SEISMIC PERFORMANCE EVALUATION OF SEISMIC RETROFITTED STEEL ARCH BRIDGE THAT AFFECTED BY 2007 NIIGATA-KEN CHUETSU-OKI EARTHQUAKE

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Abstract

A supported deck steel arch bridge that had been retrofitted after the 1995 Hyogo-Ken Nanbu, Japan, earthquake was affected by strong ground shaking during the 2007 Niigata-Ken Chuetsu-Oki, Japan, earthquake. The bridge suffered minor damage by the earthquake and no structural damage of the main members was observed. To evaluate the seismic response during the earthquake and the effect of seismic retrofit, a series of dynamic analyses was conducted. The results underscored the strengthening of the arch springing by the seismic retrofit worked to prevent the serious damage.

Introduction

The Niigata-Ken Chuetsu-Oki (Chuetsu offshore), Japan, earthquake occurred on July 16th, 2007 in the northwest Niigata region. The JMA magnitude was 6.8, and the moment magnitude was 6.6. The VI upper of the JMA intensity was observed in the Niigata and Nagano prefectures. The nuclear power plant was affected by the earthquake and some severe damage due to land slide was reported (NILIM, PWRI and BRI, 2008). There was no report of severely damaged bridges by the earthquake. Some damage of bearings and settlement of ground at bridge approaches, which were often observed in the past earthquakes, were reported. Additionally, movement of abutment, which was constructed on soft soil, was also reported (Okada and Unjoh, 2009).

Among the bridges that were affected by the earthquake, some bridges had already been retrofitted and no severe damage was observed (Unjoh et al., 2008). Although no instrumentation was provided to the bridges, it would be good examples to evaluate the effect of seismic retrofit of bridges.

In this research, a series of dynamic analyses was conducted for a steel arch bridge that had been retrofitted to evaluate the seismic response of a seismically retrofitted bridge and the effect of the seismic retrofit.

Bridge Analyzed and Damage Due to Earthquake

Photo 1 and Figure 1 show the bridge analyzed. This is a supported deck steel arch bridge. The bridge was constructed in 1965, and the design lateral seismic

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coefficient of 0.2 was used in the original design. The bridge carries two lanes of traffic and the width is 7.5 m. The total length of the bridge, including approaches, is 197 m. The main span is 120 m and the arch rise is 23m. Two single gerber spans are used for the approaches.

