Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 4920-4927

ECCOMAS Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

DETAILED FEM ANALYSIS FOR FULL SCALE STEEL STRUCTURE CONSIDERING FRACTURE OF BEAM ENDS

Yasunori Mizushima[1], Yoichi Mukai[2], and Tomoharu Saruwatari[3]

[1] Research & Development Institute, Takenaka Corporation
1-5-1 Ohtsuka, Inzai-shi, Chiba 270-1395, Japan
e-mail: mizushima.yasunori@takenaka.co.jp

[2] Department of Architecture, Kobe University
1-1 Rokodai-cho, Nada-ku, Kobe-shi, Hyogo 657-0013, Japan
ymukai@port.kobe-u.ac.jp

[3] Engineering Technology Division, JSOL Corporation
2-2-4 Tosabori, Nishi-ku, Osaka-shi, Osaka 550-0001, Japan
saruwatari.tom@jsol.co.jp

Keywords: FEM, Detailed Model, Fracture, Full Scale Shaking Table Test

Abstract. *This paper reports a non-linear analysis of a steel structure using a large-scale and detailed finite element model considering fracture phenomenon. The shaking-table test results of a 3-story full-scale steel frame structure, which were carried out at E-defense in 2013, are evaluated analytically in this paper. The analytical model used in this study is intended to replicate adequately entire shape of target steel frame structure specimen, assembling huge numbers of tiny finite elements. The damage index is introduced as the fracture criterion on steel members model for execution of FE simulations. Elements whose damage index has been reached to 1.0 are eliminated in our way of FEM analyses. The damage index shows a good correlation with the occurrence of the fracture observed in the experimental test. The timing of the first fracture of the beam end in the analysis mostly match well to that of the experiment. In addition, the structural responses obtained by the analysis agree with those of the experiment.*

.

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5772.17313

1 INTRODUCTION

There are some reports about high-precision finite-element analysis of building structure investigating their dynamic response under seismic loadings. Miyamura *et al*. report that non-linear behavior of shaking table test of a 4-story steel building can be replicated by using a fine meshed FE model with solid elements [1]. The authors also report about FE analysis examining a full-scale shaking table test of a 3-story steel structure that is the analytical target of this paper modeling mainly shell elements [2], [3]. These reports conclude that FE models that are finely meshed to reproduce the entire shape of structures as precisely as possible can appropriately replicate non-linear behaviors of building structures under earthquake excitations.

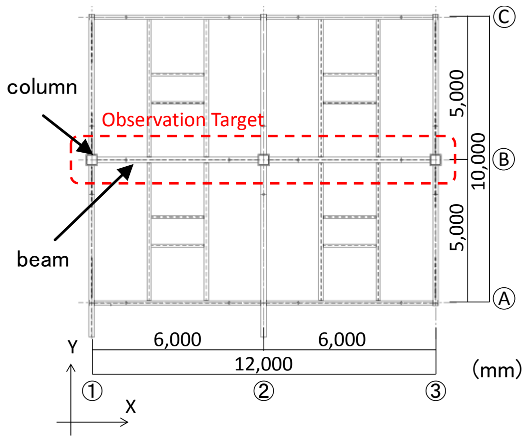
However, there are few studies that try to predict fracture behavior of members may lead to fatal collapse of buildings by using finely meshed FE models of whole building structure. Above-referenced three reports [1], [2], [3] do not simulate fracture of members in their analytical procedures. In the referenced report [1], the analytical target was the case wherein a collapse of the structure was observed because of not fracture but local buckling of the first-story columns. In the authors' previous report [3], fracture of members is not predicted but a pseudo fractures are demonstrated by eliminating elements in areas wherein the fracture occurred actually in the experimental test.

In this study, FE-analysis with consideration of fracture using damage index as failure criterion is performed for the tested structure, wherein fracture of beam ends was observed. The analytical target is a full-scale shaking table test of a 3-story steel structure as in the previous study [3]. The accuracy of the prediction for fracture-occurring timing at the steel members and validity of responses obtained by numerical simulation are investigated.

