Design of Arch Springing of Kouchigawa Bridge - Joints of Rigid Frame Members with Mixed-Composite Structure-

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Summary

Kouchigawa Bridge is a steel and concrete hybrid balanced arch bridge of the multi-span continuous type, 771 m in length, 220 m in arch span length, and about 90 m in maximum pier height. Since the member axis of the arch rib is joined to the bridge pier and the main post, which are the vertical members at an angle, when the node point of the rigid frame member is designed as a reinforced concrete structure, the lateral ties of the bridge pier and reinforcing bars, such as stirrups of the arch rib, intricately interfere, and reinforcement arrangement is difficult. Therefore, this paper adopts a concrete filled steel shell structure, which works as 1) a mold form and support for concrete work under construction, and 2) as a steel and concrete composite structure for service use and earthquakes.

1 INTRODUCTION

Kouchigawa Bridge (tentative name) of the Shin-Tomei Expressway is a steel and concrete hybrid balanced arch bridge of the multi-span continuous type with a bridge length of 771 m, arch span length of 220 m, and maximum pier height of about 90 m, which straddles Kouchi River, which flows through Yamakita-machi in Kanagawa Prefecture and prefectural road No. 76 (Figure 1).

Both ends of an arch rib of a single span deck fixing-type concrete arch bridge are independently supported by arch abutments; however, in a balanced arch bridge such as this bridge, since the member axis of the arch rib is joined to the bridge pier and main post, which are vertical members with the member axis at an angle, when the joint part of the rigid frame member is designed as a reinforced concrete structure, the lateral ties of the bridge pier and reinforcement, such as stirrups of the arch rib, intricately interfere, and reinforcement arrangement is difficult. Also, there was a concern that the support which supports the dead weight of the arch rib concrete in this section during the construction became large scale, and the construction and removal process drastically increased.

Fig.1 Rendering of the completed Kouchigawa bridge (Arch span length: 220m)

Therefore, this paper designed an arch springing to which a concrete filled steel shell structure is applied, which provides resistance as 1) a mold form and support for concrete work under construction, and 2) as a steel and concrete composite structure for service use and earthquakes. This paper reports the outline of the structure, the concept of the structural transition section at the joint of different members of steel and concrete in the arch rib, and consideration for the maintenance management. The whole length of the arch springing to which the concrete filled steel shell structure is applied is referred to as a "springing steel shell part."

2 BRIDGE OVERVIEW

Table 1 presents the bridge specifications and design conditions, while Fig. 2 shows the general drawing (inbound line). In the arch section of the bridge superstructure, the arch rib is PC cross-section of single box girder, which is a concrete member, and the stiffening girder is a two main narrow width box girder to which high-strength steel material SBHS500 is applied. The steel and concrete composite structure is applied to the arch springing, where the steel member and concrete member are joined, the end span connection, and between the stiffening girder and main post [1].

Table 1 Bridge specifications and design conditions for Kouchigawa bridge

Bridge name	Kouchigawa Bridge (tentative name)	Foundation type	Large-diameter cast-in-situ concrete pile
Location	Yamakita Town, Kanagawa Prefecture, Japan		P2・P3: φ=16.0-17.0m, L=25.0-35.0m
Owner	Central Nippon Expressway Company Limited		P1・P4-P7: φ=10.0-12.5m, L=10.0-20.0m
Detailed Design	Kajima Corporation, Taisei Corporation Joint Venture	Girder type	Steel stiffening girder: Two narrow width box section
Bridge type	8-span steel-concrete hybrid balanced arch bridge		PC girder: Single box section
Bridge length	771.000m		Arch rib: Single box section
Spans	65.1+125.0+220.0+125.0+71.0+65.5+54.5+42.1m	Erection method	Arch section: Truss balanced cantilever erection
Total width	10.700m		PC girder section: Balanced cantilever erection
Arch axis (Arch rise)	Average rise of P2 and P3: 40m P2: 45m, P3: 35m	Design specification	Specifications For Highway Bridges, March 2012 (Japan Road Association)

