

# Seismic Response and Train-running safety of Two-Story Reinforced Concrete Viaduct with Seismically Repaired Middle Beams

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**Abstract:** On March 16, 2022, a magnitude 7.4 earthquake, hereinafter referred to as the 2022 Fukushima EQ, struck off the coast of Fukushima Prefecture. The 2022 Fukushima EQ caused the derailment of a Tohoku Shinkansen bullet train and inflicted damage on seismically repaired middle beams of two-story reinforced concrete (RC) viaduct. This study evaluated the seismic performance and train-running safety of a two-story RC viaduct, specifically focusing on those with seismically repaired middle beams, using incremental dynamic analysis. To evaluate the impact of seismic repairs on train-running safety, we adopted a method that calculates the spectral intensity (SI) of the acceleration response time history at the top of the viaduct during seismic events. This study defines the SI value derived from the acceleration response at the top of the viaduct as  $SI_{top}$ , distinguishing it from the commonly used SI value, which describes the intensity of seismic waves. The numerical model representing the as-built condition of the viaduct was labeled the 'As-built Viaduct Model', while the model featuring a repaired middle beam was termed the 'Repaired Viaduct Model'. It should be noted that the aim of this study is not to determine the cause of the bullet train derailment in the 2022 Fukushima EQ, but rather to assess the impact of repairing middle beams on train-running safety

on two-story RC viaducts. The incremental dynamic analysis revealed substantial differences in maximum displacement values within a response drift range below 0.01 between As-built Viaduct Model and Repaired Viaduct Model. However, the repair of the middle beams did not significantly affect the ultimate behavior of the two-story RC viaducts. Regarding train-running safety, the  $SI_{top}$  value of Repaired Viaduct Model consistently exceeded those from As-Built Viaduct Model. In some instances, the  $SI_{top}$  value increased by approximately 1.5 times due to the repair of the middle beam. Notably, in many cases, the disparity in  $SI_{top}$  values between the two models became more pronounced as it approached the design limit value. Therefore, the alterations in dynamic response of two-story RC viaducts due to the seismic repairs on middle beams could significantly influence the train-running safety.

## Introduction

On March 16, 2022, a magnitude 7.4 earthquake, henceforth referred to as the 2022 Fukushima EQ, occurred with its epicenter off the coast of Fukushima Prefecture. According to the post-earthquake survey, damage to houses, road structures, and the ground was minor. However, significant damage was observed in middle beams of two-story reinforced concrete (RC) viaducts on the Tohoku Shinkansen Line. Notably, repair marks from past earthquake damage were reported on many of the damaged two-story RC viaducts (Inoue et al. (2024)). In some viaducts, damage was observed only on the middle beams that had repair marks, while the middle beams without repair marks showed no damage. (**Fig. 1**).

Many studies have investigated the effect of repairing earthquake-damaged RC members on their seismic performance. French et al. (1990) conducted an experimental study on RC specimens, including columns and beams, to assess the effectiveness of epoxy injection techniques for repairing moderately seismically damaged RC structures. Their findings indicated that epoxy injection successfully restored strength and energy dissipation capacity, although the initial stiffness was not entirely recovered. Moreover, repaired cracks did not reopen, and new cracks typically formed

53 adjacent to the repaired areas. Lehman et al. (2001) evaluated repair techniques for damaged bridge  
54 columns through experimental studies. They found that moderately damaged columns repaired with  
55 concrete patching and epoxy injection did not regain full stiffness, while strength and deformation  
56 capacities were comparable to those of the original columns. Additionally, severely damaged columns  
57 repaired using headed reinforcement, mechanical couplers, and newly cast concrete showed that all  
58 methods were effectively as intended. Watanabe et al. (2012) conducted an experimental study on the  
59 impact of epoxy resin injection or section restoration using non-shrink mortar on RC columns  
60 damaged by an earthquake. The findings demonstrated that the initial stiffness of the columns was  
61 restored to only 73%-80% of their original values, and there was a reduction in energy dissipation  
62 performance. In contrast, the strength of the columns exceeded the original levels. Marthong et al.  
63 (2012) investigated the efficacy of epoxy injection for repairing earthquake-damaged RC beam-  
64 column joints. Their observations indicated that while the repaired joints demonstrated slightly  
65 improved strength performance, the initial stiffness and energy dissipation were not fully restored.  
66 Marder et al. (2020) studied the impact of epoxy injection repairs on the structural behavior of plastic  
67 hinges in RC beams post-earthquake. The results indicated that epoxy-repaired plastic hinges  
68 experienced a less than 10% increase in strength, while stiffness decreased by 15%-25%. Energy  
69 dissipation and deformation capacity were found to recover to levels comparable to the original. Chiu  
70 et al. (2024) confirmed the effectiveness of various repair techniques—including surface treatment,  
71 epoxy injection, epoxy resin mortar coating, rebar planting, and steel plate retrofitting—on  
72 earthquake-damaged RC beams. Although these beams exhibited lower stiffness at early stages of  
73 deformation, their strength increased with greater deformation, eventually surpassing the maximum  
74 strength of the intact beams. Uemura et al. (2024) developed a repairable RC column where most of  
75 the concrete and longitudinal bars at the base could be replaced under axial force. Experimental results  
76 indicated that this replacement of members at severely damaged plastic hinges restored the strength  
77 and ductility of the columns, though with a slight reduction in stiffness. Saadatmanesh et al. (1997)  
78 conducted experimental investigations on the flexural performance of RC columns repaired with

79 fiber-reinforced plastic (FRP) wraps after earthquake damage. Their experiments demonstrated that  
80 FRP wraps effectively restored the flexural strength and ductility of RC columns, though the initial  
81 stiffness was lower than that of the original columns. Ma and Li (2015) examined the seismic behavior  
82 of RC columns repaired with basalt fiber reinforced polymer (BFRP) through cyclic loading tests.  
83 They found that the repair method enhanced the ductility capacity and energy dissipation of the  
84 columns, regardless of the damage level prior to repair; however, the recovery of bending capacity  
85 was limited for columns with severe damage. Moreover, the initial stiffness did not fully recover after  
86 repairs, regardless of damage severity. He et al. (2013) developed a rapid repair technique for  
87 earthquake-damaged RC columns using externally bonded carbon fiber reinforced polymers (CFRP).  
88 This method restored column strength but not the initial stiffness when no rebar rupture was present  
89 in the damage. Fakharifar et al. (2016) introduced a lightweight prestressed steel jacket repair method  
90 for severely damaged circular RC columns. While this method restored the initial stiffness to 84% of  
91 that of the original columns, it significantly improved their strength and ductility. A common finding  
92 from these studies, which depends on the degree of damage, is that while the strength and ductility of  
93 the columns can be restored, the initial stiffness was often not fully recovered. Other literature,  
94 although not directly addressing this issue, also suggests that initial stiffness was not fully restored  
95 even after repair (Hussein et al. 2013; Xiao and Ma 1997; Iacobucci et al. 2003; Jiang et al. 2016).

96 Several studies have investigated the impact of repairing RC members on the seismic  
97 response of the overall structural system. Yu et al. (2012) conducted shaking table tests on quarter-  
98 scale, two-storey, and eight-storey reinforced concrete (RC) frames to evaluate the effectiveness of  
99 epoxy injection technology. The experimental results confirmed the efficacy of the epoxy injection  
100 technique in terms of frequency, damping ratio, response displacement, and storey drift ratio in the  
101 repaired RC frames. Ma and Li (2013) and Balsamo et al. (2005) experimentally explored the effects  
102 of repairing beam-column connections in RC frames with BFRP or CFRP. Lavorato and Nuti (2015)  
103 assessed the seismic response of an entire bridge when RC piers were repaired using epoxy adhesive,  
104 stainless steel rebars, self-compacting concrete, and CFRP wrapping through pseudo-dynamic tests.

105 Di Ludovico et al. (2008) conducted shaking table tests to determine the effects of repairing columns  
106 in RC frame structures with glass fiber-reinforced polymer laminates, indicating a reduction in the  
107 natural period of the overall structure due to the repair of columns compared to the as-built structure.  
108 However, no study has examined the impact of repairing only beams on an overall structural system.  
109 The Tohoku Shinkansen construction logbook (1978) documents a case where resin injection was  
110 used to repair the middle beams of two-story RC viaducts damaged by the 1978 earthquake. The  
111 logbook notes that the natural frequency of the viaduct with the repaired middle beam was lower than  
112 that of an intact two-story RC viaduct. This indicates that the stiffness of the repaired middle beams  
113 was not fully restored, which in turn influenced the natural frequencies of the entire viaduct. Therefore,  
114 the decreased stiffness of repaired middle beams could potentially impact the seismic response of  
115 two-story RC viaducts.

116 Furthermore, the 2022 Fukushima EQ led to the derailment of the Tohoku Shinkansen bullet  
117 train. Fortunately, the bullet train was reportedly decelerating or nearly stationary at the time of the  
118 earthquake, resulting in no major human casualties. Additionally, the two-story RC viaducts at the  
119 bullet train derailment site, which had beams previously repaired, showed cracks along these repair  
120 marks from the 2022 Fukushima EQ (**Fig. 2**). Although several studies have evaluated the safety of  
121 trains running over structures during earthquakes (Yang and Wu, 2002; Yang et al., 2016; Gong et  
122 al., 2020), there is a lack of research on how seismic repairs to structures affect train safety. Therefore,  
123 it is important to examine both the seismic performance of two-story RC viaducts with repaired  
124 middle beams and the train-running safety on these viaducts.

