DEVELOPMENT AND DESIGN OF NEW STEEL PIPE INTEGRATED PIER WITH SHEAR LINK

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Abstract

We proposed an innovative integrated steel pipe pier using damage control design. The proposed pier is composed of four steel pipes interconnected with shear links along its height. Steel pipes as main members, support vertical load (such as dead load and live load). Shear links as sub members resist horizontal load (such as seismic load). The application of the damage control design can reduce a response of the pier and it can keep steel pipes wholesome during earthquakes. So, not only emergency vehicles but ordinary vehicles can pass immediately after earthquakes. This paper describes a outline of design and construction of highway viaduct supported by new steel pipe integrated pier with shear links applied to Ebie junction which connects the Yodogawa-sagan route to the Kobe route of Hanshin expressway.

Introduction

The proposed pier, steel pipe integrated pier with shear link, is composed of four steel pipes interconnected with shear links along its height (see Figure1). Steel pipes as main members, support vertical load (such as dead load and live load) and shear links as sub-members resist horizontal load (such as seismic load). The stable elastic-plastic behavior of each shear link as hysteretic dampers, which reduce the response of the pier during an earthquake. The application of the damage control design can reduce a response of the pier and it can keep steel pipes wholesome during earthquakes. So, not only emergency vehicles but ordinary vehicles can pass immediately after great earthquakes. And when a restoration is required, a change of shear panels restore the proposed pier. Therefore the seismic life cycle cost can be reduced.
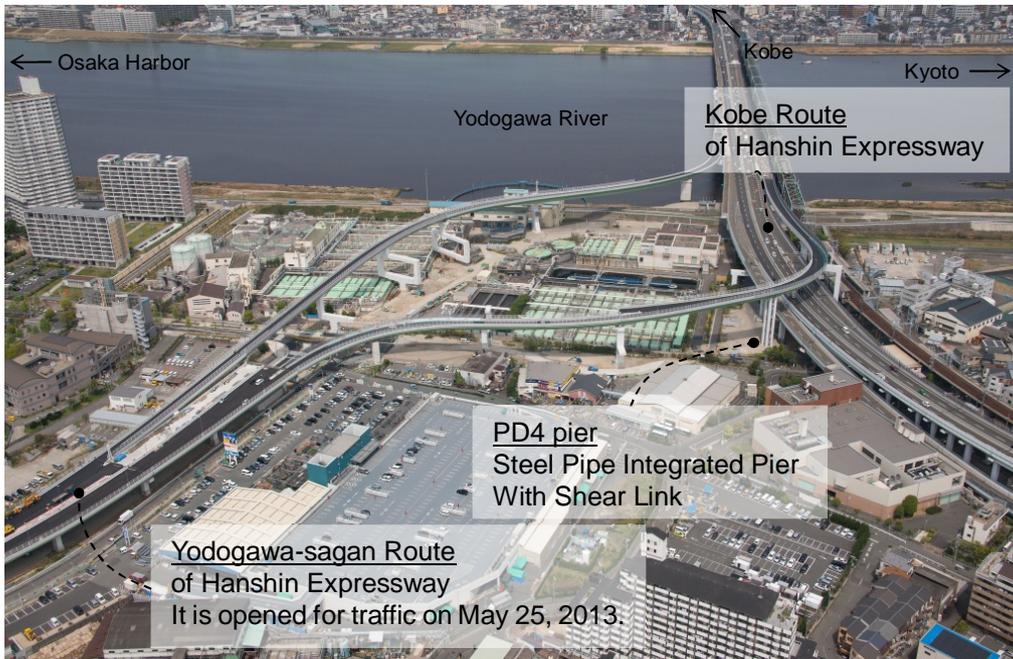

Fig-1 Steel pipe integrated pier

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This paper describes an outline of design and construction of highway viaduct supported by new steel pipe integrated pier with shear links where is Ebie junction which connects the Yodogawa-sagan route to the Kobe route of Hanshin expressway (see Pictuire1). The basic seismic performance of the proposed pier was reported in documents 1).

Picture-1 Ebie junction

1. Required performance

A required seismic performance matrix of steel pipe integrated pier is shown in Table 1. The required seismic performance of 4 phases is determined in checking a design of the proposed pier. It has been thought that it is difficult to control damages for great earthquakes in terms of cost performance so far.

