Verification of repair effect of bridge deck using UHPFRC (J-THIFCOM)

Hideki Manabe *
Chien-Wen Huang **
Yasuo Kosaka ***
Hiroshi Mitamura ****
Takashi Matsumoto *****
Takashi Imai ******

* CORE Institute of Technology Corporation; Osaka, Japan, manabe@coreit.co.jp
** CORE Institute of Technology Corporation, Tokyo, Japan, huang.chienwen@coreit.co.jp
*** J-THIFCOM Construction Association, Tokyo, Japan, kosaka@coral.plala.or.jp
**** Calamity Science Institute, Osaka/Sapporo, Japan, mitamura@sunbridge.jp
***** Hokkaido University, Hokkaido, Japan, takashim@eng.hokudai.ac.jp
****** BBM Co. Ltd., Tokyo, Japan, imai@mgb.gr.jp

Abstract

The use of Ultra-High Performance Fibre Reinforced Cement-based Composites (UHPFRC) into deteriorated bridges appears to be one of the most promising rehabilitation system in concrete structures. Past researches indicated this emerging material offers a number of advantages over concrete overlays, i.e. high strength, high stiffness and low permeability. In order to maintain and repair the objects properly based on native / local conditions, such as geography and climate, a novel material, Japan - Thixotropic Hardening Impermeable Fiber Reinforced Composite (J-THIFCOM), was developed, and examined in large-scale specimens, as well as tested on in-situ applications. Considering the superior properties of J-THIFCOM on strength, stiffness, permeability, and durability, etc., a 20 mm thick layer of J-THIFCOM was deployed to rehabilitate Matsushima Bridge. In this study, to assess the repair efficiency and performance for Matsushima Bridge deck, a series of dynamic and static loading tests were performed, analysed and compared before and after repairing for the J-THIFCOM deck. By examining the monitored data for repaired deck, the results revealed that the deflection of deck decreased approximately by 45 %, and the neutral axis depth at girder moved up about 200 mm, as well as the magnitude of crack widths were restrained effectively.

Keywords: Japan - Thixotropic Hardening Impermeable Fiber Reinforced Composite, deterioration, rehabilitation, loading test

1 Introduction

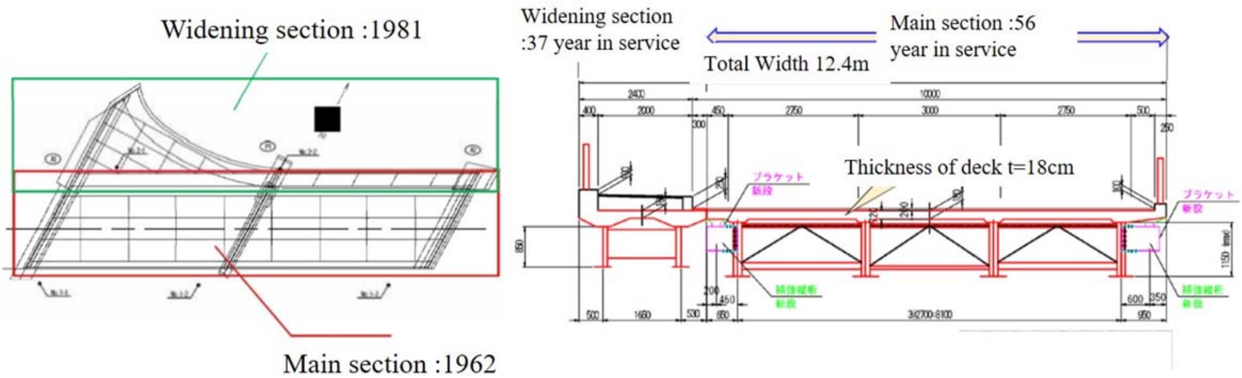
During the service life, maintenance and rehabilitation of deteriorated concrete structures is always a continual challenge in civil engineering throughout out aging Japan. Ministry of Land, Infrastructure, Transport and Tourism of Japan has to extend the services lives of existing concrete structures with limited capital and limited time needed for maintenance and rehabilitation. Constructed in 1960s, Matsushima Bridge over Pier Maizuru is a 2-span reinforced concrete girder bridge located in Kyoto, Japan. This bridge was originally designed using TL-20 live load, and although it locates in the suburban area, it carries large trucks with heavy loads passing over the thermal power plants within 55-year lifetime. Considering the stress concentrations due to repeated loads from vehicles, the tensile stresses were sufficient to cause the formation of cracking in the decks when trucks entered in and out of the bridge, and finally led to the deterioration of bridge deck. Such phenomenon may change the structure capacity and engineering properties, which in turn affect the strength, durability, and water leakage of concrete structures.