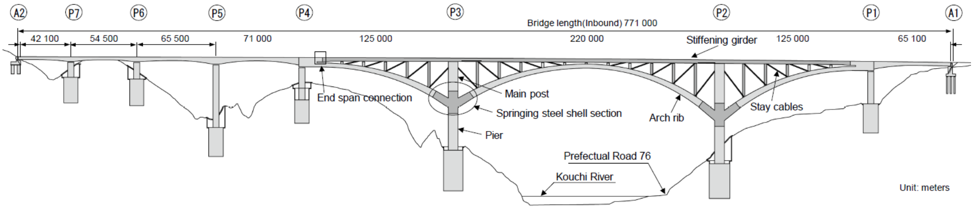


Fig. 2 General bridge plan for Kouchigawa bridge (inbound line)

3 HYBRID STRUCTURES

When the composite structure is assumed to be the third structure following the steel structure and concrete structure, it is shown in Fig. 3. Member level integration means a member which has a cross section composition composed of steel and concrete, which are different materials and are synthesized

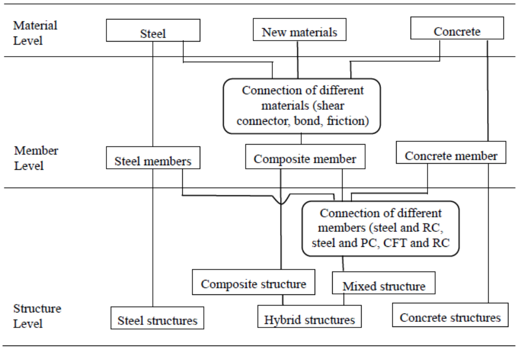
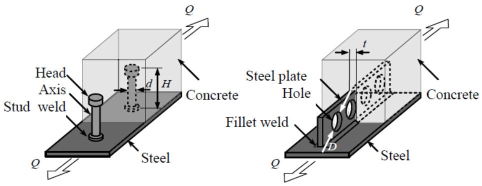


Fig. 3 Constitution and system of hybrid structures

with a binder such as a slippage stopper, and behaves as a unit. This is called composite member. As mechanical slippage stoppers, a headed stud and perfobond shear connector (hereinafter referred to as "PSC") are widely adopted (Fig. 4).

The structural level integration means the structure in which steel members, concrete members, or composite members are joined to different members. This is called a mixed structure. Though there is an application example in which bending moment, axial force and shear force are transmitted between two adjoining members through the joint part of different members, in the bridge field, a mixed girder bridge, in which a steel girder part and concrete girder part are connected in series in the member axis (bridge axis) direction, and a rigid connection structure in which a steel girder which is bridge superstructure and reinforced concrete bridge pier of substructure are connected in right angle direction, are widely known. In the Standard Specifications for Hybrid Structures [2] of Japan, "hybrid structures" are defined as a generic term combining both composite structures with composite members and mixed structures.



(a) Headed stud (b) Perfobond shear connector (PSC)

Fig. 4 Examples of mechanical shear connectors

4 CONCEPTUAL DESIGN

Since the member axis of the arch rib of this bridge is joined to the bridge pier and the main post, which are the vertical members at an angle, when the node point of the rigid frame member is designed as a reinforced concrete structure, the lateral ties of the bridge pier and reinforcing bars, such as stirrups of the arch rib, intricately interfere, and reinforcement arrangement is difficult (Fig. 5). Also, there was a concern that the temporary support, which supports the dead weight of the arch rib concrete in this section during the construction, became large-scale, and the construction and removal process drastically increased. Thus, the arch springing was adopted, to which a concrete filled steel shell structure providing resistance as 1) a mold form and support for concrete work under construction and as 2) a steel and concrete composite structure for structural design of completed system was applied. A scale model of the springing steel shell part is shown in Fig. 6.

Table 2 shows the structural planning concept of the springing steel shell part, which was determined by preliminary examination before starting the detailed design, and Fig. 7 shows the structural classification of members and parts (sections). The rigid frame member node and its vicinity are roughly classified into 1) bridge piers and main posts, which are vertical members, and 2) arch ribs, which are obliquely jointed, and it is an arch bridge which falls under "a bridge with complicated behavior in an

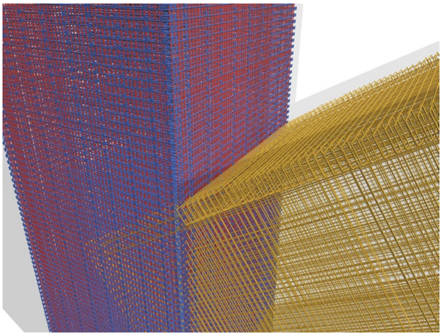


Fig. 5 Reinforcement in the vicinity of the joints of rigid-frame members in case of RC structure