Table-1 A required seismic performance matrix of steel pipe integrated pier

Seismic Performance Level	Performance I	Performance II a	Performance II b	Performance III	—
	〔Sutructure safty performance〕				
	Safty				Failure
	〔Usability after earthqueke〕				
Earthquake	No damage	Small damege	Medium damage	Big damage	
Level 1	□ △ ○		Unacceptable		
Level 2		○	△	□	

○——○　　Important bridge （Ordinary design condition）

△——△　　Important bridge （To keep small damage is illogical subject to special design condition ）

□——□　　Oirdinary bridge

The application of the damage control design enables the proposed pier to control damage of main member. The proposed pier should be intact for Level 1 earthquake (Seismic performance I). This design method leads major damages into shear panels that connect each steel pipe for level 2 earthquake and keeps steel pipe pier structural elastic-region. Structural elastic-region mean a state that a member makes locally plastic, shows elastic behavior as a structure, keeps sound state and the road can be open to the public after earthquake.

To keep small damage is illogical subject to design condition that a pier such as PD4 pier in Ebie junction resists seismic load in a curved and long span bridge. So this design method allows medium damage, same level as specifications for highway bridges, subject to special design condition (Seismic performance IIb). And this design method allows big damage of the proposed pier on less important structure (Seismic performance III).

2. Member Soundness

Seismic performance of the proposed pier is composed of soundness and damage level of each member. Member soundness matrix for seismic performance of the proposed pier is shown in Table 2. An image of damage level of each member is shown in Figure 2.

Table-2 Member soundness matrix for seismic performance of the proposed pier

Seismic perfomance		Perfomance I	Perfomance II a	Perfomance II b	Perfomance III
Earthquake level		Level1	Level2		
Steel pipe pier	Concrete hollow section	Soundness ①	Soundness ②	Soundness ③	Soundness ④
	Concrete filled section				
Shear link	Shear panel	Soundness ②	Soundness ③	Soundness ③	Soundness ④
	Joint	Soundness ①	Soundness ②	Soundness ②	Soundness ③
	Shear panel-joint	Soundness ①	Soundness ②	Soundness ②	Soundness ③
Joint part	Superstructre-pier	Soundness ①	Soundness ②	Soundness ②	Soundness ③
	Pier-Shear links				
	Pier-Cassion				
Whole structure	Residual displacement	Soundness ①	Soundness ②	Soundness ③	Soundness ④

(a) Steel pipe pier (b) Shear panel (c) Joint part
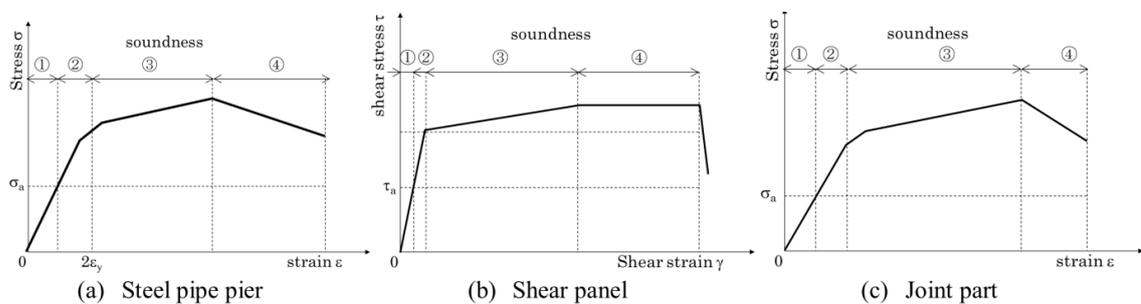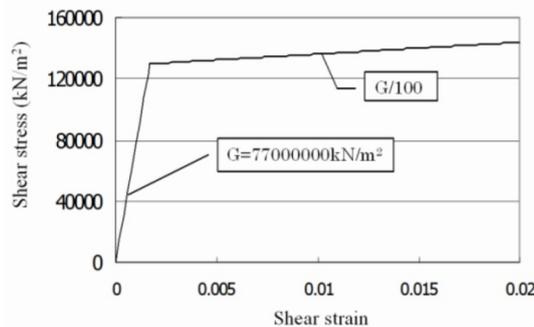
Fig-2 Steel pipe integrated pier

