Finite element analysis model of Ying-Xing timber pagoda based on the conformation character and damaged condition

Yuan Jianli*, Fang Yingcai*, Shi Ying*, Chen Wei*, Wang Jue*

SUMMARY – *Ying-Xian timber pagoda is the existing oldest and highest wooden pagoda in China. Because of strong earthquake action and material aging, Ying-Xian timber pagoda is severely damaged and needs to be strengthened urgently. Aiming at the characteristics of complicated structural conformation and numerous damaged types of the pagoda, this paper discussed practical expression technology of computer simulation, determined the conformation character of layers-superposition and the modeling method of the pagoda based on the construction rule of traditional Chinese timber structures, and proposed the adjustment method to sectional area or elastic modulus of members according to the damage degree and position by the recognition research on damaged condition and stiffness variation of the pagoda. The finite element model of Ying-Xian timber pagoda was constructed and the dynamic behavior was analyzed by program ANSYS. The analysis results indicate that this FEA model is effective to describe the conformation character and damaged condition of the pagoda, and can be applied to seismic behavior study and security evaluation for the strengthening project of the pagoda.*

Keyword: Ying-Xian timber pagoda; conformation character; damage identification; dynamic behavior; FEA model.

1. Introduction

Ying-Xian timber pagoda (Fig. 1) located in Fu-gong Temple, Ying-Xian County, Shanxi Province. It was built in 1056 (in Liao Dynasty), with a total height of 67.13 meter, and is the only existing oldest and highest wooden pavilion pagoda in China [1]. Undergone many enormous earthquakes and weather erosion nearly one thousand years, the structural deformation and damage of this pagoda is serious, so it is necessity to be strengthened urgently [2-5]. The research on strengthening project of Ying-Xian timber pagoda has been listed as a key project in "***The cultural development compendium in Eleventh Five-Year Plan in China***".

It is the premise of making strengthening plan to grasp the present damaged condition and the mechanical properties of the pagoda, and a series of corresponding research have been carried out by using the modern simulation and analysis technology [6-12].

Aiming at the characteristics of complicated structural conformation and numerous damaged types of the pagoda, this paper discussed practical expression technology of computer simulation. Combined the construction research of traditional Chinese timber structures and filed investigation, the finite element modeling method of Ying-Xing timber pagoda based on the conformation character and damaged condition has been proposed.

2. Architectural and structural features of Ying-Xian timber pagoda

Ying-Xian timber pagoda is a pavilion-style pagoda with the appearance of five-storey and inside of nine-structural layer (Fig. 2). The pagoda consists of four main parts, namely, terrace (stepped foundation), wooden body, Laksata pedestal, and Laksata (Buddhist ornamentation, finial). The two-layer stepped foundation is brick masonry, 4.40 meter high. The wooden body of 51.14 meter high is composed of five open stories, four interlayers and the tower roof. The Laksata pedestal of 1.86 meter high is made of wood and brick. The Laksata of 9.91 meter high is mainly made of a cast iron mast, the bottom of mast is fixed to the Laksata pedestal, and the upside is fastened with steel chains attached to the eight roof ridges respectively.

Ying-Xian timber pagoda is octagonal in architectural plane. The first storey has three column circles (Fig. 3), that is, corridor columns, eave columns, and internal columns. From the second storey to the fifth storey, each has only two column circles (Fig. 4).The boards were paved on the each floor. Every interlayer has two column circles too (Fig. 5), the board was only paved on the stair landing between the up and down stairs.

The structure of the wooden pagoda is elaborate, and was made by tenon-mortise joint work. Ying-Xian timber pagoda contains nearly 100,000 pieces of wooden members, and the volume is about 3,000 cubic meters. Each open storey and interlayer is composed of a bracket set (Dou-Gong) layer and paralleled column circle layer. Therefore, the whole structure can be seen as a superposition of bracket set layers and column circle layers in vertical direction. (Fig. 2, Fig. 6).

The architraves and plinth beams are main connective members in column circle layer, which integrate the eave column circle and internal column circle into two octagonal tubby structures (Fig. 5, Fig. 7). In addition, diagonal struts were set up between the eave column circles and internal column circles in interlayer, which enhance the integrity of double circles.

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Fig. 1. *Ying-Xian timber pagoda (2012).*
La pagoda lignea Ying-Xian (2012).

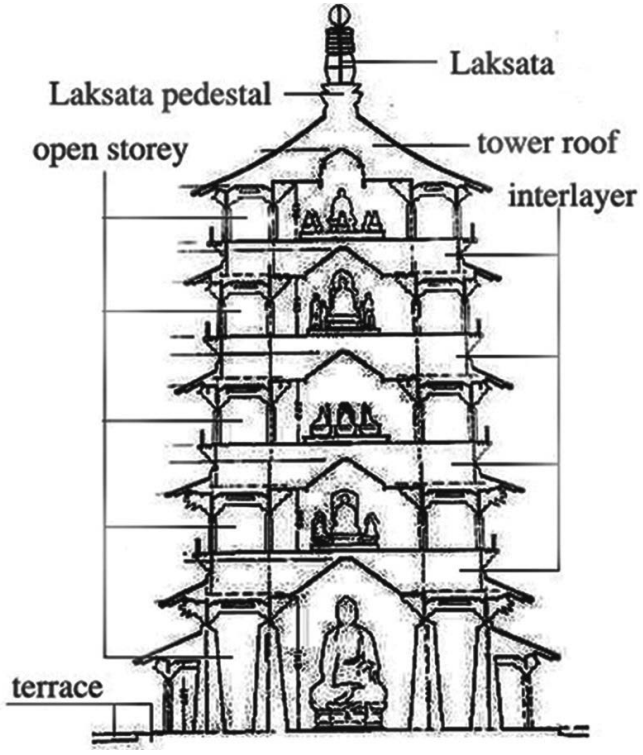

Fig. 2. *Vertical section of the pagoda.*
Sezione vertical della pagoda.