In general, the preferred repaired material to rehabilitate the deteriorated structures is conventional concrete overlays. Conventional concrete overlays have been economical and constructible options to achieve the objective requirements. However, these options also suffer from degradation mechanisms, such as cracking, spalling, and honeycomb. Therefore, developing an appropriate material for repair, maintenance and rehabilitation tasks is significant undertaking. Currently, a novel material, J-THIFCOM was developed, and applied on in-situ applications. This innovation solution has prominent findings, including mass transfer resistance, high strength and fatigue endurance, to block the deterioration factors, to protect from chloride penetration and water ingress, and to strengthening of concrete structures, as well as to improve fatigue durability. In this study, our research team performed repaired technique on deteriorated Matsushima Bridge with a 20 mm thick layer of J-THIFCOM. After the material was applied to the Matsushima Bridge and replaced the deteriorated deck, the field study were carried out and recorded by a data acquisition system. Finally, the results were compared with main girder strain distribution, deflection of deck and cracking behavior to assess the efficiency and performance of J-THIFCOM deck before and after repairing.

2 Experimental Program

2.1 Experimental Site

The selection of a rehabilitation site in this study is a concrete girder bridge for principle local route system located at Maizuru, Kyoto, Japan. Matsushima Bridge was designed in accordance with Japan road association’s Specifications for Highway Bridge (1956). This bridge, with a total length of 49.8m, has two spans of 24m. The superstructure of bridge consists of a continuous composite girder and overhangs constructed of single non-composite girder. The bridge with 62 °skew. The bridge is supported at the ends by reinforced concrete abutments and serves four lanes for traffic. The total width of the bridge is 12.4m and the deck is 18mm thick. The live load capacity used for the bridge structure is TL-20. A plan view and typical section of the bridge are shown in Figures 1.



Figures 1: A plan view and typical section of the Matsushima Bridge

2.2 Deterioration condition

Following the completion of the main lanes in 1962 and a widening lane in 1981, the Bridge Inspection Report noted some damages with surface spalling and exposed steel reinforcement in concrete walls and decks, and some major crack propagation at approximate concrete slabs. Moreover, it was observed that the condition of deck deteriorated by the cracks and ingress of moisture, causing the formation of efflorescence. It was also found that the leakage, together with efflorescence from the cracked concrete had caused extensive deterioration in some segments of the concrete surface. Figure 2 shows the damaged concrete decks.

Figure 2: Damaged concrete decks

3 Materials and rehabilitation method

To study the characteristics of J-THIFCOM, a series of experimental program on mixtures were conducted in order to evaluate the mechanical properties of J-THIFCOM. This experimental program involved compressive strength tests with cylindrical specimens at ages of 1 day and 28 days in accordance with JIS A1108, Method of Test for Compressive Strength of Concrete. Prior to the start of the Compressive strength test, Rheological properties of J-THIFCOM mixture were performed in accordance with JIS R5201, Physical testing methods for cement. The experimental methods used to determine uniaxial tensile strength, bond strength, chloride penetration resistance, and permeability are specified in JIS A1171, Test methods for polvmer-modified mortar. Test of the expansion and shrinkage strain and Torrent permeability for mixtures are standardized in JIS A6202 and SIA 262, respectively. For more details of the test apparatus, sample preparation and testing, readers can refer to the standards mentioned above.