Photo 1 Bridge analyzed

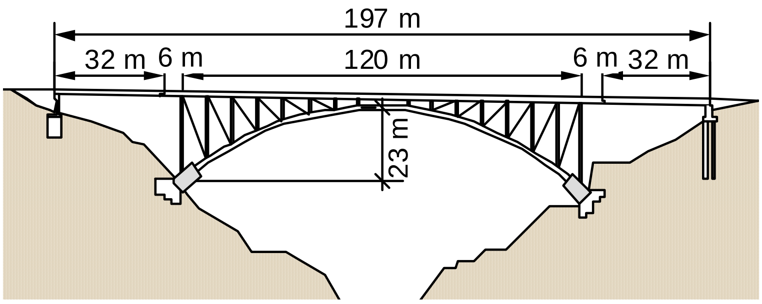


Figure 1 Bridge analyzed

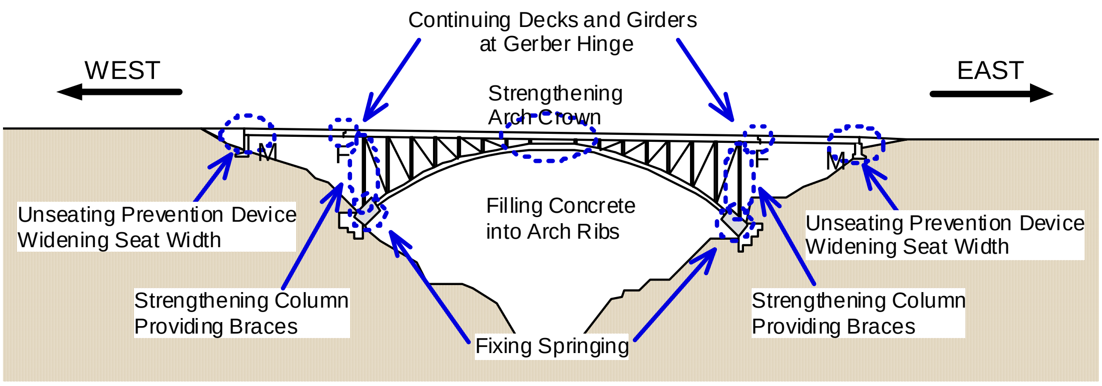


Figure 2 Seismic retrofit

The abutments are gravity type and wall type, and the spread foundations and pile foundation are used. Two pinned bearings were used to support the main span. The arch rib is the box type cross section with 1.5 m - height and 0.75 m- width, and the thickness of the steel plate of the ribs for the crown region is 19mm for upper and lower plates and 10 mm for side plates, and that for the springing region is 25 mm for upper and lower plates and 10 mm for side plates.

The seismic retrofit work was conducted in 2000 and 2001 considering the Level 2 ground motion. Behavior after yielding of the steel members was considered in the retrofit design. As shown in Figure 2, the items listed below were conducted as the seismic retrofit:

1. Fixing the pinned bearings at the both springings,
2. Filling the light-weight concrete into the arch rib,
3. Fixing the gerber bearings to have the bridge continuous,
4. Strengthening the arch crown,
5. Strengthening the bottom of the end columns,
6. Placing the braces for the end columns, and
7. Providing the unseating prevention devices.

The damage investigation reported that evidences of the pounding between the girder and the abutment were observed at the deck end. It was reported that buckling occurred at the gusset plates of lateral beams of the arch rib, but no severe damage of the main structural members was found (Unjoh, et al. 2008).

Analytical Model and Conditions

To simulate the seismic response during the 2007 Niigata-Ken Chuetsu-Oki earthquake and to evaluate the effects of the seismic retrofit to the bridges, a series of dynamic analyses was conducted for two models; one is a model for as-built bridge (As-built model), and the other is a model for the retrofitted bridge (Retrofitted model).

Although premature buckling of arch ribs was estimated to occur for the as-built bridge, nonlinear behavior after buckling was not considered in the analyses. Thus, the members of the arch rib were idealized as elastic beam elements. Other structural members were also modeled as elastic elements.

Since buckling of the members of the arch ribs were not expected but the yielding of the members were expected for the Retrofitted model, nonlinear behavior was idealized by nonlinear beam elements with the bilinear hysteretic model. The effect of variation of axial force to the arch ribs was not considered, and the effect of the axial force due to gravity load was only included in the analyses. Nonlinear behavior of the members of the main girder and supporting columns were also considered.

Table 1 compares the allowable bending moments of members at the arch springing and the arch crown. The buckling moment is shown for the allowable moment for the As-built model, and the yielding moment is shown for the Retrofitted model. The buckling moments at the crown were 5860 kNm and 2382 kNm for the longitudinal and transverse directions, respectively for the As-built model, and the allowable moment increased to 11508 kNm and 6137 kNm for the Retrofitted model because of the infilled concrete.

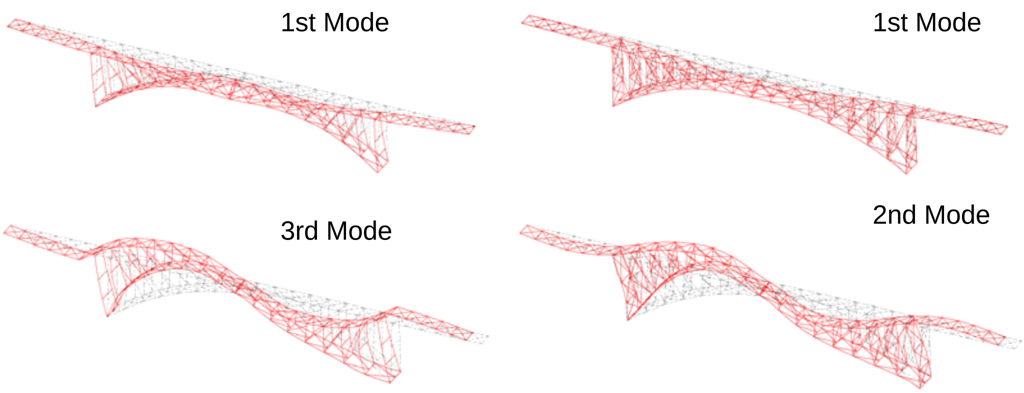
Table 2 summarizes the results from the eigen-value analyses, and Figure 3 shows the mode shapes for the dominant modes for the longitudinal and transverse directions. The deformation in the transverse direction is dominant in the 1st mode. The natural period of the 1st mode for the As-built model is 1.6 seconds, and it decreases to 1.16 seconds due to increment of the stiffness of the arch rib due to infilled concrete.