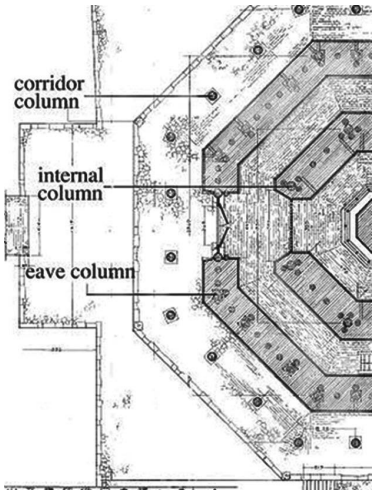

Fig. 3. *Cross section of the first storey.*
Pianta del primo piano.

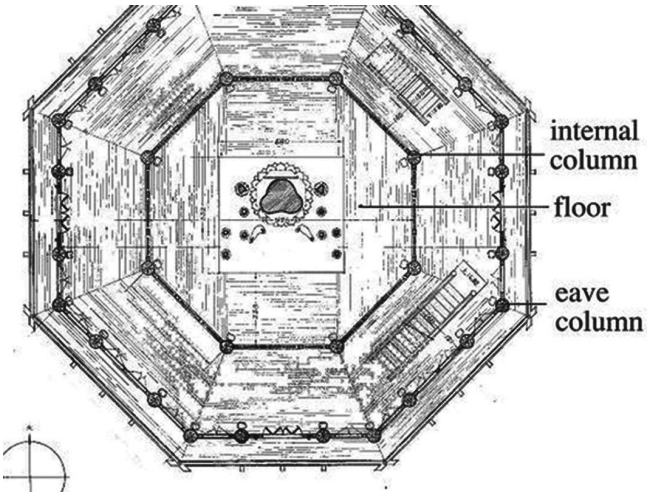

Fig. 4. *Cross section of the second storey.*
Pianta del secondo piano.

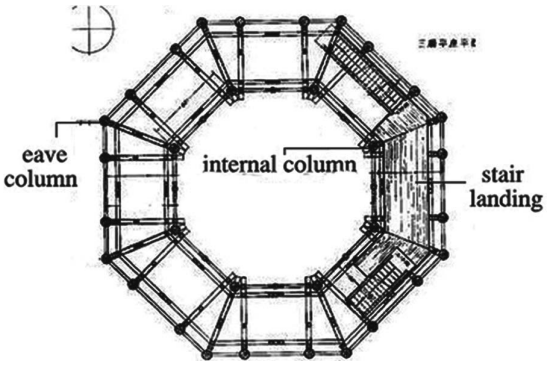

Fig. 5. *Cross section of the third interlayer.*
Pianta del terzo interpiano.

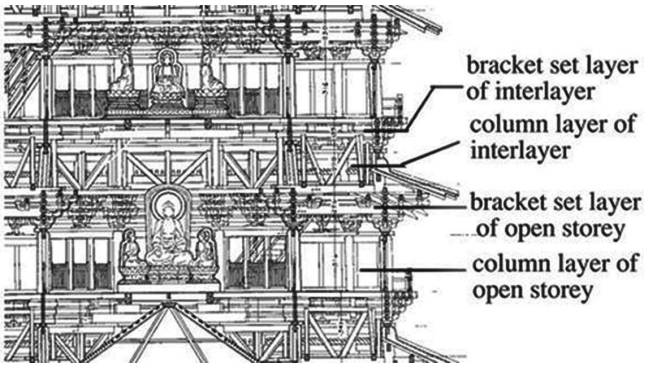

Fig. 6. *Structural layers of the pagoda.*
Livelli strutturali della pagoda.

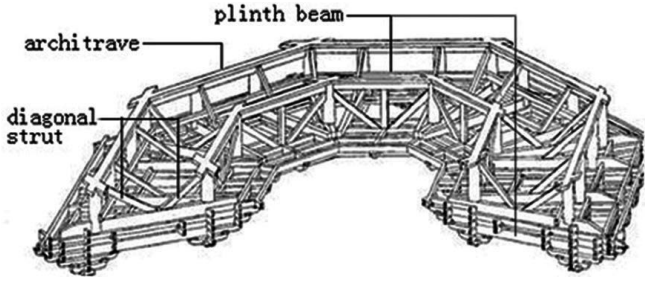

Fig. 7. *Column circle structures of the interlayer.*
Elementi strutturali dell'interpiano.

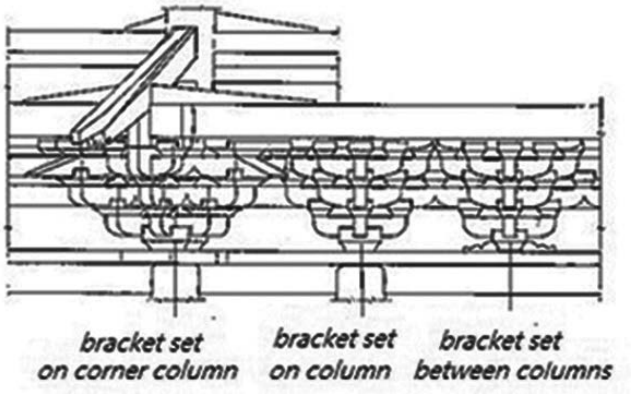

Fig. 8. *Representative Dou-Gong in the pagoda.*
Tipici Dou-Gong della pagoda.

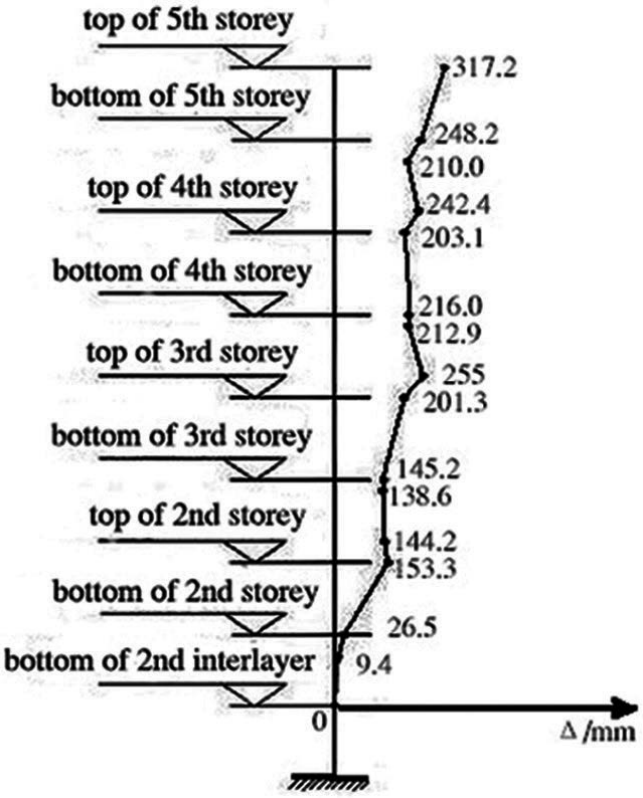

Fig. 9. *Center displacement of storey.*
Spostamento centrale ad ogni piano.

