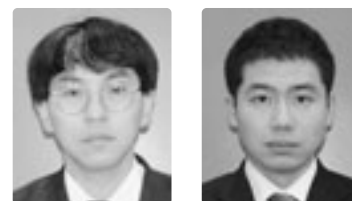


DEVELOPMENT OF A NEW VIADUCT STRUCTURE TO ACHIEVE A HIGH-AMENITY UNDER-VIADUCT SPACE



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This paper explains a new viaduct structure that improves the environment of under-viaduct space. We thought out a new structure for a low-vibration viaduct to reduce the vibration transmitted from beams to columns by inserting elastic material to the joints of beams and columns. With this joint structure, it is possible to give columns the load carrying capacity equivalent to columns of traditional structures by fitting columns to each other. We checked the low-vibration effect by analyzing trains running in this development and confirmed that the vibration acceleration level in the 30 - 60Hz band can be reduced by approx. 20 - 25dB compared to traditional structures. In order to check aseismatic performance, we carried out alternating loading tests with a model of a fit-jointed column and a portal model, built a structure model, and analyzed seismic response. This research proved that our new structure has the effect of reducing damage of columns, while seismic deformation of upper points is larger than traditional structures.

• **Keywords:** Low-vibration, Fit-jointed structure, Alternating loading test, Seismic response analysis

1 Introduction

Fig. 1 shows types of use of space according to vibration and quietness. If we can reduce the vibration caused by passing trains and improve quietness, we can use the space for uses requiring higher amenity such as hotels and houses. But spaces with much vibration and poor quietness only can be used for limited purposes such as parking, bicycle parking, and warehouses. To use under-viaduct space for higher-level purposes, we have to improve the quality of space by reducing the vibration and noise caused by trains.

In this development, we examined a new viaduct structure considering the above-mentioned condition to improve the amenity of under-viaduct space when a train passes over it.

Railway viaducts often used are rigid-frame viaducts of a reinforced concrete (RC) beam-slab type. Since columns and beams of a rigid frame viaduct are rigidly jointed to each other, slabs, beams, and columns carry the vibration by trains. That causes poor environment of under-viaduct spaces. Accordingly, we thought out a joint structure with elastic material inserted to joints of columns and beams and examined a viaduct of such a joint structure.

In the development of the viaduct of this joint structure, we examined the reduction effect of vibration acceleration at train running based on simulation analysis of structure behavior. Specified aseismatic performance is also required for viaducts. We also examined the aseismatic performance of the new structure viaduct based on the alternating loading tests using a test model and the seismic response of a modeled actual viaduct.

We will introduce an overview of the study of a new viaduct form to improve the amenity of under-viaduct space in this report.

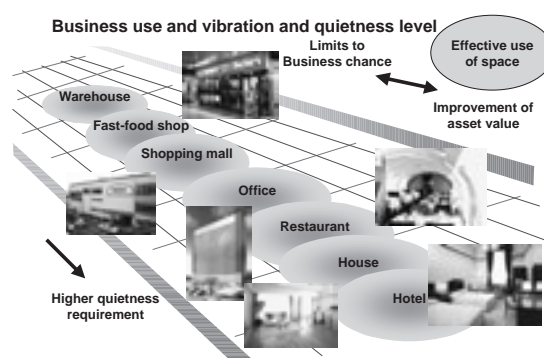


Fig. 1: Use of Space According to Vibration and Quietness Level

2 Overview of Column-Beam Joint Structure with Elastic Material Inserted

In order to improve the amenity of under-viaduct spaces when trains pass over them, the vibration from trains must not be transferred to the under-viaduct equipment. So, we thought out a structure to reduce the transmission of vibration as much as possible by inserting rubber or other elastic material into joints between columns and beams and between columns and the foundation. Fig. 2 shows an overview of the joint structure with elastic material inserted into the joint between a column and a beam with and columns fitted. In this joint structure, a beam or a footing is processed with a block out to fit a column, and the column is fit into the block out at the specified depth. Elastic material is inserted to both ends of the column, and to the side of the column in the fitting if necessary, to reduce the vibration of a passing train. The elastic material on the side of the column possibly has less effect to reduce vibration. But inserting elastic material to the side of the column and setting a given spring constant

might control the natural period of the structure; and that might also be effective in controlling seismic response. Thus, our basic approach was to consider elastic material to the side of the column in this study.

