Numerical simulation of seismic damage evolution of ancient masonry pagodas in China

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Abstract

The visualization of seismic damage evolution will be useful to elucidate the mechanism of damage progression of ancient masonry pagodas undergoing shock from earthquakes. The typical seismic damage features of ancient masonry pagodas are summarized in this paper. The methodologies for how to construct a dynamic elastic-plastic analysis model of masonry pagodas are probed. In addition, explicit dynamic analysis was conducted with an example of the Longhu Ancient Pagoda which is located at Deyang, Sichuan Province in China, and experienced the Wenchuan Earthquake in 2008. The evolution time-sequence of deforming, cracking, and local crushing of the Longhu Ancient Pagoda during the Wenchuan Earthquake is analysed. The visualization presents the main features of seismic damage evolution in different seismic vibrating stages and could serve as a useful reference for further research.

Keywords: Nonlinear Analysis, Ancient Masonry Pagoda, Dynamic Elasto-plasticity, Explicit Integral

1 Introduction

Due to the features of the heavy deadweight and the small natural vibration frequency, ancient masonry pagodas are vulnerable to shaking induced by large earthquakes. For example, in the high-intensity region of the Wenchuan Earthquake in 2008, the Kuiguang Pagoda (in Dujiangyan, Sichuan), the Zhengjuesi Pagoda (in Pengzhou, Sichuan), and the Longhu Stupas Pagoda (in Deyang, Sichuan) were heavily destroyed, with a large number of cracks and crushed local masonry body. Moreover, some pagodas were destroyed integrally, such as the Wenxing Pagoda (in Anxian, Sichuan), the Chongxia Pagoda (in Cangxi, Sichuan), etc. Substantial academic research has been conducted by many scholars to probe the reasons for the damage, the seismic damage evolution of masonry structures, and how to prevent similar structural failure. For example, Rocco et al. took ancient masonry towers as samples, investigated the problems of dynamic response, investigated how to abstract the plastic damage constitutive model, and described the continuum of damage in the structural dynamic behaviour analysis model for damaged masonry structures [1]-[5]. Gu applied the three-dimensional discrete element method to simulate the collapsing response in masonry structures [6]. Liu tried to simulate the seismic collapsing process for multi-story masonry structures [7]. According to the existing academic findings, it is a challenge for the numerical simulation of ancient masonry pagodas to define the nonlinearity in a dynamic analysis model, such as a discontinuous displacement field, and the structural damage process of large displacement and large rotation. Corresponding research needs to be conducted to address these issues.

Based on the explicit structural dynamic principle, the methodologies for the dynamic time-history analysis of ancient masonry pagodas are probed. The corresponding technologies for how to select elements and material models, how to correct seismic wave data, and how to build nonlinear equations are discussed. The evolving progress of seismic damage of an ancient masonry pagoda, and the visualization of the structure from deformation to destruction by using post-processing, are simulated and presented in this paper.

2 SEISMIC DAMAGE FEATURES OF ANCIENT MASONRY PAGODAS

The main seismic damage types caused by high intensity earthquakes are as follows [8]. (1) The top of the pagodas fall off or collapse. During the shaking of an earthquake, the top of the ancient pagodas might vibrate sharply and dramatically. Thus, the upper parts of masonry pagodas were easily damaged or even broken. For example, the top of the Zhongjiang Pagoda fell off during the Wenchuan Earthquake. (2) Pagodas are split along the vertical neutral axis section. Generally, in order to meet architectural requirements, masonry pagodas placed some doors and windows in the walls. Therefore, the shear capacity of the neutral axis section would be greatly reduced, and the composite effect of bending and shear in the neutral axial section of a pagoda during the shaking action of an earthquake would be greatly amplified. Thus, shear failure along the vertical neutral axial section would occur easily. This kind of damage is presented as vertical split destruction along the axial section. Fig. 1 shows the destroyed facade of the Longhu Ancient Pagoda after the Wenchuan Earthquake. (3) Pagodas crack along horizontal cross sections. When an ancient masonry pagoda is vibrating, the pagoda will flex perpendicularly to its height. As flexural tensile normal stress in the horizontal section exceeds the tensile strength of the masonry, the pagoda will crack along the horizontal section. Cracking along the horizontal cross section in the bottom of the Zhenguosi Pagoda in Pengzhou represents major seismic damage after the Wenchuan Earthquake. (4) Pagodas wholly collapse or locally crush. During the shaking action of an earthquake, the bottom-corner part of a

