누적된 손상을 입은 구조물의 거동

A Study on Cumulative Structural Damage

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ABSTRACT

비보강 조적조는 비균일재료로 이루어진 합성재료에 가까우므로 그거동이 하중종류와 구조물의 손상정도에 따라서 매우 달라지게 된다. 본 연구에서는 작은 지진부터 큰 지진까지 수차례의 모의지진을 받는 구조물의 손상거동을 살펴보기 위한 방법으로, 시간영역 자료를 여러구간으로 나누어서 주파수가 어떻게 변화해 가는지 살펴보았다. 또한 주파수와 강도와의 관계식을 이용하여 단자유도계의 이선형모델도 유도하였다. 하중이 커짐에 따라서 이선형 모델의 강성은 계속적으로 저하됨을 알 수 있다. 실제로 실험결과는 누적된 손상을 받는 구조물의 거동이므로, 조적조의 수치해석적 모델의 개발시 이러한 누적된 손상효과를 합리적으로 처리해야 되는 문제점이 있다.

1. Introduction

During the last decades intensive experimental research on unreinforced masonry (URM) structure subjected to seismic loading has been carried out to understand seismic behavior of URM structures. Different testing procedures including static and dynamic, cyclic and monotonic procedures have been used in order to simulate the effects of seismic loads. Unlike homogeneous material structure, the behavior of masonry structure is not perfectly elastic even in the range of small deformations because it is a nonhomogeneous and anisotropic composite structural material, consisting of masonry units, mortar, steel reinforcement, and grout. Many shake-table experimentations for URM structures have been done by applying a series of successive ground motions with varying shaking intensities to a test structure. And the experimental test results reveal that the structural performance depends on loading types and the extent of residual damage. Therefore experimental evaluation of URM structures must be considered differently than any other types of structures. This paper proposes a simplified way of investigating the evolution of the deformation and damage of the structure tested on shaking table and outlines some critical issues that must be addressed to make a quantitative assessment of the seismic lateral loading capacity of the test structure.

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2. Investigation of Frequency Changes

Research on vibration based damage identification has been expanding rapidly over the last decade. In this paper windowed Fourier analysis will be adopted to investigate the evolution of the deformation and damage of the URM structure which was tested on shaking table (Kim and Kim 2004). To investigate changes of frequencies of the test structure during shaking, the complete time-history of each load step was analyzed by moving the time window along the whole duration of the test. The dominant frequency of the displacement response for several intervals was found using the FFT algorithm and then associated with the time corresponding to the center of each segment. Since the ability of the FFT to represent the frequency spectrum of the input signal depends very heavily on the number of the input signal data points being processed, a size of window must be selected as large as to provide an acceptable frequency resolution in the FFT. After some trials, it was decided to move the time window along the time-history at intervals shown in Table 1 to realistically capture the evolution of the vibration frequency of the test structure. Some of the signal data were overlapped. All the signal data were band-pass filtered in the frequency ranges of (0.0, 0.5, 14, 19.5).

Table 1. Window time duration

Time segment	Seg 1	Seg 2	Seg 3	Seg 4	Seg 5	Seg 6	Seg 7
Time duration (sec)	0 – 7.5	7-12	9-14	11-16	15-20	20-27.5	27.5-40.96

Table 2 summarizes the results of frequency analysis made for all the load steps using the displacement and acceleration time-history records. The peak values of displacement and acceleration for each time segment are also provided in the table. The values of the frequency analysis for the whole time-story records provide dominant values of the test structure for each load step while those of time segmental analyses reveal the evolution of frequency change for each load step. Comparison of the two results of frequency analyses for the displacement and acceleration time-histories shows that the test structure oscillated essentially with the same one frequency. Note that the dominant frequency for the whole time-history record is the same as that of Seg 4 where the peak displacement and acceleration of the load step occurred.

