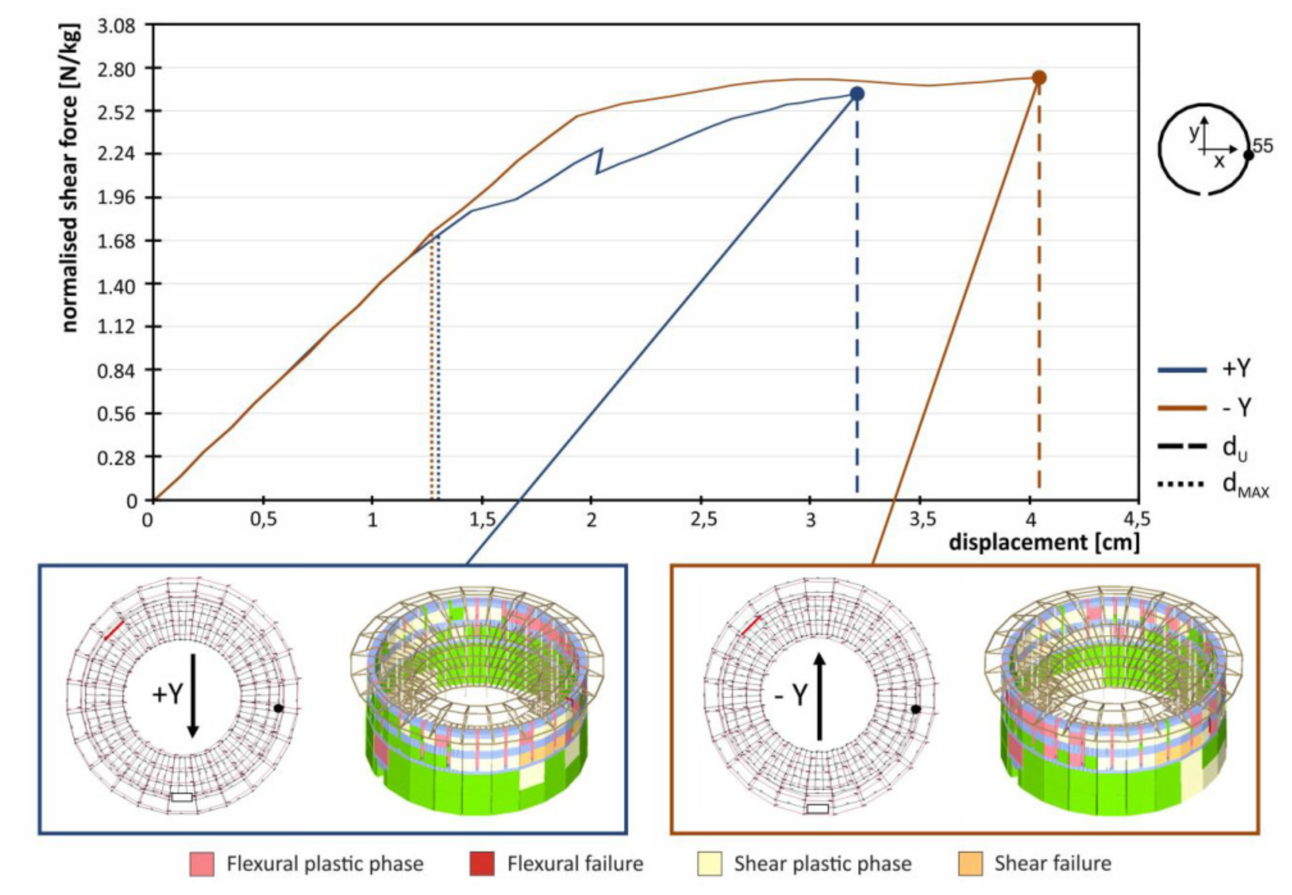


Figure 12. Pushover curves in the Y direction

In Figure 11 and Figure 12 the two curves show the responses in the positive and negative directions. On each curve, two displacements are reported. The final displacements correspond to a loss of strength of 20% or larger with respect to the peak base shear. The drop is not visible because it corresponds to the shear failure of one or more macroelements, which is very sudden. Immediately after the reported capacity displacements, all the curves drop abruptly. The dotted displacement vertical lines on the curves represent the displacement demands computed by comparing the pushover curves with the ADRS spectrum. In all shown load cases, the seismic response of the Tulou is rather ductile, with mean displacement capacity of 3.30 cm and a range between 2.64 and 4.04 cm. For all examined cases, the displacement demand for the seismic action considered is always close 1.5 cm, therefore much lower than the capacity displacement.