125 This study investigated the seismic performance and train-running safety of a two-story RC  
126 viaduct with seismically repaired middle beams using incremental dynamic analysis. The subject of  
127 the study was a standard two-story RC viaduct from the Tohoku Shinkansen Line, which sustained  
128 damage during the 2022 Fukushima EQ. The repair method for the middle beams was assumed to be  
129 the resin injection method, which was employed at the viaduct where the bullet train derailed.

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## **Validation of numerical model for as-built two-story RC viaduct**

### ***General design concept of two-story RC viaduct***

In a two-story RC viaduct, the inclusion of middle beams ensures horizontal forces are distributed evenly across the upper and lower columns, which in turn lessens the bending moment at the column bases during earthquakes (Japanese National Railways (1965)). This reduction in bending moment at the column base also contributes to a more efficient foundation design. Another concept is that by appropriately calibrating the strength of the middle beams, these beams can be designed to incur damage before the columns, dissipating seismic energy and thereby minimizing damage to the viaduct columns during an earthquake.

### ***Experimental study subject to numerical analysis***

As a preliminary step in incremental dynamic analyses for the Tohoku Shinkansen viaduct, the validity of the two-story RC viaduct model developed in this study was confirmed. Specifically, the numerical analysis was performed to replicate the pseudo-dynamic experiment conducted on a two-story RC viaduct by Kamiyama et al. (1996). Kamiyama et al. (1996) investigated the seismic response of a two-story RC viaduct specimen, approximately 1/6 the size of a real-life viaduct, using a pseudo-dynamic experiment that combined seismic response analysis and static loading. The input seismic motion was the NS component from the 1995 Hyogo-ken Nanbu earthquake, as recorded at the Kobe Marine Meteorological Observatory by the Japan Meteorological Agency. Due to the scaled-down nature of the test specimen, the time scale of the input seismic wave was reduced to half of the original to maintain the relative relationship between the natural period of the viaduct and the seismic wave's periodic characteristics. Furthermore, Kamiyama et al. adjusted the maximum acceleration of the input seismic wave to 0.8 G, considering the maximum stroke capacity of the actuator. **Fig. 3** illustrates the acceleration time history and response spectrum of the input seismic wave. **Fig. 4** shows the dimension and rebar arrangement of the specimen, and **Fig.5** illustrates the state of damage to the specimen following the experiment.

## Detail of numerical model

### Modeling of column and upper beam

**Fig. 6** shows a schematic diagram of the numerical model of a two-story RC viaduct simulating the experimental specimen by Kamiyama et al. In a standard two-story RC viaduct, the beam-to-column connections and upper beams are designed to prevent damage. No damage was observed in the beam-to-column connections during the 2022 Fukushima EQ and the experiment by Kamiyama et al. (1996); therefore, they were modeled as rigid in the numerical analysis. The columns were modeled using fiber elements. The cross-sectional shapes of the members, rebar arrangement, and mechanical properties of the materials in the numerical model were consistent with those of the experimental specimens by Kamiyama et al. (1996). The mass at the top of the viaduct was set to 6750 kg, in accordance with the specifications used by Kamiyama et al (1996). The lengths of the elements at the column end in the numerical model were determined using the following equation proposed Sakai and Hoshikuma (2014) to calculate the plastic hinge lengths of RC columns.

$$L_p = 9.5 \cdot f_y^{\frac{1}{6}} \cdot \left( \frac{384E_0I_h}{n_s l_w^3 s} + 0.01c_o \right)^{\frac{1}{3}} \cdot d_{bl} \leq 0.15L \quad (1)$$

Where  $f_y$  is the yield stress of longitudinal bars (N/mm<sup>2</sup>),  $n_s$  is the number of compression-side longitudinal bars in the largest confining concrete section,  $l_w$  is the largest horizontal length of the concrete section confined by the stirrup parallel to the lateral load direction (mm),  $s$  is the interval between stirrups (mm),  $E_0$  is the Young's modulus of the stirrups (N/mm<sup>2</sup>),  $I_h$  is the sectional secondary moment (mm<sup>4</sup>),  $c_o$  is the thickness of the cover concrete (mm),  $d_{bl}$  is the diameter of longitudinal bars (mm), and  $L$  is the height of column (mm).

The numerical analysis was performed using the OpenSees software. The concrete was modeled using Concrete01 material in OpenSees, and Steel02 material model was adopted for the longitudinal bars. **Tables 1** and **2** list the material properties of the numerical model.

### ***Modeling of middle beam***

The middle beam was modeled as an elastic beam with rotational springs at both ends. In this model, the axial stiffness of the middle beam was determined from the properties of the elastic beam element, while the bending stiffness was represented by the combined properties of the elastic beam element and the elastoplastic rotational springs. Young's modulus of the elastic beam element was set at 30000 MPa. Moments and member angles at the initiation of concrete cracks and at the yielding of the middle beams were calculated using cross-sectional analysis. The  $M-\theta$  relationship of the rotation spring was then determined to ensure that the  $M-\theta$  relationship at the end of the middle beam aligned with the results of the cross-sectional analysis, depicted in **Fig. 7**. For the hysteresis loops, a degrading bilinear model commonly used for RC members exhibiting flexural failure was employed.

### ***Numerical result***

**Fig. 8** illustrates the hysteretic response, the time history of displacement response, and the time history of acceleration response of the viaduct obtained from the experimental results of Kamiyama et al. and from this numerical analysis, respectively. The displacements and accelerations depicted in the figures represent the horizontal displacements and accelerations at the top of the viaduct, while the loads refer to the total horizontal reaction forces at the bottom of the columns. The displacements, accelerations, and loads discussed henceforth correspond to these locations and directions.

**Fig. 8** reveals that the maximum values of response displacement and load in the experiment were approximately 30 mm and 40 kN, respectively, with minimum values of about -80 mm and -50 kN. The numerical analysis yielded maximum displacement and load values of 22.7 mm and 42.3 kN, respectively, and minimum values of -88.0 mm and -48.3 kN. Thus, the numerical analysis indicates a slight shift in the displacement of approximately 8 mm towards the negative direction, as compared to the experimental results. However, the amplitude of both the specimen and the viaduct model was approximately 110 mm, and the variation in response displacement due to this slight shift towards the negative direction was only about 7% of the total amplitudes. Additionally, the time histories of

208 displacement response (**Fig. 9**) and acceleration response (**Fig. 10**) from both the experiment and  
209 numerical analysis demonstrate that the behavior of the specimen was generally captured when  
210 displacement responses exceed 25 mm in absolute value, and acceleration responses exceed 3 m/s<sup>2</sup> in  
211 absolute value. In conclusion, this numerical model is sufficiently valid for evaluating the seismic  
212 response of a two-story RC viaduct.

213 Incidentally, the slight displacement shift observed in the numerical result compared to the  
214 experimental result can likely be attributed to the omission of strain penetration of the longitudinal  
215 bars from the footing in the numerical model. This is supported by the difference in stiffness of the  
216 hysteresis response between the numerical and experimental results, as depicted in **Fig. 8**. It is well  
217 established that the impact of strain penetration from the footing is more significant in scaled-down  
218 specimens, such as the target structure in this numerical analysis. The strain penetration effect  
219 diminishes as the size of the structure increases and the ratio of longitudinal bar diameter to column  
220 height decreases (Priestley et al. (1996)). Given that the numerical model is applied to a full-scale  
221 two-story RC viaduct in the following section, the influence of strain penetration becomes even less  
222 significant. Consequently, detailed modeling of the strain penetration of longitudinal bars was not  
223 undertaken in this study.

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## 226 **Numerical analysis for two-story RC viaduct with seismically repaired middle beams**

### 227 ***Numerical model for as-built two-story RC viaduct on Tohoku Shinkansen Line***

228 **Fig. 11** shows the dimensions and rebar arrangement of a two-story RC viaduct built to the standard  
229 specifications for the Tohoku Shinkansen Line. **Fig. 12** presents a schematic of the numerical model,  
230 developed using the same methodology validated in the previous chapter. The values of the material  
231 parameters in the fiber elements are listed in **Tables 3** and **4**. In this study, the numerical model  
232 representing an as-built two-story RC viaduct is termed the 'As-built Viaduct Model'.

233

## ***Repair method for middle beam of two-story RC viaduct on Tohoku Shinkansen Line***

When an earthquake damages middle beams of two-story RC viaducts on Tohoku Shinkansen Line, resin injection is commonly employed to repair the resulting cracks (**Fig. 14 (a)**). When concrete spalling occurs, cross-sectional restoration using mortar is also utilized. In certain instances, RB method is applied for shear retrofitting of the middle beams (**Fig. 14 (b)**). This method involves adding external transverse reinforcements around the existing RC members, with the four corners secured by L-shaped steel plates.

In this study, the repair method for middle beams is assumed to be resin injection, the same method used at the viaduct where the bullet train derailed. Therefore, any reference to the repair of middle beams will specifically refer to the resin injection method.