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pagoda is in a complex stress state of tension, compression, shear, and torsion. Consequently, the weak part of a pagoda will be seriously damaged or even collapse. For example, the Wenxing Pagoda in Anxian and the Chongxia Pagoda in Cangxi were destroyed by the Wenchuan Earthquake in this manner. (5) Pagodas tilt. Due to differences in the foundations and the distribution of weak soil, the non-uniform deformation of a pagoda's foundation will be easily produced by the shaking of an earthquake. Furthermore, the pagoda's body will lean to the weak side of the foundation. For example, the Shenba Pagoda, located near the bank of a river in Nanbu county, experienced a major tilt caused by the Wenchuan Earthquake.

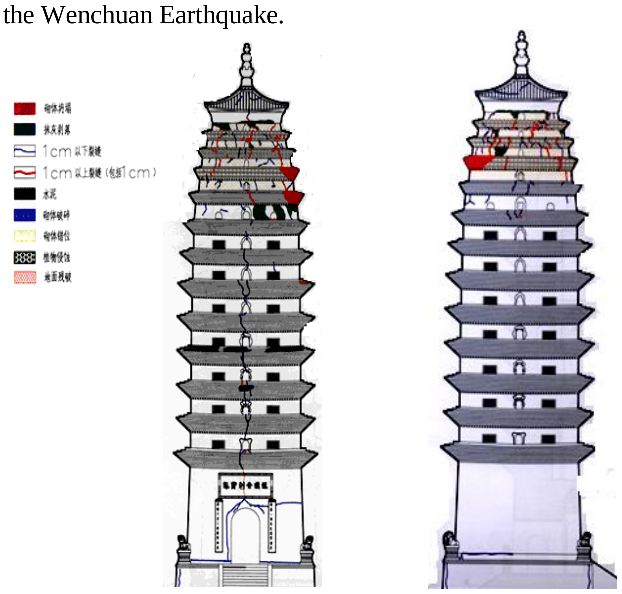


FIGURE 1 The elevation of a damaged masonry ancient pagoda

3 simulating methodologies based on explicit integral

The explicit integral method, which is based on centreed finite difference theory, can meet the requirements of nonlinear analysis of masonry structures with large deformations and discontinuities. Thus, it is suitable for simulating the seismic failure process of ancient masonry pagoda structures [7].

3.1 THE EXPLICIT DYNAMIC THEORY

Under the action of an earthquake, the dynamic equilibrium equation of a pagoda at a certain moment is as follows:

$$Ma(t)+Cv(t)+Ku(t)=F(t), \tag{1}$$

where M represents the mass matrix; a(t) represents the acceleration vector; C represents the damping matrix; V(t) represents the velocity vector; K represents the stiffness matrix; u(t) represents the displacement matrix; and F(t) represents the external force vector.

High nonlinearity is the key to simulate the seismic failure process of a masonry structure. As cracks are generated, the ways that they evolve and the stiffness degradation of masonry are quite intricate. An integral step length must be smaller than the lowest value of the natural vibration period of all elements, so as to be in agreement with the assumption that the acceleration remains the same within the time increment in the dynamic explicit integral analytical method. The integral time step is about 1/1000 ~ 1/100 that of an implicit integral.

