ANALYSIS OF DAMAGE ON SHINAKANSEN VIADUCT CAUSED BY THE GREAT EAST JAPAN EARTHQUAKE BASED ON NONLINEAR DYNAMIC ANALYSIS

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ABSTRACT

We tried to clarify damage mechanisms on Shinkansen ramen viaduct during the Great East Japan Earthquake. The observed damage characteristic is that columns at end of the blocks had greater damages than those in the middle of blocks. To examine this phenomenon, we conducted nonlinear dynamic analysis with three dimensional frame model. As a result, we clarified 1) Difference in damage levels among columns can be explained by considering differences in shear-spans of columns, 2) Differences in states of axial force can lead to comparatively large differences in damage levels of columns, 3) Effects of three dimensional torsional behavior due to viaduct asymmetry can also cause the different damage levels of columns.

Keywords: the Great East Japan Earthquake, Shiankansen ramen viaduct, Nonlinear Dynamic Analysis, Shear damage, three dimensional torsional behavior.

1. RESEARCH BACKGROUND AND OBJECTIVES

Focusing on damage of Shinkansen ramen viaducts after the Great East Japan Earthquake on March 11 in 2011, greater damages were seen on end-columns of the viaduct blocks in comparison with middle-columns of the blocks as shown in Figure 1. Mizuno *et al*. (2012) reported that bending-shearing damage mode was predominant. To examine the damage mechanisms, we conducted nonlinear dynamic analysis using three dimensional frame model by focusing on the fact that the shear-span of the end-columns are shorter than that of the middle-columns, and the three dimensional torsional behaviors caused by viaduct asymmetry.

Fig.1 Damage of Shinkansen ramen viaduct (Minami Nagamachi in Tohoku Sendai) after the Great East Japan Earthquake

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2. FRAME MODEL OF SHINKANSEN RAMEN VIADUCT

We focused on a certain block in Tohoku Shinakanse RC ramen viaduct in Sendai Minami-Nagamachi area as our analysis target. The viaduct was constructed in 1979, and exists between Shiraishi-station and Sendai-station on the Tohoku Shinkansen Line.

The cross-sections of the viaduct in transvers and longitudinal direction are illustrated in Fig.2. As shown in this figure, the viaduct has asymmetry caused by following several facts; 1) Load asymmetry exists in transvers direction; 2) The viaduct is on a 0.287 degree slope; 3) The shear-span of end-columns is shorter than that of the middle columns. 4) Each column has different number of piles.

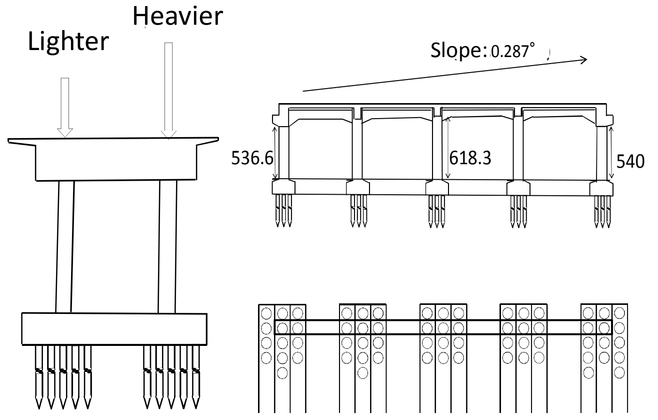


Fig.2: Cross-sections of Transverse and Longitudinal direction of Shinkanse Viaduct

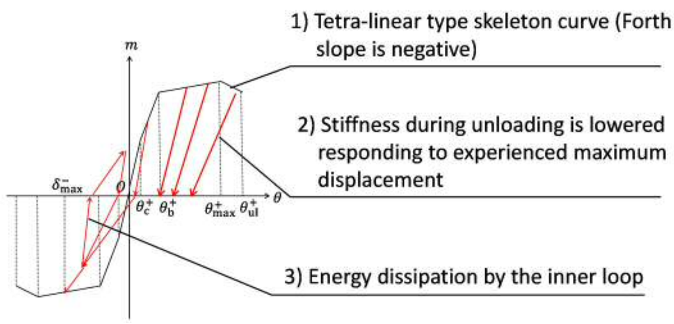


Fig.3: Nonlinear Restoring Force Characteristics

Based on design drawings, three dimensional frame model of the viaduct using End-spring beam model (Giberson (1967, 1969)) is constructed. End-spring beam model makes nonlinear analysis with very few elements possible by inserting nonlinear spring on positions where plastic hinge occurrence is expected. The hysteresis characteristics of RC element which are described in Japan railroad seismic design standards as shown in Figure 3 (Railway Technical Research Institute (2007)) are used as the end-spring nonlinearity. The features of this model are 1) Tetra-linear type skeleton curve whose forth slope is negative; 2) Stiffness during unloading is lowered responding to experienced maximum displacement; 3) Energy dissipation by hysteretic damping of the inner loop is expressed by renewing the stiffness during unloading on the way of re-loading after unloading.