3 Examination of Vibration Generation Based on Train Running Analysis

3.1 Overview of Analysis Method

Fig. 3 shows the brief illustration of the applied analysis method. The analysis model consists of a dynamic model of a running train and a dynamic model of a structure, which are defined as substructures. For both models, the elapsed time from analysis start defines the nodes. The deformation and the force at a time t are transmitted to individual dynamic models, and sequential calculation is carried out to make both models meet compatibility conditions for deformation and force.

The nodes that link both models to each other constantly change from the start to reproduce the train running at the set speed.

3.2 Overview of Train Running Analysis

(1) Overview of Dynamic Model

(a) Running Train

We specified the axle arrangement in the dynamic model of a running train (hereinafter "train model") to conform to M-load, a standard live load. M-load is a model of the standard train load of the load of electric railcars or internal combustion railcars. Fig. 4 indicates the image of the train model.

The train model was set with the same number of connected cars as a running train has. For the train model, we placed nodes and beam elements that modeled car bodies, bogies and axles, as well as spring elements and damper elements to indicate the vibration characteristics and damping characteristics between the car body and the bogie and between the bogie and the axle. We also connected cars with up-and-down spring elements and damper elements to consider the conditions of connections between cars.

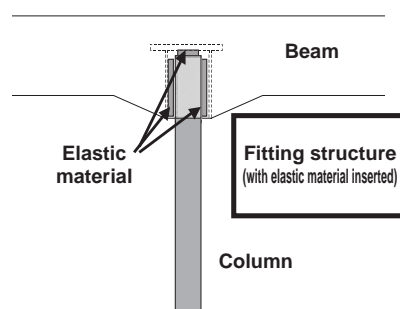


Fig.2: Simplified Illustration of Fit-Joint Structure (Example at Upper End of Column)

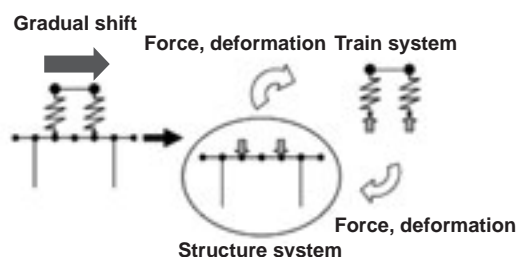


Fig.3: Simplified Illustration of Train Running Analysis

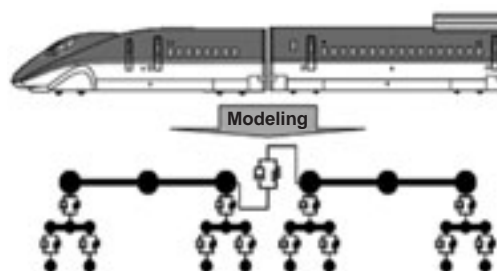


Fig.4: Image of Train Model

(b) Structure

Fig. 5 shows a general view of the analyzed viaduct. We selected a viaduct that is jointed with Gerber girders at both ends. The standard span length is 10 m and the viaduct has seven spans longitudinally. The height from the top of the footing to the top of the slab is approx. 8.0 m.

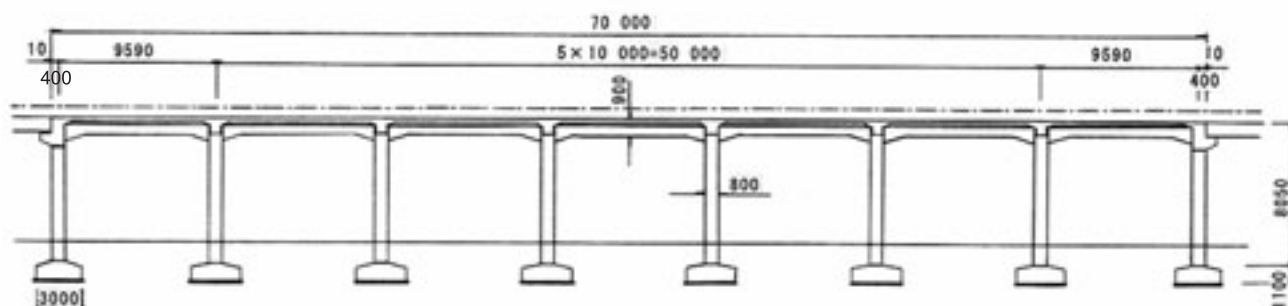


Fig.5: General View of Analyzed Viaduct

We used a model that replaced columns and beams of the viaduct with wire rods as the dynamic model of the structure (hereinafter "structure model"). We inserted spring elements representing dynamic behavior of elastic material in the joints of columns and beams to model the fit-joints. To each node of the structure model, we set the value of the mass of the fixed dead loads of each component equally divided with the number of nodes. To upper beams, we also set the value of the mass of the additional dead loads of tracks etc. equally divided with the number of nodes.