## ***Modeling of seismically repaired middle beam***

A numerical model of a repaired middle beam mirrored the properties of the restoring force in seismically repaired RC members, as previously described by Watanabe et al. (2004). They reported that the post-repair yield stiffness of RC members decreases compared to the as-built state, while the maximum moment capacity either returns to or exceeds the level observed in the as-built state. Based on these findings, the impact of the repair was modeled as follows:

- The first inflection point was defined as the yield point.
- The yield stiffness ratio  $\alpha$  (where  $0 < \alpha \leq 1$ ) was defined as the ratio of the yield stiffness of the repaired member to that of the as-built member. The value of  $\alpha$  is set based on the extent of damage and the state of repair.
- The maximum moment capacity was equated to that of the as-built member.

**Fig. 13** illustrates the image of  $M-\theta$  relationship at the end of a repaired middle beam. This figure also presents the parameters of the  $M-\theta$  relationship at the end of the middle beam in the As-built Viaduct Model. In this study, the numerical model representing a two-story RC viaduct with a seismically repaired middle beam is termed the 'Repaired Viaduct Model'.

## **Identification of the yield stiffness ratio $\alpha$ for Repaired Viaduct Model**

On June 12, 1978, a major earthquake with Richter magnitude of 7.4 occurred off the Pacific coast of Miyagi Prefecture in northeastern Japan. According to the Tohoku Shinkansen Line Construction Log (1978), a real-life two-story RC viaduct that was damaged during the earthquake in 1978 exhibited a natural frequency of 2.42 [Hz] and a corresponding natural period of 0.413 [s]. After the cracks were repaired using resin injection, the viaduct's natural frequency slightly increased to 2.52 [Hz], with a corresponding natural period of 0.397 [s]. In contrast, another nearby intact RC viaduct with the same structural characteristics demonstrated a natural frequency of 2.91 [Hz], corresponding to a natural period of 0.344 [s]. These findings suggest that the stiffness of the viaduct was not fully restored even after resin injection repairs of middle beams were performed to address the actual earthquake damage.

In this study, the yield stiffness ratio  $\alpha$  of the repaired beam model was determined to ensure that the ratio of the natural period between the As-built Viaduct Model and Repaired Viaduct Model matched the value of 1.16, as derived from the Tohoku Shinkansen Line Construction Log (1978). **Fig. 15** illustrates the variation in the ratio of the natural period between the As-built Viaduct Model and the Repaired Viaduct Model as the yield stiffness ratio  $\alpha$  changes. The figure reveals that when  $\alpha$  is 0.62, the natural period ratio becomes 1.16.

Compared to previous experimental studies, the value of  $\alpha = 0.62$  is slightly smaller. For instance, Watanabe et al. (1984) demonstrated that the yield stiffness of resin-injected RC members, depending on the extent of damage, decreased to about 76-80% of that of the as-built members. This suggests that repair work conducted immediately after an earthquake in an emergency field may be less accurate than repair work carried out in the controlled environment of an experimental study. In fact, it was observed that the actual repair conditions of the middle beams on the two-story RC viaduct at the Shinkansen derailment site were poor (**Fig. 16**). On the other hand, the natural period of the real-life intact and repaired viaducts, as recorded in the Tohoku Shinkansen Line Construction Log (1978), was obtained from another nearby viaduct. Therefore, even though the structural parameters

were the same, the geotechnical conditions did not perfectly align, which may have resulted in a smaller estimated  $\alpha$  value. Nevertheless, to conservatively evaluate the effect of repairing the middle beams, this study decided to use a repaired beam model with a yield stiffness ratio of  $\alpha = 0.62$ .

### **Methodology of numerical analysis**

In this study, incremental dynamic analyses were conducted using both the As-built Viaduct Model and the Repaired Viaduct Model to examine the seismic response and train-running safety of a two-story RC viaduct with a repaired middle beam. Specifically, seismic response analyses were performed using the multiple input seismic motions listed in **Table 5** as reference seismic waves, with the peak ground acceleration (PGA) incrementally increased from 1.0 [m/s<sup>2</sup>] to 8.0 [m/s<sup>2</sup>] in steps of 1.0 [m/s<sup>2</sup>]. The acceleration response spectrums of the input seismic waves, used as reference waves, are shown in **Fig. 17**.

The impact of the repairs on a seismic response of a two-story RC viaduct was evaluated using the maximum response displacement at the top of the viaduct as an indicator. Additionally, to assess the impact of these repairs on train-running safety over the viaduct during earthquakes, the method proposed by Luo (2005) was employed. This method involves calculating the spectral intensity (SI) of the acceleration response time history at the viaduct top caused by seismic motion (Eq. (2)) and comparing the SI value with the critical spectral intensity (**Fig. 18**).

$$SI_{top} = \int_{T_1}^{T_2} S_v(h, T) dT \quad (2)$$

where  $SI_{top}$  is the spectral intensity of the acceleration response time history at the viaduct top (m),  $S_v$  is the velocity response spectra for the acceleration response time histories of the viaduct top (m/s),  $h$  is damping ratio,  $T_1$  and  $T_2$  represent the upper and lower values of the target natural period (s), and  $T$  is natural period (s). The values  $h = 0.05$ ,  $T_1 = 0.1$  (s), and  $T_2 = 2.5$  (s) were adopted in accordance with the methodology proposed by Luo (2005). It should be noted that this study distinguishes  $SI_{top}$  from the commonly used SI value, which describes the intensity of seismic waves. The method

proposed by Luo (2005) is also used for verifying the train-running safety of railroad structures during earthquakes in Japan. According to the Railway Technical Research Institute (2006), the limiting spectral intensity  $SI_L$  is defined as follows:

$$SI_L = \begin{cases} -8.5T_{eq} + 6.65 & (T_{eq} < 0.3) \\ 4.1 & (0.3 \leq T_{eq} < 1.2) \\ 1.375T_{eq} + 2.45 & (1.2 < T_{eq}) \end{cases} \quad (3)$$

where  $SI_L$  is the limiting spectral intensity (m) and  $T_{eq}$  is the equivalent natural period of the structure under consideration (s). The  $SI_L$  value for both the As-built Viaduct Model and the Repaired Viaduct Model were determined to be 4.1 (m) by Eq. (2).

## Numerical results

### ***Seismic response of two-story RC viaduct with seismically repaired middle beam***

The IDA curves, indexed by the maximum response displacement of the viaduct, are shown in **Fig. 19**. Damage events that occurred on the viaduct are also illustrated in the figure. In this figure, 'Yield of column' refers to the event when the longitudinal bar of the column yields for the first time, while 'Ultimate state of column' is defined as the point at which the compressive strain of the confined concrete reaches the ultimate value calculated by Eq (4), in accordance with Railway Technical Research Institute (2004).

$$\varepsilon_{cu} = \frac{155 - f_c}{30000} \leq 0.0035 \quad (4)$$

where  $\varepsilon_{cu}$  is ultimate strain of concrete and  $f_c$  is compressive strength of concrete (N/mm<sup>2</sup>). The figure indicates that the maximum displacement values of the Repaired Viaduct Model generally exceeded those of the Intact Viaduct Model in all cases. In particular, the difference between the maximum displacement values of the Repaired Viaduct Model and the As-built Viaduct Model was relatively large in the drift range below 0.01, whereas the difference was small in the drift range above 0.01. As an example, **Fig. 20** illustrates the hysteretic response for cases with PGA = 3.0 [m/s<sup>2</sup>] and

335 8.0 [m/s<sup>2</sup>], using the 2022Soma as the input wave. In the case of PGA = 3.0 [m/s<sup>2</sup>], the hysteretic  
336 response was generally linear for both viaduct models, but a slight difference in the initial stiffness  
337 of the entire viaduct can be observed. This indicates that the reduction in the stiffness of the middle  
338 beam led to a reduction in the stiffness of the entire viaduct. In contrast, in the case of PGA = 8.0  
339 [m/s<sup>2</sup>], the response displacements and loads were generally similar between the two viaduct models,  
340 indicating that the impact of the middle beam repair was not distinctly evident. A comparison of the  
341 maximum response displacements for PGA=3.0 [m/s<sup>2</sup>] and PGA=8.0 [m/s<sup>2</sup>] in all cases is presented  
342 in **Table 6**. The table shows that, on average, the repair of the middle beam increased the maximum  
343 response displacement by a factor of 1.13 at PGA=8.0 [m/s<sup>2</sup>], corresponding to a difference of about  
344 0.0008. In contrast, for PGA = 3.0 [m/s<sup>2</sup>], the maximum response displacement increased  
345 significantly by a factor of 1.68 on average, but the absolute difference is about 0.0016.

346 Focusing on the damage events, in several cases (2021Soma, 2024Shoin, 2024Anamizu),  
347 the middle beams of the Repaired Viaduct Model yielded at a lower PGA than those of the As-built  
348 Viaduct Model. The results are similar to those observed in the 2022 Fukushima EQ, where the degree  
349 of damage differed between the real-life repaired and as-built middle beams. However, the difference  
350 in PGA at which the middle beams yielded was minor in some cases (1999Tsaoling, 2021Soma,  
351 2024Shoin, and 2024Anamizu), and in all other cases, the yielding occurred at the same PGA for both  
352 viaduct models. These results indicate that the impact of the middle beam repairs on its damage events  
353 was minimal. In contrast, the longitudinal bars in the columns of the Repaired Viaduct Model yielded  
354 earlier in all cases. This can be attributed to the increased response displacement, resulting from  
355 reduced stiffness in the entire viaduct due to the middle beam repairs. However, the PGA at which  
356 the column element reached the ultimate state was similar for both the As-built Viaduct Model and  
357 the Repaired Viaduct Model across all cases. In conclusion, although the repair of the middle beams  
358 affects the seismic response to the extent that yielding of the middle beams and columns occurs, it  
359 does not significantly impact the ultimate behavior of the two-story RC viaducts.