The acceleration of each elemental node of the pagoda at the end of tn can be calculated by the following formula:

$$\{a(t_n)\}=\left[M^{-1}\right]\left(\left[F^{ext}(t_n)\right]-\left[F^{\text{int}}(t_n)\right]\right), \tag{2}$$

where a is the acceleration; M is the mass; Fext is the external force vectors on the node at the moment of tn (including the equivalent nodal force transformed from the distributed load on the elements); and Fint is the internal force vector at the moment of tn. It consists of a few parts, which are shown in the following formula:

$$F^{\text{int}}=\sum\left(\int_\Omega B^T\sigma_n d\Omega+F^{hg}\right)+F^{contact}, \tag{3}$$

where the first item on the right-hand side of the equation is the equivalent nodal force of the element stress field at the time of tn and the hourglass resistance Fhg; the nodal force is equivalent to the internal force of the dynamic equilibrium equation; BT is the strain transformed matrix; σn is the element stress; dΩ is the deformation incremental as a unit; and the second item Fcontact is the vector of contact force.

The first-order central difference of the velocity is acceleration, and the first-order central difference of the displacement is velocity. Their relationships are shown as follows:

$$[v(t_{n+\frac{1}{2}})-v(t_{n-\frac{1}{2}})]/[\frac{1}{2}(\Delta t_{n-1}+\Delta t_n)]=a(t_n), \tag{4}$$

$$[u(t_{n+\frac{1}{2}})-u(t_n)]/\Delta t_n=v(t_{n+\frac{1}{2}}), \tag{5}$$

where u, v and a represent the vectors of displacement, velocity and acceleration, respectively. The step length of the time step and time point at the start and end can be defined as follows:

$$\Delta t_{n-1}=t_n-t_{n-1},\ \Delta t_n=t_{n+1}-t_n, \tag{6}$$

$$t_{n-\frac{1}{2}}=\frac{t_n+t_{n-1}}{2},\ t_{n+\frac{1}{2}}=\frac{t_{n+1}+t_n}{2}, \tag{7}$$

where the difference formula for the nodal velocity vector and the nodal displacement vector can be defined as:

$$v(t_{n+\frac{1}{2}})=v(t_{n-\frac{1}{2}})+\frac{1}{2}a(t_n)(\Delta t_{n-1}+\Delta t_n), \tag{8}$$

$$u(t_{n+1})=u(t_n)+v(t_{n+\frac{1}{2}})\Delta t_n. \tag{9}$$

The equations which are solved with the explicit integral are all with single-variables. Moreover, they could be solved without iteration and can be converged at each step. The requirement of capacity for data storage in a computer depends on the number of elements. The speed of solving is determined by the computer CPU floating-point computation speed. So, the explicit integral method is suitable to deal with problems of the dynamic elastic-plastic time-history analysis of ancient masonry pagodas.

3.2 FAILURE ELEMENT

In order to simulate the seismic dynamic response of ancient masonry pagodas, the failure criterion of a structure is defined by the material models. As the stress or strain of a masonry element reaches a critical indicator, the masonry element will fail and be removed from subsequent calculation. Thus, the corresponding masonry elements are referred to as "failure elements". When the stress or strain of a masonry element changes at a certain calculation time, the failure masonry elements can be judged by the failure criteria immediately. The stiffness and mass of failure masonry elements are multiplied by a minimal coefficient, so that the stiffness and mass of these failure elements could contribute nothing to the pagoda structure, and the failure elements do not participate in subsequent calculations. The failure elements will also not appear in the post-processing. The failure time and location of structural elements can reflect the dynamic process of the local cracking, crushing, and collapsing in ancient masonry pagodas.

3.3 MATERIAL MODEL

The masonry equivalent volume element method is developed by using compound material mechanics [9], which treat the masonry as a periodic composite continuum. According to the constitutive relations of the masonry, the Von Mises Bilinear strengthening criterion could be chosen as a reference for the definition of relevant parameters.

