International Journal of Impact Engineering 36 (2009) 1150–1155

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Photoelastic analysis of stress waves in building subjected to vertical impact under laboratory earthquake experiments

Ryoei Hayasi [a,*], Yoshiharu Masuda [b], Shozo Hashimoto [b], Shinhou Kuriyama [a]

[a] Faculty of Engineering, Saitama Institute of Technology, Fukaya, Saitama 369-0203, Japan
[b] High-Tech Research Center, Saitama Institute of Technology, Fukaya, Saitama 369-0203, Japan

ARTICLE INFO

Article history:
Received 21 May 2008
Received in revised form
2 March 2009
Accepted 3 March 2009
Available online 19 March 2009

Keywords:
Stress wave
Building
Vertical impact
Dynamic photoelastic method
Dynamic stress concentration

ABSTRACT

In an earthquake occurring directly under a city, the vertical impact induced from the source may cause a large amount of damage to a column and beam of the building. Model-based simulations are carried out with photoelastic material in order to examine the effect of a vertical impact on the building in the case of a near-field type earthquake. The dynamic photoelastic method combined with strain gages is utilized to conduct direct full field and real time observations of stress waves in a building due to vertical impact in laboratory earthquake experiments. The conditions under which vertical impact loading is applied to the model building in a controlled laboratory environment are derived from the data recorded for the 1995 Hanshin-Awaji earthquake in Japan. The experimental apparatus with which an impact of a longitudinal stress pulse is able to be applied to a model of a real building is shown. It is estimated from our earthquake simulations that large dynamic stress concentrations are produced in the beam–column joints of the building by the vertical impact arising from a seismic source located directly below a surface.

1. Introduction

The Kobe area sustained heavy damage from the Hanshin-Awaji earthquake of Richter-magnitude 7.2 on 17 January 1995 in Japan. The earthquake is to be classified as a near-field type. In a case of near-field earthquake a large vertical impact in a short duration of shock is generated in the initial stages of earthquake, thereafter a transverse vibration continues for several seconds. Significance of the vertical impact arising from near-field earthquake had been underestimated since buildings and structures were destroyed by the transverse vibration of long duration. It was shown by Kawata, on the other hand, that a method of longitudinal stress wave analysis, different from a conventional lateral vibration analysis, is an effective means of examining a propagation behavior of stress waves in columns of structure [1], and was pointed out that the first axial longitudinal impact may cause great damage to an architectural column [2].

Dynamic stress distribution in bounded solid media has been a problem of interest in engineering for many years. In a study of stress wave propagation behavior in complex shaped solids, it is necessary to observe the stress wave field not only on a surface of a solid but also within the solid. The dynamic photoelastic technique is a powerful tool for analyzing dynamic stress distribution, which utilizes a birefringence exhibited by some transparent materials, and provides an experimental method of visualizing the stress wave field at discrete times over an entire dynamic event [3]. Xia et al. [4–6] employed the photoelastic technique combined with high-speed photography, and observed the earthquake rupture processes in the two-dimensional model composed of two photoelastic plates in the laboratory experiments. Kawata et al. [7] examined the dynamic stress concentration in a column under axial impact through use of two methods, i.e. the dynamic photoelastic method and the longitudinal stress wave analysis method. In this study, we carried out model-based simulations in order to know what would happen to the building due to vertical impact. The dynamic photoelastic method in combination with strain gages is used to analyze dynamic stress distribution caused in the model building subjected to impact of a longitudinal stress pulse.

The purpose of this paper is to examine dynamic stress distribution produced in a building by vertical impact of short duration, and to verify visually that this vertical impact can create a large amount of damage to the columns and beams of the structure.

2. Modeling of simulation system

A building system is simulated by two-dimensional modeling of a real building heavily damaged in the Hanshin-Awaji earthquake

* Corresponding author. Tel.: +81 48 585 6870; fax: +81 48 585 7207.
E-mail address: hayasi@sit.ac.jp (R. Hayasi).

0734-743X/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijimpeng.2009.03.003

[8], and the experimental conditions under which the vertical impact loading is applied to the model are derived using the similarity law. A shape and size of the model building are decided on a condition that the model and real buildings have a size-ratio of 1–50, and the ratio is symbolically denoted by $B = X_M/X_R$, X being the length, where M and R in the suffix denote the model and the real, respectively.

A vertical impact setup by the sinusoidal load of frequency $\omega/2\pi$ is assumed to be applied to the model during one period, where ω is the angular frequency, and consequently acceleration a, velocity v and displacement x of the load are given by

$$a = A\cos\omega t, \tag{1}$$

$$v = (A/\omega)\sin\omega t = V\sin\omega t, \tag{2}$$

$$x = -(V/\omega)\cos\omega t = -X\cos\omega t, \tag{3}$$

where A, V and X are amplitudes of acceleration, velocity and displacement, respectively. The period $T = 2\pi/\omega$ is equal to Λ/C, where Λ is the wavelength of the vibration and C is the speed of propagation of impact stress wave, so that