As regards seismic performance   , all members except shear panel should satisfy soundness 2 which have a safety factor for yield resistance. And the stress of shear panel is below yield resistance. As regards seismic performance   a, steel pipe pier should satisfy soundness 2 which is structural elastic-region, shear panel should satisfy soundness 3 which has stable performance, Horizontal member and connection should satisfy soundness 1 which is below allowable stress. As regards seismic performance   b, steel pipe pier should satisfy soundness 3 which is limiting value for steel pipe pier ruled on specifications for highway bridges. As regards seismic performance   , steel pipe pier should satisfy soundness 4 that steel pipes don't collapse, joints between shear panels and steel pipes satisfy soundness 3 which is below load capacity.
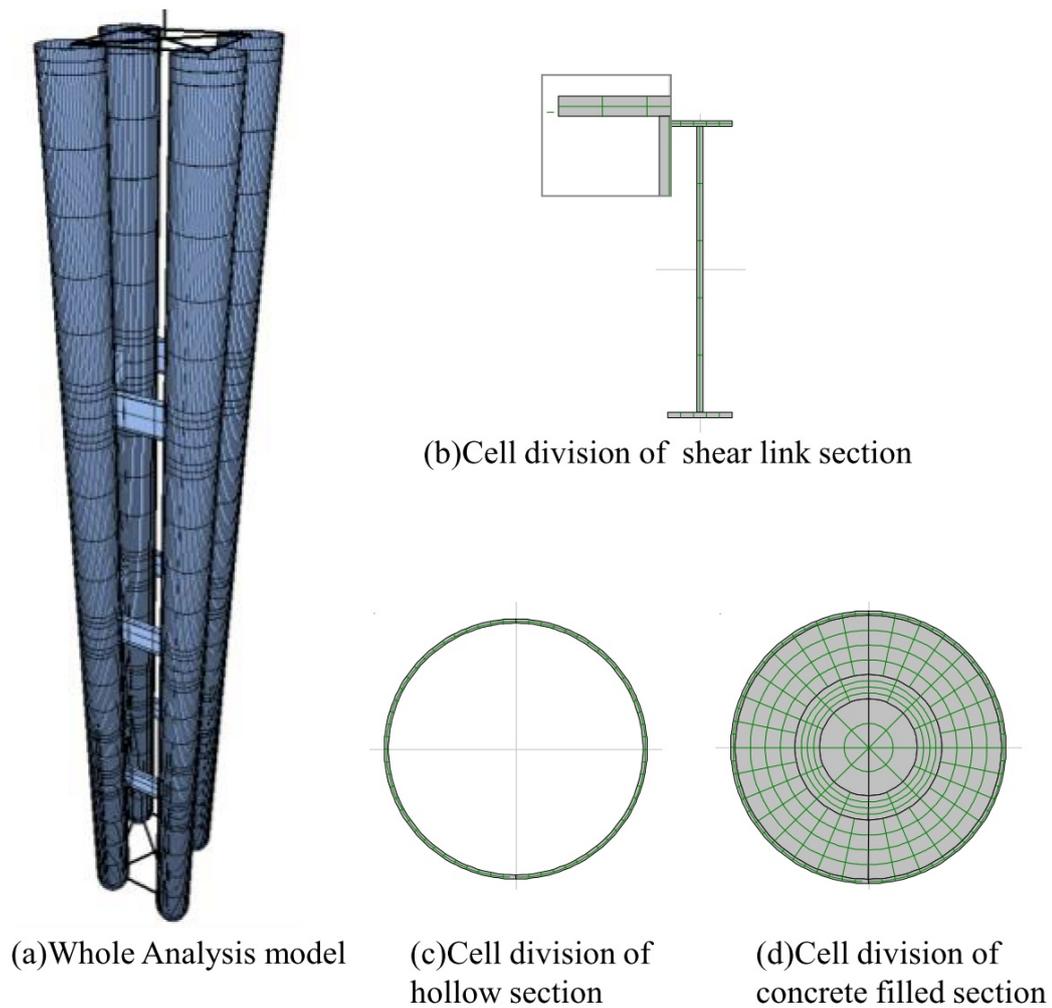
3. Analysis Model

