HOKKAIDO UNIVERSITY

Title	IMPACT OF CONSTRUCTION SEQUENCE ON STUCTUAL SEISMIC PERFORMANCE - A VIRTUAL LOAD METHOD
Author(s)	ZHAO, X.; DONG, P. W.
Description	The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan.
Relation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan, E-3-6.
Citation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), E-3-6
Issue Date	2013-09-12
Doc URL	https://hdl.handle.net/2115/54352
Type	conference paper
File Information	easec13-E-3-6.pdf

Hokkaido University Collection of Scholarly and Academic Papers

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

IMPACT OF CONSTRUCTION SEQUENCE ON STUCTUAL SEISMIC PERFORMANCE – A VIRTUAL LOAD METHOD

X. ZHAO[1], P.W. DONG[2*]

[1]*Tongji Architectural Design (Group) Co., Ltd., China*
[2]*Department of Building Engineering, Tongji University, China*

ABSTRACT

The consideration of the construction sequence of buildings under gravity load will significantly change the internal forces of the structural members, especially for super high-rise and long span structures. The elasto-plastic performance assessment of building structures under earthquakes commonly start with the internal forces of structural members under gravity load. Due to its loading history dependent behavior, the seismic performance of the building structures will be different with different initial internal forces under moderate rare earthquakes. However, the construction sequence of building structures is commonly not considered during the seismic assessment process in practices due to the high computing capacity and complicated algorithm requirements. An innovative virtual load method is proposed in this study to evaluate the impact of construction sequence on the seismic performance of building structures. By using the virtual load vectors, the proposed method can reproduce the construction sequence based internal forces of critical structural members using traditional gravity load analysis method. A reinforced concrete moment frame structure is employed in this study to illustrate the application of the virtual load method. Inelastic time history analysis procedure was finally applied to assess the impact of construction sequence on the structural performance of the structure under rare earthquake. From the comparative study, one can find that the consideration of construction sequence will not only result in different plastic hinges time instants and positions, but also will change the acceleration and displacement responses.

Keywords: seismic performance, construction sequence, virtual load method.

1. INTRODUCTION

The building structures are time dependent during construction by nature, for the loadings, material properties and structural systems vary with the construction process. The consideration of the construction sequence of buildings under gravity load will significantly change the internal forces of the structural members, especially for super high-rise and long span structures (Xia 2007, Fang 1997, Zhang 2011, Liu 2011 and Zhao 2011). The impact of construction sequence is widely considered during the design and construction of super high-rise and long span under elastic behavior scenarios. However, for those scenarios which have to consider elasto-plastic behavior of building structures, the impact of construction sequence is rarely considered in practice.

The elasto-plastic performance assessment of building structures under earthquakes commonly start with the internal forces of structural members under gravity load. Due to its loading history

* Corresponding author: Email: 463110106@qq.com

dependent behavior (Chen 2004), the seismic performance of the building structures will be different with different initial internal forces, especially under rare earthquakes. However, the construction sequence is commonly not considered during the seismic assessment process in practice due to the high computing capacity and complicated algorithm requirements.

An innovative virtual load method is proposed in this study to evaluate the impact of construction sequence on the seismic performance of building structures. The core idea of the virtual load method is to simulate the construction sequence based internal forces of critical structural members using traditional gravity analysis by introducing the virtual load vectors.

2. VIRTUAL LOAD METHOD FOR CONSTRUCTION SEQUENCE SIMULATION

The introducing of virtual load is to simulate the construction sequence based internal forces of critical structural members using traditional gravity load analysis method. The building structures can be generally considered elastic under gravity load. According to superposition principle of the elastic system, a set of virtual load vectors are constructed and applied at the same time with gravity load to obtain the internal forces of critical structural members. The virtual load vectors have to be carefully constructed to ensure that the obtained internal forces from traditional gravity analysis are almost the same as those obtained from construction sequence based gravity analysis.