Table 1 Moment capacity of arch rib (kNm)

	Arch Crown		Springing	
	LG	TR	LG	TR
As-Built	5860	2382	6661	2229
Retrofitted	11508	6137	14836	7148

Table 2 Results from eigen-value analyses

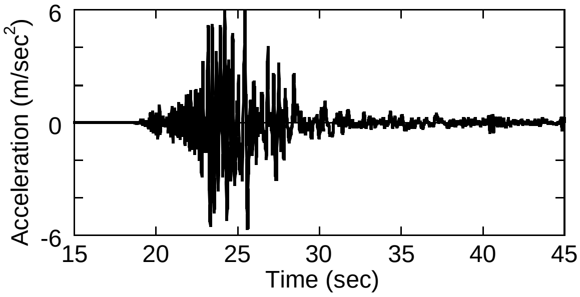
	As-built			Retrofitted		
Mode	Natural Period (sec)	Effective Mass Ratio (%)		Natural Period (sec)	Effective Mass ratio	
		LG	TR		LG	TR
1	1.596	0	79.4	1.159	0	66.2
2	0.839	0	0	0.757	51.6	0
3	0.780	54.9	0	0.575	0	0
4	0.479	0	4.8	0.505	0	0
5	0.423	0	0	0.475	0	0



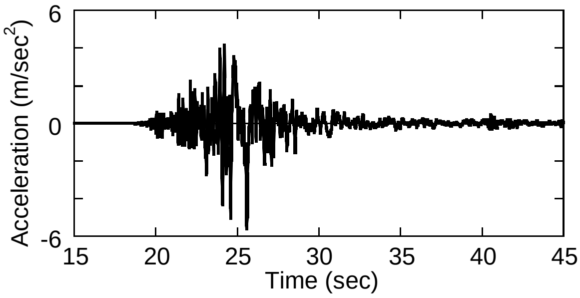
(a) As-built model (b) Retrofitted model

Figure 3 Mode shapes

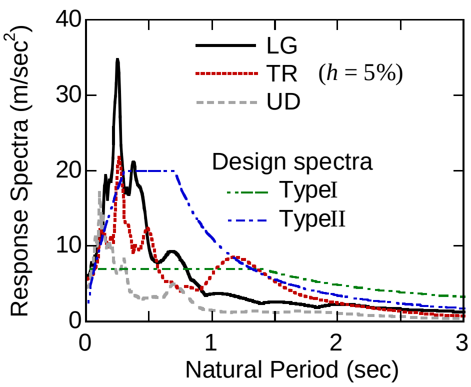
For the dynamic analyses, records obtained near the bridge during the 2007 earthquake were used, and three dimensional analyses were conduced considering two horizontal and one vertical ground motions. The input ground motions and their response spectra are shown in Figure 4. The design spectra of Japanese design specifications for highway bridges (Japan Road Association, 2002) are shown here for comparison. The peak ground accelerations are 5.95 m/sec^2, 5.61 m/sec^2 and 4.52 m/sec^2, respectively. The horizontal records have peaks over 20 m/sec^2 at around 0.25 seconds in natural period, which is larger than the design spectra, while the spectra between 0.5 seconds and 1 second in natural periods are smaller than the design spectra. The spectrum of the transverse direction has similar or even larger intensity than the design spectra around the natural period of the 1st mode while that of the longitudinal direction has smaller intensity.