3.4 SIMULATION OF STRUCTURAL DAMAGE

Dynamic analysis of the seismic damage of masonry structures involves contacting pairs, collision, and the relative slide between neighboring elements. In order to analyze the collisions between cracking parts of an ancient masonry pagoda and possible subsequent damage, algorithms for searching contact points, contact force, and friction force are adopted. In addition, the contact model for "contact – collision" dynamic analysis is constructed. The deformation equation is applied to construct a rigid surface model. The nodes or internal contact points are taken as reference points. The superficial nodes are assigned to the corresponding collections by the searching algorithm. When the possible contact pairs are searched out, local search is adopted to check whether there is any mutual penetration between neighboring elements. Then, corresponding contact pairs are activated by the algorithm for simplifying a small ball. The symmetric penalty function method is suitable for the algorithm of collision contact for ancient masonry pagodas. In the algorithm, the two surfaces which might contact are respectively termed the main surface and the secondary surface. Accompanying the calculation progress, it is determined whether the nodes have penetrated through the surface of related elements. If this occurs, a larger interface contact force should be applied between the nodes and the penetrated surfaces. The magnitude of the force is referred to as the "penalty function value", which is proportional to the penetration depth and the main slice's stiffness, so that the penetration from the nodes to the main surface could be constrained. The algorithm of the contact surface friction is determined by the contact surface roughness, velocity, pressure, etc. The model is based on the Coulomb friction equation, so that fixed connections and failure slippage could be calculated.

4 Results and discussion combined with a case

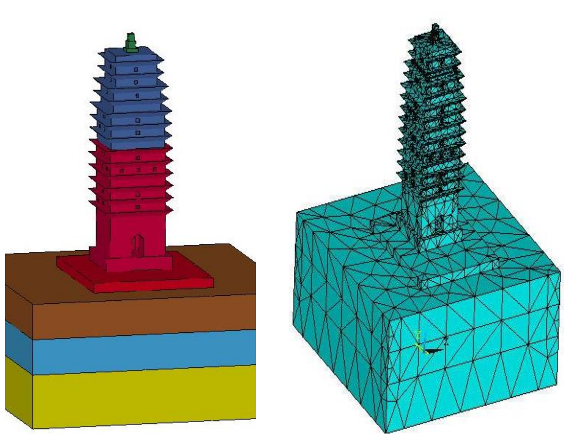
4.1 BASIC INFORMATION AND ANALYSIS MODEL

The Longhu Ancient Pagoda is located in Deyang, and was built during the Yuan Dynasty. The form of its plane is square. It is a five-story pagoda with 13-level eaves around its facade. The side length of the ground floor is 7.96 m. Its height is about 33 m. Fig. 2 shows the appearance and plane of the pagoda. Through on-site survey, mapping and testing, information regarding structural size, masonry strength, and modulus of elasticity has been acquired. Taking the contribution of gravity into account [10], the composite shear strength of masonry, respectively, is 0.131MPa, 0.125MPa, 0.161MPa, 0.186MPa, 0.213MPa, and 0.232MPa (from the top to the ground floor). The value of the nominal elastic modulus of the masonry from the first floor to fourth floor is 1.26e9Pa. The nominal elastic modulus of the masonry on the fifth floor and above is 0.637e9Pa. The pagoda was badly damaged in the Wenchuan Earthquake.

The dynamic analysis model is constructed with three-dimensional entity elements. Fig. 3(a) shows a solid model, which is considered to be the interaction of soil and the upper structure [11]. Foundation edges are applied the assumption condition with no reflection boundary. The finite element model is shown in Fig. 3(b). By comparing the frequency and vibrating modes of the on-site dynamic test with that of theoretical analysis, the dynamic analysis model is determined to be appropriate [12].