In the bracket set layer, three main types of Dou-Gong (Fig. 8), bracket set on corner column, bracket set on column and bracket set between columns, together with upper tie-beams and lower architraves, form an octagonal space structure layer.

The structural feature of this pagoda is it can be divided into layers horizontally, and every layer has an integral construction. The whole wooden structure is built by layers-superposition from base to top, and therefore the tall columns are unnecessary. This layers-superposition structure is an outstanding creation in ancient Chinese architectural history, it with higher flexibility and stability, and is extremely fit to the large area or high rise buildings.

3. **Damaged condition of Ying-Xian timber pagoda**

3.1. *Damaged condition of the main structure*

Undergone many enormous earthquakes [5] and weather erosion nearly one thousand years, the main structure of Ying-Xian timber pagoda has been severely damaged, and the damaged condition will be continuously deteriorated with the material aging and the deformation development of the wooden members.

Testing and analysis reports [2] [3] [12] show that the main damage character of the structure is lateral displacement and torsion between stories. Except for the second storey has a northwestward displacement, the others have a northeastward displacement basically. According to the surveyed displacements at the centre of every storey (Fig.9), the largest relative torsional displacement between the top and bottom of column is 126.79 mm occurred at the second storey, the next torsional displacement is 69.05 mm occurred at the fifth storey, and the following is 56.09 mm occurred at the third storey. The inclination of columns caused the increase of eccentricity and the decrease of bearing capacity. A few of tilted columns even reach the ultimate state of eccentric compression.

3.2. *Damaged condition of the structural members*

The damaged condition of the structural members is aggravating from the upper storey to the lower storey, and the second storey is more serious. The overmuch inclination of the frame caused the split of top and bottom of the columns (Fig. 10a), as well as the down deflection and fracture of the architraves (Fig. 10b, Fig. 10c). The main damages of bracket sets are the split and twist of flower arm and the crush of bracket base (Fig. 10d).

4. **The construction method of FE model of Ying-Xian timber pagoda**

4.1. *The layers-superposition model of the main structure*

The main structure of the pagoda can be divided into five open stories, four interlayers and the tower

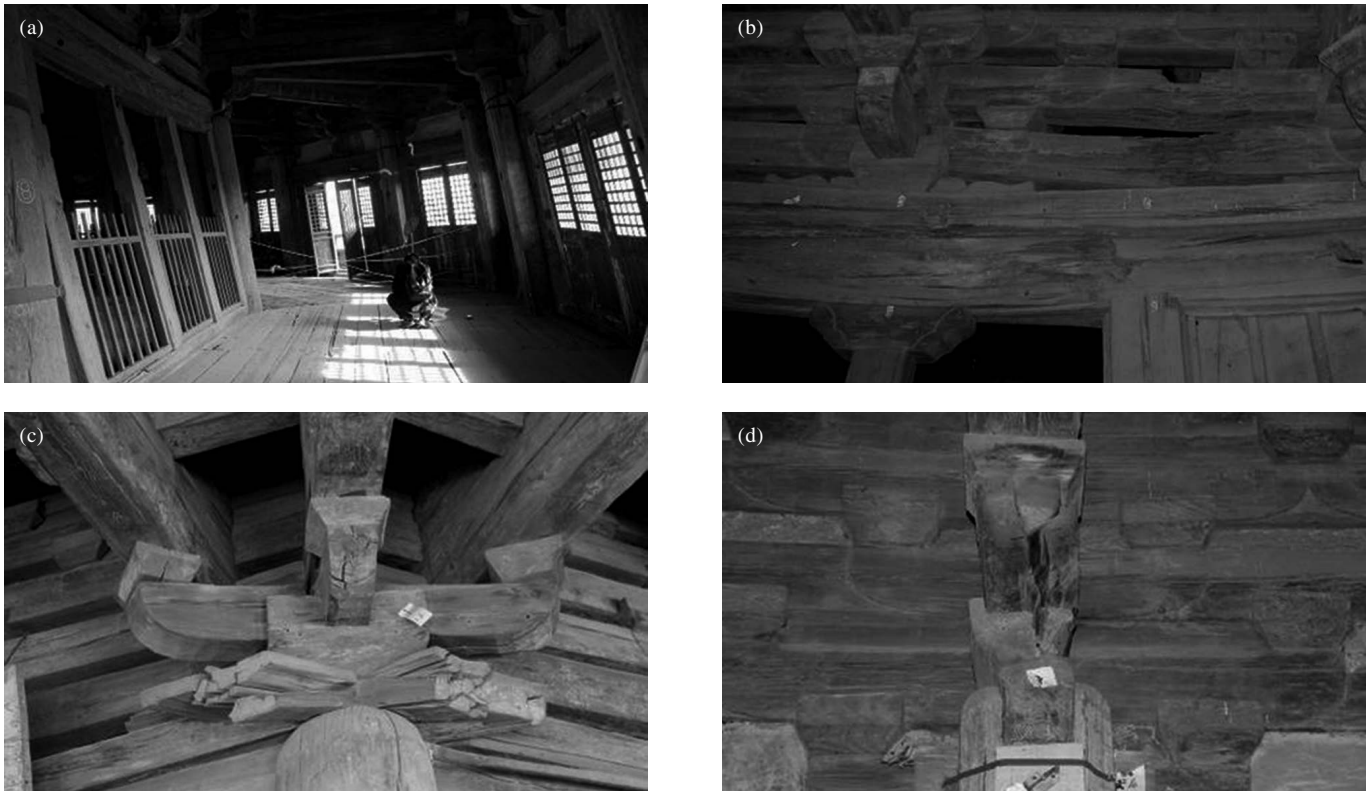

Fig. 10. *Damaged condition of the structural members (2012).* (a) *Inclination of the frame* (b) *Down deflection of Architrave* (c) *Fracture of architrave ends* (d) *Split and twist of Dou-gong.*
Danneggiamento degli elementi strutturali (2012). *(a)* Inclinazione della struttura *(b)* Inflessione dell'architrave *(c)* Fratture delle estremità dell'architrave *(d)* Fessurazione e rotazione di un Dou-gong.