(2) Analysis Parameters

The parameters that would affect the vibration characteristics of columns of a viaduct when a train passes are span length, spring constant of the elastic material inserted to the joints of columns and beams, and speed of the train. Hence, we carried out tests with different parameters in the examination. Table 1 shows the brief explanation of analysis parameters.

4 Result of Study of Vibration Generation by Train Running Analysis

(1) When Varying Spring Constants at Both Ends of Columns

We studied the vibration acceleration level at the upper end of a column of a viaduct as the effect of the spring constant of the elastic material inserted into both ends of the column. In the analysis, we fixed the train speed at 60 km/h and varied the spring constant of the elastic material. Fig. 6 shows the vibration acceleration level at the upper end of the column.

Fig. 6 has the vibration acceleration level calculated using Formula (1) as the vibration acceleration at the upper end of the column obtained by train running analysis. Plotted on the graph are the relationships for a viaduct of a conventional joint structure (shown as "rigid joint") and viaducts of the new structure with typical examples of spring constants at 3 kN/mm, 30 kN/mm and 300 kN/mm.

We found that the vibration acceleration level at the upper end of the column is over 80 dB in the low frequency band under 10 Hz when we calculated with the spring constant 3 kN/mm. Comparing the results in the frequency band around 31.5 Hz where the vibration acceleration level of a conventional viaduct becomes predominant proved that inserting an elastic material with approx. 30 kN/mm spring constant into the column joint can reduce the vibration acceleration level by approx. 20~25 dB.

$$L_v = 20 \text{ Log } (a/a_0) \quad (1)$$

Here,

L_v : Vibration acceleration level (dB)

a : Root mean square value of vibration acceleration after weighting vibration sensation

a_0 : Standard acceleration (10^{-3}m/s^2)

(2) Effect of Running Train Speed

Fig. 7 shows the results of a study where the speed of a running train was varied between 40, 80, 120, and 160 km/h with spring constant of the elastic material at the upper and bottom end of a column fixed at 60 kN/mm.

Vibration acceleration level at the upper end of the column tended to become larger as the train speed becomes faster. However, we could not view a prominent difference in vibration acceleration level at speeds of 80 km/h or faster.

Table.1: Analysis Parameters of Train Running Analysis

Analyzed case
1. Span: Two spans of 10 m and 15 m
2. Spring constant at upper and bottom end of column: $k = 3 \sim 5,000$ kN/mm, 26 constants for rigid-joint
3. Speed: Six speed levels of $V = 30 \sim 160$ km/h
4. Running train: One axle arrangement for M-load (modeled E3 train)
5. Total number of analyzed cases: 220

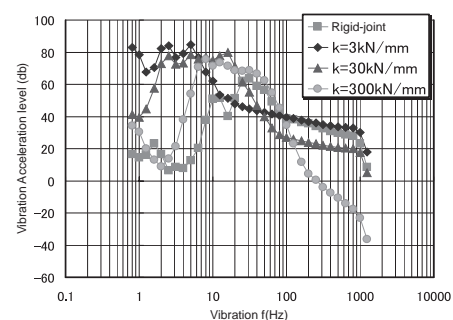


Fig.6: Relationship Between Spring Constant at Upper End of Column and Vibration Acceleration Level (Viaduct with 10 m Column Interval)

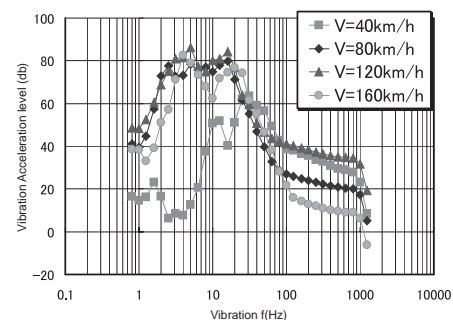


Fig.7: Relationship Between Train Speed and Vibration Acceleration Level

5 Overview of Alternating Loading Test with Test Model¹⁾²⁾

The structure with inserted elastic material to reduce vibration by train running differs much from conventional viaduct structures with unified columns and beams. But aseismic performance is required for this new structure too, and we need to identify the deformation behavior of this new viaduct structure to verify the aseismic performance. So, we carried out alternating loading tests with a column test model and a portal test model of this joint structure. An overview of the alternating loading tests with a portal test model is as follows.