2.3 Materials Used

The use of steel fiber reinforcement into a ready-mixed cement appears to be one of promising repaired materials in concrete structures. In this study, application of the J-THIFCOM is composed of ready-mixed cement, fiber reinforcement, chemical additives and specific admixtures, which impart controlled strength performance and compensated for deterioration factors. The mechanical properties of the tested materials are listed in Table 1.

Table 1: The mechanical properties of J-THIFCOM

Items	Test results	Remarks
Compression strength	130 MPa	100 MPa at 1 day, Over 130 MPa at an age of 28 days
Uniaxial tensile strength	9.0 MPa	post-crack tensile strength of 6 N/mm2
Young’s modulus	40,000 MPa	At an age of 28 days
Flow characteristic	Self-compacting	JIS R5201
Bond Strength	2.1 MPa	JIS A1171
Expansion and shrinkage strain	111×10^{-6} %	JIS A6202
Chloride penetration resistance	0 mm	JIS A1171
Permeability	10-19 m^2	Torrent method

J-THIFCOM is a very high strength fiber reinforced material with compressive strengths that typically reaches about 130 MPa at an age of 28 day, and post-cracking tensile strength greater than 6 MPa. Typically, the percentage of fiber per unit volume of material is equal to 2.5 %. This allows J-THIFCOM to bear large tensile deformation prior to loss of tensile capacity. Moreover, J-THIFCOM is designed to be flowable and self-compacting under gravity without mechanical assistance. According to the chloride penetration resistance and permeability results as shown in Table 1, the positive effects of J-THIFCOM cause an increase of resistance to chloride penetration and a significantly decreases permeability to aggressive fluids such as chloride or sulphate solution, thereby contributing to considerable pore refinement process (densification). On the other hand, as a direct result of this material, it can be effectively achieved a high compressive strength of 100 MPa at an age of 1 day which contributes to early strength development. In addition to the strength, efficient J-THIFCOM also improved an important engineering property on shrinkage strain, approximately 111×10^{-6} %, which reduced the potential for shrinkage-induced cracking.

A laboratory durability investigation was conducted on a deteriorated deck specimen with a 20 mm thick J-THIFCOM overlay. The deck was subjected to 2,000,000 cycles of repeated load corresponding to load of 150kN. The results show that the measurement points with a thin layer of J-THIFCOM had an excellent resistance to fatigue, although the boundaries of existing structures tended to deform. Consequently, the use of this innovative overlay had been proven in large-scale experiments to be effective material offering a number of advantages over conventional concrete, including enhanced durability characteristic, high strengthen development and low permeability.

3.2 Rehabilitation Method

Inspectors noted that a reinforced concrete deck of Matsushima Bridge suffered from the crack propagations and resulted in water leaks, thereby affecting the durability of concrete structures. In this direction, when the bridge decks were subjected to significant crack propagations, it caused the concrete structures to damage and decreased stiffness of bridge deck, subsequently leading to greater spalling and cracking. Moreover, cracks provided the paths for a rapid ingress of moisture into the deteriorated concrete structures, thereby initiating corrosion of reinforcing steel bars in concrete. When the reinforcing steel bars corroded, the resulting rust occupied a major volume than the steel, which created expansion and causes tensile stresses to the concrete, eventually causing cracking, delamination and spalling. Therefore, a desired thickness of overlay materials should be apply on bridge decks to provide a good resistance to ingress of moisture. Due to limited spacing and limited time needed for rehabilitation, a relative quick and simple solution should be developed to different properties. An innovative material, J-THIFCOM, is advanced to the rehabilitation of damage structures, and are effective to protect the concrete element damage caused by chloride penetration and water ingress, as well as to fill the narrow sections of concrete structures. Through an appropriate mix design, this material has advantages on mass transfer resistance, high strength development and fatigue endurance. Thus, applying a thin J-THIFCOM to an existing deteriorated concrete structure could provide water barriers, minimize required material volume and additional dead load on the bridge structures, and allow for early opening to traffic.