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### ***Train-running safety over two-story RC viaduct with seismically repaired middle beam***

The IDA curves, indexed by the  $SI_{top}$  values derived from the acceleration response time histories of the viaduct topsides, are illustrated in **Fig. 21**. The figure demonstrates that the  $SI_{top}$  values of the Repaired Viaduct Model consistently exceeded those of the As-Built Viaduct Model. Notably, in the cases of 2004Ojiya, 2026Mashiki, 2022Soma, and 2024Shoin, the difference in the  $SI_{top}$  values between the two viaduct model became more pronounced near the  $SI = SI_L (= 4.1 \text{ [m]})$ . For instance, under the input seismic wave labeled 2022Soma, with PGA of  $3.0 \text{ [m/s}^2\text{]}$ , the  $SI_{top}$  value of the Repaired Viaduct Model was  $3.59 \text{ [m]}$ , whereas the  $SI_{top}$  value of the As-built Viaduct Model was about  $2.47 \text{ [m]}$ . Similarly, for the 2004Shoin, with PGA of  $3.0 \text{ [m/s}^2\text{]}$ , the  $SI_{top}$  value of the Repaired Viaduct Model was  $4.02 \text{ [m]}$ , while the  $SI_{top}$  value of the As-built Viaduct Model was about  $2.85 \text{ [m]}$ . Consequently, in these scenarios, the  $SI_{top}$  value has increased by approximately 1.5 times due to the repair of the middle beam.

**Fig. 22** displays the velocity response spectrum for the acceleration response time histories of the viaduct topsides at a  $\text{PGA} = 3.0 \text{ [m/s}^2\text{]}$ . This figure reveals that while the periodic bands exhibiting significant velocity responses remained the same for both viaduct models, the peak values of these responses differed substantially. For example, when 2004Ojiya was used as the input seismic wave, the maximum velocity response spectrum reaches approximately  $3.11 \text{ [m/s]}$  for the As-built Viaduct Model and about  $4.92 \text{ [m/s]}$  for the Repaired Viaduct Model, indicating an increase of approximately 58.2% in response due to the repair of the middle beams.

Therefore, the change in the dynamic response of the viaduct attributable to repairing middle beams may significantly alter the velocity response of trains on the viaduct, potentially impacting train-running safety. The results suggest that simply injecting resin into cracks may not be a sufficient repair method for earthquake-damaged middle beams of two-story RC viaducts. It is necessary to grasp the alterations in the stiffness of the entire viaduct due to repairing middle beams and to evaluate the impact of the repair on the train-running safety.

## Conclusions

This study investigated the seismic performance and train-running safety of a two-story RC viaduct, specifically one with seismically repaired middle beams, using incremental dynamic analysis. To assess the impact of seismic repairs on train-running safety, we employed a method proposed by Luo (2005), which calculates the spectral intensity (SI) of the acceleration response time history at the viaduct's top during seismic events. This study defines the SI value derived from the acceleration response at the top of the viaduct as  $SI_{top}$ , distinguishing it from the commonly used SI value, which describes the intensity of seismic waves. The numerical model representing the original condition of the viaduct was referred to as the 'As-built Viaduct Model', while the model representing the viaduct with a repaired middle beam was called the 'Repaired Viaduct Model'. Initially, the validity of the As-built Viaduct Model was verified by replicating the experiment conducted by Kamiyama et al. Subsequently, the stiffness reduction ratio of the repaired middle beam was identified using actual natural period measurements from real-life two-story RC viaducts to create the Repaired Viaduct Model. Findings from the incremental dynamic analysis using the two models are as follows:

The maximum displacement values differed substantially within a response drift range below 0.01 between the As-built Viaduct Model and Repaired Viaduct Model. However, on average, the maximum difference in response displacement was approximately 0.0016 between the two viaduct model. Therefore, the repair of the middle beams did not significantly impact the ultimate behavior of the two-story RC viaducts. Regarding train-running safety, the spectral intensity  $SI_{top}$  values derived from the acceleration response of the Repaired Viaduct Model consistently exceeded those of the As-Built Viaduct Model. In some cases, the  $SI_{top}$  value increased by approximately 1.5 times due to the repair of the middle beam. Notably, the difference in  $SI_{top}$  values between the two models became more pronounced near the limiting spectral intensity ( $SI_L$ ). Thus, the changes in dynamic response of two-story RC viaducts due to the seismic repairs on middle beams could significantly impact train-running safety. These results highlight the importance of grasping changes in the stiffness of viaducts due to repairing middle beams and assessing their effect on the train-running

safety.

Future studies should aim to quantify the degree of stiffness reduction in the middle beams due to repairs and their impact on train-running safety more quantitatively. Additionally, the effects of repairs on train-running safety during earthquakes in this study were preliminarily verified using  $SI_{top}$  values. It would be beneficial to conduct a detailed investigation using a train-track-structure coupled model and compare the outcomes with those of this study.

## Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

## Acknowledgments

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## Tables and Figures

**Table 1.** Material properties of longitudinal bars for numerical model.

| Material model | Young's modulus (N/mm <sup>2</sup> ) | Yield strength (N/mm <sup>2</sup> ) | Secondary stiffness ratio |
|----------------|--------------------------------------|-------------------------------------|---------------------------|
| Steel02        | 200000                               | 359.6                               | 0.01                      |

**Table 2.** Material properties of concrete for numerical model.

| Material model | Maximum compressive stress (N/mm <sup>2</sup> ) | Strain at maximum compressive stress |
|----------------|-------------------------------------------------|--------------------------------------|
| Concrete01     | Cover concrete: 34.3                            | Cover concrete: 0.00200              |
|                | Confined concrete: 38.8                         | Confined concrete: 0.00430           |

**Table 3.** Material properties of longitudinal bars for numerical model.

| Material model | Young's modulus (N/mm <sup>2</sup> ) | Yield strength (N/mm <sup>2</sup> ) | Secondary stiffness ratio |
|----------------|--------------------------------------|-------------------------------------|---------------------------|
| Steel02        | 200000                               | 345.0                               | 0.01                      |

**Table 4.** Material properties of concrete for numerical model.

| Material model | Maximum compressive stress (N/mm <sup>2</sup> ) | Strain at maximum compressive stress |
|----------------|-------------------------------------------------|--------------------------------------|
| Concrete01     | Cover concrete: 23.0                            | Cover concrete: 0.00200              |
|                | Confined concrete: 24.3                         | Confined concrete: 0.00296           |

534 **Table 5.** Details of input seismic waves.

| Earthquake Label | Year | Region           | Staion            | Magnitude | PGA (m/s <sup>2</sup> ) |
|------------------|------|------------------|-------------------|-----------|-------------------------|
| 1995Kobe         | 1995 | Kobe, Japan      | JMA kobe          | 6.9       | 818                     |
| 1995Takatori     | 1995 | Kobe, Japan      | Takatori          | 6.9       | 666                     |
| 1999Tsaoling     | 1999 | ChiChi, Taiwan   | Yunlin - Tsaoling | 7.6       | 831                     |
| 2004Ojiya        | 2004 | Niigata, Japan   | K-NET OJIYA       | 6.6       | 1311                    |
| 2016Mashiki      | 2016 | Kumamoto, Japan  | KiK-net MASHIKI   | 7.0       | 1150                    |
| 2021Soma         | 2021 | Fukushima, Japan | K-NET SOMA        | 7.1       | 586                     |
| 2022Soma         | 2022 | Fukushima, Japan | K-NET SOMA        | 7.3       | 728                     |
| 2024Shoin        | 2024 | Noto, Japan      | K-NET SHOIN       | 7.5       | 595                     |
| 2024Anamizu      | 2024 | Noto, Japan      | K-NET ANAMIZU     | 7.5       | 1141                    |

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537 **Table 6.** Comparison of the maximum response displacements for PGA=3.0 [m/s<sup>2</sup>] and PGA=8.0  
538 [m/s<sup>2</sup>].