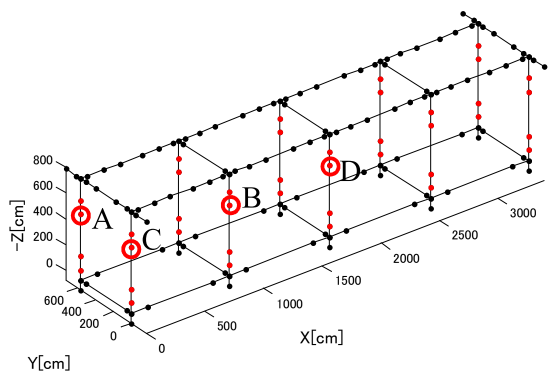
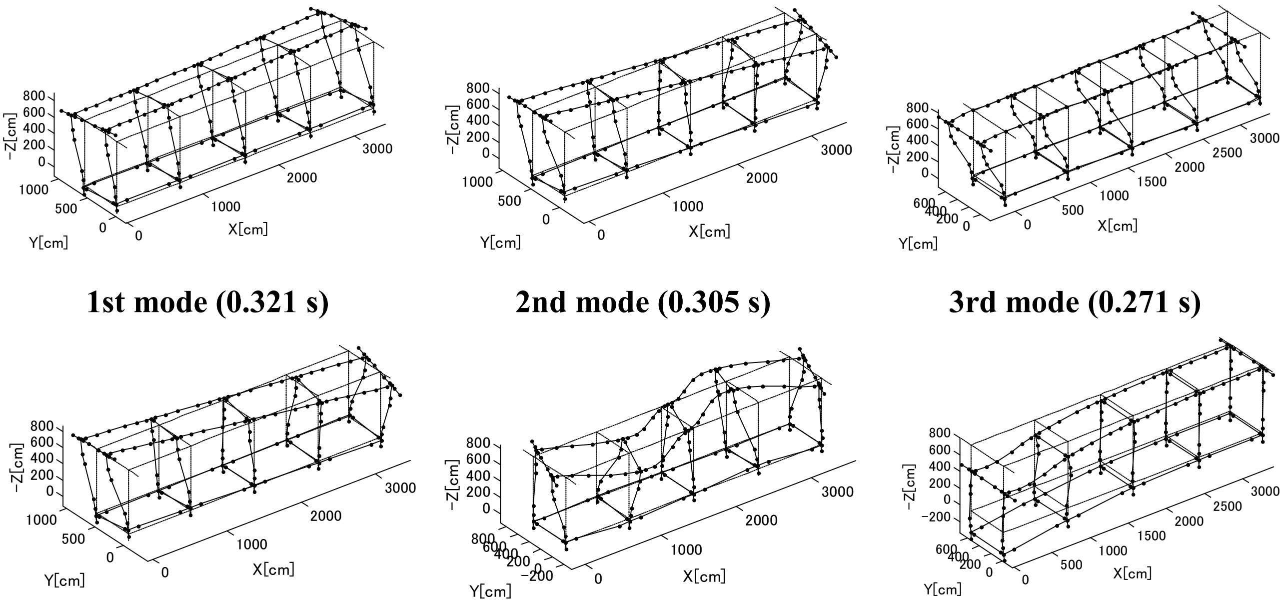


Fig.4: Frame Model of Shinkansen Viaduct

The constructed model is shown in Figure 4. Several nodes of the intermediate part of columns shown in red are parts that can be regarded as rigid body on the analysis, joining part of col-



1st mode (0.321 s) **2nd mode (0.305 s)** **3rd mode (0.271 s)**

5th mode (0.162 s) **2nd mode (0.106 s)** **3rd mode (0.0916 s)**

Fig. 5: Mode Shapes and Natural Periods from 1st to 6th mode

umns, and stepped rebar arrangement area respectively. These points are considered to be the position where plastic hinge occurs, thus we inserted nonlinear springs in these positions.