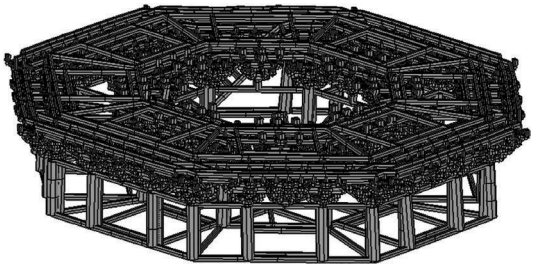

Fig. 11. *The minor structure of open storey.*
La sottostruttura di un piano aperto.

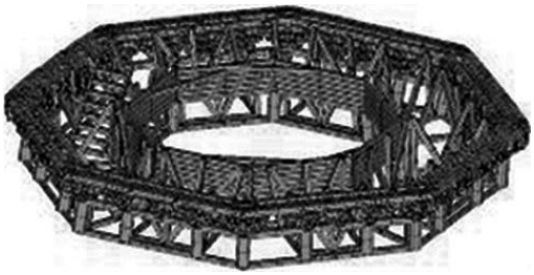

Fig. 12. *The minor structure of interlayer.*
La sottostruttura dell'interpiano.

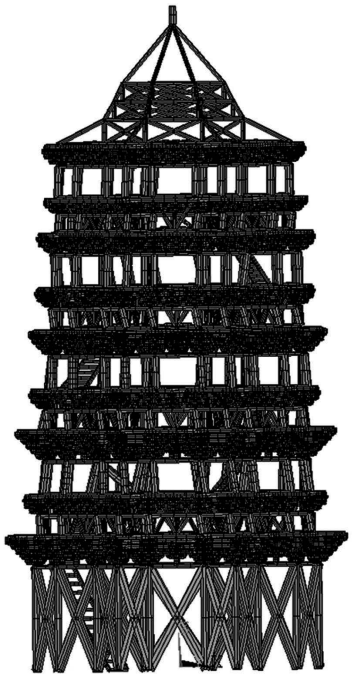

Fig. 13. *The layers-superposition model.*
Il modello di sovrapposizione dei vari livelli.

roof to construct each minor structure model based on the construction rule respectively. The minor structure of open storey is composed of the column circle and bracket set layer (Fig. 11), and the minor structure of interlayer is composed of the column circle and brackets layer too (Fig. 12). Then, these minor structures are superposed in turn to form the FE model of main structure (Fig. 13).

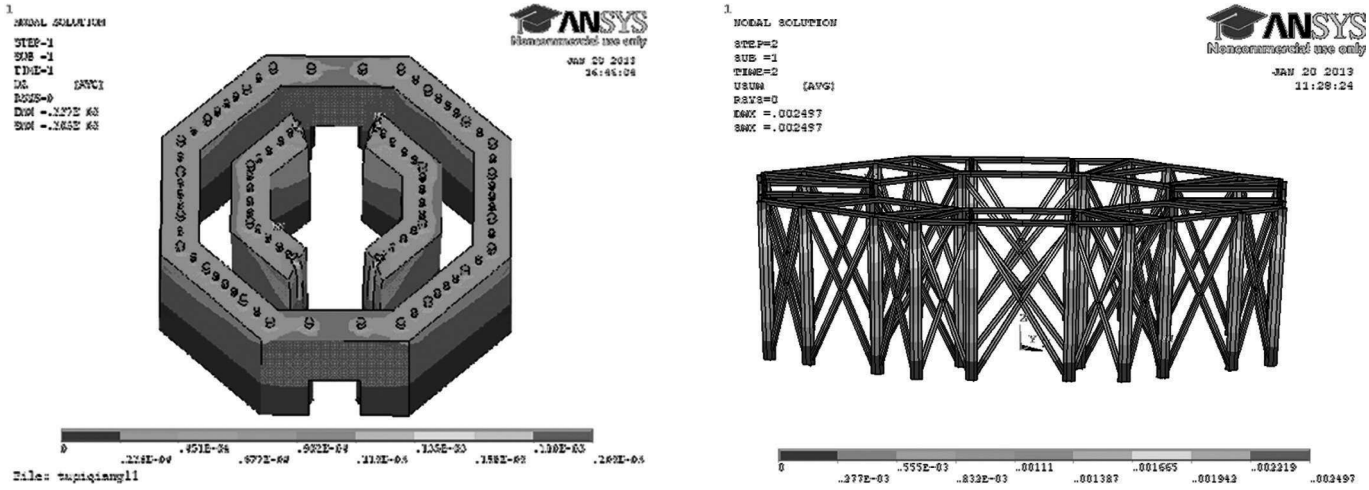

Fig. 14. *FE model of wooden diagonal struts instead of adobe walls.*
Modello a Elementi Finiti di diagonali in legno sostitutivi delle pareti in adobe.

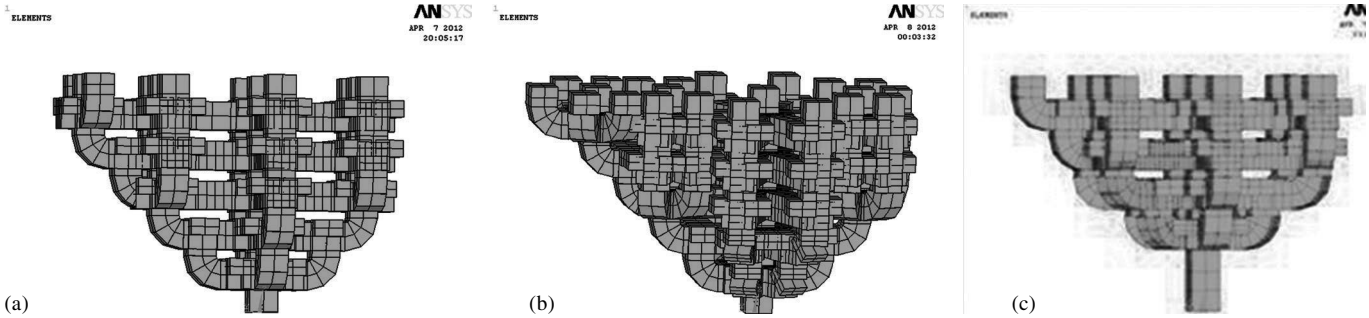

Fig. 15. *The FE models of three typical bracket sets in Ying-Xian timber pagoda.* (a) *Bracket set on column* (b) *Bracket set on corner column* (c) *Bracket set between columns.*
Modelli a Elementi Finiti di tre tipiche mensole della pagoda Ying-Xian. *(a)* Mensola su colonna *(b)* Mensola su colonna d'angolo *(c)* Mensola tra colonne.