| Earthquake Label | Maximum response displacement [m] (Maximum response drift ratio) |                      |                     |                               |                      |                     |
|------------------|------------------------------------------------------------------|----------------------|---------------------|-------------------------------|----------------------|---------------------|
|                  | PGA = 3.0 [m/s <sup>2</sup> ]                                    |                      |                     | PGA = 8.0 [m/s <sup>2</sup> ] |                      |                     |
|                  | As-built Viaduct Model                                           | Repair Viaduct Model | Repaired / As-built | As-built Viaduct Model        | Repair Viaduct Model | Repaired / As-built |
| 1995Kobe         | 0.057 (0.0040)                                                   | 0.065 (0.0046)       | 1.14                | 0.10 (0.0074)                 | 0.12 (0.0083)        | 1.12                |
| 1995Takatori     | 0.044 (0.0032)                                                   | 0.056 (0.0040)       | 1.27                | 0.23 (0.016)                  | 0.22 (0.016)         | 0.977               |
| 1999Tsaoling     | 0.033 (0.0023)                                                   | 0.044 (0.0031)       | 1.37                | 0.17 (0.012)                  | 0.16 (0.012)         | 0.925               |
| 2004Ojiya        | 0.049 (0.0035)                                                   | 0.078 (0.0056)       | 1.61                | 0.15 (0.011)                  | 0.17 (0.012)         | 1.08                |
| 2016Mashiki      | 0.030 (0.0021)                                                   | 0.059 (0.0042)       | 1.95                | 0.091 (0.0065)                | 0.14 (0.0099)        | 1.53                |
| 2021Soma         | 0.043 (0.0030)                                                   | 0.056 (0.0040)       | 1.31                | 0.13 (0.0094)                 | 0.16 (0.011)         | 1.18                |
| 2022Soma         | 0.035 (0.0025)                                                   | 0.070 (0.0050)       | 2.02                | 0.19 (0.014)                  | 0.20 (0.014)         | 1.02                |
| 2024Shoin        | 0.023 (0.0017)                                                   | 0.060 (0.0042)       | 2.56                | 0.15 (0.010)                  | 0.16 (0.012)         | 1.10                |
| 2024Anamizu      | 0.024 (0.0017)                                                   | 0.047 (0.0036)       | 1.93                | 0.098 (0.0070)                | 0.098 (0.0069)       | 0.996               |
| Average          | 0.038 (0.0027)                                                   | 0.059 (0.0042)       | 1.68                | 0.147 (0.010)                 | 0.16 (0.011)         | 1.10                |

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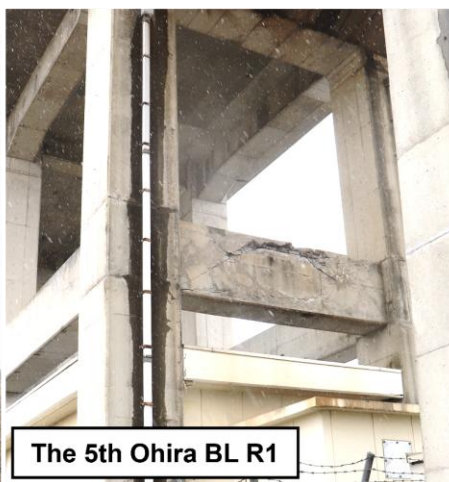


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**Fig. 1.** Damage to middle beams with repair mark, photographed on 18 March 2022.

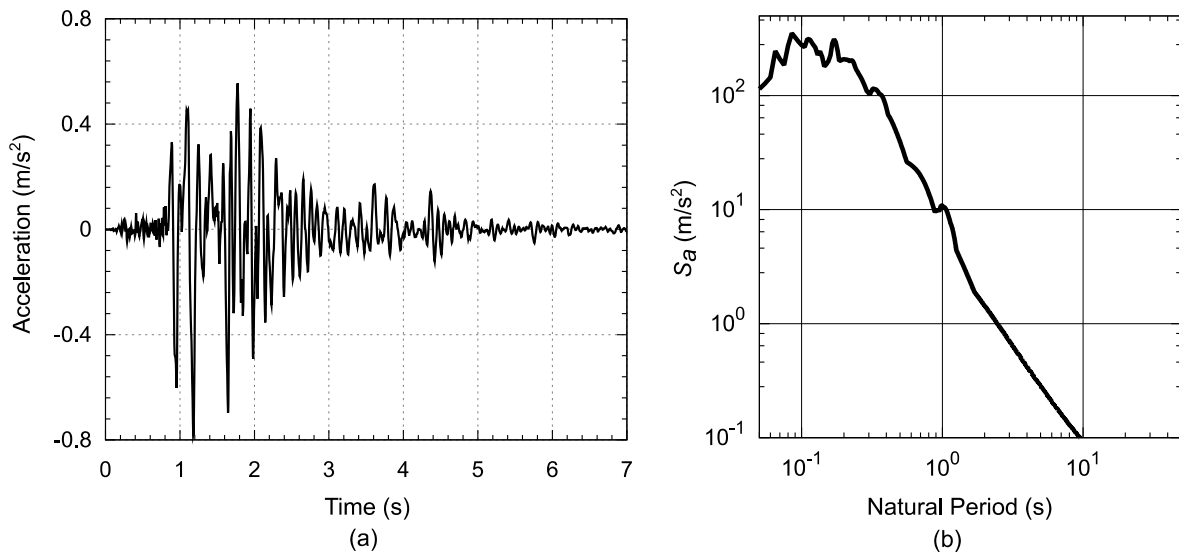


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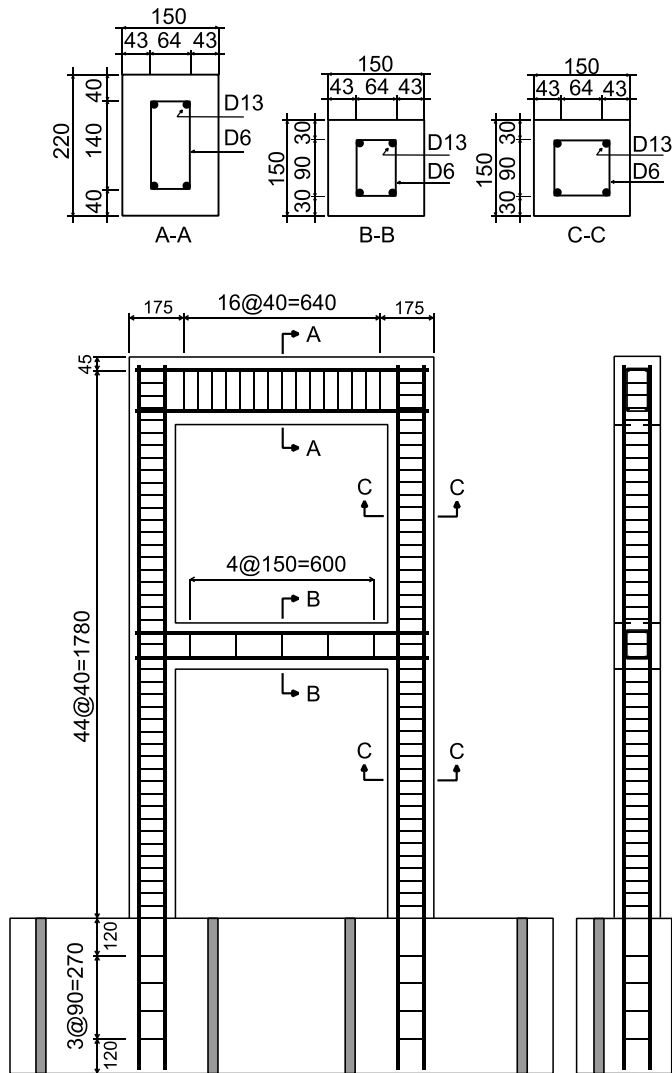
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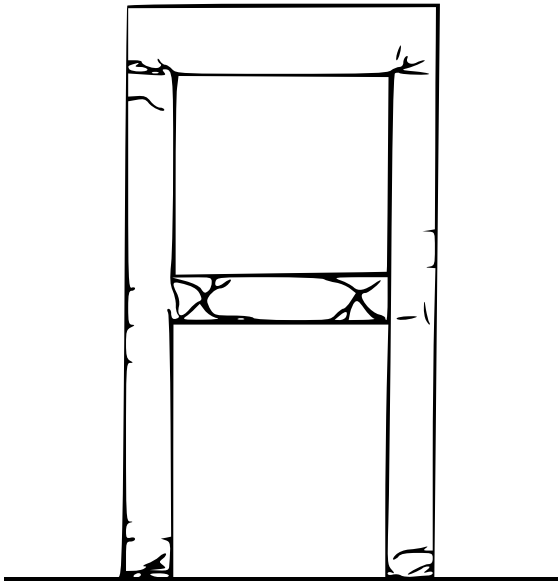
**Fig. 2.** Damage to two-story RC viaduct at the site of the bullet train derailment, photographed on 18 March 2022.



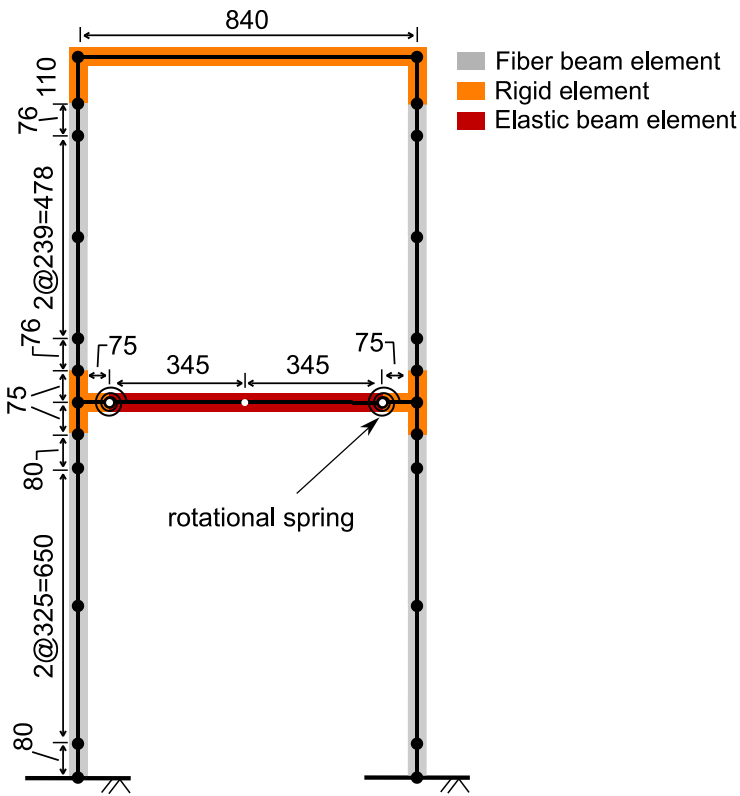
**Fig. 3.** (a) Acceleration time history; and (b) response spectrum of input seismic wave.