The virtual load vectors are constructed using basis virtual loads. A basis virtual load can be a unit load which is an element distribution load or a node concentrated load. The virtual load vector can be expressed as linear combination of some basis virtual loads. The combination coefficients can be obtained by equating the internal forces obtained from traditional gravity analysis and construction sequence based gravity analysis.

A two storey reinforced concrete (RC) moment resisting frame was taken as an example to explain the virtual load method. The parameters of the structural model are listed as follows: beam span l=6m, storey height H=4m, strength grade of concrete C30，elasticity modulus E=3×10^{10} Pa， Poisson's ratio v=0.2, column section 500mm×500mm， beam section 250mm×400mm. Gravity load q=24kN/m was applied on the beam. The structural analysis sketch is shown in Figure 1.

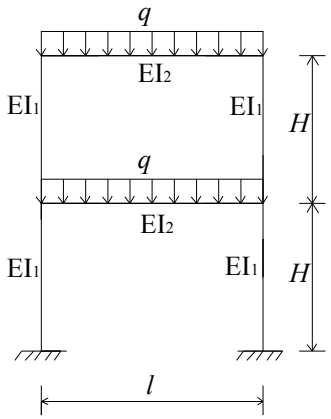


Figure 1 : Structural analysis sketch.

For a frame structure, the end moments of columns and beams and the axial forces of columns are key internal forces for elasto-plastic analysis. In the case that no vertical load applied as basis virtual load, the key internal forces can just be end moments. For the symmetric structure and

moment's equilibrium condition, the key internal forces can just be end moments of left columns. Then, the four internal forces are the key condition for date fitting. The four internal forces of loading at a time and construction sequence simulation were listed in Table 1, and they were represented by vectors $\boldsymbol{f_0}$ and $\boldsymbol{f_1}$ respectively. The difference of the two vectors can be called key internal force vector $\Delta\boldsymbol{f}$:

$$\Delta\boldsymbol{f} = \begin{pmatrix} \Delta f_1 \\ \Delta f_2 \\ \vdots \\ \Delta f_n \end{pmatrix} = \boldsymbol{f}_1 - \boldsymbol{f}_0 = \begin{pmatrix} 25001 \\ 49878 \\ 17876 \\ 65417 \end{pmatrix} - \begin{pmatrix} 11747 \\ 22311 \\ 47886 \\ 66945 \end{pmatrix} = \begin{pmatrix} 13254 \\ 27567 \\ -30010 \\ -1528 \end{pmatrix} \tag{1}$$

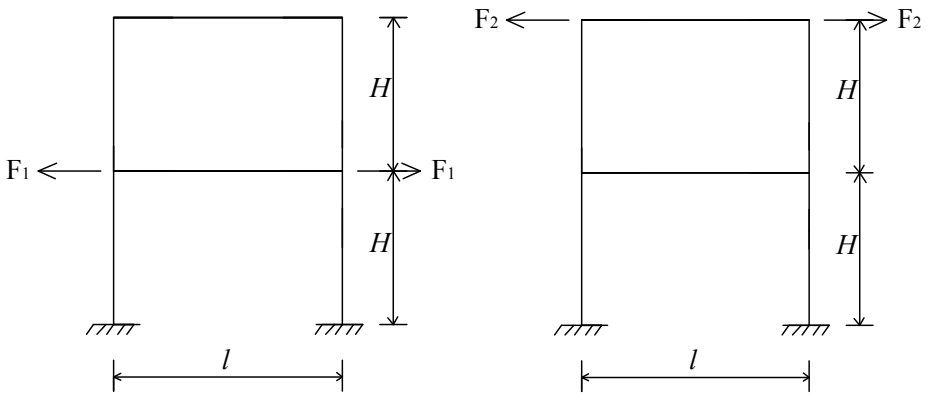
where Δf_i is the i_{th} internal force of vector $\Delta\boldsymbol{f}$, n is number of key internal forces.