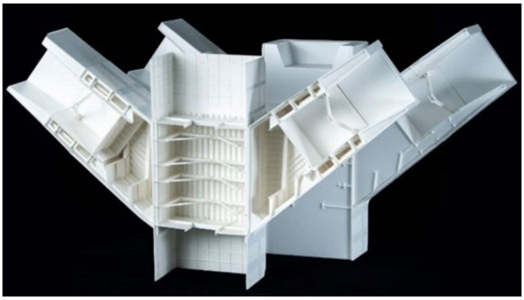


Fig. 6 Scale models of springing steel shell sections with steel shell concrete filled structures applied

Table 2 Structural planning concept of springing steel shell part defined in the detailed design

1) These are roughly divided into the rigid frame member node part and its vicinity into the bridge pier and main post, which are vertical members, and arch rib, which joins obliquely.
2) Under a level 2 earthquake, only the lower end of P2/P3 bridge pier is considered to be plasticized, and the springing steel shell part, which is the node part of the rigid frame member, including the adjacent concrete member, is not plasticized.
3) The joining of concrete members and composite members provides the structural transition section to clarify the transmitting force, the transmitting element, and their resistance mechanism.
4) Though bridge piers and main posts, which are concrete members, are respectively shifted to a concrete filled steel shell structure, considering the continuity of vertical direction RC members to ensure aseismic capacity, the axial reinforcement of bridge piers are arranged continuously through node parts.
5) The arch rib of PC cross-section of one-room box girder, which is a concrete member, shifts to a concrete filled steel shell structure, which is an SC composite cross section, through the intermediary of a steel shell cell structure.
6) A shape and dimension capable of installing a very large form traveller to use for cantilver erection of arch ribs is considered.
7) In addition to the mold form function, the steel shell also functions as a support, supporting dead weight when placing concrete.
8) In the joint structure of a steel member block, a bolted joint is adopted, prioritizing the erection process in the field.

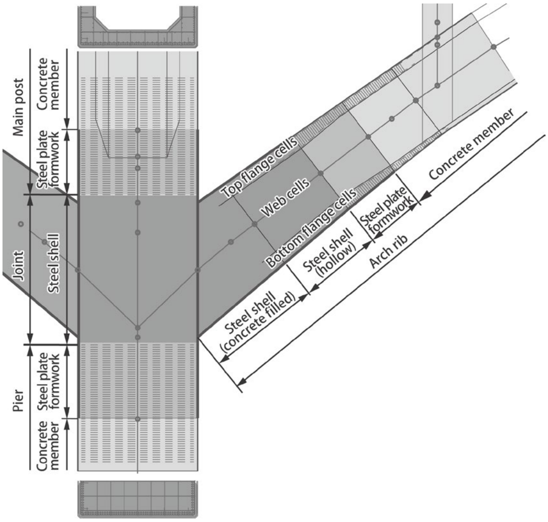


Fig. 7 Classification of members and sections of the springing steel shell section

earthquake" [3] in the earthquake-resistant design. And the superstructure, including the arch springing, is not to be plasticized because arch ribs and springing are members which play a large role in the behavior and stability of the whole bridge system [1].

Cross sections of bridge piers and main posts shift from RC bridge piers with solid cross sections from the column base side to RC main posts with hollow cross sections through steel plate mold form, steel shell, which is the node of rigid frame members, and steel plate mold form section again.

The arch rib shifts from the concrete member of the PC cross-section of single box girder to a steel shell (filling part) through steel plate mold form and steel shell (hollow part), and it is separated from the steel shell of the bridge pier by a steel plate, and there is no continuity of the inside filling concrete.

Table 3 shows the design method of the member cross section for each member and part of the springing steel shell, the force transmission element and the applied slippage stopper, Table 4 shows the main materials used, and Fig. 8 shows the whole temporary assembly in the steel member manufacturing factory. In the joint structure of a steel member block, the bolted joint is adopted, prioritizing the erection process in the field.