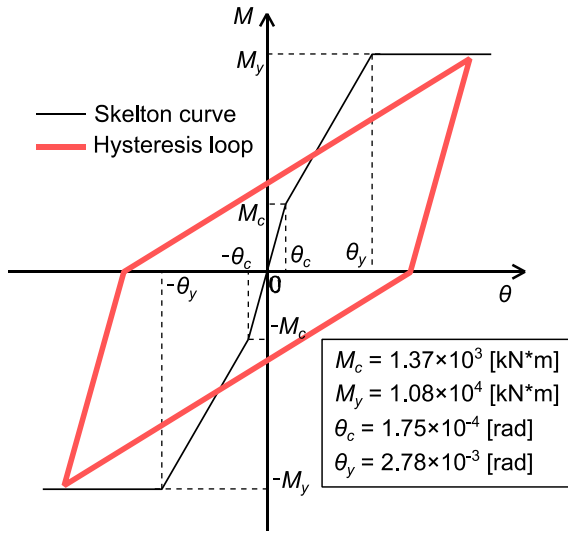
**Fig. 4.** Dimension and rebar arrangement of specimen (Dimension: mm, Kamiyama et al. (1996)).



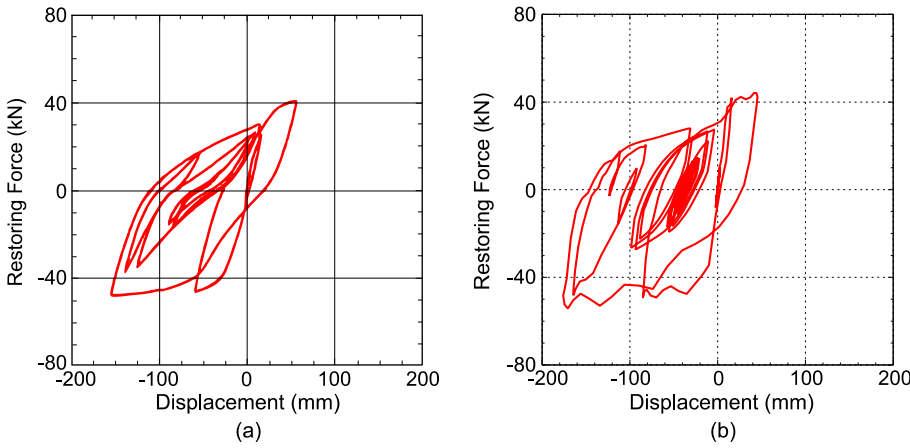
**Fig. 5.** Damage state of specimen at the end of experiment (Kamiyama et al. (1996)).



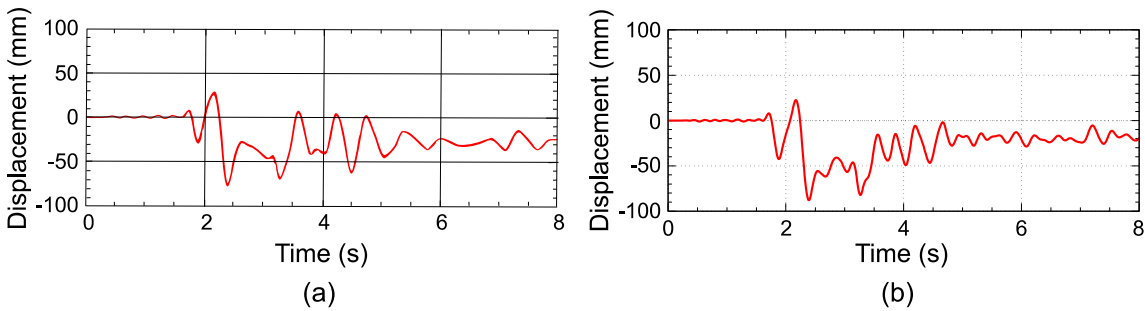
**Fig. 6.** Schematic diagram of numerical model (dimension: mm).



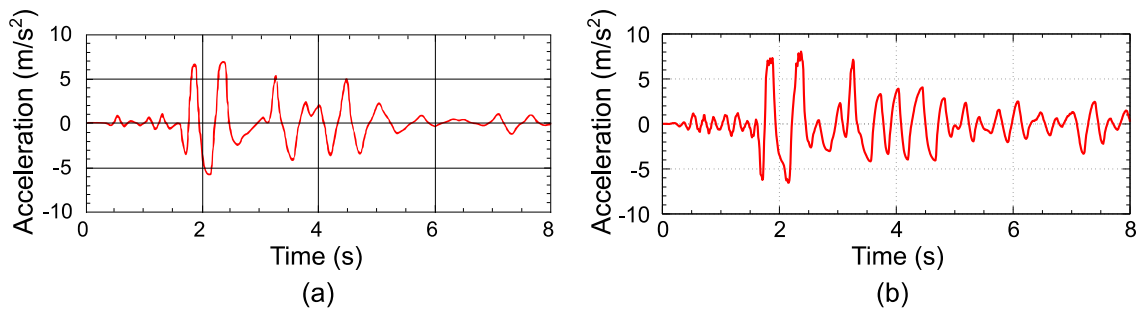
**Fig. 7.**  $M$ - $\theta$  relationship at the end of the middle beam in numerical analysis.



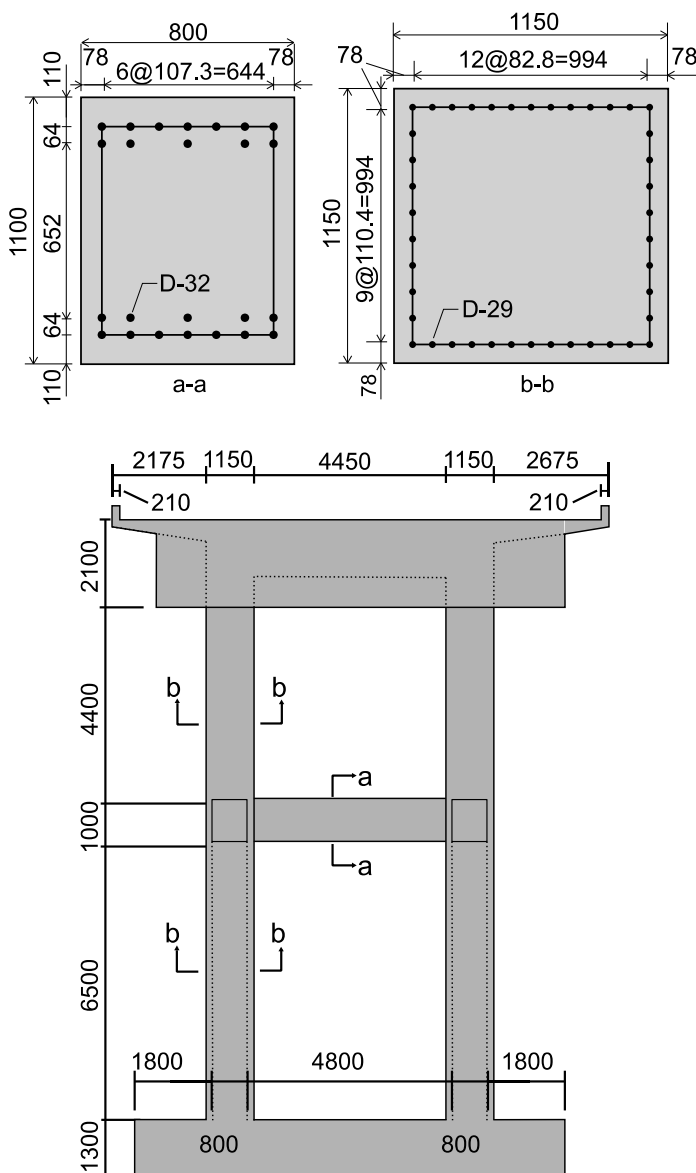
**Fig. 8.** Hysteretic response: (a) experimental result (Kamiyama et al. (1996)); and (b) numerical result.



**Fig. 9.** Time histories of displacement response: (a) experimental result (Kamiyama et al. (1996)); and (b) numerical result.



**Fig. 10.** Time histories of acceleration response: (a) experimental result (Kamiyama et al. (1996)); and (b) numerical result.



**Fig. 11.** Dimensions and rebar arrangement of a two-story RC viaduct built to the standard specifications for Tohoku Shinkansen Line (dimension: mm).