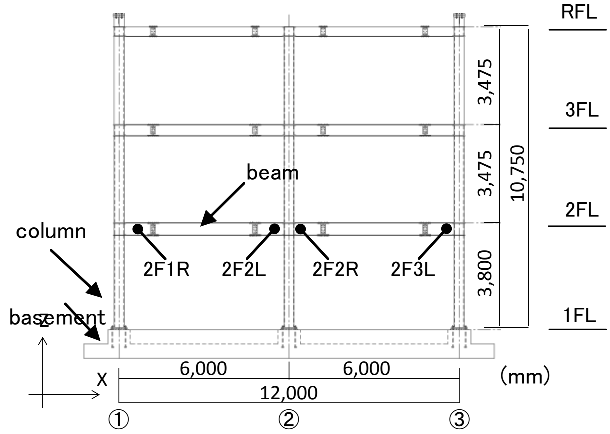
2 OUTLINE OF ANALYTICAL TARGET FOR SIMULATING SHAKING TABLE TEST

The analytical target is a 3-story and 2-bay steel frame structure that was used for a full scale shaking table test in 2013 at E-defense[4]. During multiple seismic strong motion inputs in the shaking table test, fractures of beam ends of this frame structural specimen were observed.

The specimen for the shaking table test is shown in Figure 1. Only the single frame on the center line in x-direction (line B in Figure 1) was a moment resistant frame. Columns on outside lines, which are shown as line A and C in Figure 1, were provided with hinges at both their top and bottom ends not to be resist horizontal loads. The columns and beams were made of square-shaped tube and H-shaped steel, respectively. The reinforced concrete slabs were constructed on steel deck plates.



(a) Frame Plan at 2nd floor



(b) Frame Elevation on Line B

Figure 1: Outline of 3-story steel frame structure specimen

From a series of performed cases in the experiments, the case wherein fracture at beam ends was observed was focused as analytical target case. The experiments were conducted using a seismic input motion, the NS-direction component of JR Takatori records of the Hyogoken-Nambu earthquake in 1995 (JR-Takatori) as shown in Figure 2and a synthetic input motion, Nankai-Trough earthquake (Nankai) which is artificially generated. Nine experimental cases were carried out with adjusted scale of the input motions. Input motions and scale factors of acceleration amplitude of each experimental case are listed in Table 1. The case of JR-Takatori 100% (full scale acceleration) is the analytical target case in this study because fracture of beam ends was observed.

Sequence No.	Excitation	Factor	Remarks
1	Nankai	50%	
2	Nankai	100%	
3	JR-Takatori	40%	
4	JR-Takatori	60%	Non-linearity was clearly observed during the test (Considered as excitation history in analysis)
5	JR-Takatori	80%	Non-linearity was clearly observed in several cycles during the test (Considered as excitation history in analysis)
6	JR-Takatori	100%	Analytical Target, Fractures were observed.
7	Nankai	50%	
8	Nankai	100%	
9	Nankai	150%	