Table 3 Design methods for member cross-sections, force transfer elements and shear connectors in each part of springing steel shell section

Member	Section		Design methods for member cross-sections *1		Force transfer element		Shear connector type	Remarks
			Bending moment or axial force	Shear force	Bending moment or axial force	Shear force		
Arch ribs	Concrete member		PC	RC	— *3	—	—	Single box girder PC section
	Steel plate formwork [lapped section]			RC／S		Shear connector	Headed stud	Outer steel plate web formwork
	Steel shell (hollow section) [rebar anchorage section]	Top flange cells	PC	S	Bearing, Shear connector *3	（Friction）	PSC	Steel-shell cell structure Shear connector connection
		Web cells			(Bearing, Shear connector)	（Friction）		
		Bottom flange cells			Bearing, Shear connector	（Friction）		
	Steel shell (concrete filled section)		**SC**	**S**	Bearing, Shear connector	Shear connector	PSC	Steel-shell concrete-filled structure
Main posts	Concrete member		RC	RC	—	—	—	Hollow rectangular section
	Steel plate formwork		RC *2	RC／S		Shear connector	Headed stud	Shear connector connection
Joints	Steel shell			**S**		Shear connector	PSC	Steel-shell concrete-filled structure
Piers	Steel plate formwork			RC／S		Shear connector	Headed stud	Shear connector connection
	Concrete member		RC	RC		—	—	Rectangular section

▨ : Force transfer section

*1 : SC means composite section of outer steel plate and filled concrete, S means outer steel plate web only and RC/S means both structures alone, respectively

*2 : The internal RC alone, without the expected effect of the outer steel plate

↓ Force transfer section with shear connector

*3 : Longitudinally PT bars used for cantilever erection of arch ribs to apply prestressing forces

Table 4 Main materials used in springing steel shell sections

Member	Classification		Specification	Remarks
Piers／Main posts	Concrete		σck＝40N/mm^2	
	Reinforcement		SD490	Axial reinforcement bars
			SD345	Lateral confining reinforcements
Arch ribs	Concrete		σck＝50N/mm^2	
	Reinforcement		SD345	
	Prestressing steel		φ40（1B40B2）	Pre-grouted type
Springing steel shell sections	Concrete		σck＝50N/mm^2	Arch ribs
			σck＝40N/mm^2	Joints
	Reinforcement		SD490	Longitudinal reinforcement bars
	Structural steel		SM570	t=31mm
			SM490Y	t=31, 22, 16mm
		PSC	SM490YB	t=22mm
	Shear connectors	Headed stud	φ22x110	for structural steel plates t=31mm
			φ16x130	for structural steel plates t=16mm
		PSC	φ90	with two-layer arrangement of PSC

Fig. 8 Overall temporary assembly of the springing steel shell section (with the whole section overturned)

5 DESIGN OF SPRINGING STEEL SHELL PART

5.1 Design of bridge piers, main posts, and nodes of rigid frame members

The internal structure of the steel shell of the bridge pier and main post is shown in Fig. 9. Reinforcing ribs on the back of top and bottom flanges are installed at the height of top and bottom flange steel plates, which are the main structural parts of arch ribs, and furthermore, shape retaining ribs are installed at four places dividing the height direction between them into five parts. These are designed in consideration of stability retention during the erection of steel member blocks and mold form in placing concrete.

Fig. 10 shows the arrangement of reinforcing bars in the springing steel shell part and the steel shell in the vicinity. A cross section design for bending moment of the bridge pier and main post, which are vertical members, is made to be only RC members, and axial reinforcing bars are continuously arranged from the bridge pier lower end to the rigid frame member node and main post.

For shearing force, the force is transmitted from concrete to steel plate by the slippage stopper action of a headed stud installed in the outside steel plate of the steel plate mold form section, and the thickness of steel plate is determined so that an RC member or S member can be established separately in this section. The steel member block of the bridge pier steel plate mold form section is shown in Fig. 11.

In the steel shell section, which is the node part of the rigid frame member, only axial reinforcing bars of the bridge pier are arranged, and lateral ties and intermediate lateral ties are not arranged.