Seismic analysEs in the +X and –X directions show that flexure yielding of the piers adjacent to the large entrance of the Tulou is followed by shear yielding of the neighboring piers at the first level. When flexural-compression failure takes place at the piers next to the Tulou entrance, shear failure of many adjacent piers almost parallel to the direction of the seismic action also occurs, and the force capacity drops.

The pushover curve in the +Y direction shows that after flexural yielding of the pier over the spandrel of the Tulou entrance, and of other piers at the upper level of the opposite part of the Tulou, sudden shear failure of some piers and flexural failure of few spandrels, both parallel to the loading directions, occur.

The asymmetry due to the large entrance plays an important role in the different behaviour of the Tulou structure in the +X/-X and in the +Y/-Y directions. The issue is going to be further discussed hereafter.

The typical failure sequence is analysed in more detail by looking at the macro-elements' status in significant points along the pushover curve along the -Y direction (Figure 13). The status at four points along the curve of Figure 13a is analysed. At the first point (Figure 13b-I) there is flexural yielding in the wall above the Tulou entrance.

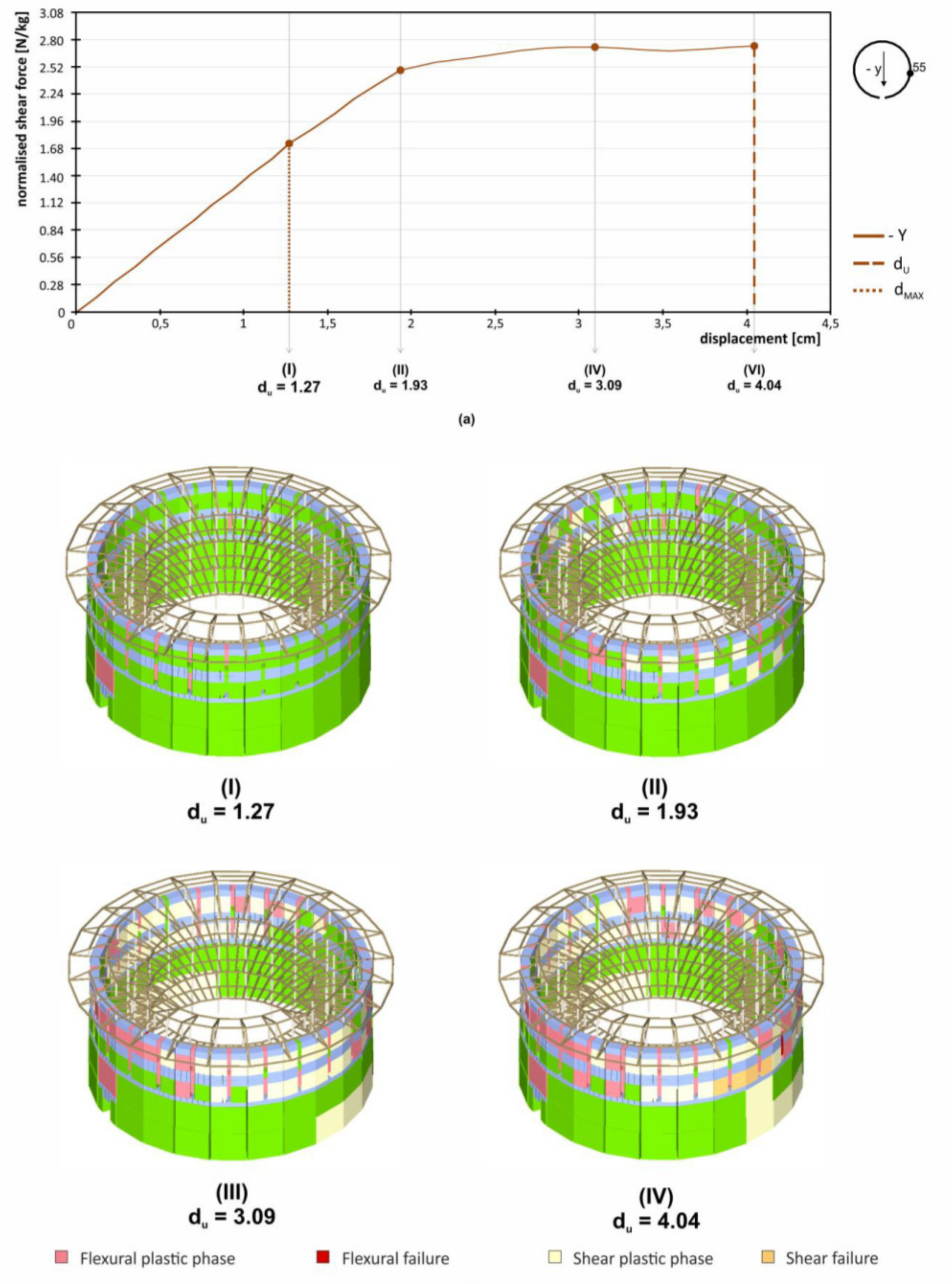


Figure 13. Damage sequence at a few significant points in the –Y direction pushover: a) Pushover curve; b) damage distribution at different displacement: 1.27 cm (I), 1.93cm (II), 3.09 cm (III), 4.04 (IV).