Table 1: Shaking input-sequence through experiments

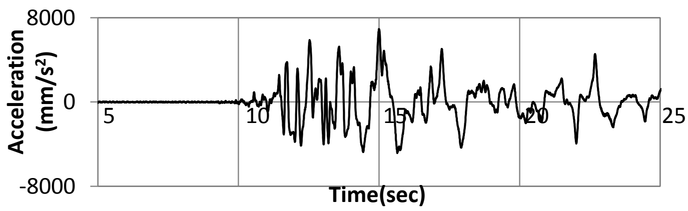


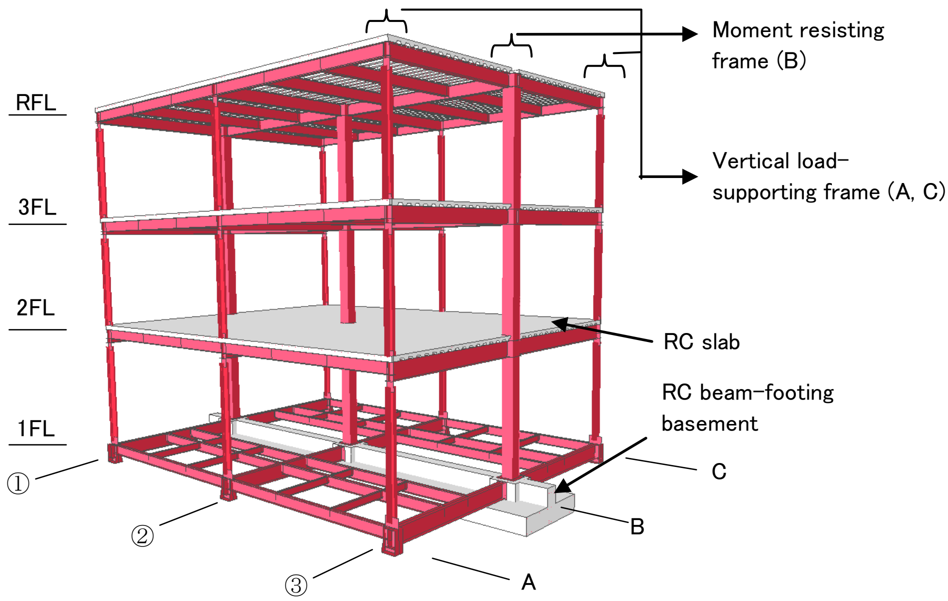
Figure 2: Seismic acceleration wave form of JR-Takatori

3 ANALYTICAL MODEL

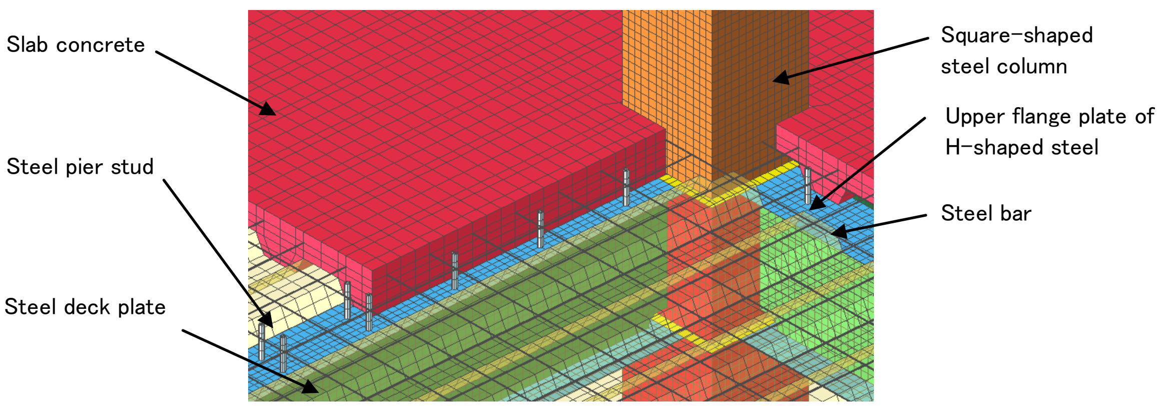
3.1 Finite Element Model and Computational Resources

The finite element model used in this study is elaborated to replicate adequately entire shape of the specimen assembling with over 2 million tiny elements, as shown in Figure 3. Shell, solid and beam elements are used for steel members, for concrete parts and for reinforcement bars, headed stud and anchor bolts in the model, respectively. Contact condition was considered for adopting to parts that was actually in contact between separated members. The further modeling details are described in previous studies [3], [4]. It is confirmed that natural periods obtained by eigenvalue analysis using this model agree with observed result of the actual specimen in the previous study [3].

The dynamic explicit method based on the central difference method is adopted for the time integration scheme using FE analysis code LS-DYNA. The time steps used in the analysis are determined from the Courant condition with an initial time interval of 3.5×10^{-6} second. The seismic wave, a set of sequencial waves JR-Takatori 60%, 80% and 100%, to input for has totally 80 seconds. The entire execution time for 80 seconds of time-history analyses is approximately 80 hours, using 504 cores of a supercomputer of the Institute for Information Management and Communication, Kyoto University in Japan.