The model of the proposed integrated steel pipe pier was created using a fiber model of the beam elements. A biaxial moment and a change of axial load are considered in this analysis. And material nonlinear configuration rules and geometrical nonlinear are considered also. The analysis model of the highway viaduct supported by steel pipe integrated pier is shown in Figure 3, the fiber model is shown in Figure 5 (a) and the fiber cell division of the steel pipe and shear link cross-section is shown in Figure 5 (b)(c)(d). The relationship between shear stress and shear strain is shown in Figure4.
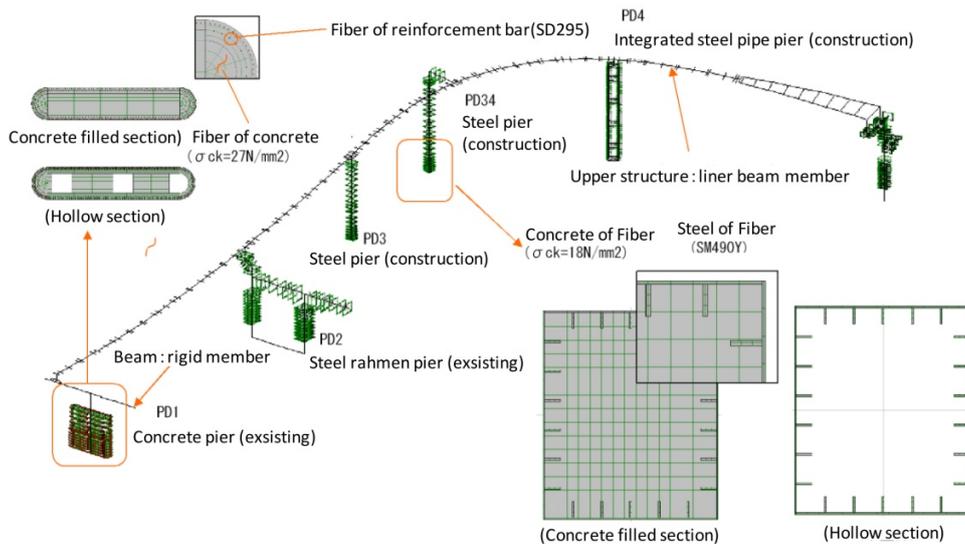
Fig-3 The analysis model for of Highway Viaduct Supported by New Steel Pipe Integrated Pier

**Fig-4 The relationship between shear stress and shear strain**

(a)Whole Analysis model

(b)Cell division of shear link section

(c)Cell division of hollow section

(d)Cell division of concrete filled section

Fig-5 The fiber model of Steel Pipe Integrated Pier

4. Material Configuration rules

With regards to the material configuration rules, those proposed in the documents 2) were used for SM490Y of the steel pipes, beams, horizontal structural member flanges, and the material of the filler concrete. For the dynamic analysis of the strain hardening of the steel materials, the bi-linear model, in which the secondary gradient should be 1% of the primary gradient, was used as the material configuration rule. A representation of the relationship between the shear stress and strain of LY225, used for the web plate of the horizontal structural members, is depicted as a bi-linear model.

5. Pushover Analysis

A pushover analysis was conducted to investigate the deformation performance, load capacity, and plasticization rate. For the load, a dead load was applied in the vertical direction and then a load was gradually increased in the horizontal direction. And a fiber model and shell model for a horizontal member were analyzed to investigate an acting of both models.
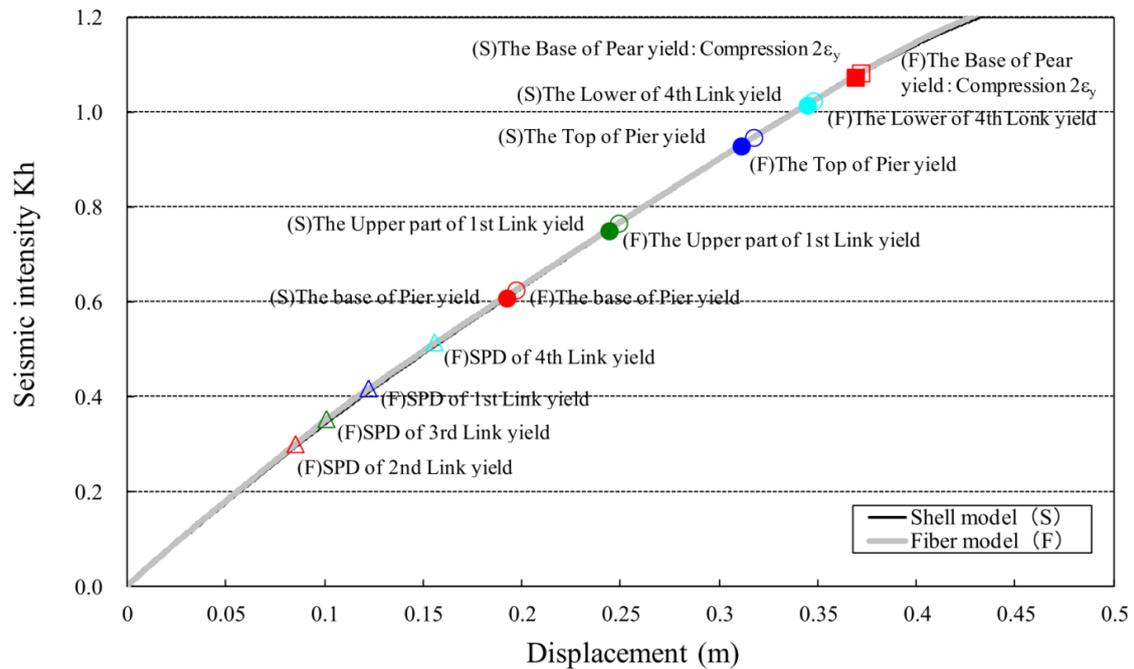
**Fig-6 The load-displacement curve resulting from the pushover analysis of the Shell and Fiber models**

The load–displacement curve resulting from the pushover analysis of the both models is shown in Figure 6. No significant difference of whole stiffness, a deformation performance, and load capacity of both models was found. The load capacity became larger after a shear panel was yielded. Whole bridge stiffness was controlled by the stiffness of the piers except for PD4 after a shear panel yielded. The plasticization rate (ultimate displacement / yield displacement) of the proposed type was determined to be 2.23. So absorption effects of energy can be expected in this structure.