(a) Longitudinal direction



(b) Transverse direction



(c) Response spectra

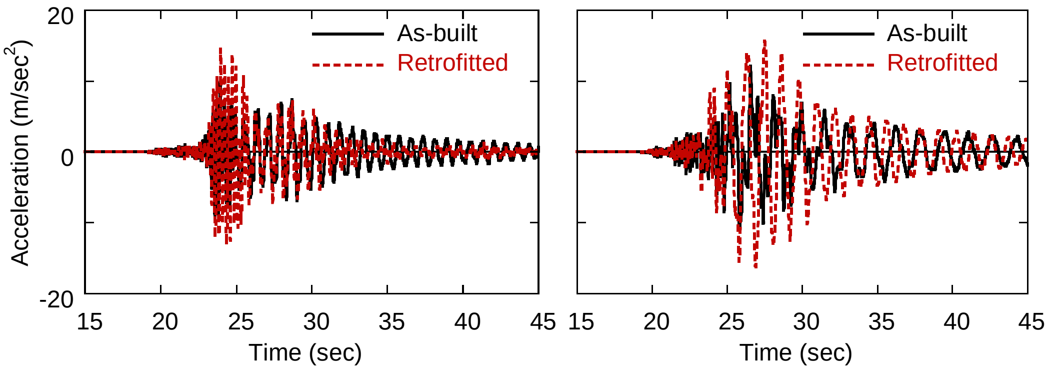
Figure 4 Input Ground Motions

Evaluation of Effects of Seismic Retrofit

Figure 5 compares the response acceleration and displacement time histories at the arch crown between the As-built model and the Retrofitted model. **Figure 6** shows the deformation mode when the maximum response occurred for each direction. Based on the results for the Retrofitted model, the lateral displacements over 70 mm and 500 mm are estimated to occur in the longitudinal and transverse directions, respectively, during the 2007 earthquake. Response acceleration increases by about 30% due to strengthening of the bridge.

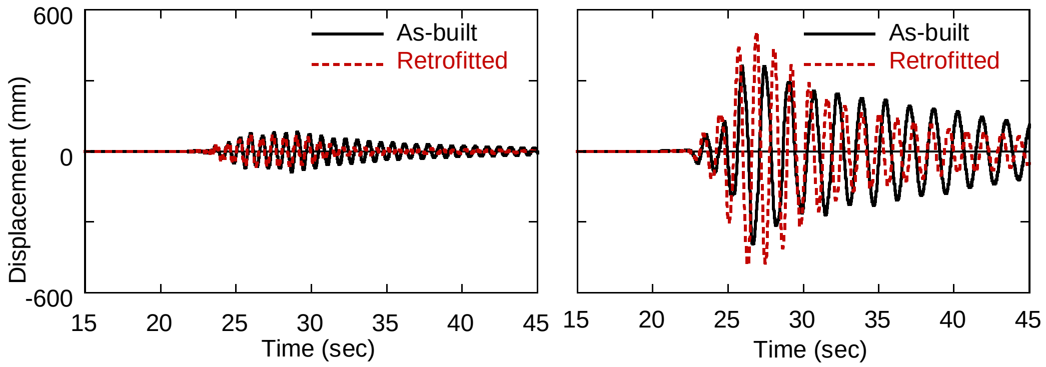
Figure 7 compares the allowable moment and the response moment. The response moment is compared to the buckling moment for the As-built model, while that is compared to the yielding moment for the Retrofitted model. Based on the results for the Retrofitted model, large bending moment occurs at the arch springings and the crown, and the response bending moment at the crown is close to the yielding moment.

At the springings, the response moments are about 75% and 65% of the yielding moment for the longitudinal and transverse directions, respectively.



(a) Longitudinal direction (b) Transverse direction

(1) Response acceleration



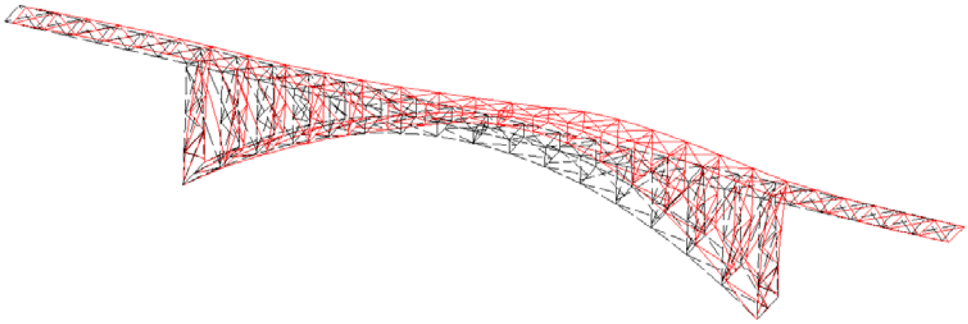
(a) Longitudinal direction (b) Transverse direction