(a): Whole view



(b): Close view

Figure 3: Outline of FE model for full-scale shaking table test specimen

3.2 Analytical Cases and Seismic Input Motions

Two analytical case studies were performed for simulating the experimental test results. Targeted experimental case is the sequence No. 6 in Table 1. wherein fracture at beam ends were observed in the actual specimen. In both analytical cases, 60 and 80% scales of JR-Takatori (sequence No. 4 and 5) were included in input motions histories because non-linear behaviors were observed in the experimental cases after than the sequence no.4. Those two analytical cases are differentiated with or without considering fracture-operation in FE analysis. The case without considering fracture at beam endsis called Case-1 and the other case is called Case-2. Consideration of fracture in Case-2 is demonstrated in the analyses by eliminating damaged elements.

3.3 Fracture Criterion of FE Model

A damage index based on Manson-Coffin's law [5] and Miner's rule [6] is introduced as the failure criterion for Case-2. Manson-Coffin's law expresses the characteristics of low-cycle fatigue for steel material and it is represented as Eq.(1)

$$\tilde{\varepsilon}_p \times N^{\alpha} = C \tag{1}$$

Where $\tilde{\varepsilon}_p$: Plastic strain amplitude, N: Cycles in which material reaches fracture for specified plastic strain amplitude $\tilde{\varepsilon}_p$, C and α : Material Constants

Miner's rule expresses the fatigue life of a material under a variable load. The linear cumulative damage indicate D is given by the Miner's rule as Eq.(2).

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{2}$$

Where n_i : number of cycles under the i th plastic strain amplitude $\tilde{\varepsilon}_{p,i}$, N_i : number of cycles to failure for $\tilde{\varepsilon}_{p,i}$.

A damage index DI is expressed by Eq.(3) using Eq.(1) and (2) in accordance with Xue's study [7]. The material constants C and α to determine m and $\tilde{\varepsilon}_{p,i}$ in Eq.(3) were evaluated from comparison of a component-analysis with a component-experiment conducted before shaking table test[8].

$$DI = \int m \left(\frac{\varepsilon_p^*}{\tilde{\varepsilon}_{p0}} \right)^{m-1} \frac{1}{\tilde{\varepsilon}_{p0}} d\varepsilon_p \tag{3}$$

Where $\varepsilon_p^* = \sqrt{2/3 \varepsilon_{ij}^p \varepsilon_{ij}^p}$, m: material constant of Manson-Coffin's low (=1/α), $\tilde{\varepsilon}_{p,0}$: material constant (=2^{α}×C), $d\varepsilon_p$: plastic strain increment

4 ANALYTICAL RESULTS

4.1 Prediction of Fracture Behavior

The times timing of fracture at the beam ends of the 2nd floor obtained by the numerical simulation and observed in the experimental test are indicated on the time-history of the story drift of the 1st story in Figure 4. In which, a story drift ratio is defined from the story drift per its story height. Time-history of the damage index DI calculated at elements for the beam ends are shown in Figure 5.

As shown in Figure 4, timings of the fracture of beam ends at 2nd floor in the analysis much well to that of the experiment. The timings of fracture in the analysis delay only one cycle from the experimental results. As displaying in Figure 5, from the beginning part of the time-history analysis using JR-Takatori 100%, values of *DI* depicted 4 elements placing beam ends as Figure 5 have already reached close to 1.0. Although fully fractured beam ends were not observed before the experimental case applying JR-Takatori100%, some fine cracks were observed. Hence, it seems that the DI time-history can be correlated with the occurrence of cumulative damage in the experiment. It should be noted that any fracture of beam ends at 3rd floor did not occur in the analysis although it particularly occur in the experiment.