6. Nonlinear Time History Response Analysis

This analysis was a time history response analysis incorporating geometrically and materially nonlinearity. Six standard seismic waves (Type1:3waves, Type2: 3waves), commonly used for road bridges in Japan, were used. And three scenario seismic waves (Nankai-Tonankai earthquake, Arima-Takatsuki dislocation earthquake, Uemachi dislocation earthquake) were used also. Type III soil, a comparatively poor soil, was employed, while the Newmark-beta method of numerical integration ($\beta = 1/4$) was adopted. The dominant oscillation mode is shown in Table 3. The dominant oscillation mode was in primary mode and secondary mode. In the both modes, PD4 pier was warped as contrasted with other piers.

The time history response displacement of the top of the PD4 pier for standard seismic wave (EW03) is shown in Figure 7. The maximum response displacement of the longitudinal direction was determined to be 0.299m. The maximum response displacement of the transvers direction was determined to be 0.360m. These response displacements were corresponding to allowable residual displacement.

Table-3 The dominant oscillation mode

The primary mode (T=1.06(s), f=0.04(Hz))	The secondary mode (T=0.95(s), f=1.05(Hz))
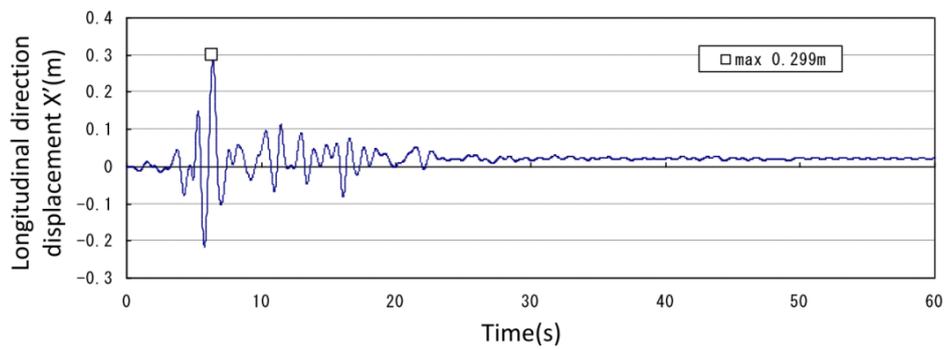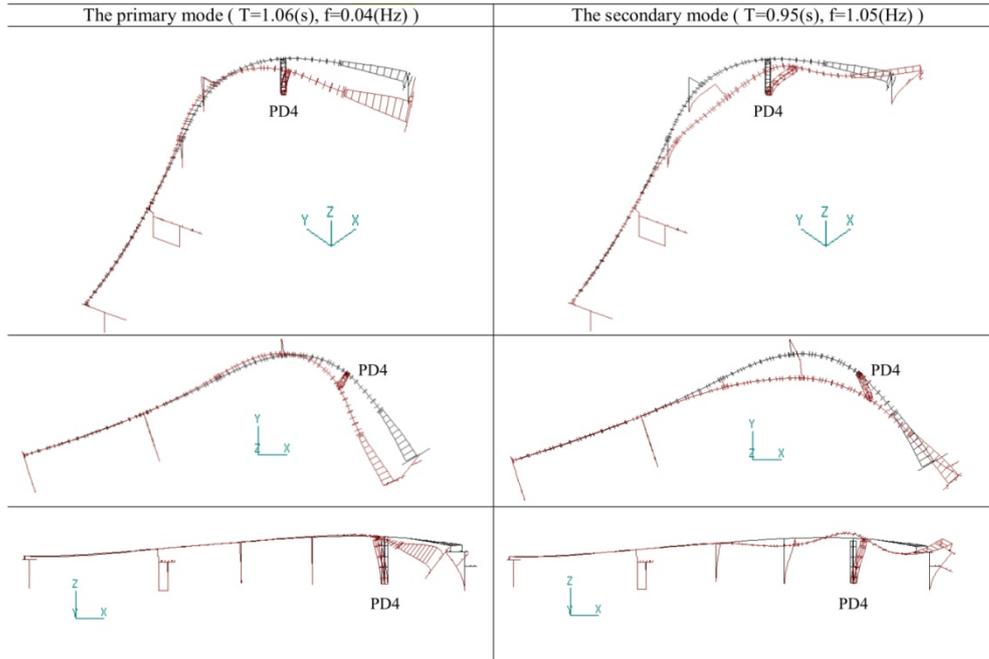
(a) Longitudinal direction
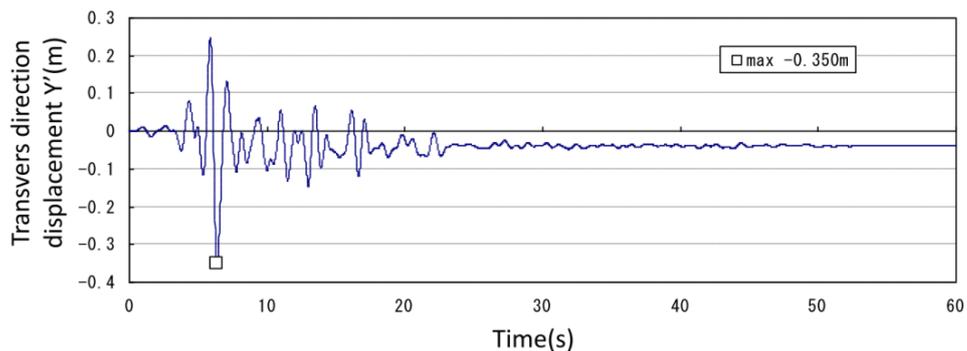
(b) Transvers direction