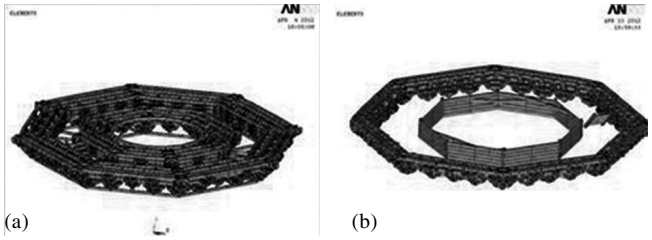

Fig. 16. *The FE models of bracket set layers. (a) Bracket set layer in open storey (b) Bracket set layer in interlayer.*
Modelli a Elementi Finiti di strati di mensole. *(a)* Livello di mensole in un piano aperto *(b)* Livello di mensole in un interpiano.

4.2. *The equivalent stiffness replacement of adobe wall by wooden struts in first storey*

The eave columns and internal columns of the first storey are embedded in the adobe walls, which increase the stiffness of the storey. In order to facilitate to use the BEAM element modeling, the adobe walls is replaced by wooden diagonal struts between the eave columns and internal columns (Fig. 14).The size and arrangement of wood diagonal struts are determined by the principle of equal compressive stiffness and lateral stiffness with the adobe walls.

4.3. *The FE model of bracket set layer*

There are total 416 bracket sets in Ying-Xian timber pagoda. Although these bracket sets with various shapes and functions, they were made according to the basic rule of ***Construction Rule in Song Dynasty*** [13]. In order to reduce the FE model types, the 416 bracket sets can be classified into 22 types base on their layout and construction character, which including 17 types in the open storey and 5 types in interlayer [12]. On the basis of the experimental research of physical model of bracket sets, Jianli Yuan et al. proposed the FE modeling methods of typical bracket sets for BEAM element model and SOLID element model [14] [15], respectively. Figure 15 shows the BEAM element models of three typical bracket sets, and figure 16 shows the assembled FE models of bracket set layers in open storey and interlayer, respectively.

4.4. *The FE model of top structure of the pagoda*

As shown in figure 17, the top structure of the pagoda is composed of tower roof, laksata pedestal and laksata. In conformation, the cast iron mast of laksata is fixed into brick pedestal, and the brick pedestal is

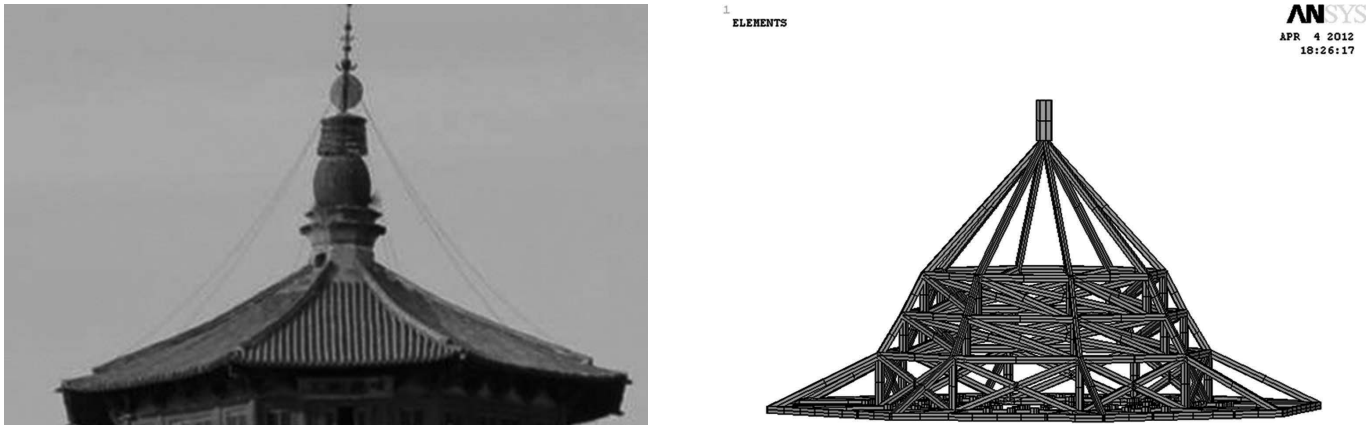

Fig. 17. *The FE model of top structure of the pagoda.*
Modello a Elementi Finiti della copertura della pagoda.