Table 1 The key internal forces of left columns of related load cases

Position of left columns	$\boldsymbol{f_1}$	$\boldsymbol{f_0}$	$\Delta\boldsymbol{f}$	F_1=1kN	F_2=1kN
Bottom moment of the first story	25001	11747	13254	49.4	-7.88
Top moment of the first story	49878	22311	27567	42.3	-16.43
Bottom moment of the second story	17876	47886	-30010	-41.1	17.89
Top moment of the second story	65417	66945	-1528	-5	3.86

Note: the unit of the moment is N.m; F_1 and F_2 are load cases of basis virtual load.

The selection of basis virtual loads should considering type of the key internal forces. In this case, the basis virtual load can be selected as horizontal concentrated force couple. Figure 2 has shown the selected basis virtual load F_1 and F_2.



（a）F_1=1kN　　（b）F_2=1kN

Figure 2 : Basis virtual load.

The key internal forces of basis virtual load F_1 and F_2 were also listed in Table 1. Then the internal force matrix of basis virtual load can be obtained from Table 1, which was expressed as:

$$\boldsymbol{S}_{n\times m} = \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1m} \\ s_{21} & s_{22} & \cdots & s_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nm} \end{pmatrix} = \begin{pmatrix} 49.4 & -7.88 \\ 42.3 & -16.43 \\ -41.1 & 17.89 \\ -5 & 3.86 \end{pmatrix} \tag{2}$$

Where, m is the number of basis virtual loads, s_{ij} is the i_{th} key internal force of the j_{th} basis virtual load case. A virtual load can be expressed as linear combination of some basis virtual loads. The combination coefficients can be represented by vector $\boldsymbol{c}$:

$$\boldsymbol{c} = \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{pmatrix} \tag{3}$$

where, c_i is combination coefficient of the i_{th} basis virtual load case. To make the key internal forces of the virtual load case equal to that of $\Delta\boldsymbol{f}$, equations were established as:

$$\boldsymbol{S} \times \boldsymbol{c} = \Delta\boldsymbol{f} \tag{4}$$

In this case, equations were established as:

$$\begin{pmatrix} 49.4 & -7.88 \\ 42.3 & -16.43 \\ -41.1 & 17.89 \\ -5 & 3.86 \end{pmatrix} \times \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} 13254 \\ 27567 \\ -30010 \\ -1528 \end{pmatrix} \tag{5}$$

As the rank of matrix $\boldsymbol{S}$ is less than the dimension of vector $\Delta\boldsymbol{f}$. The solution of the equations is approximate below:

$$\boldsymbol{c} = \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} \approx \begin{pmatrix} 33 \\ -1558 \end{pmatrix} \tag{6}$$

A virtual load was obtained and expressed as:

$$L_V = 33 * F_1 - 1558 * F_2 \tag{7}$$

An equivalent load case for construction simulation was obtained:

$$L_{EQ} = L_V + \text{Gravity} = 33 * F_1 - 1558 * F_2 + \text{Gravity} \tag{8}$$

The equivalent load case was shown in Figure 3, and the key internal forces of this load case were listed in Table 2. One can find from Figure 3 that the internal forces of equivalent load case are very close to that of construction simulation $\boldsymbol{f_1}$. The equivalent load case in Figure 3 can then be taken as the case of construction simulation.

Table 2 The key internal forces of the equivalent load case

Position of left columns	$\boldsymbol{f_1}$	$\boldsymbol{f_0}$	L_{EQ}	$\boldsymbol{f_0}$ / $\boldsymbol{f_1}$	L_{EQ} / $\boldsymbol{f_1}$
Bottom moment of the first story	25001	11747	25658	47%	103%
Top moment of the first story	49878	22311	49312	45%	99%
Bottom moment of the second story	17876	47886	18649	268%	104%
Top moment of the second story	65417	66945	60765	102%	93%

Note: the unit of the moment is N.m; F_1 and F_2 are load cases of basis virtual load.