The reduction of the fundamental vibration frequency was first made during the run of LS4 which was about 23%. It is evident that the structure suffered a noticeable degradation in its lateral stiffness and probably went through several cycles of inelastic deformation. Note that the frequency of the oscillations towards the end of the test was almost restored to the original value at the beginning. Further reduction of the fundamental frequency did not occurr during the run of LS5, which indicated that in this case the stiffness degradation was not so dramatic. In the run of LS6, the fundamental vibration frequency was one more time reduced significantly by about 20%. Again, the structure suffered another noticeable degradation in its lateral stiffness. Then, the same pattern of the frequency change of LS6 appeared during the run of LS7, which indicated that in this case the stiffness did not degrade further.

Table 2. Results of FFT Analysis along time windows

		Whole	Seg 1	Seg 2	Seg 3	Seg 4	Seg 5	Seg 6	Seg 7
LS1 0.05g	D	13.0	5.46	12.4	12.3	13.0	12.9	12.9	5.46
	A	13.0	12.9	12.4	12.3	13.0	12.9	12.9	12.98
	dm	0.189	0.014	0.1	0.189	0.189	0.038	0.03	0.012
	am	0.177	0.008	0.1	0.177	0.177	0.047	0.034	0.012
LS2 0.1g	D	13.0	5.56	12.4	12.3	13.0	12.9	12.9	5.51
	A	13.0	13.6	12.5	12.3	13.0	12.9	12.9	5.76
	dm	0.502	0.01	0.271	0.502	0.502	0.101	0.049	0.016
	am	0.323	0.005	0.204	0.323	0.323	0.09	0.047	0.015
LS3 0.15g	D	13.0	12.9	12.4	12.3	13.0	13.2	12.9	12.9
	A	13.0	12.9	12.4	12.3	13.0	13.2	12.9	12.9
	dm	1.137	0.022	0.73	1.137	1.137	0.313	0.165	0.025
	am	0.546	0.022	0.374	0.546	0.546	0.191	0.113	0.027
LS4 0.2g	D	8.78	12.4	12.4	12.3	8.78	12.9	12.9	12.5
	A	8.78	12.9	12.5	12.3	8.78	12.9	12.95	12.8
	dm	2.094	0.038	1.412	2.094	2.094	0.663	0.335	0.041
	am	0.84	0.038	0.626	0.84	0.84	0.347	0.218	0.041
LS5 0.25g	D	8.78	12.9	5.61	5.64	8.78	12.9	12.9	12.9
	A	8.78	12.9	5.61	5.64	8.78	12.9	12.9	12.9
	dm	2.897	0.115	1.915	2.897	2.897	0.988	0.534	0.073
	am	0.802	0.083	0.67	0.802	0.802	0.365	0.246	0.046
LS6 0.3g	D	5.64	12.9	5.61	5.64	5.7	10.5	12.9	12.5
	A	5.64	12.9	5.61	5.64	5.7	10.5	12.9	12.8
	dm	3.627	0.062	2.4	3.627	3.627	1.089	0.641	0.09
	am	0.938	0.045	0.759	0.938	0.938	0.4	0.272	0.067
LS7 0.35g	D	5.64	12.9	5.59	5.61	5.73	7.66	12.9	12.8
	A	5.64	12.9	5.59	5.61	5.73	7.66	12.9	12.8
	dm	4.634	0.084	3.02	4.634	4.634	1.244	0.705	0.119
	am	0.952	0.064	0.796	0.952	0.952	0.456	0.317	0.076

*D: displacement time history
*A: acceleration time history

3. Correlation of Frequency with Stiffness

Assuming that frequency changes are very closely related with stiffness changes, the results obtained from the frequency analysis of the response of URM can be used to relate the variation of the vibration frequency of the structure with the variation of its mechanical property. The linearization of the response is achieved by defining an average stiffness, K, which depends on the frequency value. When a structure is considered as a single degree of freedom system with mass M and lateral stiffness K, its vibration frequency f is written as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{1}$$