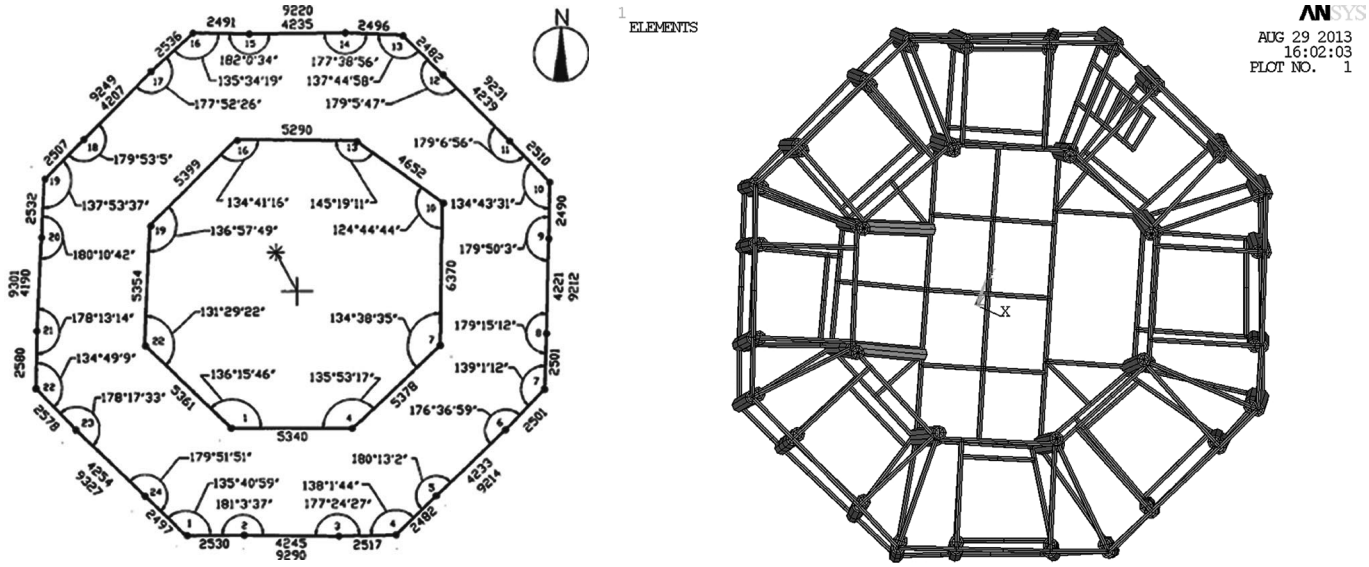

Fig. 18. *The plan of bottom of columns in second story.* (a) *The measured coordinates [8]* (b) *The plane of FE model.*
Pianta alla base delle colonne al secondo piano. *(a)* Coordinate misurate [8] *(b)* Pianta del modello a Elementi Finiti.

built on the wooden roof. During model building, following the rule of stiffness equivalence, the members of laksata pedestal and laksata are replaced by wooden diagonal poles and tie-beams, and the equivalent mass is set on the tower roof.

5. The expression of structural deformation and damaged condition of Ying-Xian timber pagoda

5.1. *The expression of structural deformation of the pagoda*

Based on the measurement data [8] and field verification [12], the total displacement of each storey and the deformations of columns and beams have been identified. The observation and analysis indicate that the displacement of the main structure as well as the deformations of beams and bracket sets is caused by inclination and displacement of columns. In the process of building finite element model of the main structure, first, an ideal situation without any deformation and displacement has been established as standard situation, and the coordinates of columns under standard situation is identified. Then, the coordinates of the columns under standard situation will be adjusted according to the actual deformation values on site. Further more, the coordinates of the architraves, beams and bracket sets connected with columns, are identified accordingly. Figure 18 shows the coordinates of the bottom of columns in second storey.

5.2. *The expression of damaged condition of structural members*

5.2.1. *The expression of damaged condition of the columns*

Ying-Xian timber pagoda includes 312 columns. The field inspection report indicates that the main damage of columns is cracking [8] [12]. Referring to the appraisal method for timber column in literature [16], the damage of columns can be classified into four types. (1) In

the first type, there is no obvious crack in the whole column and the strength bearing capability is intact. (2) In the second type, the width of the crack in the column is no more than 1cm and the length is no more than 50 cm. (3) In the third type, the width of the crack in the column is between 1 to 2.5 cm, and the length is between 50cm to 150 cm. (4) In the fourth type, the width of the crack in the column is more than 2.5cm and the length is more than 150cm. During the construction of finite element model, according to the length and width of the crack, the reduction factor of the sectional area in the damaged column is identified. The reduction factors for four types listed above are 100%, 95%, 90% and 85%, respectively.

Next, based on the three different distributions of the cracks in the height of the columns, the applying area for the sectional area reduction factor is identified. (1) For the distribution 1, the crack only lies in top, middle segment or the bottom of the column, respectively; the column is divided into three equal proportions, and each proportion is to multiply the sectional reduction factor according to the corresponding damaged type. (2) For the distribution 2, due to the crack only distributed in half of the column, the height of the column is divided into two equal proportions, and the applying area of each proportion is to multiply the corresponding sectional reduction factor, respectively. (3) For the distribution 3, due to the crack distributed in the whole column, the sectional reduction factor is applied the area of the whole column.

5.2.2. *The expression of damaged condition of the beams*

The pagoda includes 152 beams (architraves and tie-beams). Via field inspection, the beams in the first storey are intact due to the protection from the adobe wall. The beams in the second storey suffered severe damage. The damage of the beams in the third storey is less severe than the second storey. The beams in the fourth and fifth storey are intact basically.

The sectional area reduction factor is used to expression of damage of the beams. To simplify the FE model, the reduction factor is identified based on the whole damaged condition of beams in each storey. For the beams in second storey with severely damage, the sectional area reduction factor is 80%. For the beams in third storey with less damage, the reduction factor is 90%.

5.2.3. *The expression of damaged condition of the bracket set*

The pagoda includes 416 bracket sets. The field inspection indicates that the damaged condition of the bracket sets is similar to the beams. The bracket sets in the second storey suffered severe damage, and the damage of bracket sets in third storey is less severe than the second floor. The bracket sets in other stories are intact basically.

The structure of bracket set is complicated and contains various components. To simplify the FE model, the reduction factor of elasticity modulus is adopted to express the damaged condition of bracket sets. First, the reduction factor is identified based on the whole damaged condition of bracket sets in each storey. The bracket sets in second storey suffered severe damage, and the reduction factor of 80% is applied. The bracket sets suffer less damage in third storey, the reduction factor is adjusted into 90%. Next, a second reduction factor of 90% is applied again to the bracket sets in every storey with the seriously damaged components.

6. **Modal analysis of the Ying-Xian timber pagoda base on the damaged condition**

6.1. *Element type and material parameters of the FE model*

The FE model of the pagoda was built by program ANSYS. Because the main structure of the pagoda consists of beams and columns, and to reduce the total number of elements and save the computation time, the BEAM188 element is adopted as the basic element. Considering the fact that the wooden structure has been compressed for almost one thousand years and the junctures of members are close to integral connection, the joints in the FE model were managed as rigid connection.