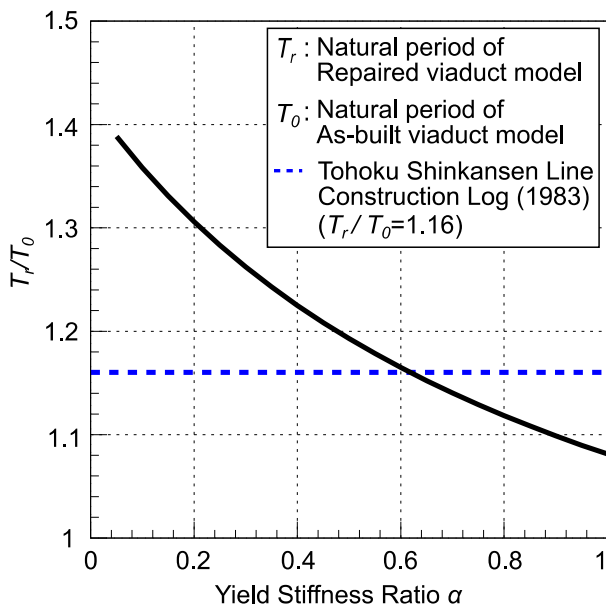


(a)



(b)

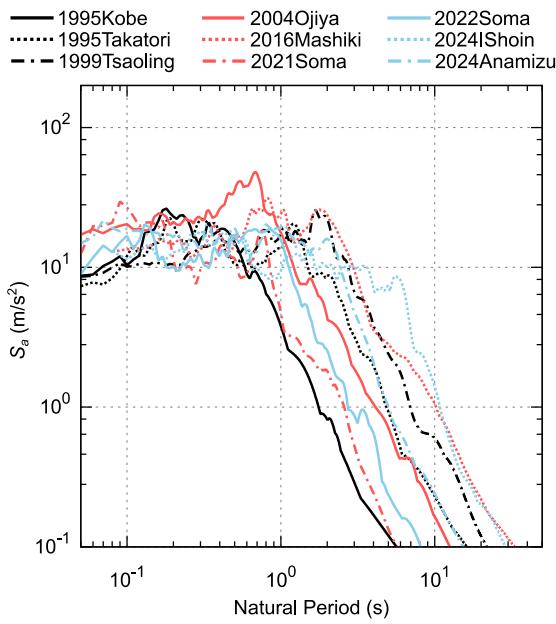
**Fig. 14.** Repair method for middle beams of real-life two-story RC viaducts, photographed on 20 February 2021: (a) resin injection method and cross-sectional restoration using mortar; and (b) RB method.



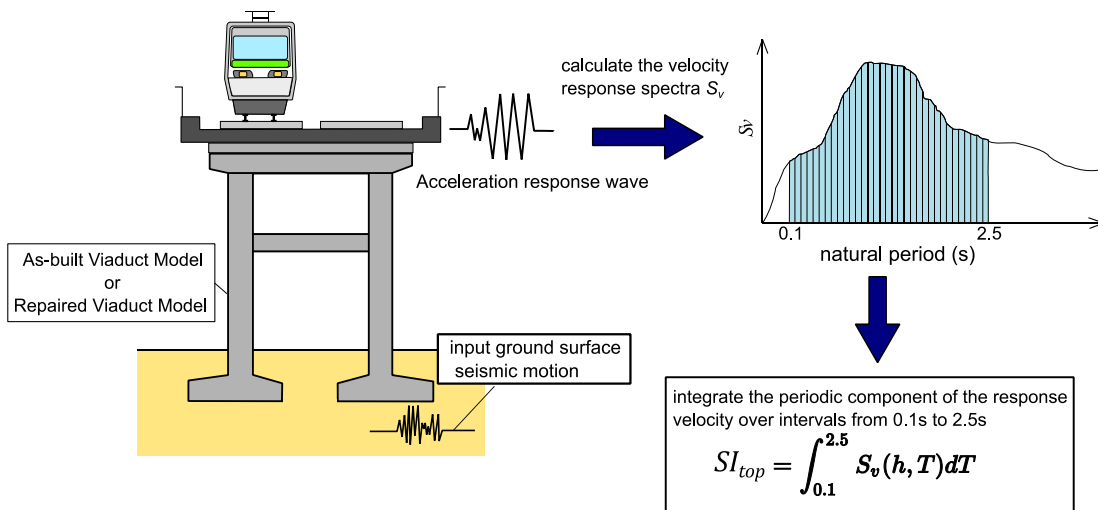
**Fig. 15.** Variation in ratio of natural period between As-built Viaduct Model and Repaired Viaduct Model with yield stiffness ratio  $\alpha$ .



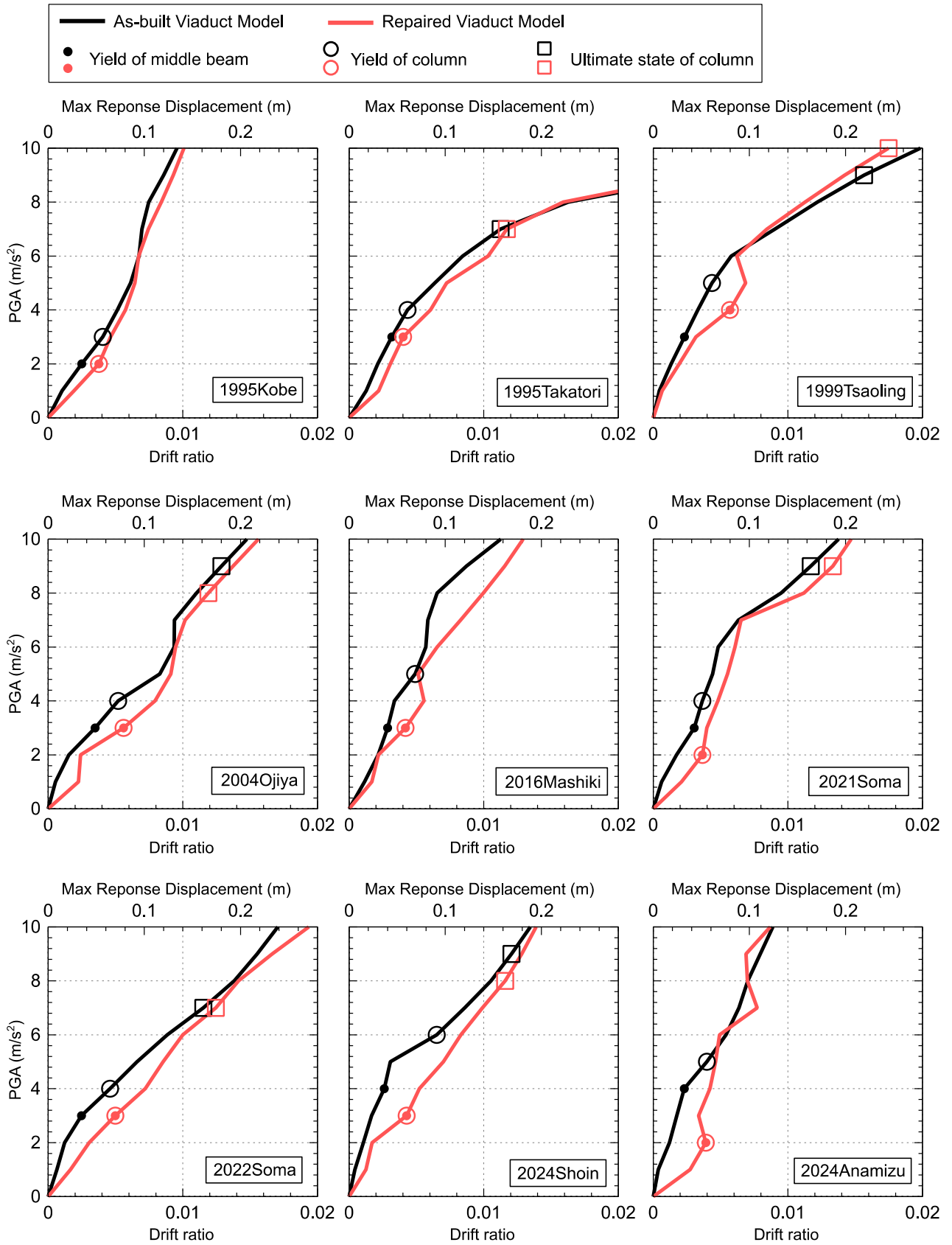
**Fig. 16.** Actual repair conditions on the middle beams of two-story RC viaduct at the site of bullet train derailment, photographed on 20 February 2021.



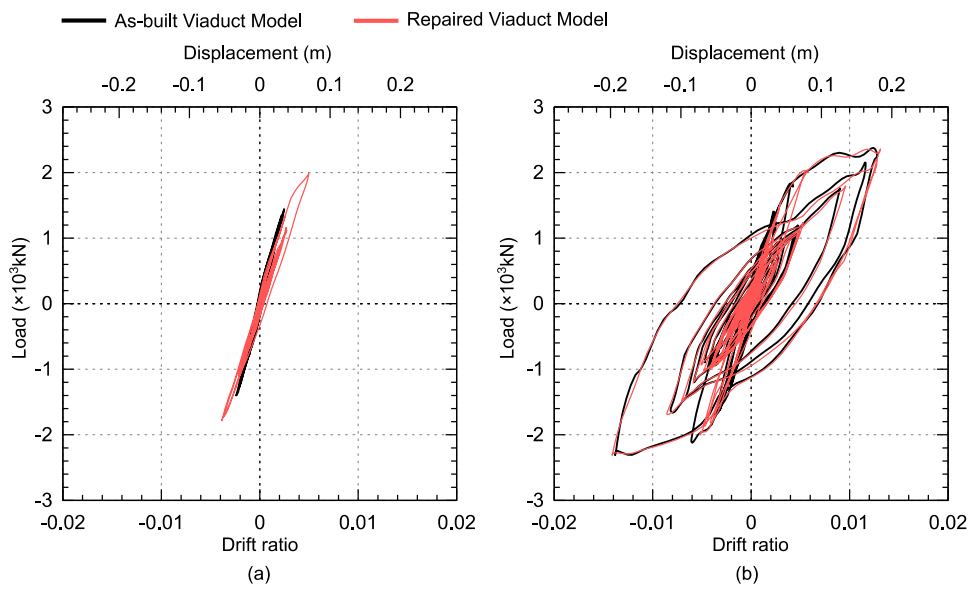
**Fig. 17.** Acceleration response spectrum of input seismic wave.