Using Eq. (1), if the vibration frequency during a certain time interval is known, the corresponding average stiffness is given by the following equation:

$$K = M(2\pi f)^2 \tag{2}$$

For the initial frequency f_0, the initial elastic stiffness can therefore be evaluated as follows:

$$K_0 = M(2\pi f_0)^2 \tag{3}$$

Combining equations of (2) and (3) yields the following expression:

$$K = K_0\left(\frac{f}{f_0}\right)^2 \tag{4}$$

The results of FFT analysis for the run of LS7 are summarized in the 2nd column of Table 3. Moreover, the ratio of frequency changes and the ratio of the corresponding stiffness changes are evaluated using the equations described above and given in the 3rd and the 4th columns of Table 3 respectively. The frequency value had been significantly dropped during run of Seg 3 where the test structure experienced the noticeable damage. After this, values of the frequency did not present significant changes. Figure 1 plots the average stiffness for each segment in comparison with the initial stiffness obtained for the first segment Seg. 1. It seems that the slope of the average stiffness obtained by transforming the frequency value is very close to the average slope of force-displacement curve ranging from the maximum values of displacements and accelerations in the previous segment to the maximum values in the current segment. Note that the ratio of the average stiffness is closer to that of the tangential values. Therefore, it is possible to state that the average stiffness represents the tangential stiffness of the concerned segment not the stiffness of the whole time duration.