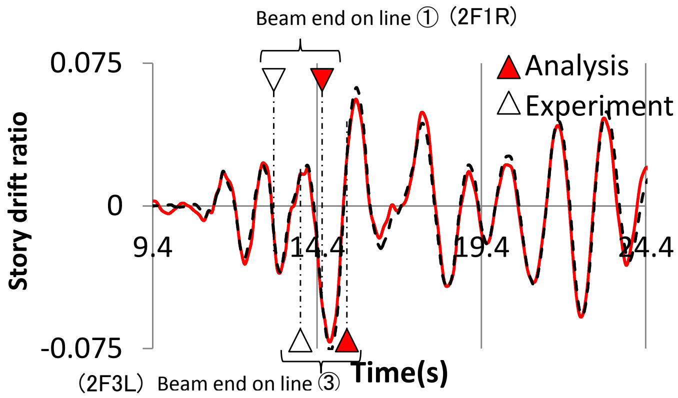
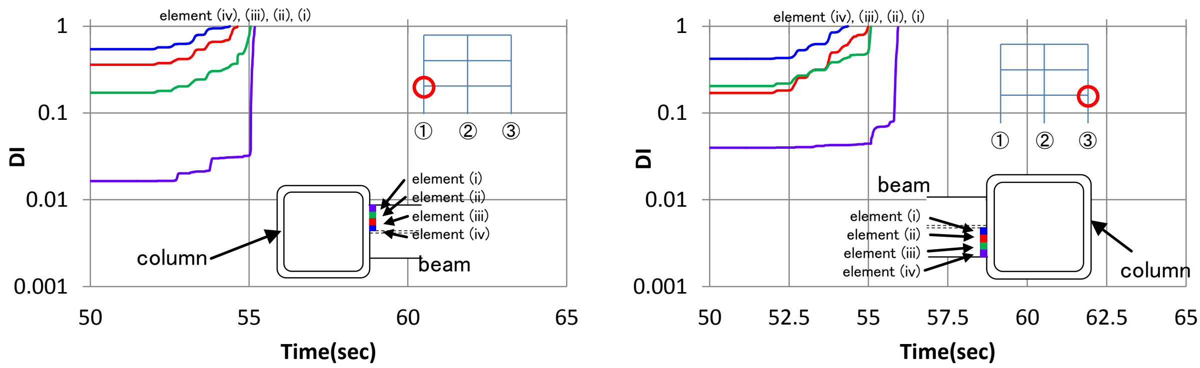


Figure 4: Timing of fractures at beam ends of the 2nd floor

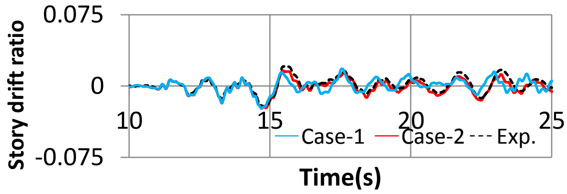


(a) On line ① (2F1R) (b) On line ③ (2F3L)

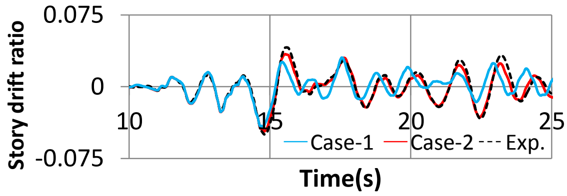
Figure 5: Time histories of DI for beam ends at 2nd floor

4.2 Floor Responses

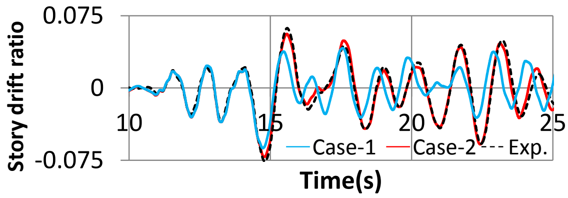
The time-histories of the story drift ratios and story shear forces are shown in Figure 6 and 7, respectively. Results obtained by the analysis of Case-2, in which the fracture at beam ends is considered, are more accurate than those obtained by Case-1. It is remarkably mentioned that the behaviors after 15s, when the fracture of beam ends at 2nd floor occurred in the experiment, can be consistently simulated in Case-2 while the analytical results of Case-1 produce much more errors from the experimental results.