Fig-7 The time history response displacement of the top of the PD4 pier

In the case of severe seismic direction for PD4 pier, the maximum response strain of steel pipes is shown in Table 4. The maximum response strain of shear panel is shown in Table 5.The average of the maximum response strain of steel pipes on all members

was below $5\varepsilon_y$ correspond to soundness three of seismic performance IIb. Tension strain was determined to be $4.17\varepsilon_y$ in the base of steel pipe, $3.35\varepsilon_y$ in the upper of 1st horizontal member. Compressive strain was determined to be $2.45\varepsilon_y$ in the base of steel pipe, $1.55\varepsilon_y$ in the upper of filled concrete section. The average of maximum shear strain of shear panel was below 8% correspond to soundness three of seismic performance IIb in all shear links. The shear strain of shear panel was determine to be 3.58% as maximum strain in the shear link of 2nd, 3.40% in the shear link of 3rd. It is possible to thin thickness of steel pipe or reduces a number of shear links so that the shear panel was below allowable strain for Level 2 earthquake. But we allow shear panel to yield particularly during for Level 1 earthquake. As regards a number of shear link, energy absorption of 4 links was larger than that of three links as a result of comparison that of three shear links with that of 4 shear links during Level 2 earthquake.

Table-4 The maximum response strain of steel pipes

Part	Concrete	Tension strain $\varepsilon_{max}/\varepsilon_y$				Compressive strain $\varepsilon_{max}/\varepsilon_y$			
		Type2-1	Type2-2	Type2-3	average	Type2-1	Type2-2	Type2-3	average
The top of pier	Hollow	0.96	1.04	0.87	0.96	1.16	1.24	0.78	1.06
The upper part of 4th link	Hollow	0.52	0.56	0.36	0.48	0.58	0.58	0.5	0.55
The lower part of 4th link	Hollow	1.05	1.12	0.89	1.02	1.16	1.2	1.2	1.19
The upper part of 3rd link	Hollow	0.61	0.67	0.72	0.67	0.83	0.92	0.97	0.91
The lower part of 3rd link	Hollow	0.83	0.79	0.83	0.82	1	1.01	1.43	1.15
The upper part of concrete filled section	Hollow	0.76	0.82	0.88	0.82	1.16	1.58	2.51	1.75
The upper part of 2nd link	Concrete Filled	1.04	1.07	1.32	1.14	0.68	0.7	0.76	0.71
The lower part of 2nd link	Concrete Filled	0.82	0.81	0.9	0.84	0.47	0.44	0.5	0.47
The upper part of 1st link	Concrete Filled	3.44	2.99	3.63	3.35	1.55	1.36	1.75	1.55
The lower part of 1st link	Concrete Filled	1.02	1.01	1.26	1.1	0.93	0.9	0.97	0.93
The base of pier	Concrete Filled	4.55	3.78	4.17	4.17	2.79	2.08	2.49	2.45
maximum		4.55	3.78	4.17	4.17	2.79	2.08	2.51	2.45