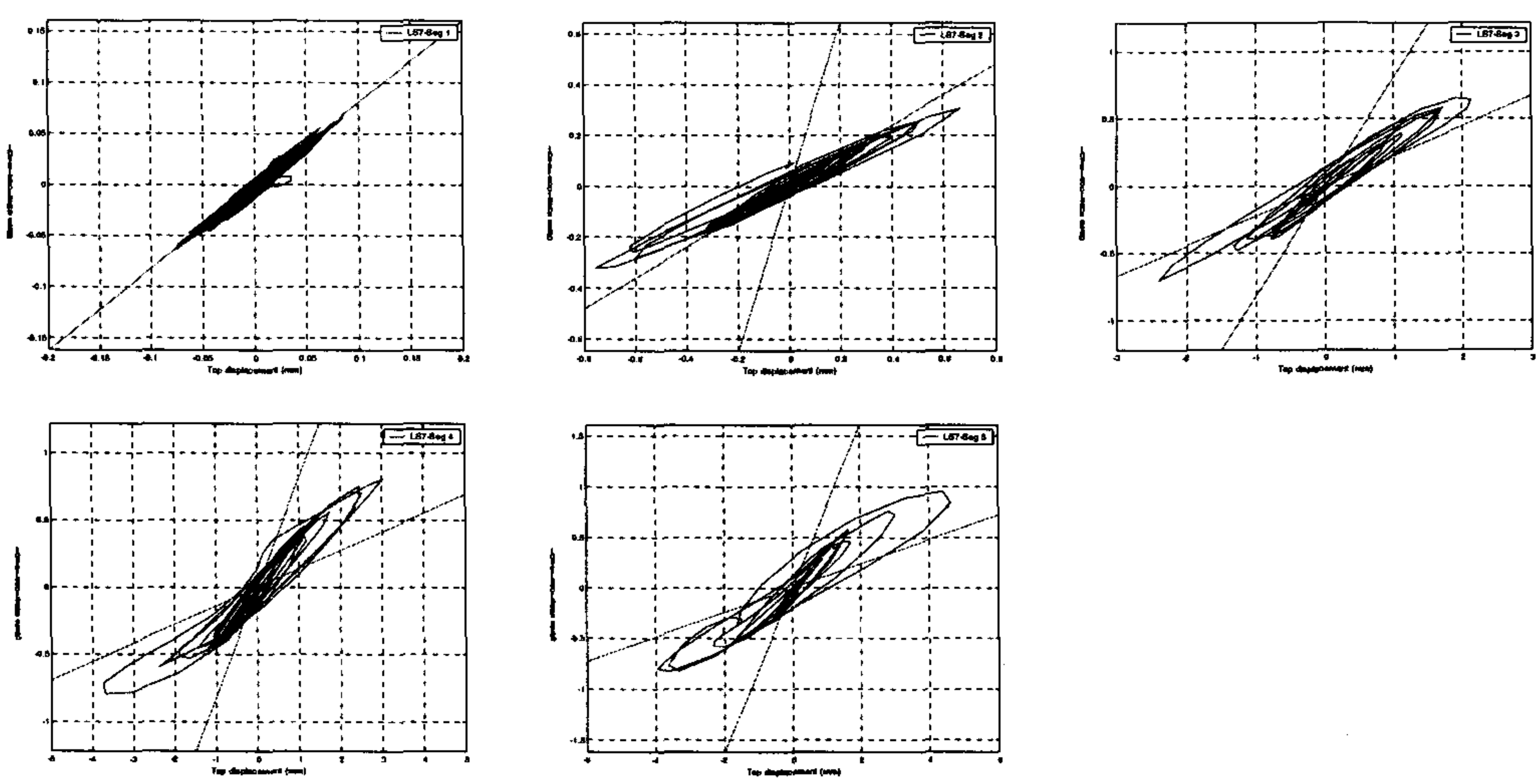

Figure 1. Stiffness changes during the run of LS7

Table 3. Frequency changes and corresponding stiffness changes in the run of LS7

Seg No.	f_i (Hz)	f_i / f_0	K_i / K_0
1	12.909	1.000	1.000
2	11.127	0.862	0.743
3	6.784	0.526	0.276
4	5.320	0.412	0.170
5	5.539	0.429	0.184

4. Approximation of Bi-linear Curve

In this study a bi-linear curve was developed to be used for an equivalent SDOF system to the URM structure. The development of the bi-linear curve grounded on frequency changes of the test structure using the equations discussed previously. The completion of the model needs of defining its yield resistance R_y, its initial elastic stiffness K_o, the maximum displacement, d_{max} , (not necessarily the maximum displacement during the interval under consideration), and its tangential stiffness K_t. Note that the tangential stiffness K_t is determined by the representative tangential stiffness for the ranges where the frequency values had been dramatically reduced. Finally, the stiffness model of the structure can therefore be completely defined in terms of its mass M, its initial and average vibration frequencies, f_0 and f, and its resistance, R_y, whose value can be obtained from the measured values using engineer's insight.

Figure 2 plots the bi-linear curves for each load step from LS1 thru LS7. Note that the initial stiffness has been decreased continuously as the extent of the damage of the test structure has been increased. Also, the bi-linear curves represent the structural behavior for the structure which was continuously damaged not for the undamaged. Therefore, the development of numerical analytic model will be different depending on the experimental test results to be used. For example, if the development of the numerical model begins with the test results of LS1, then the pushover curve may follow the dotted line of Figure 1 which accompanies large differences from the other test results.

4. Conclusions

When the URM test structure on the shaking table subjected to a series of successive ground motions with varying shaking intensities, the experimental test results revealed that the structural performance included a considerable amount of residual damage. Therefore experimental evaluation of URM structures must be considered differently than any other types of structures. This paper adopted the windowed Fourier analysis as a simplified way of investigating the evolution of the deformation and damage of the structure tested on shaking table. However, there still remain many uncertain critical issues to be addressed to make a quantitative assessment of the seismic lateral loading capacity of the test structure.