(a) (b)

FIGURE 2 (a) facade; (b) ground- and second-floor plane

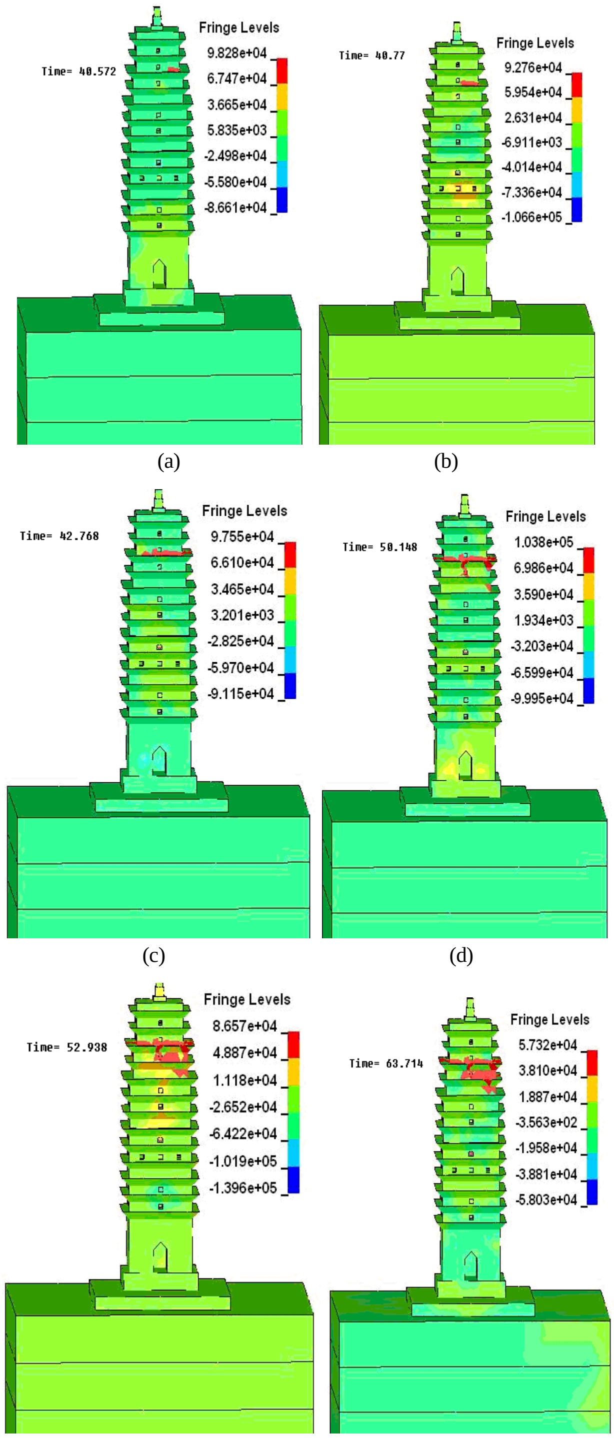


(a) (b)

FIGURE 3 Analysis model in Longhu Ancient Pagoda (a) solid model; (b) finite element analysis model

4.2 DYNAMIC RESPONSE AND DAMAGE EVOLUTION

Analysis of the seismic dynamic elastic-plastic failure process of the Longhu Ancient Pagoda is conducted with the LS- DYNA explicit dynamic analysis module. SOLID164 is a type of element which could meet the requirements for simulating the relations of contact and collision in masonry structures. The reduced integration method and viscous hourglass control are selected for the analysis of the non-uniform and large deformation of masonry whose compre-ssive capacity is greater than its tensile capacity. Plastic Kinematic is chosen as the material model of masonry. Von Mises bilinear strengthening criterion is selected as the yield criterion of masonry. In order to reproduce the seismic response progress of the Longhu Ancient Pagoda in the 2008 Wenchuan Earthquake, the raw seismic wave data of the Wenchuan Earthquake recorded at Shifangbajiao Station, which is the nearest station to the Longhu Ancient Pagoda, are selected as the input seismic wave. The original wave is filtered and corrected with Seismosignal (specialized software), so that the waveform's characteristics of the original wave are accurate by removing noise, and the sampling frequency and time interval are suitable for dynamic analysis. In this case, the time duration of the modified seismic wave is 90 s, and the time interval is 0.01 s. The peak value of ground acceleration is 0.56 g. Through the EDLOAD command in ANSYS/DYNA, the accelera-tion time history record of seismic wave is inputted. The dynamic elastic-plastic calculation and analysis of the Longhu Ancient Pagoda are performed and the related analytical data are post-processed, so that the result of the seismic response and damage evolution could be visualized and replayed in the form of animations.