(2) Response displacement

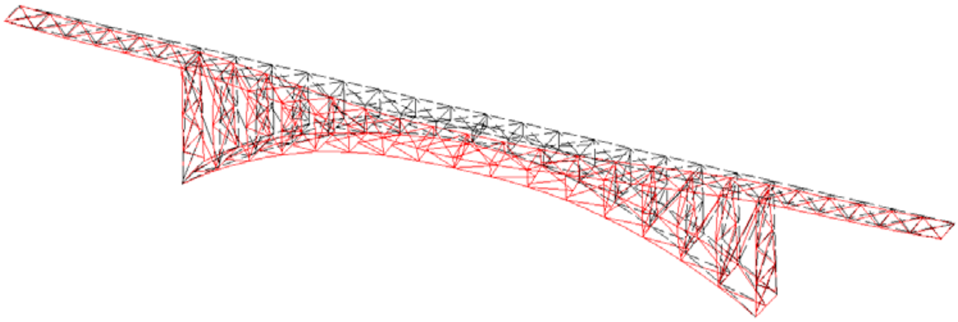
Figure 5 Response of deck at arch crown

For the As-built model, response bending moment exceeds by 40% the buckling moment at the arch crown. The response force at the bearings of the arch springings are estimated to be about 10 times larger than the horizontal and vertical capacity of the bearings, and thus it is estimated that the bearings suffer serious damage.

Based on the analytical results, the bearings of the arch springings could suffer serious damage, which affects the structural stability of the arch bridge. The arch rib could also suffer some damage at the arch crown. The responses for the Retrofitted model do not exceed the elastic limit states, and this matches observed damage.

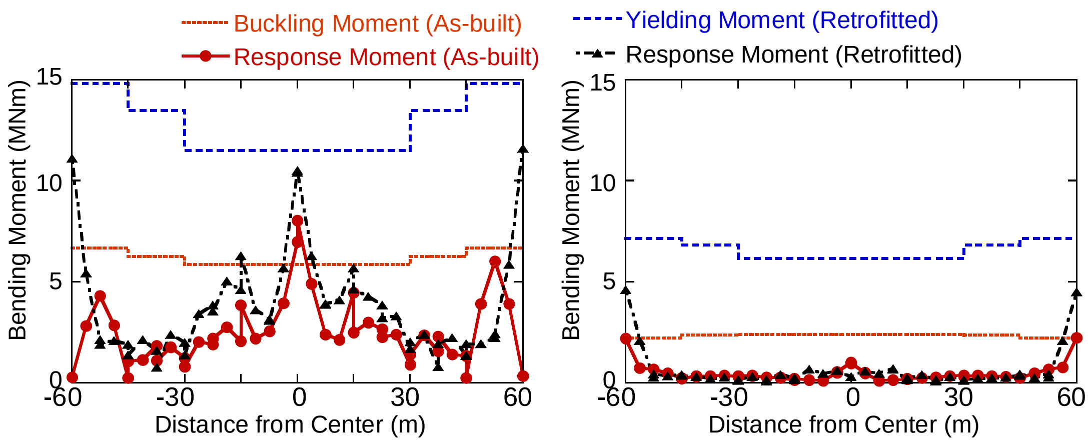


(a) Maximum response displacement in longitudinal direction (= 27.46 seconds)



(b) Maximum response displacement in transverse direction (= 26.89 seconds)

Figure 6 Deformation modes of retrofitted model



(a) Longitudinal direction (b) Transverse direction

Figure 7 Maximum response moment at arch rib

Conclusions

A series of dynamic analyses was conducted for a steel arch bridge that had been retrofitted to evaluate the seismic response of a seismically retrofitted arch bridge and the effect of the seismic retrofit. Below are the conclusions determined from the study:

1. The lateral displacements over 70 mm and 500 mm are estimated to occur in

longitudinal and transverse directions, respectively, during the 2007 earthquake.