The loading direction -Y is orthogonal to this wall. Some spandrels also yield at the upper level over it. Yielding of the macroelements in -.TREMURI entails that the macroelement has reached its flexural capacity but there is still some ductility available in the element. These are not failure points. At the second point (Figure 13b-II), shear yielding of some piers almost parallel to the loading direction starts to occur. Again, these are not failure points, because some small ductility is also provided in shear. At the third point (Figure 13b-III), more elements almost parallel to the loading direction yield in shear, but even now the overall curve does not drop, because no element fails. It is important to point out that some elements over the Tulou entrance and orthogonal to the loading direction, also yield (in flexure).

This is an interesting point that is related to the adopted equivalent frame model. Loads are applied at all nodes with mass, therefore all nodes along the ring are loaded.

More specifically, the nodes orthogonal to the loading direction are also loaded. In order to resist the applied nodal loads, the macroelement walls develop very high shear forces. At the node, the applied load is equilibrated by the forces coming from the macro-elements. Since the element direction is almost at 90°, very large shear forces are generated for equilibrium in the wall plane of loading. Finally, at the fourth point (Figure 13-IV), shear failure occurs in a few piers already yielded in shear for lower displacement values in the wall region almost parallel to the seismic action. This causes a sudden drop higher than 20% of the overall shear resistance at the Tulou base.

A closer look at the deflected shape of the ring in the two loading directions shows the effect of symmetry on the deflected shape. The structure is not symmetric with respect to the X loading direction because of the main entrance, and the deflected shape shows a loss of shape that is more significant on the entrance side. In the Y direction, the deflected shape is mostly symmetrical.

Because there is a significant degree of uncertainty regarding the value of the earth material elastic modulus, a sensitivity analysis of the structural response to the elastic modulus E of the earth material was performed, with its value ranging between 200 and 1000 MPa, the latter being the value used for the analyses presented above.

Sensitivity analysis to elastic modulus was carried out for the –Y loading direction of the seismic action using the control node 55, as shown in Figure 14. For E=1000 MPa, the main failure mode was shear failure of the upper piers more closely parallel to the seismic action, together with flexural failure of four upper lintels at the four boundaries of the two sets (one per side) of failed piers. The same shear failure mode occurred for all the E values considered, with a shift in displacements at yield and at failure. However, for E=200 MPa (that is for a really low value of E) the structure becomes very flexible and shows a brittle behaviour.