(e) (f)

FIGURE 4 Shear stress nephogram of the southern facade (a) t=40.572s, (b) t=40.77 s, (c)t=42.768s, (d) t=50.148s, (e) t=52.938s, (f) t=63.714s (note: the red-brown color indicates the failure unit area in the figure)

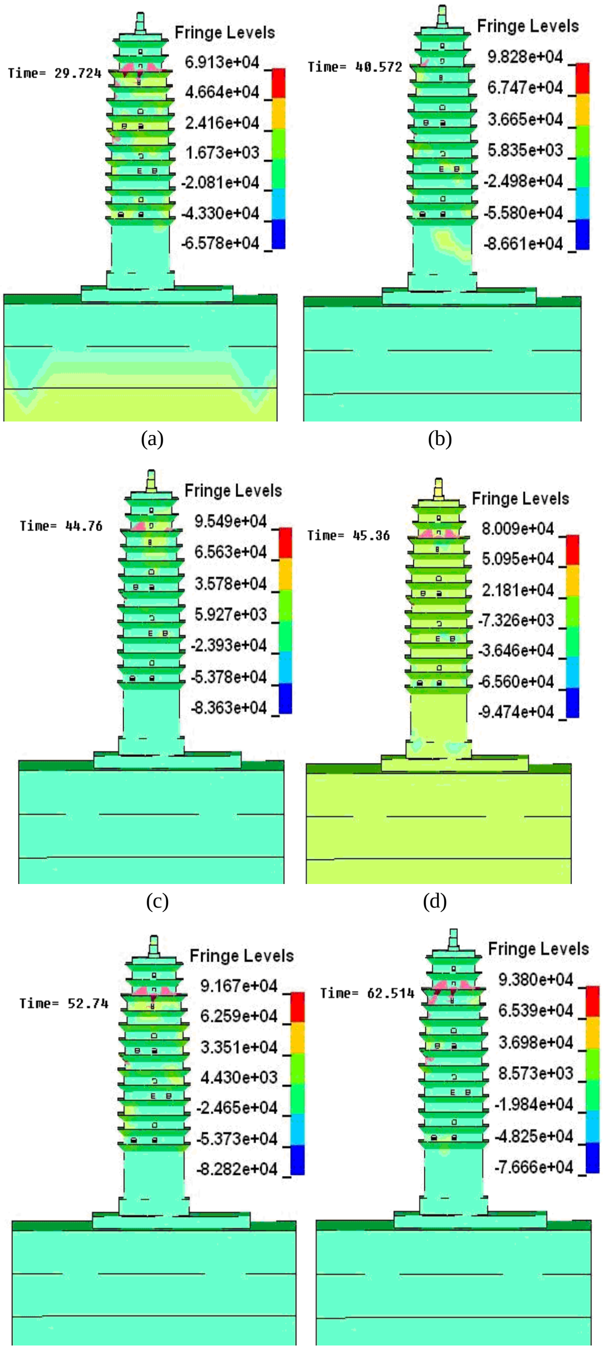


FIGURE 5 Shear stress nephogram of the western façade (a) t=29.724s, (b) t=40.572s, (c)t=44.76 s, (d) t=45.36 s, (e) t=52.74 s, (f) t=62.514s (note: the red-brown color indicates the failure unit area in the figure)

The shear stress nephogram of the southern and western facade of the Longhu Ancient Pagoda at a few different time points are shown in Fig. 4 and Fig. 5. Through further analysis of the data, the maximum horizontal shear stress in the pagoda is determined to be 0.109MPa. The corresponding part is located in the bottom of the fourth story. Moreover, the maximum vertical shear stress is 0.226MPa. The corresponding part is located in the middle of the third story, and the maximum tensile strain is 0.00172. The corresponding part is located in the bottom of the fourth story.