2. The response bending moment at the crown is close to the yielding moment. At the springings, the response moments are about 75% and 65% of the yielding moment for longitudinal and transverse directions, respectively. The responses for the retrofitted bridge do not exceed the elastic limit states, and this matches observed damage.

3. Without the seismic retrofit, the response bending moment exceeds the buckling moment at the arch crown, and the response force at the bearings of the arch springings are estimated to be about 10 times larger than the horizontal and vertical capacity of the bearings. The analyses underscored that the bearings could suffer serious damage, which affects the structural stability of the arch bridge.

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References

Japan Road Association (2002). *Specifications for highway bridges. Part V Seismic design*, Japan.

NILIM, PWRI and BRI (2008). “Report on damage to infrastructures and buildings by the 2007 Niigata-ken Chuetsu-oki earthquake.” *Technical Note of PWRI*, No. 4086. (in Japanese)

Okada, T. and Unjoh, S. (2009). “Analyses of damaged bridge by ground displacement during Niigata-ken Chuetsu-oki earthquake.” *Proc. of 25th US-Japan Bridge Engineering Workshop*, Tsukuba, Japan.

Unjoh, S., Sugimoto, T., Sakai, J. and Okada, T. (2008). “Damage of bridge structures during recent earthquakes and the effectiveness of seismic retrofit.” *Proc. of 40th Joint Meeting US-Japan Panel on Wind and Seismic Effects UJNR*, Gaithersburg, USA.

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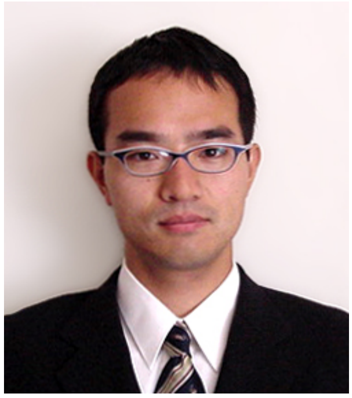

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Research and Academic Interests

Dr. Sakai's research interests focus primarily on seismic response of bridges and structural testing of reinforced concrete members. He has performed significant amount of testing on seismic performance of reinforced concrete bridges, including shaking table tests and quasi-static loading tests on bridge column specimens, and uniaxial loading tests on confined concrete cylinders. He also has experience in nonlinear dynamic analyses of bridges using fiber elements.

Degrees and Recent Professional Experiences

Dr. Sakai obtained his Bachelor, Master and Doctor degrees in civil engineering from Tokyo Institute of Technology, Japan, in 1996, 1998 and 2001, respectively. He stayed at the Pacific Earthquake Engineering Research Center, University of California at Berkeley as a post-doctoral researcher from July 2001 to April 2005. He has worked for PWRI since May 2005.

Professional Service (or Memberships and Affiliations)

Member of Japan Society of Civil Engineers

Honors and Awards

- James D. Cooper Best Paper Award of 5th National Seismic Conference on Bridges & Highways, FHWA & MCEER, 2006.
- Award for excellent doctoral dissertation, Tejima Seiichi Commemorative Foundation, 2002.
- Certificate of excellence for the presentation in the 2nd Intl. Summer Symp., JSCE, 2000.
- Award for excellent paper in the 45th Symp. on the Structural Engrg., JSCE, 1999.

Selected Publications

- Sakai, J. and Mahin, S. A.: Mitigation of residual displacements of circular reinforced concrete bridge columns, *Proc. of 13th WCEE*, No. 1622, Vancouver, Canada, 2004.
- Sakai, J. and Kawashima, K.: Unloading and reloading stress-strain model for confined concrete, *Journal of Structural Engineering*, ASCE, Vol. 132, No. 1, pp. 112-122, 2006.
- Sakai, J. and Unjoh, S.: Earthquake simulation test of circular reinforced concrete bridge column under multidirectional seismic excitation, *Earthquake Engineering and Engineering Vibration*, Vol. 5, No. 1, 103-110, 2006.
- Sakai, J. and Unjoh, S.: Quick Earthquake Damage Detection System for Bridges, *Proc. of 41st Joint Meeting US-Japan Panel on Wind and Seismic Effects UJNR*, Tsukuba, Japan, 2009.