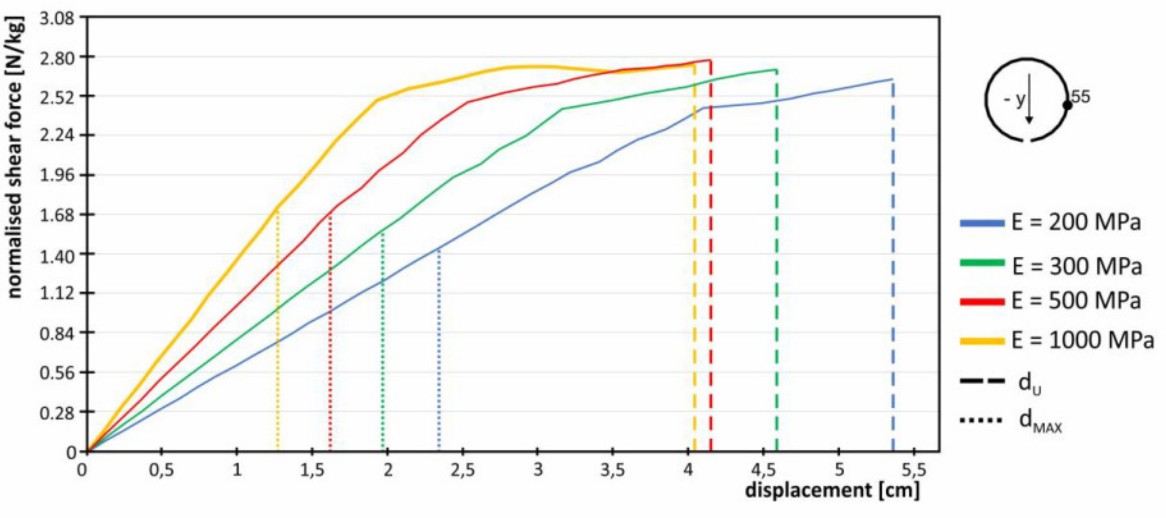


Figure 14. Sensitivity analysis to elastic modulus

Finally, a few considerations regarding local mechanisms are needed. Mechanisms involving the upper level of the earth wall were checked. A smaller yield curve along the upper level involving three sides extruded by the polyline - more precisely passing through the two windows of the lateral sides and below the window of the central side - was tried first. The capacity/demand (C/D) ratio in terms of acceleration for this mechanism is 2.13, thus showing that this local mechanism cannot occur. Local mechanisms at the upper level involving larger yield curves (and therefore more sides) lead to higher C/D value.

In general, circular masonry walls provide better out-of-plane response than plane walls (Vanggaard 2003), as also shown by static tilt table tests performed on adobe models at the University of Technology Sydney (Samali et al. 2011).

5. Conclusions

Fujian Hakka Tulous are very popular earth constructions that are part of the UNESCO World Heritage list. Unfortunately, no detailed study has been carried out to date on their structural performance and seismic characteristics.

The pioneering study presented in this paper intends to start filling this gap. Since in the Fujian Province medium magnitude earthquakes may occur, the overall response of a circular Tulou prototype subjected to an assumed seismic action is investigated.

Since no full survey of an existing Tulou is available, while geometric data of Hianji Tulous are found in the scientific literature, a prototype Tulou with geometry very similar to that of the Hianji Tulou was defined. Unlike the Hianji Toulu, regular window spacing was assumed. Vertically aligned windows with constant spacing in each windows' row were therefore used in the Tulou prototype. This opening layout is often observed in Fujian Tulous.

From the assumed prototype geometry a numerical model of the Tulou was derived. Since a Tulou is quite a complex structure, and the non-linear seismic response of the Tulou was to be investigated, the macro-element approach was preferred to the finite element approach, because non-linear static analysis (pushover) of a complex masonry structure through a FE micro-mechanical model is computationally demanding and prone to converge problems.

The macro-element approach is instead more suitable to investigate the overall seismic response of a Tulou, even though a number of approximations are needed when defining the geometry of each macroelement as well as its mechanical behavior. The advantage is that the pushover analysis is then carried out through the Equivalent Frame Method, where each wall's piers and spandrels correspond to columns and beams of the equivalent frame. The Equivalent Frame Method allows much simpler calculations when compared to a FE model, with fewer convergence issues and faster runs.

Because of their circular shape, the application of the EFM to a Tulou is not common with this analysis method. The circular wall was approximated through the extrusion of a polyline with a row of window openings in each plane wall related to each polyline side. In so doing, an equivalent frame corresponding to each wall could be defined, thus allowing the use of the EFM. An extension to circular masonry structures of the analysis by macroelements through the EFM is proposed.

Since the only masonry wall of the Tulou structure is the perimetral one, the transverse bearing beams of the floors and the wood truss of the gable roof were supported by only one side by the wall, and by the opposite side by wooden columns. Hence, only one floor side coincided with the masonry wall, while the others sides were defined by wood beams supported by the columns. Wooden columns and beams define wooden frames that are analysed contemporary to the equivalent frames corresponding to each wall obtained from extrusion of the polyline. The horizontal forces were hence shared among the masonry equivalent frames and the wooden frames by flexible diaphragms with low rigidity.

The EFM is capable of capturing the overall response of the Tulou subjected to the seismic forces, with overall failure occurring when, in the upper floors, the pier and spandrel macro-elements almost parallel to the seismic action fail in shear and flexure, respectively.

The circular form of the Tulou has shown to be very effective in resisting to the seismic action with only small deformations with respect to the original circular form.

The application of the EFM to a Tulou needs to be further investigated. It is first necessary to better evaluate the Tulou architecture and structure through a through survey in order to achieve a sufficiently precise geometry of the Tulou and of its structural elements, including the connections. Further tests are also needed to evaluate the mechanical properties of the construction materials (mostly earth and timber). More specifically, a better assessment of the stiffening effect of the wooden frames on the circular earth wall is needed. Since both the floors and the pitches of the gable roof are modelled as partially stiff diaphragms, the evaluation of their low rigidity is an important issue to be considered in future enhancements of the Tulou model. Although it is difficult to implement a full finite element model of a Tulou for a non-linear static analysis (pushover), this step is deemed necessary to validate the results obtained with the macro-element model (mainly, deformations and damage mapping of the circular wall at different stages of the pushover analysis need to be checked). Initial stiffness values and mode shapes also need to checked and compared with a FE model of the prototype Tulou.

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