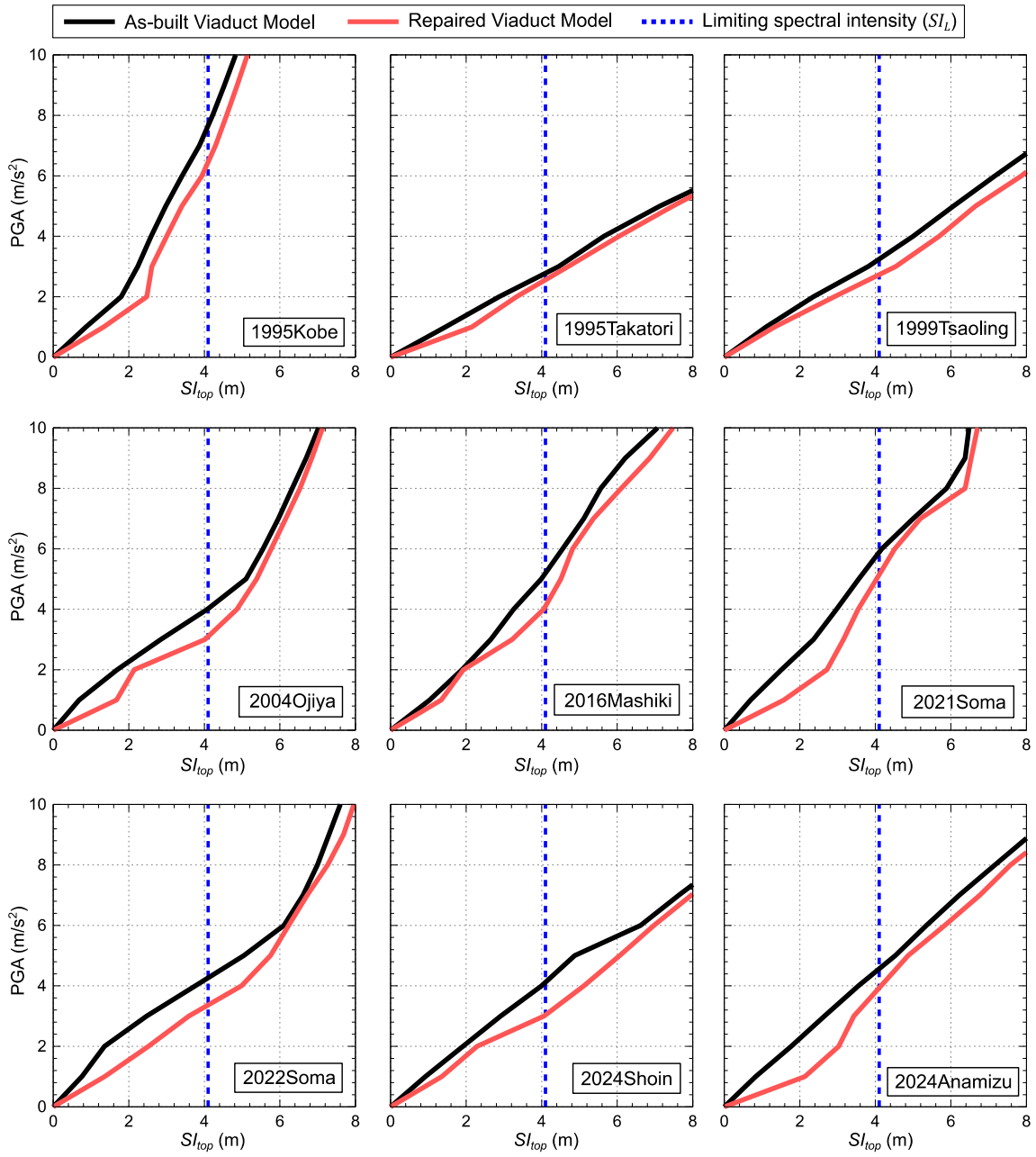
**Fig. 18.** Verification method to evaluate potential impacts on train-running safety during earthquakes, based on Luo (2005).



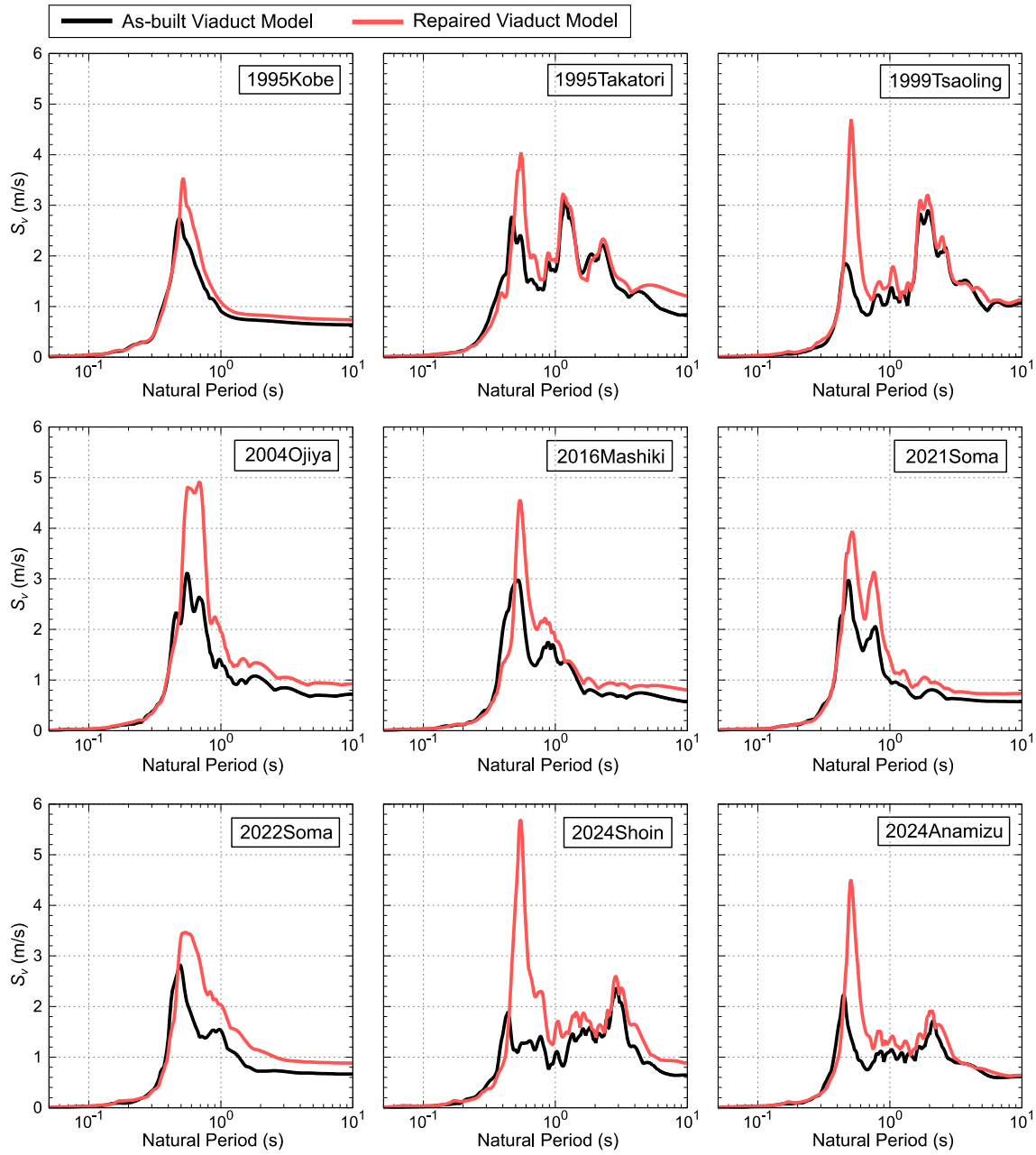
**Fig. 19.** IDA curves indexed by maximum response displacement of viaduct.



**Fig. 20.** Hysteretic response: (a)  $\text{PGA} = 3.0 \text{ [m/s}^2\text{]}$ ; and (b)  $\text{PGA} = 8.0 \text{ [m/s}^2\text{]}$ .



**Fig. 21.** IDA curves indexed by  $SI_{top}$  values derived from acceleration response of the viaduct topside.



**Fig. 22** Velocity response spectrum for acceleration response of viaduct top at a  $\text{PGA} = 3.0 \text{ [m/s}^2\text{]}$ .