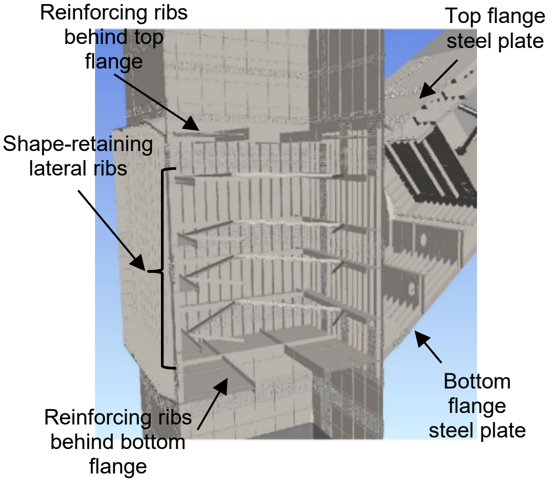


Fig. 9 Internal structure of steel shells of piers and main posts

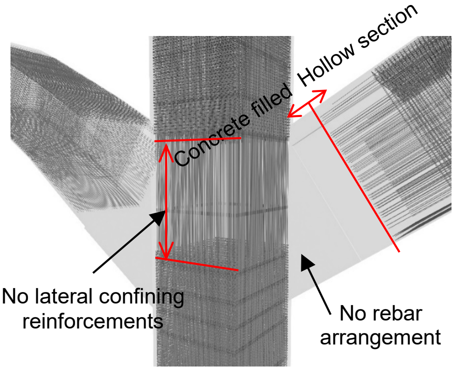


Fig. 10 Rebar arrangement inside the steel shell in and near the springing steel shell section

Fig. 11 Steel member blocks in pier steel formwork sections

5.2 Design of joint of different members of an arch rib

The internal structure of the steel shell of the arch rib is shown in Fig. 12. Steel plate mold forms for placing top and bottom slab and web and concrete are arranged in the steel plate mold form section adjacent to the arch rib of the PC cross-section of single box girder, and headed studs as slippage stoppers are arranged in the outside steel plate for the web. The force is transmitted from the concrete to the steel plate in this section for shearing force, and the thickness of the steel plate is determined so that an RC member or S member can be established separately.

Subsequently, steel shell cells with PSC are arranged in the top and bottom flanges and the web as a steel shell (hollow part) section, and a truss-type diaphragm is installed to maintain the shape of the hollow part.

In addition, the structure shifts to a steel shell (filling part), which is an SC composite cross section, and a filling part closing plate of concrete is provided in the boundary between hollow part and filling part, and two horizontal anti-swelling ribs are provided inside in order to suppress flexural deformation of the steel plate as a mold form in concrete placing.

Fig. 13 shows the structural transition of the joint of different members of the series type in the arch rib. Among the sectional forces acting from the arch rib on the right side in the figure, the shear force acting mainly on the web is transmitted by the steel plate mold form (lap section) as described above.

Bending moment and axial force are transmitted in the steel shell (hollow part) (reinforcing bar anchorage section), and among the axial forces acting on top and bottom flange cells, which are couple components of bending moment, 1) a compressive force is transmitted from concrete to steel shell through PSCs, which are slippage stoppers, and bearing pressure, and 2) a tensile force is indirectly transmitted to the steel shell through concrete and PSCs by the anchorage action of axial reinforcing bars. It is a feature of the series type joint of different members in the springing steel shell of this bridge that the transmission position of shearing force and bending moment and axial force is shifted in the member axial direction.