5.1 Overview of Alternating Loading Tests with Portal Test Model⁽²⁾

(1) Overview of Portal Test Model

Fig. 8 shows an example of the shape of the test model. The shape of the model is a portal picking up a span of an actual viaduct (hereinafter "portal test model"). This portal test model has two columns and a beam between the columns.

We made components of columns, a beam, and footings separately and assembled them using a stand. First, we attached a specified elastic material to both sides of columns and inserted the columns to the fitting parts of footings using a crane. After setting each component at specified places, we filled the gaps of the fit-joints with high strength grout.

(2) Overview of Test

We attached a loading plate of a horizontal loading actuator to both sides of the beam of the test model by clipping the plate with high strength prestressing steel, and then carried out alternating static horizontal loading tests. Defining the displacement that the longitudinal reinforcement of the column of the test model yields as $1\delta_y$, the displacement unit, we gradually increased the horizontal displacement by integrally multiplying $1\delta_y$ in the alternating loading process.

(3) Brief Explanation of Test Results

Fig. 9 shows the load-displacement curves at the loading point as the results of alternating loading tests on the portal test model. Fig. 9 also shows the analysis results to be explained later.

We confirmed that the cracks occurred on the columns were similar to the cracks on the columns of a conventional viaduct. Elastic material located to the sides of the columns was compressed and deformed greatly on the compressed side, but no piece of elastic material shifted or came away off.

6 Examination of Aseismic Performance of Low-Vibration Viaduct

This new type viaduct also needs to meet aseismic requirements. In order to examine the aseismic performance, we built a structure model that can show the deformation behavior of this structure precisely.

We examined the structure model and its accuracy based on the alternating loading test results by the portal test model. We enlarged the built structure model to the size of an actual structure, and further examined the behavior of the new viaduct in earthquakes based on the analysis of an actual viaduct in a large earthquake. The examination results are as follows.

6.1 Examination Based on Test Results of Portal Test Model

In the structure model for this joint structure, column components were fit in the rigid joints and spring elements were placed around

the columns to represent elastic material. Fig. 10 shows an overview of the structure model of the fit-joint. We placed a vertical spring and a rotating spring at both longitudinal ends of the column and horizontal springs on both sides of the column as spring elements to be considered. Fig. 11 shows the analysis model of the portal test model. We carried out the analysis in accord with the alternating loading test process. The analysis results are shown in Fig. 9. Test results and analysis results agreed with each other relatively well on the load-displacement relationship.