$$T_M/T_R = \Lambda_M C_R/\Lambda_R C_M = B(C_R/C_M), \tag{4}$$

$$\omega_M/\omega_R = T_R/T_M = (1/B)(C_M/C_R). \tag{5}$$

From Eqs. (3) and (5) we obtain

$$V_M/V_R = X_M\omega_M/X_R\omega_R = C_M/C_R. \tag{6}$$

From Eqs. (2), (5) and (6) we obtain

$$A_M/A_R = V_M\omega_M/V_R\omega_R = (1/B)(C_M/C_R)^2. \tag{7}$$

Hence from Eqs. (4), (6) and (7) derived by using the similarity law, the relations of the period, velocity and acceleration of the load between model and real building can be represented as

$$T_M = B(C_R/C_M)T_R, \tag{8}$$

$$V_M = (C_M/C_R)V_R, \tag{9}$$

$$A_M = (1/B)(C_M/C_R)^2 A_R. \tag{10}$$

From data on the vertical vibration in the Hanshin-Awaji earthquake observed in the Kobe Marine Observatory, the values of maximum acceleration and maximum velocity are as follows:

$$A_R = 332\,\text{gal} = 3.32\,\text{m/s}^2,\; V_R = 0.4\,\text{m/s}.$$

Using A_R and V_R, the period and maximum displacement in real building system can be estimated as

$$T_R = 2\pi V_R/A_R = 0.75\,\text{s},\; X_R = A_R(T_R/2\pi)^2 = 0.049\,\text{m}.$$

The M building is adopted, which was a 5-story commercial reinforced concrete building, and was reported as a real building heavily damaged in the earthquake [8]. Young's modulus E_R, density ρ_R and Poisson's ratio ν_R for the building are then approximately $E_R = 19.3$ GPa, $\rho_R = 2400\,\text{kg/m}^3$ and $\nu_R = 0.2$, so that the propagation speed of longitudinal stress wave in the real building is estimated as $C_R = \sqrt{E_R/\rho_R(1-\nu_R^2)} = 2894\,\text{m/s}$ [9]. On the other hand, a model building is made of an epoxy resin plate of 6 mm in thickness, so the material constants for the model are $E_M = 3.5$ GPa, $\rho_M = 1200\,\text{kg/m}^3$ and $\nu_M = 0.41$. The propagation speed of longitudinal stress wave in the model building is given by $C_M = \sqrt{E_M/\rho_M(1-\nu_M^2)} = 1872\,\text{m/s}$. By using C_R and C_M, displacement X_M, velocity V_M, acceleration A_M and period T_M of load for the model building are evaluated from Eqs. (8), (9) and (10) as:

$$X_M = BX_R = 0.98\,\text{mm} \cong 1\,\text{mm},\; V_M = (C_M/C_R)V_R = 0.26\,\text{m/s},$$

$$A_M = (1/B)(C_M/C_R)^2 A_R = 69.5\,\text{m/s}^2,\; T_M = B(C_R/C_M)T_R = 0.023\,\text{s}.$$

On the basis of these calculations, the experimental equipment is designed to give a vertical displacement of 2 mm to the model building with a velocity of 0.26 m/s. In deriving the above numerical results, we have assumed that stress waves propagate through linear elastic medium, although the response of the building to seismic vibration was clearly non-linear.

Dimensions of columns and beams in the real and model buildings are shown in Table 1, and the static loads on their columns are shown in Table 2. The cross-section of column in the real building is square in shape.

3. Experimental apparatus and experiment

An experimental apparatus was constructed under conditions calculated in the previous section. The vertical impact loading is simulated by uniaxial compression and tension exerted at a bottom of the building system with convex and concave guides.

Fig. 1 illustrates displacement in vertical compressive impact and a shape of convex guide which causes a longitudinal compressive stress pulse to the model building. A form of the guide is not sinusoidal, but is approximated by the form with two linear slopes. Fig. 2 shows a schematic diagram of the building system and the experimental apparatus with which vertical displacement of 2 mm is given to the model building with a velocity of around 0.26 m/s. The vertical displacement is caused by the guide with a bump of linear slope 2 mm/25 mm as shown in Fig. 1. Similarly, a concave guide of linear slope 2 mm/25 mm was prepared as shown by a broken line in Fig. 2 in order to generate incident tensile stress by a vertical impact loading. Compressive springs were designed to force the guide of 50 mm in width to move a distance of 50 mm horizontally for one period of around 0.023 s, whose wire diameters are $d = 4.5$ mm and 5.0 mm. Weights of lead were used as the loads applied to columns in the model building statically. The static loads on the columns are around 0.1 times as small as those which should be actually applied to the model in order to do no damage to the model due to vertical impact. In the model and real buildings, two and three beams are connected to one column as shown in Fig. 3, respectively. Hence in the model building the stress or strain, actually produced in the columns becomes approximately 20/3 times as large as the experimentally measured value.

Table 1
Dimensions of the real and the model for the M building (unit: mm).

Floor	Sectional dimension of column		Long side of beam		Distance between adjacent columns		Height of floor	
	Real	Model	Real	Model	Real	Model	Real	Model
R			600	12				
5	400	8.0	600	12	4800	96	3000	60
4	420	8.4	600	12	4800	96	3000	60
3	460	9.2	600	12	4800	96	3000	60
2	500	10.0	600	12	4800	96	3000	60
1	560	11.2	800	16	4800	96	3600	72