3.3 J-THIFCOM Overlay Details

J-THIFCOM was used in this study to repair the deteriorated bridge decks. Figure 3 shows the plan view of Matsushima Bridge. As shown in figure, the red line corresponds to 20mm thick of the J-THIFCOM overlay. The overlay was constructed in three stages. The overlay was placed on Land 1 and Lane 2 (Stage I) and Lane 3 and Lane 4 subsequently (Stage II and Stage III). When developing mixture proportions for J-THIFCOM, three fundamental factors must be considered in order to meet requirements, including mechanical properties of the aggregates, mechanical properties of the paste, and bond strength at the paste-aggregate interfacial transition zone. In this study, at a compressive strength of 130 MPa, the J-THIFCOM contained 2.5 percent (by volume) steel fiber reinforcement with ratio of water-bind ratio at 21 %. The details of J-THIFCOM mix design is shown in Tables 2.

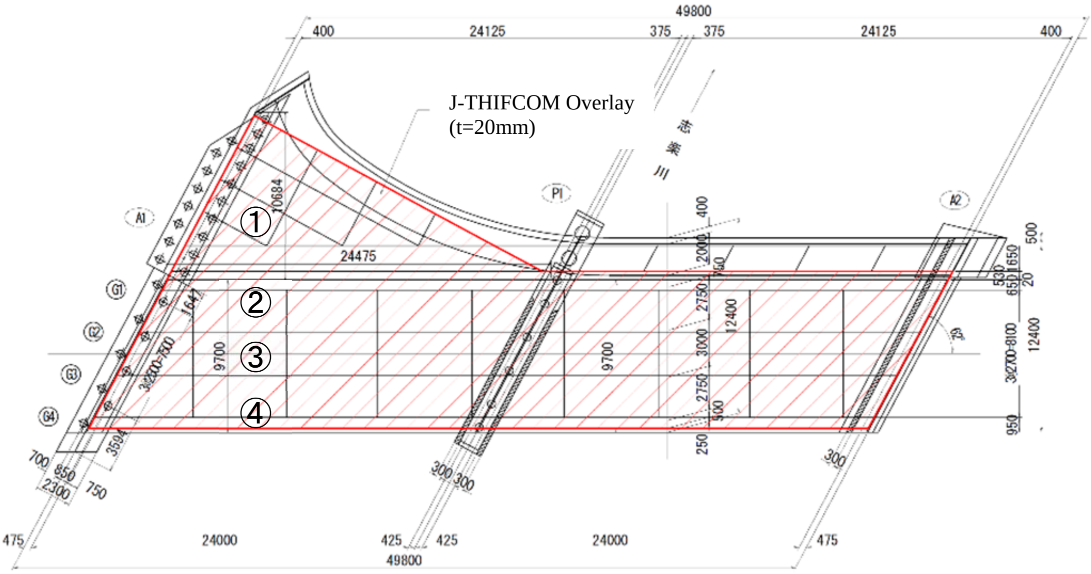


Figure 3: Plan View of Matsushima Bridge

Tables 2: Mixture Proportions of J-THIFCOM

Designed compressive strength	Water –bind Ratio	J-THIFCOM mixed cement	Water	Steel Fibers	Steel wool	J-T Admixtures
(MPa)	(%)	Unit (kg/m^3)				
130	21	1750 above	250-300	190 above	190 above	25-35