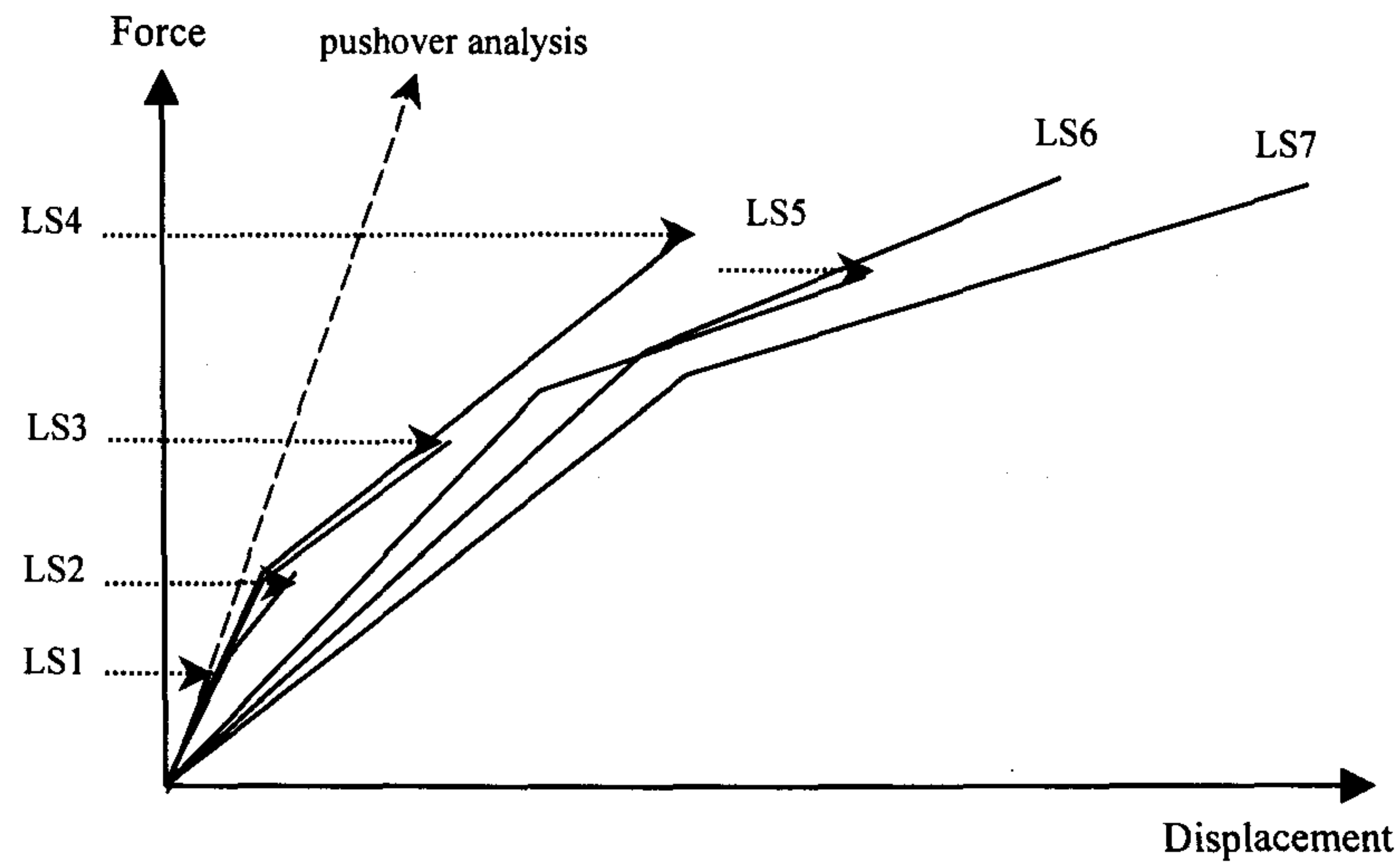

Figure 2. Bi-linear Curves

Reference

1. Bruneau, Michel (1994), State-of-the-Art Report on Seismic Performance of Unreinforced Masonry Buildings, Journal of Structural Engineering, ASCE, Vol. 120, No.1, pp. 230-251.

2. Costley, A. C. and Abrams, D. P. (1996), Dynamic Response of Unreinforced Masonry Buildings with Flexible Diaphragms, Report No. NCEER-96-0001, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Buffalo, New York, USA.

3. Kim, Namhee and Kim, Jaekwan (2004), Dynamic Response of Unreinforced Masonry Building, Journal of Earthquake Engineering Society of Korea, EESK, Vol. 8, No. 5, pp. 1-14.