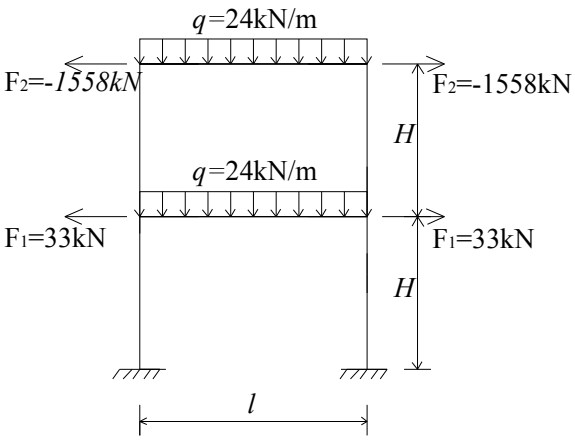


Figure 3 : Sketch of the equivalent load case.

3. ELASTO-PLASTIC ANALYSIS CONSIDERING CONSETRUCTION SEQUENCE

As aforementioned, the structural status obtained under both virtual loads and gravity load shown in Figure 3 was equivalent to the structural status obtained under construction sequence based gravity load analysis. To compare the seismic performance of building structures under traditional gravity load analysis and construction sequence based gravity load analysis, elasto-plastic analyses under rare earthquake were conducted on both structures shown in Figure 3 and Figure 1.

Inelastic finite element method was employed to do the elasto-plastic analysis. FEMA beam element property was applied on beams and FEMA column element property was applied on columns to simulate the elasto-plastic behavior. P-M interaction was considered in column elements.

The El Centro N-S earthquake ground motion was used as seismic input here, which was shown in figure 4. It is recorded in CALIF in 1940, which has a record step 0.02, acceleration amplitude 341.7gal, and a duration time 30s.

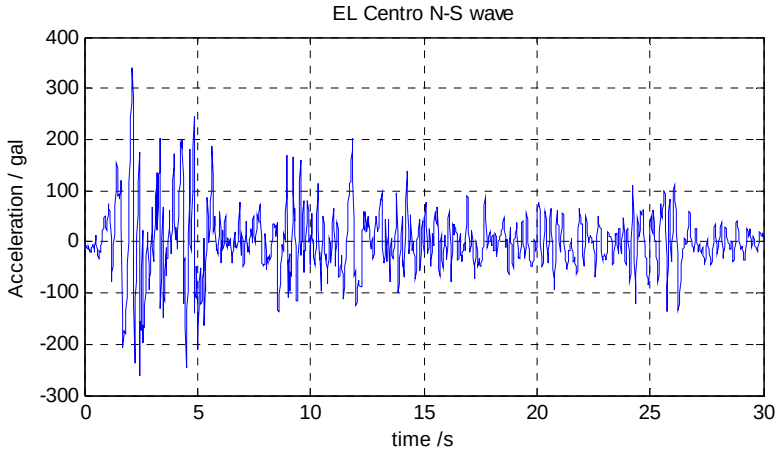
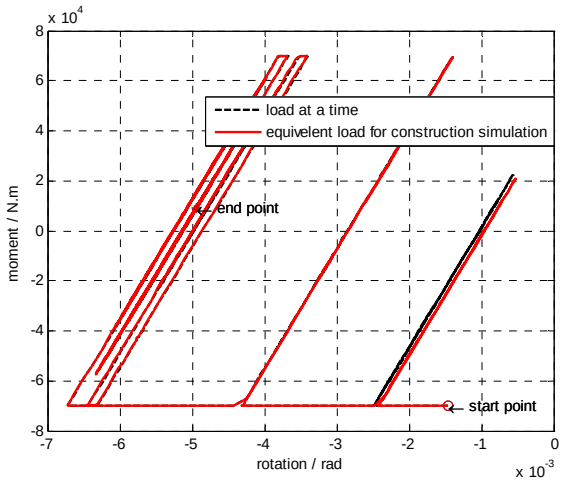
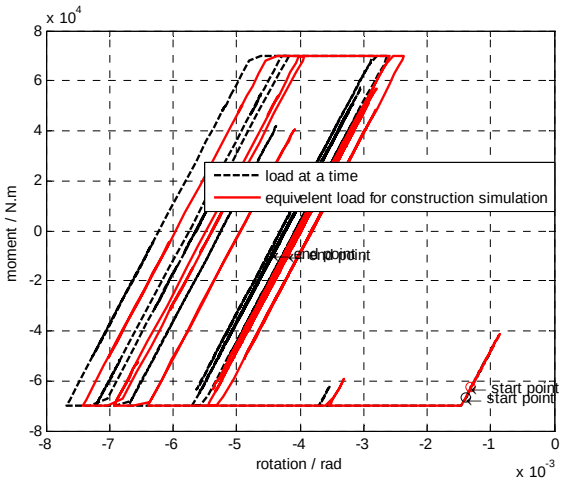