3.4 J-THIFCOM installation process

The repaired process of Matsushima Bridge is shown in Figure 4. Prior to placing the J-THIFCOM, the existing deck was ground to remove excessive concrete by water jet and provided a roughened surface to promote bond between the concrete substrate and the J-THIFCOM. Following the completion of the excessive concrete removal, surface was pre-moistened a few hours prior to applying the J-THIFCOM. Figure 5 shows the deck surface after water jetting. After preparing the recipes of J-THIFCOM, the constituents were mixed in a large drum evenly with the powder matrix. Because this material is sensitive to mixing deviations, the timing and mix proportions must be followed the J-THIFCOM specification. Once the J-THIFCOM was ready, this mixture was then discharged through the dump mixer and delivered to the location. Figure 6 shows the in-situ placement of J-THIFCOM. Time limit situation, placement of J-THIFCOM must be done on time so that segregation of the various constituent ingredients was avoided and fully consolidation was required in order to eliminate air voids. Inadequately consolidated overlays would reduce strength and durability. J-THIFCOM has flowable, and self-compacting characteristic, so the repaired objects made of J-THIFCOM were fabricated by placing the material at a certain point and allowing it to flow (Yoo, et al 2014, Yang et al 2010). This led to fiber alignment in the direction of the tensile stress, because when filling the J-THIFCOM into the formwork, the fibers in the zones near the surface are predominantly oriented parallel to the formwork wall (Mechtcherine et al, 2011), so-called wall effect (Garboczi and Bentz 1991). No other techniques was used to align the fibers. As a 20mm thickness of J-THIFCOM was achieved, vibratory screed was drawn down the lane properly. J-THIFCOM requires finishing, a hard trowel finish was used. From the time concrete was placed to the time finishing was complete. Figure 7 show in-situ condition on the surface of bridge deck after finishing.

Once levelling, curing by water sprinklers properly reduced the development of internal temperature differential. When compaction was achieved and the pavement had sufficiently cooled, the next layer was placed. Prior to applying the asphalt, the deck surface was cleaned thoroughly. Between each layer of a pavement, J-primer, J- coat and silica sand were applied on the surface area to fill the surface voids, to waterproof during pavement construction, and to generate adequate bond between an existing pavement surface and a new pavement surface (Figure 8). Finally, the deck surface was finished by paving an asphalt overlay. The completion of pavement is given in Figure 9.

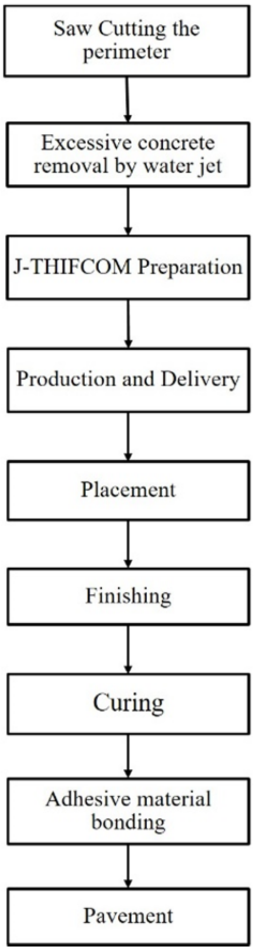


Figure 4: Repair process

Figure 5: Excessive concrete removal by water-jetting

Figure 6: Placement of J-THIFCOM

Figure 7 : Curing process

Figure : 8 In-Situ condition of bridge deck

Figure 9: Apply J-Primer on the surface area

Figure 10: The completion of pavement process

4 Loading test for Matsushima Bridge

In order to evaluate the efficiency and performance of J-THIFCOM, dynamic and static loading tests were carried out before and after the bridge rehabilitated to measure the crack behavior, deflection of deck and main girder strain distribution under the assumed loads on Matsushima Bridge.

4.1 Test Procedures and Instrumentation

The vehicle used for excitation of bridge in this experiment was a 2-axle truck with a total weight of 25 tons. During each loading, the test vehicle was driven at a constant speed, along the longitudinal bridge axis and always in the same direction. In this study, the measurements were taken and recorded by data acquisition system which consists of two subsystems for static and dynamic testing. The sensors were connected through separate channels to the data acquisition system and measured the changing when the experiment was performed. Those sensors included strain gauges, crack gauges, and deflection gauges. Seven strain gauges for girders were placed on an upper flanges a lower flange and a mid-point of column to evaluate location of neutral axis. The deflection was measured at the midpoint of G3-G4 span deflection gauges. Total of 9 crack gauges for girders were coupled to beams to observe the crack behavior. The details dimensions of test vehicle and sensor locations employed for this study is schematically shown in Figure 11. A data acquisition setup in shown in Figure 12.