3. EIGEN VALUE ANALYSIS ON SHINKANSEN VIAUCT MODE

In this part, we conducted eigen value analysis using the constructed three dimensional frame model of Shinakansen viaduct. Lumped mass matrix was used as mass matrix.

Fig.5 shows natural periods and mode shapes of the model from 1st to 6th mode. 1st mode is transverse mode although displacement is slightly different at each node along longitudinal axis. 2nd, 4th and 5th modes show torsional behaviors. 6th mode is the mode which has large ground spring effect. By calculating effective mode masses, we found that 6th and 3rd modes are the top two predominant modes.

4. NONLINEAR DYNAMIC ANALYSIS

By conducting nonlinear dynamic analysis of the three dimensional frame model of Shinkansen ramen viaduct, we analyzed phenomenon that greater damage can be seen on end-columns by focusing on three dimensional torsional behavior caused by the difference of the shear span among columns and the viaducts asymmetry as mentioned in the objectives.

4.1. NUMERICAL CONDITIONS

As the input ground motions to the model, we used the ground acceleration in vertical direction and two horizontal directions (North-South direction and East-West direction) observed in a K-NET (National Research Institute for Earth Science and Disaster Prevention (2013)) measurement point in Sendai during the Great East Japan Earthquake (Sampling frequency: 100 Hz, Number of Samples: 25,000) and in Takatori during Kobe Earthquake (Sampling frequency: 100 Hz, Number of Samples: 4,095). Those acceleration and absolute acceleration spectrum are shown in Fig. 6 and Fig.7 respectively. The property of the Great East Japan Earthquake is that two large peaks of acceleration occurred and that duration was long. On the other hand, it is seen that Kobe Earthquake has short duration and large acceleration occurred in early time. The peak frequency of absolute acceleration spectrum of the Great East Japan Earthquake is around 0.6~0.8 s whereas the peak frequencies of Kobe Earthquake are around 0.2, 0.4, and 1.0 s. Thus, these two earthquakes have different characteristics each other both in time domain and frequency domain. We simultaneously input EW, NS and UD acceleration of each earthquake in the model, and calculated the responses by Newmark β method (β=0.25) for dynamic analysis. Lumped mass matrix and Rayleigh damping matrix were used. Rayleigh damping matrix was decided by two strain energy proportional damping of 6^{th} and 3^{rd} mode which are two predominant modes as discussed above.

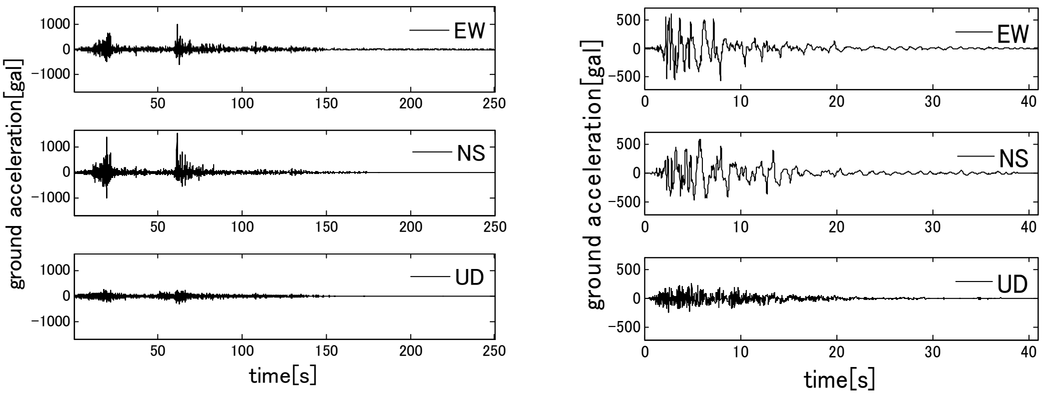


Fig.6: Input Goround motions in EW, NS and UD direction (Left: the Great East Japan Earthquake; Right: Kobe Earthquake)