In order to emphasize on the mechanical property of the main structure, the sectional dimensions of eaves, roof boards and tiles are not included in the model, only their mass is set up the corresponding position by adding mass method. MASS21 element is utilized to distribute the added mass of each storey to the top of eave columns and internal columns.

The pagoda was made of larch planted in northeast of China. The anisotropy material parameter was adopted in the FE model. According to the test data from the literature[4], parallel-grain elastic modulus is 2.755E10N/m^2 , the across-grain elastic modulus is 6.72E9 N/m^2, the shear modulus is GXY = GYZ = GZX = 9.54E8 N/m^2, Poisson ratio is $\mu XY = \mu YZ = \mu ZX = 0.1$, and the density is 510.2 Kg/m^3. The reduction factors of the sectional area and elastic modulus are applied to the members based corresponding damaged condition.

The FE model of the pagoda consists of 81,512 joints and 108,163 members, with total 216,652 elements, including 216,235 BEAM elements and 417 MASS elements.

6.2. *Modal analysis of the pagoda*

The modal analysis of the pagoda is carried out by subspace method, and the flexure mode shapes have been obtained (Fig.19). The frequencies of the first four order mode shapes are listed in table 1. For the comparison, the frequencies of the pagoda without damaged condition are given in table 1 also.

Tieying Li et al. [17] utilized the ambient vibration method to test the dynamic behavior of Ying-Xian

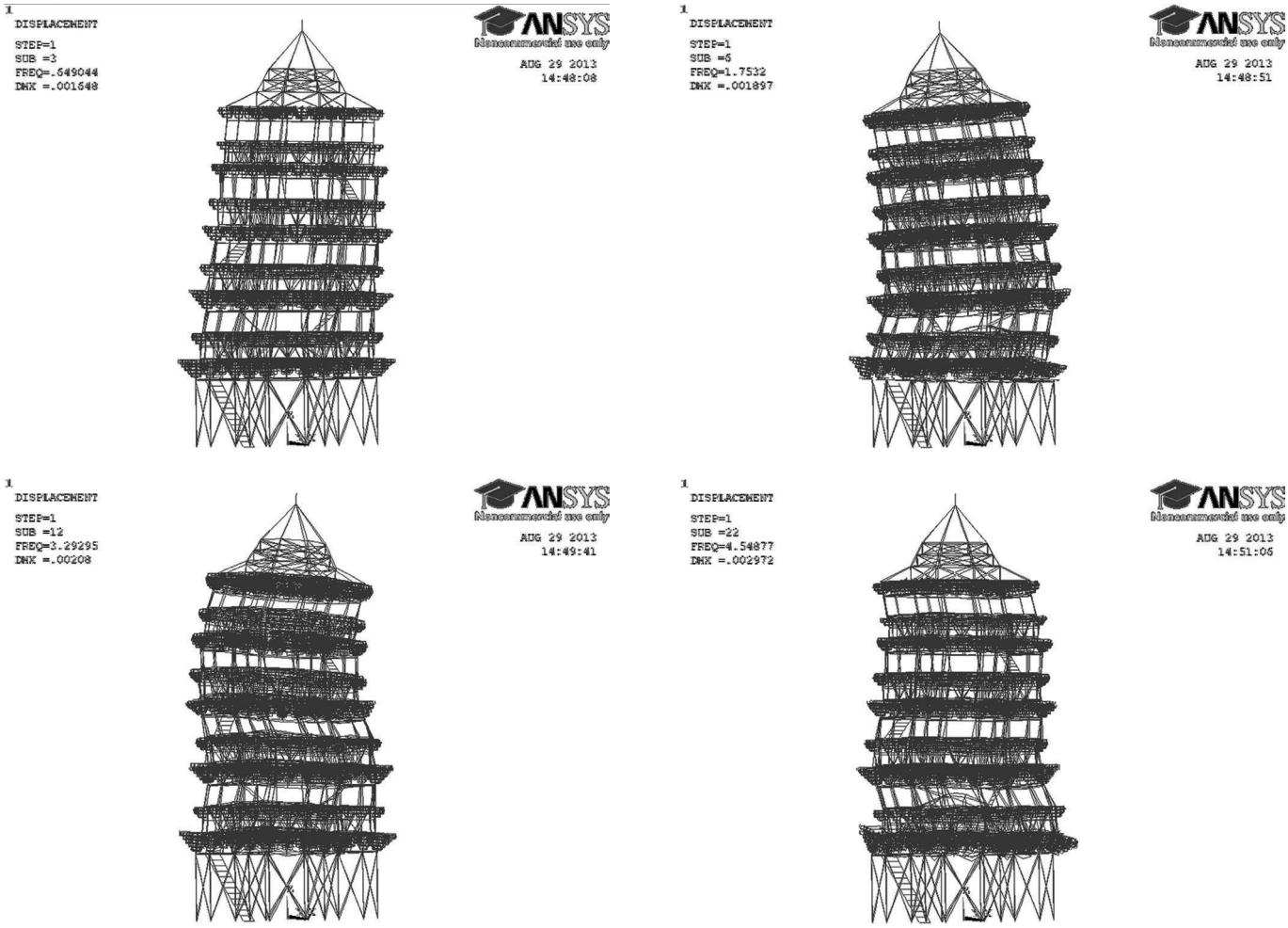

Fig. 19. *Analyzed mode shapes of the pagoda based on damaged condition. (a) First order mode shape (b) Second order mode shape (c) Third order mode shape (d) Fourth order mode shape.*
Forme modali della pagoda sulla base delle condizioni di danneggiamento. *(a)* Prima forma modale *(b)* Seconda forma modale *(c)* Terza forma modale *(d)* Quarta forma modale.

Tab. 1. *The analytical and tested frequency of first four order mode shapes.*
Frequnze analitiche e sperimentali dei primi quattro modi.

Frequency (Hz)	**First order**	**Second order**	**Third order**	**Fourth order**
Tested value on site	0.64	1.70	3.03	4.0
Analytical valve without damaged condition	0.71	1.92	3.44	4.29
Analytical value based on damaged condition	0.65	1.75	3.29	4.55

timber pagoda. The mode shapes of first-four orders obtained by this test are showed in figure 20, and the corresponding frequencies are listed in table 1 too.