In the experiment of static loading test, the truck was driven and placed at critical cracked positions on the bridge, which was able to measure the strain distribution at main girder and deflection of deck. For the specified load position, strain and deflection readings were measured and recorded by the PC through bridge box and multi-channel digital strainmeter. While the dynamic loading test was conducted by driving over the bridge using the allowed lane with a constant speed. During dynamic loading test, the bridge was instrumented with a monitoring system. When the concrete bridge was loaded by a 20-ton truck, the waves were penetrated from the crack location and reached the crack guages at the surface of girders. The data for crack behavior was collected and stored in the multi-channel digital strainmeter, and then transferred into the PC computer system for data interpretation and presentation.

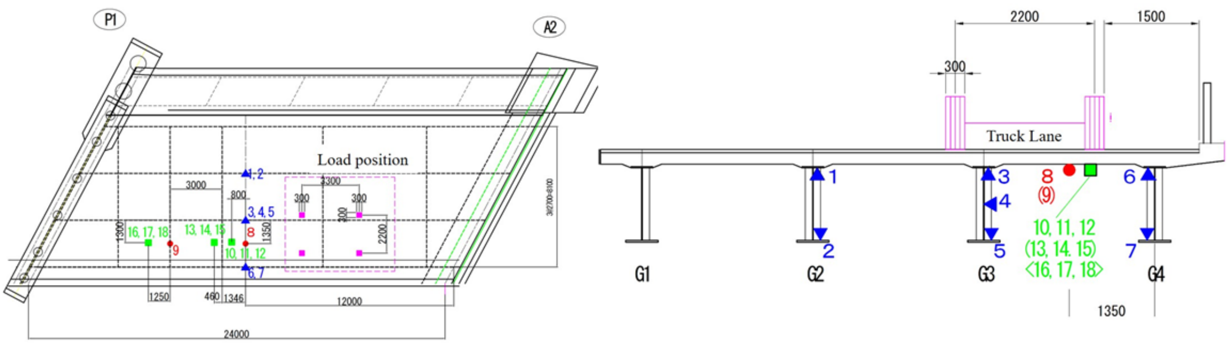


Figure 11: Schematic diagram of Vehicle loading test and sensor locations

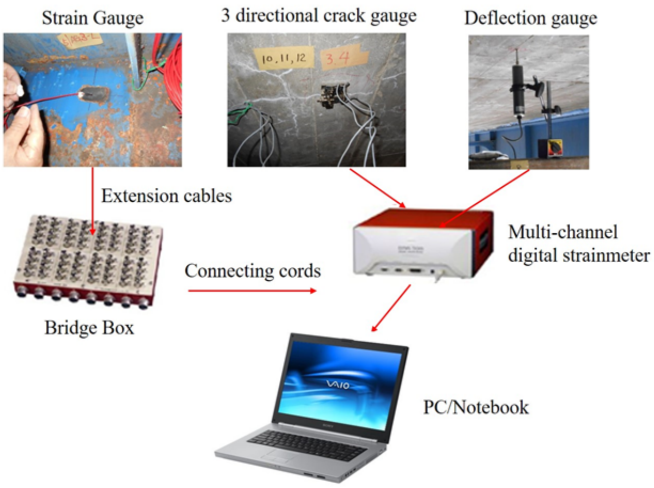
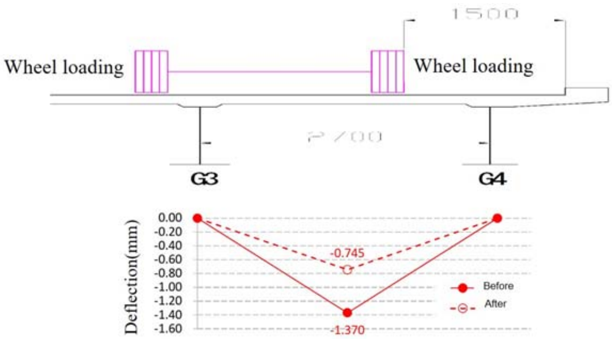