Table-5 The maximum response shear strain of shear panel (Unit :%)

Shear link position	Allowable Shear Strain	Maximum Shear Strain				Check
		Type2-1	Type2-2	Type2-3	Average	
4th link	8.00	1.53	1.65	1.43	1.54	OK
3rd link	8.00	3.43	3.53	3.23	3.40	OK
2nd link	8.00	3.64	3.67	3.44	3.58	OK
1st link	8.00	1.88	1.85	1.76	1.83	OK

7. Fabrication Accuracy of Steel Pipes

Spiral steel pipes applied to the proposed pier are usually supplied for piles. Therefore the pipe suppliers don't manufacture pipes with high accuracy such as steel piers. The manual for design of the proposed pier[3] requires that the steel pipe of the proposed pier should meet the accuracy same as general ordinary steel piers. Differences of the fabrication accuracy between the manual and JIS (Japanese Industrial Standards) A 5525 is shown in Table 6. If a manufacture supplied isn't satisfied with the manual, a

fabricator must revise a manufacture to satisfy accuracy of steel pipes. In this construction, a fabricator didn't need to revise a manufacture so that the manufacture supplied was satisfied with the manual. It seems the opportunity to use spiral steel pipes for steel pier increase in the future. So we need to discuss with mill makers about the accuracy of steel pipes.

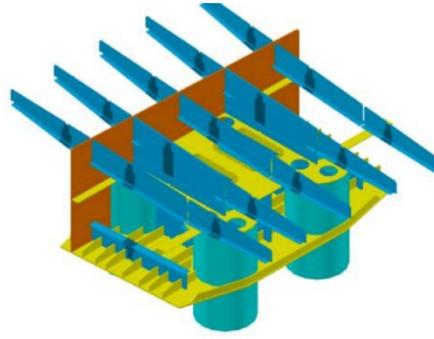**Table-6 Differences of fabrication accuracy between the manual and JIS A 5525**

	The manual of design and construction for Integrated Steel Pipe Pier	JIS A 5525 Japanese Association for Steel Pipe Piles
Circularity of Steel Pipe	Below 0.5% for the internal diamiter	Below 1.0% for the internal diamiter
Dislocation between both plates	±2mm	±4mm
Sampling level of radiographic examination for shop welding joints	1 joint every 1group	1 joint every 10 joints and a fraction

8. Welding Workability

In the junction where a superstructure meets steel pipes, it is worried that an interference of members and a deterioration in the quality of welding workability. So we made sure about interferences of members and the deterioration of welding workability using 3D-CAD. A example of checking interferences of members are shown in Figure 8. Situations of checking the quality of welding workability using full scale model are shown in Picture 2.
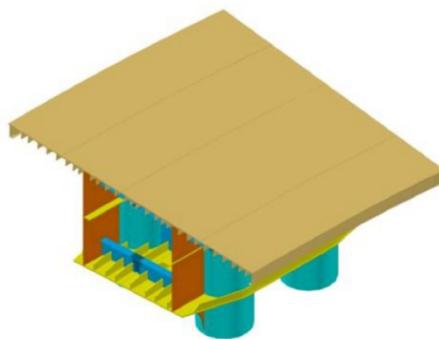
(a) 3D CAD with Deck model   (b) 3D CAD without Deck model
Fig-8 3D-CAD example for checking interferences of members
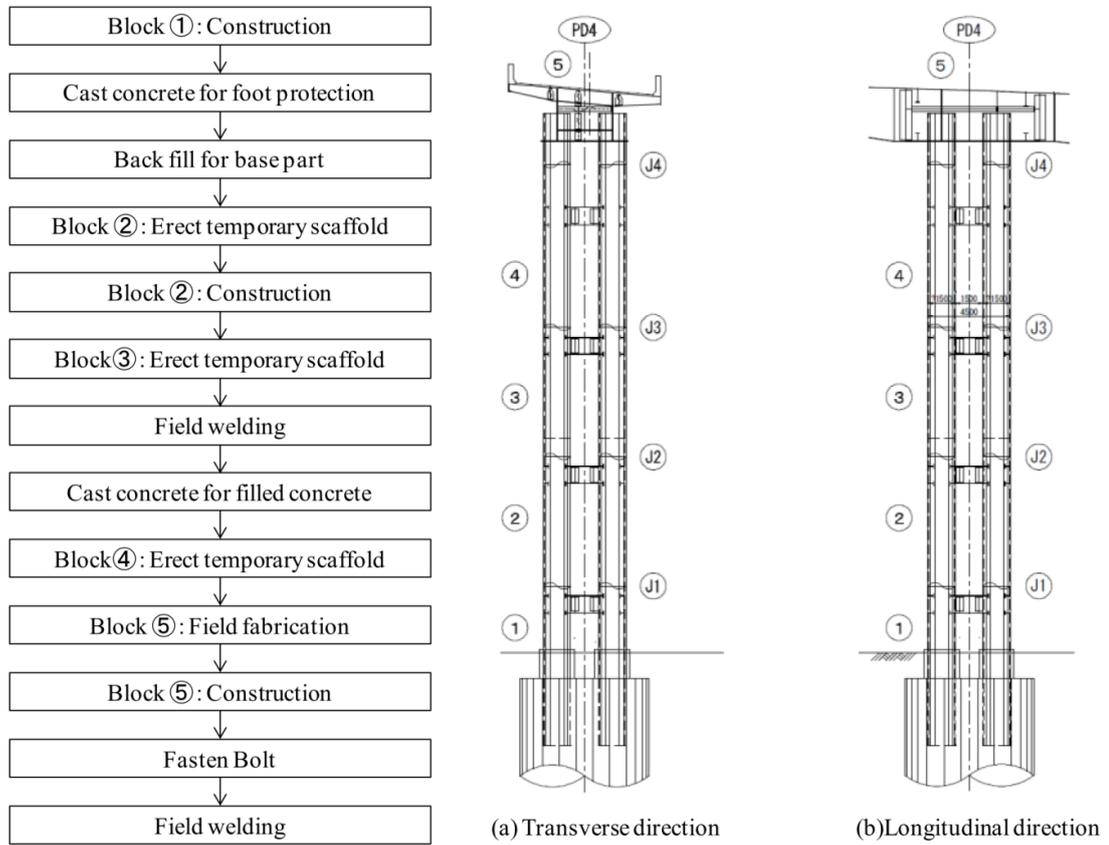