Figure 4 : Time history of El Centro N-S earthquake ground motion.

The different behaviors of the two structures were presented by moment-rotation hysteresis loops of plastic hinges of structural component in Figure 5 and Figure 6.

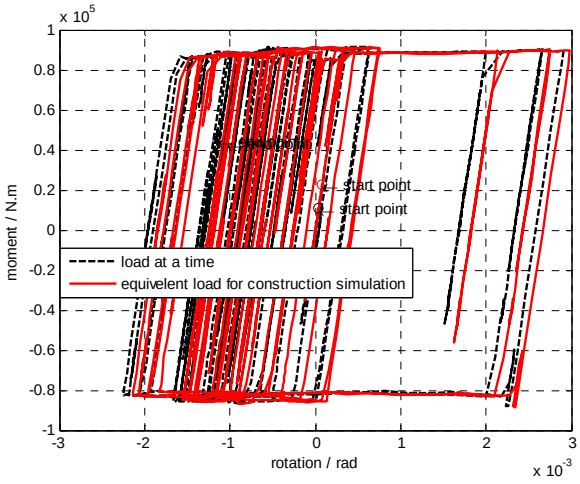


（a）Left end of the beam of first storey

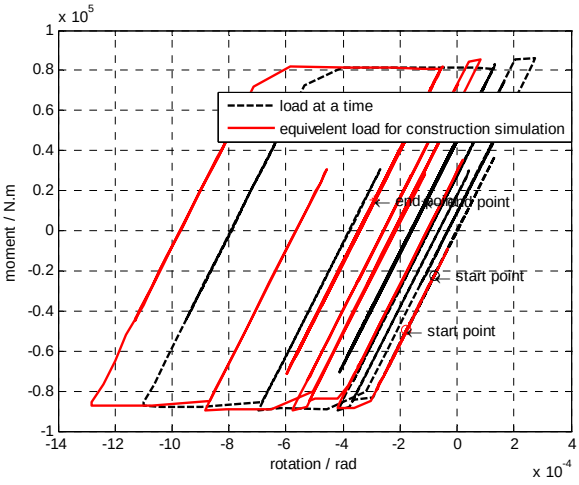


（b）Left end of the beam of second storey

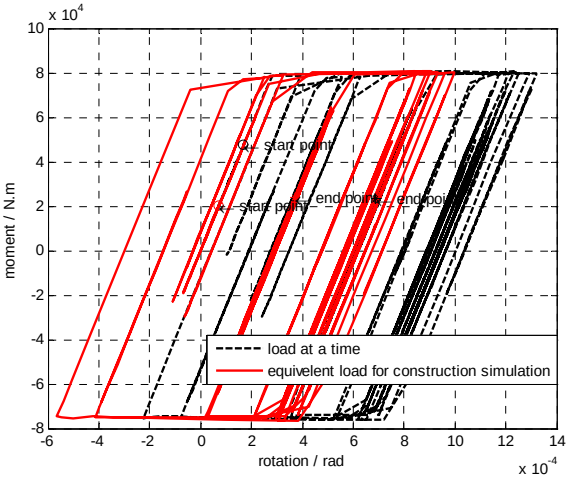
Figure 5 : Moment-rotation hysteresis loops of plastic hinges of beams.