(a) 3rd story

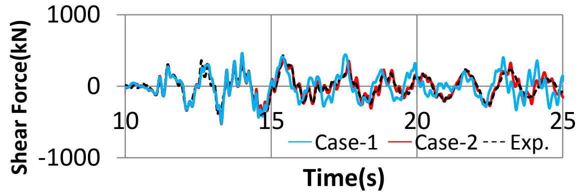


(b) 2nd story

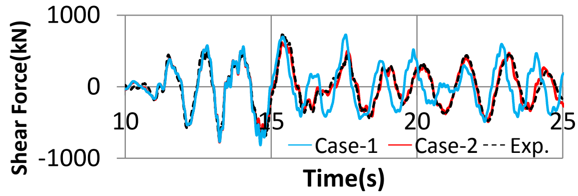


(c) 1st story

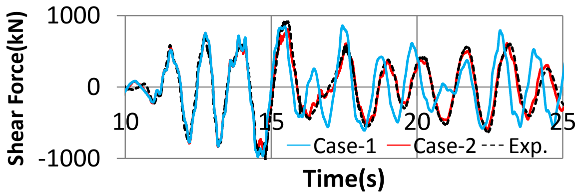
Figure 6: Time histories of the story drift ratio



(a) 3rd story



(b) 2nd story



(c) 1st story

Figure 7: Time histories of the story shear force

5 CONCLUSIONS

- The non-linear analysis of steel structures, which is for examining by the shaking table test results at E-defense, is conducted considering its fracture. The analytical models are intended to replicate adequately entire shapes of the specimen assembling huge numbers of tiny elements. The damage index DI is introduced as the fracture criterion of steel members for FEM simulations. Elements whose damage index DI reaches 1.0 are eliminated to demonstrate fracture behavior in this study..
- The timing of the first fracture of the beam end in the analysis mostly match well to that of the experiment and the damage index DI shows well correlation to occurence of cumulative damage in the specimen.
- Considering fracture in FE analyses for the detailed model gives improvement of the accuracy of the analytical results for time-histories of story responses.

ACKNOWLEDGEMENTS

This research used computational resources provided by the Kyoto University through the HPCI System Research project (Project ID:hp150152). A part of this work was supported by JSPS KAKENHI Grant Number 16H03124.

REFERENCES

[1] T. Miyamura, T. Yamashita, H. Akiba, M. Ohsaki, Dynamic FE simulation of four-story steel frame modeled by solid elements and its validation using results of full-scale shake-table test, *Earthquake engineering & structural dyanamics*, Vol.44, 1449-1469. 2015.

[2] Y. Mizushima, Y. Mukai, T. Saruwatari, Detailed FEM Simulation for Shaking Table Test of Three-Story Full Scale Steel Building Structure, *Proceedings of the 16th International Conference on Computing in Civil and Building Engineering*, Japan, 192-199, 2016.

[3] Y. Mizushima, Y. Mukai, H. Namba, K. Taga, T. Saruwatari, Super-detailed FEM Simulation for Full Scale Steel Structure Caused Fatal rupture at its Joint Parts between Members - Shaking Table Test of Full Scale Steel Frame Structure to Estimate Influence of Cumulative Damage by Multiple Strong Motion Part1 -, *Journal of Structural and Construction Engineering (Transaction of AIJ)*, Vol.81, No.719, 61-70, 2016. (in Japanese)

[4] H. Namba, H. Fujitani, K. Taga, A. Tani, Y. Mukai, Y. Yamanabe, K. Kajiwara, K. Tani, T. Yamashita, S. Shiraga, D. Fukuoka, S. Morikawa, E-defense shaking table test for full scale steel building on cumulative damage by sequential strong motion (Part 1 Outline of test), *Summaries of technical papers of annual meeting AIJ*, Structures III , 975-976. 2014. (in Japanese)

[5] Coffin Jr. L.F., A study of the effects of cyclic thermal stresses on a ductile metal, *Transaction of ASME*, 76, 931-950, 1954.

[6] M. A. Miner, Cumulative Damage in Fatigue, *Journal of Applied Mechanics*, Vol.12, A565-571, 1951.

[7] Liang Xue, A Unified Expression for Low Cycle Fatigue and Extremely Low Cycle Fatigue and Its Implication for Monotonic Loading, *International Journal of Fatigue*, Vol.30, 1691-1698, 2008.

[8] D. Fukuoka, H. Namba, S. Morikawa, E-defense shaking table test for full scale steel building on cumulative damage by sequential strong motion (Part 2 Subassemblage Tests), *Summaries of technical papers of annual meeting AIJ*, Structures III, 977-978, 2014. (in Japanese)