(a) Full scale model   (b) Situation for checking the quality of welding workability using full scale model.
Picture-2 Checking the quality of welding workability using full scale model

9. The outline of Construction

The construction flowchart of the proposed pier is shown in Figure 9. The proposed pier under construction is shown in Picture 3 and 4.

Fig-9 Construction flowchart

Block ①: Construction
Cast concrete for foot protection
Back fill for base part
Block ②: Erect temporary scaffold
Block ②: Construction
Block③: Erect temporary scaffold
Field welding
Cast concrete for filled concrete
Block④: Erect temporary scaffold
Block ⑤: Field fabrication
Block ⑤: Construction
Fasten Bolt
Field welding

(a) Transverse direction   (b)Longitudinal direction

Picture-3 A steel pipe under erection

Picture-4 The proposed pier under construction

10. Conclusion

  This paper describes the outline of design and construction of highway viaduct supported by new steel pipe integrated pier with shear links where is Ebie junction which connects the Yodogawa-sagan route to the Kobe route of Hanshin expressway (see Picture 5). The following conclusions were made:

(1) We proposed an innovative integrated steel pipe pier using damage control design. This design method leads major damage into shear panels that connect each steel pipe.

(2) The required seismic performance of four phases is determined in checking a design of the proposed pier. It has been thought it is difficult to control damage for great earthquake in terms of cost performance so far. The application of the damage controlled design enables the proposed pier to control damage of main member.

(3) A pushover analysis was conducted to investigate the deformation performance, load capacity, and plasticization rate. The plasticization rate (ultimate displacement / yield displacement) of the proposed type was determined to be 2.23.So absorption effects of energy can be expected in this structure.

(4) As result of time response analysis, the average of the maximum response strain of steel pipes on all members was below $5\varepsilon_y$ correspond to soundness three of seismic performance IIb.

(5) Finally, this paper describes measures against problems on fabrication and the outline of construction of PD4 pier, steel pipe integrated pier.

Picture-5 Steel Pipe Integrated Pier with Shear Link (Ebie junction)

11. References

1) Masatsugu SHINOHARA, Hidesada KANAJI:"Seismic performance of Integrated Steel Pipe Bridge Pier", IABSE Symposium London 2011: Taller, Longer, Lighter, September 2011.
2) Steel Bridge Seismic Resistance Subcommittee of the Performance-based Design Research Committee of the Japanese Society of Steel Construction: Fundamentals and Applications of Seismic Resistant Design for Piers, September 2002.
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4) Masatsugu SHINOHARA, Hidesada KANAJI, Takashi KOSAKA, Tsutomu IMAI: Design and Construction of Highway Viaduct Supported by New Steel Pipe Integrated Pier with Shear Link, 9th German - Japanese Bridge Symposium, September 2012.