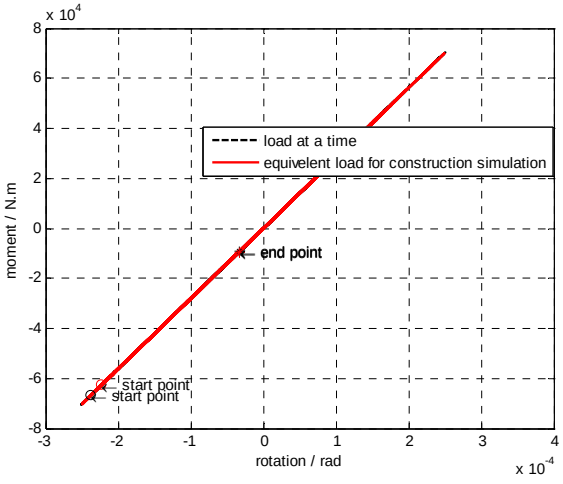
（a）Bottom of the left column of first storey



（b）Top of the left column of first storey



（c）Bottom of the left column of second storey



（d）Top of the left column of second storey

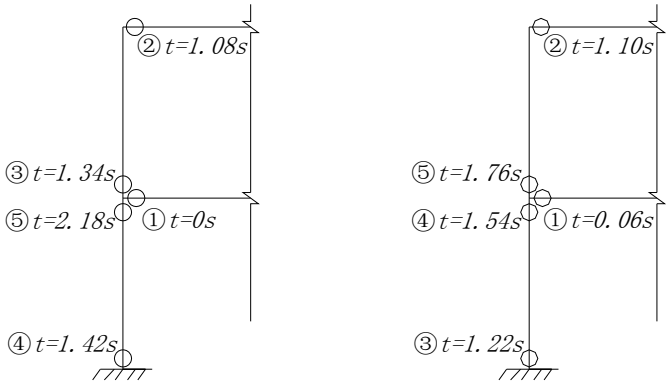
Figure 6 : Moment-rotation hysteresis loops of plastic hinges of columns.

It can be seen from Figure 5 and Figure 6 that plastic hinges are developed in end of components,

except the top of left column of second storey. The initial time of the plastic hinges was listed in Table 3, as well as the end moments and rotations of the components. The developing sequence of plastic hinges of the left half of the structures was shown in Figure7.

Table 3 The initial time of the plastic hinges

Position of the plastic hinges	Loading at a time			Equivalent load case		
	Time /s	Moment /N.m	Rotation /rad	Time /s	Moment /N.m	Rotation /rad
Left end of first-storey beam	0.00	-70000	-1.46E-03	0.06	-70000	-1.46E-03
Left end of second-storey beam	1.08	-70000	-1.46E-03	1.10	-70000	-1.46E-03
Bottom of the left first-storey column	1.42	88400	3.41E-04	1.22	88000	3.13E-04
Top of the left first-storey column	2.18	-84400	-3.63E-04	1.54	-88400	-3.63E-04
Bottom of the left second-storey column	1.34	78900	3.70E-04	1.76	79800	4.78E-04