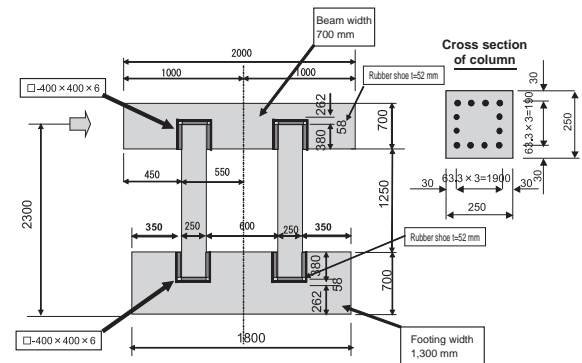


Fig.8: Shape of Portal Test Model

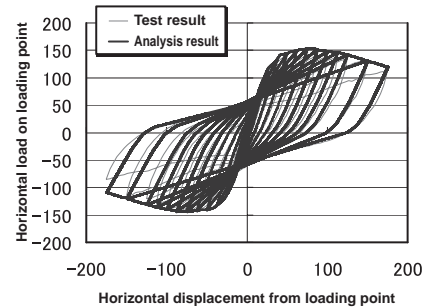


Fig.9: Load-Displacement Curve of Portal Test Model

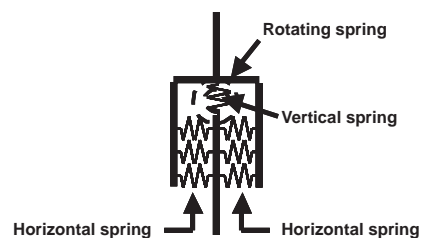


Fig.10: Overview of Structure Model of Fit-Joint

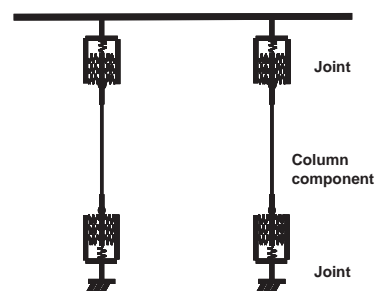


Fig.11: Overview of Analysis Model of Portal Test Model

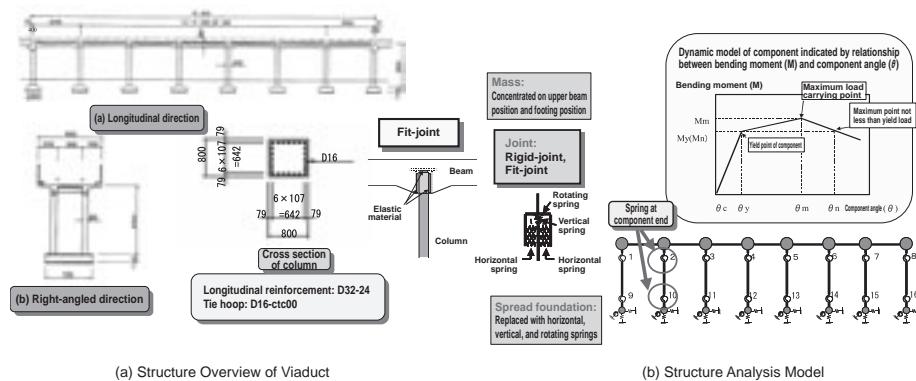


Fig.12: Analyzed Viaduct and Analysis Model

6.2 Examination of Supposed Behavior of Actual Viaduct in Earthquake

(1) Overview of Structure of Analyzed Viaduct

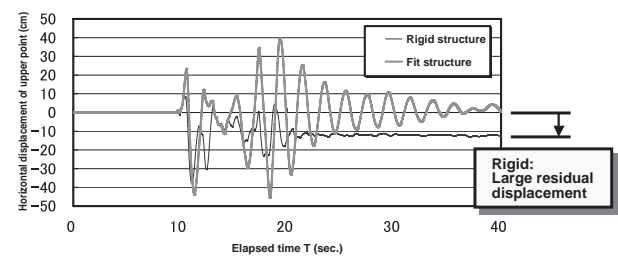
We carried out analysis assuming a viaduct with 10 m column interval, seven longitudinal spans and approx. 8 m height. Fig. 12 (a) and (b) show the simplified structure and the analysis model of the analyzed viaduct. The viaduct is of fit-jointed structure with careful thought given to elastic material in the joints of columns. For comparison purpose, we also examined a conventional viaduct of the same structure specification but with rigidly jointed columns. The seismic wave used was the wave specified in current aseismatic standards³⁾.

(2) Overview of Analysis Results

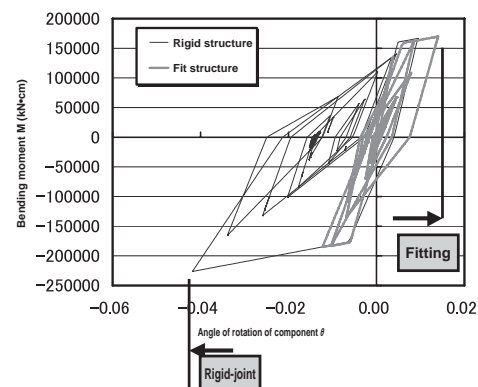
An example of the analysis results is shown in Fig. 13 (a) and (b), indicating the conventional viaduct as "rigid-joint structure" and the low-vibration viaduct as "fitting structure". Fig. 13 (a) indicates the displacement wave shape at the upper point and Fig. 13 (b) indicates the response results of the bending moments of the column and the angle of rotation of the component. This means the angle of rotation of the component on the horizontal axis is the deformation of the column; and the higher the value, the larger the deformation was. The displacement at the upper point showed that the horizontal displacement tended to become larger because the elastic material on the column joint achieved less horizontal rigidity than that of the conventional viaduct. But the residual displacement at the end of the earthquake tended to be smaller than that of the conventional viaduct. We think this is because the horizontal displacement at the upper points was added with the deformation of the elastic material, and the plastic deformation of the column of the new viaduct itself became smaller than that of the conventional viaduct.

7 Conclusion

This is the report of our examination of a new viaduct to improve the environment of the under-viaduct space when trains pass. We will further explore the issue to make proposals regarding design methods.



(a) Response Displacement of Upper Point



(b) Deformation of Column Component (M-θ history)

Fig.13: Example of Analysis Result

Reference:

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