The comparison of tested value and analytical value shows that, the frequencies obtained from the FE model based on damaged condition is close to the tested result on site, which validates that this FE model can effective express the dynamic behavior of the pagoda. Besides, due to the great stiffness of the first storey, the significant displacements are occurred at the second storey and third storey during the vibration process of the pagoda, which is easy to cause the deformation and damage of the second floor and third floor. This phenomenon is consistent with the current damaged condition of the Ying-Xian timber pagoda.

7. **Conclusion and suggestion**

Combined the construction research of traditional Chinese timber structures and filed investigation, an FEA model of Ying-Xian timber pagoda based on the conformation character and damaged condition has been developed. The model owns following characteristics. (1) Determined the composing relation between the main structure and the minor structures. The complicated FE model of the pagoda can be superposed by simple minor structures of open storey and interlayer. (2) Determined the deformation relation between the columns and the whole structure. By identifying the measured coordinates of 316 columns, the actual deformation condition of the pagoda is constructed. (3) Pro-

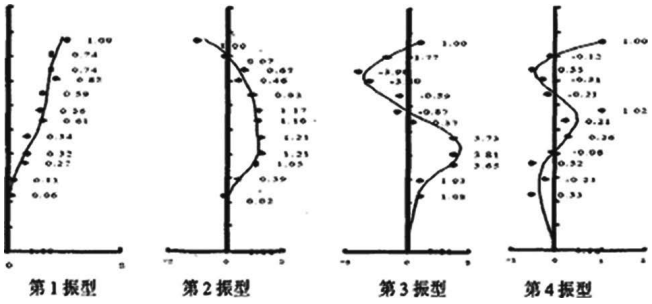

Fig. 20. *Mode shapes of the pagoda from the test* [17].
Forme modali della pagoda da vibrazioni ambientali.

posed the reduction factors of sectional area and elastic modulus to reflect the degradation of mechanical property of damaged wooden members, which can express the basic damaged condition of the pagoda reasonably.

In order to express the dynamic behavior and seismic performance of the pagoda perfectly, the following aspects need to be improved. (1) Carrying out the mechanical property test of joints of wooden members, and to establish the effective stiffness model of tenon-mortise joints that is accordant with the damaged condition of the members. (2) Deepening the research of expression technology on detailed conformation of bracket sets [15], and to develop the simple BEAM element model to express the energy dissipation behavior of bracket sets under the seismic action.

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Modello di analisi agli elementi finiti della pagoda in legno Ying-Xing basato sulla conformazione strutturale e condizione di danno

La pagoda di Ying-Xian costruita nel 1056 nel Fugong Temple della contea di Ying-Xian è la più antica ed alta pagoda in legno di tutta la Cina. Lo stato di danneggiamento dell' antica struttura, causato da numerosi terremoti ed erosione dovuta a fenomeni ambientali, è cosi significativo da richiedere un intervento di consolidamento urgente, il cui progetto di ricerca è considerato un elemento fondamentale del piano quinquennale di sviluppo culturale della Cina. Ying-Xian si erige su un basamento in muratura ed è costituita da 5 livelli strutturali, che all'esterno sono suddivisi orizontalmente così da apparire come nove. È coronata da un tetto ed un pinnacolo. La pagoda ha una pianta ottagonale ed è formata da due livelli concentrici di colonne uno interno che sostiene le scale e il piano di calpestio ed uno esterno che sostiene la falda del tetto ad ogni piano. Al piano terra c'è un terzo livello esterno di colonne in pietra. La struttura in legno della pagoda è molto elaborata con un lavoro di carpenteria finissimo, costituito da 100000 elementi circa connessi con giunti a tenone e mortasa. Particolarmente caratteristici sono i livelli sovrapposti di mensole, dette Dou-Ghon, che formano una struttura ad albero al disopra di ogni colonna e sostengono gli orizzontamenti e le falde del tetto ad ogni livello. Questi strati di mensole hanno una conformazione diversa a secondo della posizione nella struttura e rappresentano una delle realizzazioni più tipiche ed al contempo robuste dell'architettura in legno Cinese.

Misuramenti in situ ed analisi precedenti hanno evidenziato che il danneggiamento ha causato un'inclinazione laterale cospicua ed un movimento relativo torsionale tra i piani. Il danneggiamento appare più severo al secondo piano della struttura, dove lo spostamento relativo torsionale tra la base e il colmo delle colonne è superiore a 120 mm. Questa deformazione globale ha causato fessurazioni nelle colonne.

Il modello agli Elementi Finiti della struttura, descritto in questo articolo, rappresenta uno strumento efficace per descrivere accuratamente la complessa conformazione strutturale e la condizione di danneggiamento della pagoda. In particolare il metodo pratico proposto per la modellazione agli elementi finiti della pagoda si articola nei seguenti tre punti: (1) Determinazione delle interazioni tra i 5 livelli strutturali attraverso la modellazione di ogni piano in due sottostrutture, quella di piano (colonne principali e set di mensole, e colonne più basse secondarie e set di mensole. (2) Determinazione della relazione tra la deformazione delle colonne e quelle dell'intera struttura. L'implementazione nel modello delle deformazioni misurate sulle 316 colonne consente una realistica valutazione della condizione di deformazione della pagoda. (3) Proposta di fattori di riduzione della sezione e del modulo elastico per gli elementi lignei danneggiati che sono rappresentativi della condizione danneggiata della pagoda.

L'analisi agli elementi finiti è stata condotta usando il programma commerciale ANSYS. Il modello FEM è stato validato confrontando le frequenze dei primi quattro modi ottenute sul modello della pagoda nella condizione danneggiata con le corrispondenti 4 frequenze misurate con identificazione dinamica in situ. Tale modello è stato utilizzato poi per simulare la condizione non danneggiata e confrontarla con quella danneggiata. Il modello nella configurazione originaria, sottoposto ad oscillazioni libere, ha evidenziato un'accentuata deformabilità laterale e torsionale al secondo e terzo piano e quindi è consistente con l'ipotesi che la corrente condizione di danno osservata in situ sia dovuta all'azione sismica e del vento.

Una più accurata modellazione di questa struttura richiede una migliore caratterizzazione della rigidezza del giunto a tenone e una simulazione oltre il limite elastico del comportamento dei set di mensole.