Figure 12: A data acquisition setup

5 Results and discussions

5.1 Deflection of Deck

Figure 12 presents that evolution of deflection curves at span before and after repairing. The experimental results indicate that the deflection curves obtained after repairing depend on the strength of J-THIFCOM and testing condition. Comparisons of the results obtained from before and after repairing, the value of deflection at point 8 and point 9 decreased from -1.37 mm to -0.745 mm and from-1.194 mm to -0.66 mm, respectively. This difference in behavior was clearly revealed that the performance of J-THIFCOM on the deck deflection was improved. Based on these results, it was concluded that after the deck was repaired, J-THIFCOM provided the sufficient strength for deck to restrict the deflection from heavy loads. The changing of deck deflection after repairing was approximately 45 % less than the value of deck deflection before repairing.



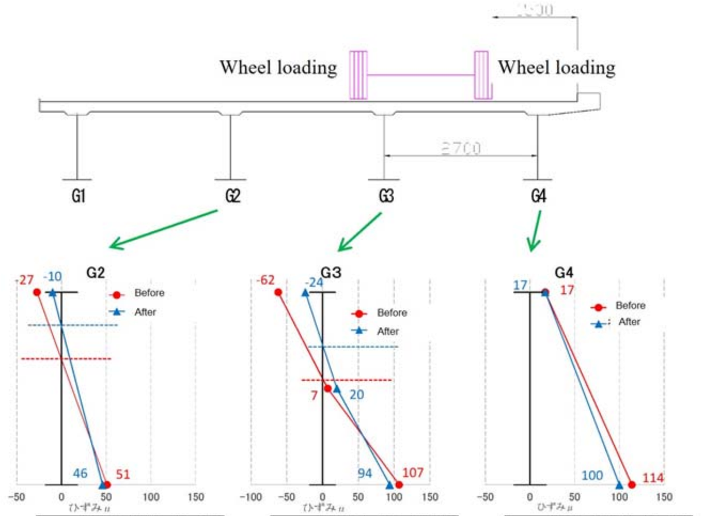
	Before	After	Ratio
Point 8	−1. 370	−0. 745	0. 54

	Before	After	Ratio
Point 9	−1. 194	−0. 660	0. 55

Figure 13 Deflection of deck before and after repairing

5.2 Main Girder Strain

Figure 14 shows a reading of strain gages mounted on girders to examine the neutral axis location. After the deck was repaired, the strain at upper flange shifted from -27 mm to -10 mm at G2, while the lower flange moved from 51mm to 46mm. Similarity, at G3, the strain at upper flange shifted from -62 mm to -24 mm, and the strain at lower flange evolved from 107 mm to 94 mm. When G4 was recorded and analyzed, the results shows that at upper flange, the strain shifted from 17mm to 13mm and the strain at lower flange moved from 114 mm to 100 mm. A direct comparison of the difference in neutral axis for three girder, when the excitation was triggered by truck, deteriorated girder 2, girder 3 and girder 4 had a higher likelihood that the neutral axis and centroid are not the same. After repairing, at G2 and G3, neutral axis depth moved up about 200 mm. G4 is not so much significant due to the stiffness of residual section which supported to the G4. Therefore, the results illustrate that the neutral axis of the girder was improved with the addition of the J-THIFCOM deck, and the strain distribution of the perpendicular direction of the bridge axis was restricted.



	U-FLG	Web	L-FLG
Before	−27	−	51
After	−10	−	46
Ratio	−	−	0.90

	U-FLG	Web	L-FLG
Before	−62	7	107
After	−24	20	94
Ratio	−	−	0.88

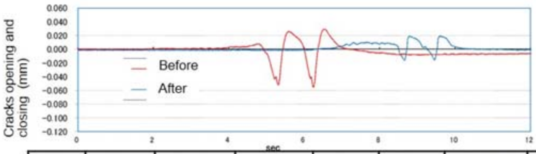
	U-FLG	Web	L-FLG
Before	17	−	114
After	13	−	100
Ratio	−	−	0.88