（a）Loading at a time　　（b）Equivalent load case

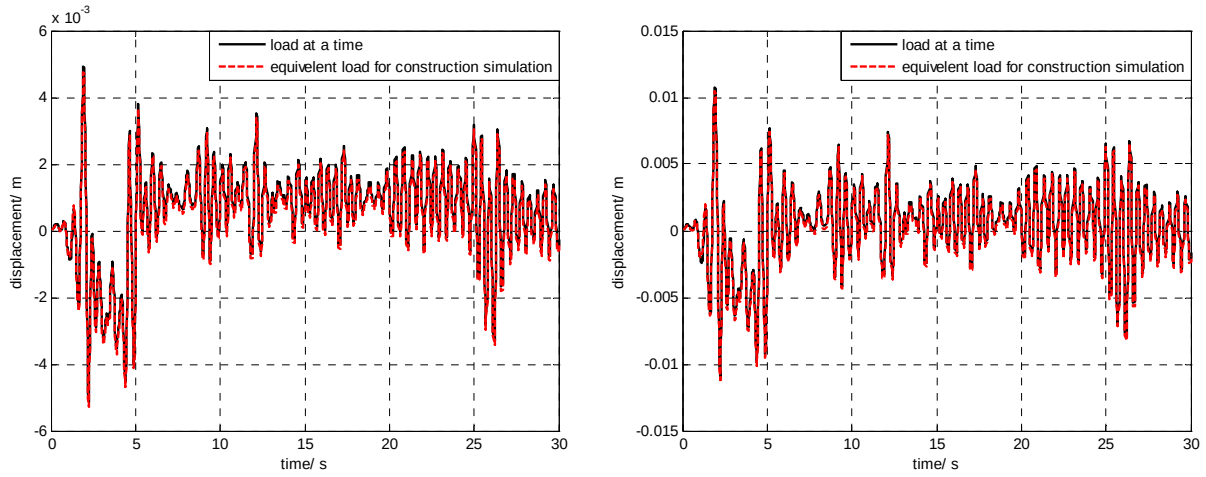
Figure 7 : Sketch of developing sequence of plastic hinges of the left half structures.

It can be seen that the initial structural internal force of the two structures are different, which has made the developing time and level of plastic hinges different under rare earthquake ground motion (see Figure 5~7). For example, the initial moments at bottom of the left second-storey column of the two structures are very different, thus influencing the developing time and level of plastic hinge very much (see Figure 6(c)). The overall responses of the two structures under rare earthquake ground motion were shown in Table 4 and Figure 8.

Table 4 Overall responses of the two structures under rare earthquake ground motion

	Storey	Loading at a time	Equivalent load case	Ratio
Storey shear (N)	first	86372	86261	0.999
	second	73601	73792	1.003
Overturning moment (N.m)	first	440273	441394	1.003
	second	295450	295984	1.002
Displacement (m)	first	0.00513	0.0526	1.025
	second	0.0109	0.0112	1.018

Note: "Ratio" means ratio of the value of equivalent load case to that of loading at a time.



（a）First storey　　（b）Second storey

Figure 8: Time history of node displacement under rare earthquake ground motion.

It can be seen that the overall responses of the two structures under rare earthquake ground motion have little difference. It means that the local plastic development has little influence on the overall response. This can be explained by that the developing sequence of plastic hinges has little influence on the story stiffness.

4. CONCLUSIONS

A virtual load method was proposed in this paper to assess the impact of construction sequence on the seismic performance of building structures. A two story RC frame structure is employed to illustrate the effectiveness of the proposed method. According to the virtual load method based assessment results, the consideration of construction sequence will not only change the local plastic development of critical structural members, but also result in different overall responses under rare earthquake.

5. ACKNOWLEGEMENT

The authors gratefully acknowledge the financial support provided by the Post Shanghai Rising-Star Program (11QH1402700) of Science and Technology Committee of Shanghai.

REFERENCES

Xia XH (2007). Research on the effects of construction progress and dynamic behavior of tall hybrid-structures, Ph. D. thesis, Department of Civil Engineering, Hunan University.

Fang YM and Wei CJ (1997). Comment on construction simulation analysis methods of high-rise building structures. Journal of Shanghai Tiedao University (Natural Science). 18(4), pp. 50-54.

Zhang PP (2011). Time-varying effect analysis of super tall composite building, MS. thesis, Department of Civil Engineering, Tongji University.

Liu NX (2011). Performance Research and Control during Construction of High-rise Mixed Structure with Outriggers, MS. thesis, Department of Civil Engineering, Tongji University.

Zhao X, Liu NX, Sun HH, Zheng YM, Ding JM (2011). Structural performance assessment and control of super high-rise building during construction. Journal of Building Structures. 32(7), pp. 22-30.

Chen HF (2004). Elasticity and Plasticity. China Architecture & Building Press.