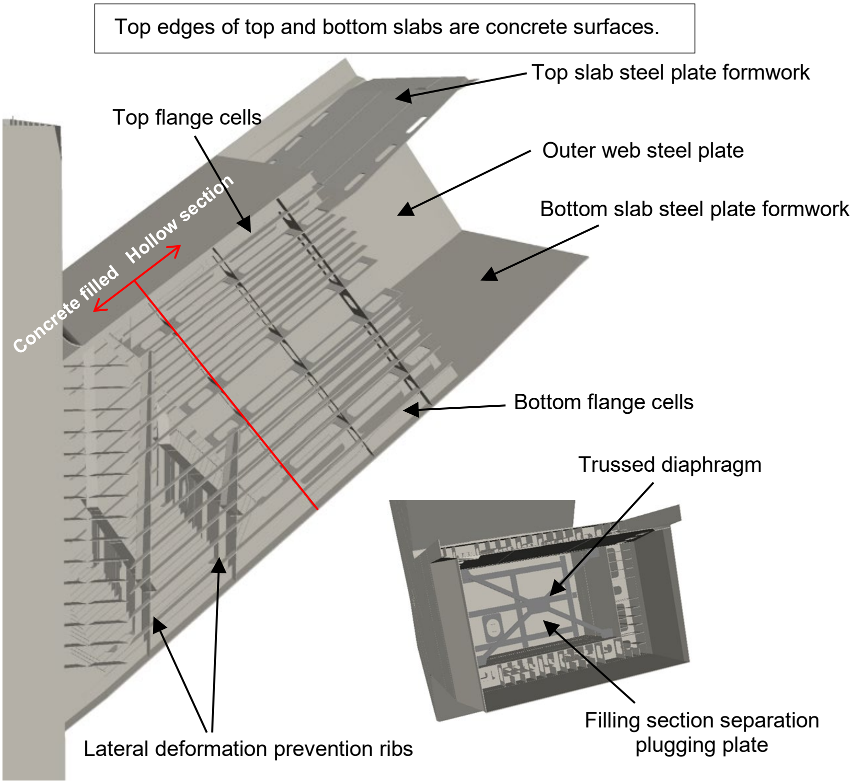

Top edges of top and bottom slabs are concrete surfaces.

Fig. 12 Internal structure of the steel shell of an arch rib

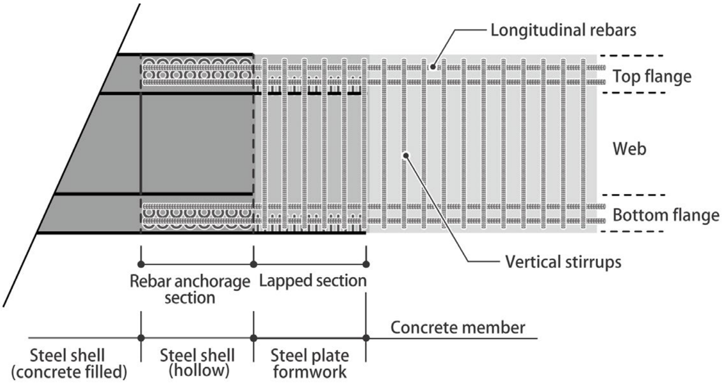


Fig. 13 Structural transition of series connection of different members in arch rib

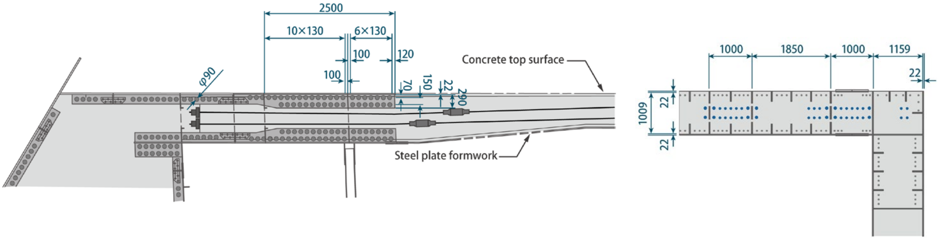


Fig. 14 Steel shell cells applied to the top flange

The minimum dimension of the steel shell cell is 1,000 mm in height (thickness) in consideration of the manufacturability of welding work, etc. in a factory, and as the design of the slippage prevention by PSC placed in the cell, the joint length is 2,500 mm, and the steel plates of 22 mm thickness having holes of 90 mm in diameter are arranged in two steps (Fig. 14).

6 CONCLUSIONS

This paper reports on the design outline of the springing steel shell, which is a steel and concrete composite structure, applied to the arch springing of the Kouchigawa bridge, the concept of the structural transition section in the joint of different members of steel and concrete in the arch rib.

This paper mainly examines the application of a steel and concrete composite structure for solving problems in construction related to the arrangement of reinforcement and support in the case of a reinforced concrete structure, as a result of which this part can be structured with toughness, robustness, and redundancy, and it leads to improved maintainability.

References

[1] Keiji, Yamazaki and Dai, Wakabayashi. 2023. "Design of Steel-Concrete Hybrid Balanced Arch Bridge. ", fib International Symposium on Conceptual Design of Concrete Structures Oslo 2023.

[2] Japan Society of Civil Engineers. 2014. *Standard Specifications for Hybrid Structures.*

[3] Japan Road Association. 2012. *Specifications for Highway Bridges, PartV Seismic Design.*