By comparing the shear stress nephogram in Fig. 4 and Fig. 5, it can be found that the failure elements emerge on the external side wall of the fifth story at the moment of 35.784 s. In addition, the number of failure elements increases as the vibrating time becomes longer. The outer corner of the pagoda on the fifth story collapses at the moment of 63.714 s. Many failure elements appear near the door and window area in the third and fifth stories. The failure elements emerge at the eaves in the fifth story on the western facade of the pagoda at the moment of 34.968 s. The damaged masses stop extending and increasing at the moment of 62.514 s. The extent of the damage in the western facade is not as serious as that in the northern and southern facades. The simulation results are roughly the same as the damage of the actual pagoda (the onsite investigation of the Longhu Ancient Pagoda is shown in Fig. 1). The vertical cracks mainly emerge near the central axis of the pagoda. The oblique cracks are mainly concentrated in the pagoda corners. The heavily damaged parts are located at the top of the fifth story of the pagoda.

5 Conclusion

From the above elastic-plastic dynamic analysis of the seismic response, the following conclusions could be drawn. (1) Numerical simulation and replaying the process of the seismic damage formation constitutes a new approach to studying the structural damage evolution of ancient masonry pagodas. (2) The finite element explicit dynamic algorithm based on explicit dynamic theory could meet the requirements of dynamic analysis of ancient pagodas with nonlinear problems of discontinuous displacement field, large displacement, and large rotation. (3) LS-DYNA is a useful tool for simulating the seismic response of ancient pagodas. It could accurately present the evolution of seismic deformation and damage with its post-processing module. (4) Due to the limitations of visual observation for simulating structures, determining how to observe the inner damage evolution process in ancient masonry pagodas with LS-DYNA should be explored further.

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References

[1] Rocco D, Marco M, Stefano P and Matteo P 2012 Bull Earthquake Eng. 10(4) 1221-35

[2] Marco R, Alessandra F and Pietro M. 2013 Adv. Struc. Eng. 16(5), 791-803

[3] Chavez C M and Meli R. 2010 Adv. Mater. Res, 133-134, 683-8

[4] Carpinteri A, Invernizzi S and Lacidogna G. 2005 11th Int Conf. Fract. (Turin, Italy), vol 5, International Congress on Fracture: Japan pp 3223-28

[5] Silva B, Guedes J M, Arêde A And Aníbal C 2012 Bull Earthquake Eng. 10(1), 211-34

[6] Xianglin G, Bin P and Qinghua H 2007 J. of Natural Disasters. 16(2), 92-100
[7] Haiqing L, Zhenguo N and Jinping O. 2008, J. of Earthquake Eng. and Eng. Vibration. 28(5), 38-42
[8] Pineda P, Robador M D, and Gil-Martí M A. 2011, The Open Constr. and Build. Technol. J. 5 (Suppl 1-M4),71-9
[9] Daquan W and Jianhua W 2002 J. of Chongqing Jianzhu University, 24 (4), 35-9
[10] Yong C 2011 Build. Struc. 41(2), 74-7
[11] Junlong L, Boquan L, Yin Z, Bin H and Chunyan Y 2012 Industrial Constr. 42 (6), 102-5
[12] Shengcai L, Yu L and Jianli Y. 2012 Proc. Int. Conf. on Struc. Analysis of Historical Constr (Wrocław, Poland), vol 2 DWE: Poland pp1709-15

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