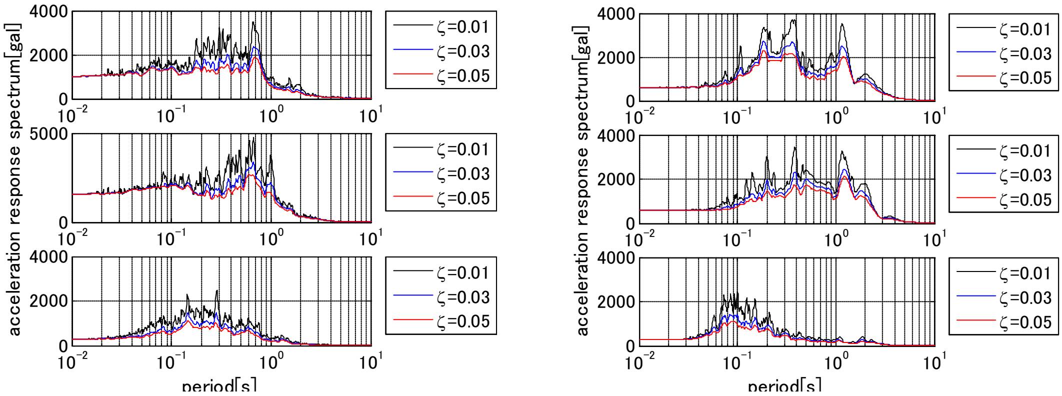
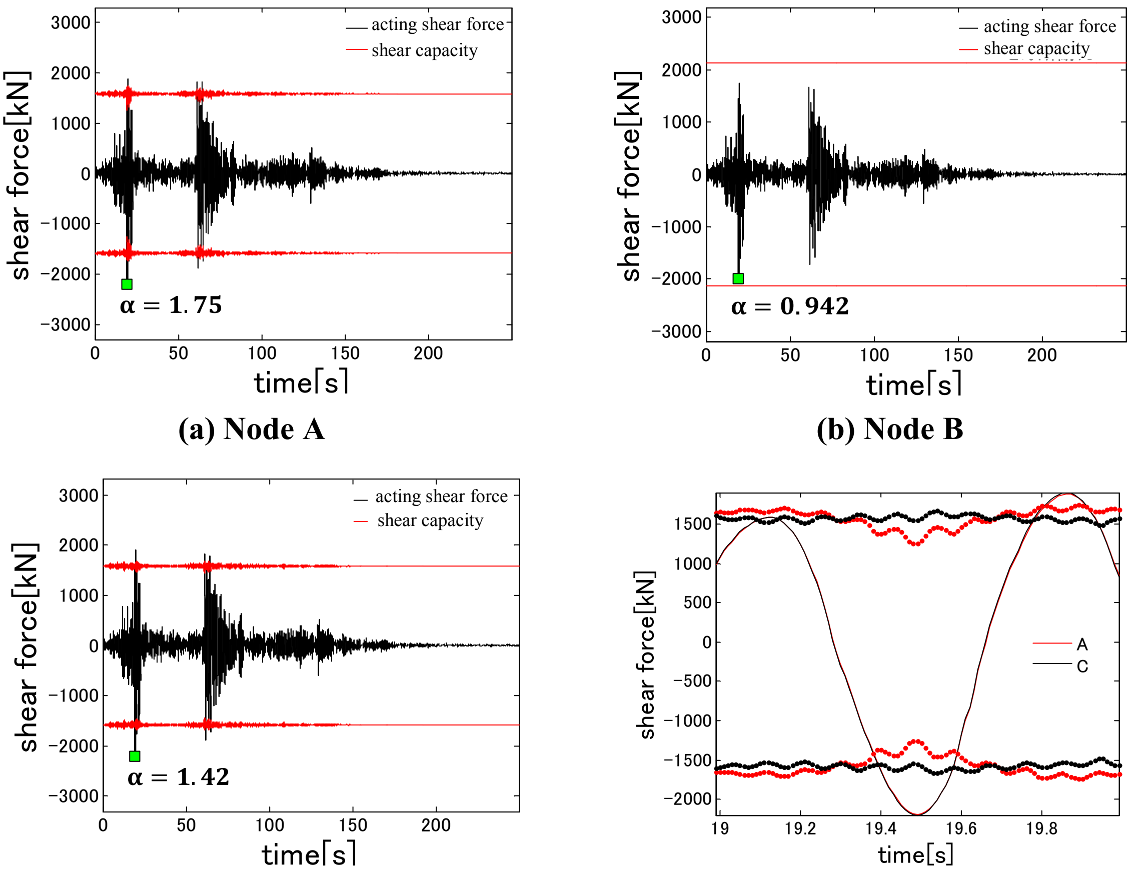


Fig.7: Absolute Acceleration Spectrum in EW, NS and UD direction (Left: the Great East Japan Earthquake; Kobe Earthquake)



(a) Node A (b) Node B

(c) Node A (d) Zoom of Node A and C

Fig. 8: Shear Force Responses

4.2. EVALUATION OF DAMAGE CAUSED BY SHEARING

Based upon the results of dynamic analysis, we evaluated the damage caused by shearing. Fig. 8 (a), (b) and (c) shows the time history of the acting shear force in longitudinal direction simulated by inputting the ground motion of the Great East Japan Earthquake and shear capacity on node A, B, and C in Figure 4 respectively. We defined an index which indicates extent of shear damage of columns as follows.

$$\alpha = \max\left(\frac{\text{acting shear force at each time}}{\text{shear capacity at each time}}\right) \quad (1)$$

α is 1.75, 0.942, and 1.42 on node A, B, and C respectively. Also by inputting the ground motion of Kobe Earthquake, α is 1.82, 0.927, and 1.44 on node A, B, and C respectively. From these results, it is said that greater damage is caused by shearing on end-columns in comparison with intermediate columns.

In the cases of the Great East Japan Earthquake and Kobe Earthquake, paying attention to the node A and C on two end-columns whose shear spans are same each other, it is ensured that difference of maximum ratio of acting shear force to shear capacity is more than 20%. In case of the

Table 1: The ratio of the force acting on the Shinkansen viaduct model for forces acting imaginary symmetrica model (Input: the Great East Japan Earthquake)

	End-columns	*Middle-columns*
Axial force	0.991	0.978
Shear force (x direction)	1.00	0.970
Shear force (y direction)	0.978	0.942
Torsional moment	13.8	78.0
Bending moment (around y axis)	0.977	0.966
Bending moment (around z axis)	1.00	0.996

Table 2: The ratio of the force acting on the Shinkansen viaduct model for forces acting imaginary symmetrica model (Input: Kobe Earthquake)

	End-columns	*Middle-columns*
Axial force	0.991	0.978
Shear force (x direction)	1.00	0.970
Shear force (y direction)	0.978	0.942
Torsional moment	13.8	78.0
Bending moment (around y axis)	0.977	0.966
Bending moment (around z axis)	1.00	0.996

Great East Japan Earthquake, we showed the acting shear force and shear capacity at around the time when this ratio becomes maximum in Fig.8 (d). The solid line shows the acting shear force and the dashed line shows shear capacity. It is seen that difference of the maximum value of the ratio between node A and C is mainly dependent on difference of shear capacity which fluctuates due to the axial compressive stress.

4.3. OBSERVATION OF THREE DIMENSIONAL TORSIONAL BEHAVIOR

In this part, we discuss influence of three dimensional torsional behavior due to viaduct asymmetry on damage. For this discussion, we calculate a ratio obtained by dividing maximum value of responses of Shinkansen viaduct model (asymmetric model) with that of imaginary model excluding asymmetry (symmetric model), then investigate the influence of asymmetry by comparing the ratio of each point. If this ratio at a certain point is larger than that at other point, we can say that larger force is distributed to the certain point by influence of the asymmetry.

Table 1 shows the comparison of the ratio between node C (end-column) and node D (intermediate column) in analysis using ground motion of the Great East Japan Earthquake and Kobe Earthquake respectively. From Table 1, it is confirmed that due to asymmetry, torsional moment around axis direction occurs, shear force on end-column becomes 3~3.8% larger than that on intermediate column, bending moment on end-column becomes approximately 1% larger than that on intermediate column. Also from Table 3, we can find similar trend that shear force and bending moment act on end-column disproportionately under ground motion of Kobe Earthquake.

5. CONCLUSIONS

In this research, we tried to clarify the mechanisms of phenomenon that columns at end of the blocks of Shinkansen ramen viaduct had severe damages than those in the middle of blocks during the Great East Japan Earthquake by taking into consideration shear damage and effects of three dimensional torsional behavior.

First, by considering damage mode by shear force, we succeeded in simulating the phenomena that greater damage occurs in end-columns in comparison with middle-columns. Additionally, it is seen that even if the shear-span is same, difference of more than 20 % occurs on the extent of the damage caused by the difference of the axial force conditions. Furthermore, it is explained that 1~4 % larger shear force and bending moment is applied to the end-columns because of three dimensional behaviors which causes asymmetry.

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