Figure 14 Main girder strain before and after repairing

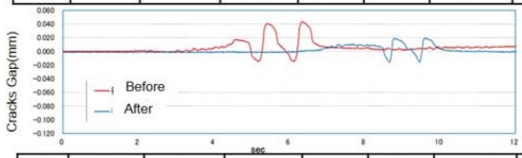
5.3 Behavior of cracks

After being subjected to dynamic loading test, the waveforms were captured and recorded by 3 directional crack gauges. Dynamic loading test values for crack 1 and crack 2 resulted from truck travelled at a constant speed on the bridge. Figure 15 and Figure 16 shows the magnitude of crack widths and amplitudes on crack opening, crack gap and crack step induced at mid-span of Matsushima Bridge by truck. In the case of crack opening, after repairing, the responses of crack 1 and crack 2 were smooth and slightly increase with time; while before repairing, the response of crack 1 and crack 2 on a deteriorated deck was strong and rapid. The responses in crack gap and crack step also show the same patterns. As expected, after repairing, the results of the crack 1 exhibited 35 % reduction of in opening and closing, 45 % reduction in gap, and 35 % reduction in step. Same process of detailed analysis as crack 2, after repairing, the results of the crack 2 indicated 38 % reduction of in opening and closing, 55 % reduction in gap, and 14 % reduction in step. These implied that Matsushima Bridge repaired by J-THIFCOM resulted in higher strength and stiffness performance and led to a marked reduction in magnitude of crack widths during loading tests.

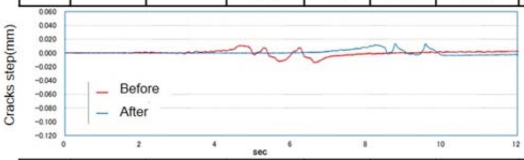
In this section, the loading tests were conducted in order to observe the efficiency of J-THIFCOM in Matsushima Bridge. The results of strain and deflection show that the capacity of the repaired bridge in strength and stiffness was enhanced. The magnitude of crack width measurements also indicates that the durability of this rehabilitation deck was expected. Therefore, the remarkable performance on Matsushima Bridge can be achieved by the use of J-THIFCOM and proved by experiments in practice.



No	Item	Location	Repairing	Max	Min	Amplitude	Unit
10	AS-CX	Opening & Closing	Before	0.029	-0.055	0.084	mm
			After	0.016	-0.039	0.055	mm
			Ratio	55%	71%	65%	

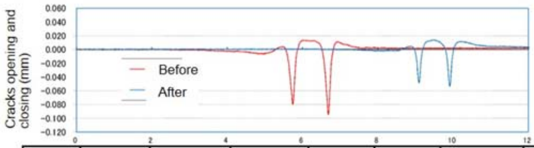


No	Item	Location	Repairing	Max	Min	Amplitude	Unit
11	AS-CY	Gap	Before	0.043	-0.014	0.057	mm
			After	0.020	-0.016	0.036	mm
			Ratio	47%	114%	63%	

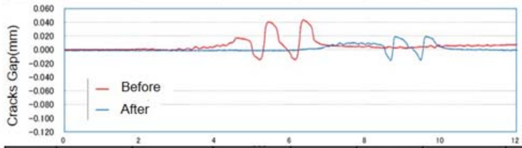


No	Item	Location	Repairing	Max	Min	Amplitude	Unit
12	AS-CZ	Step	Before	0.011	-0.014	0.025	mm
			After	0.013	-0.004	0.017	mm
			Ratio	118%	29%	68%	

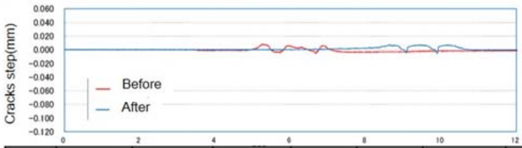
Figure 15 Behavior of crack 1 before and after repairing



No	Item	Location	Repairing	Max	Min	Amplitude	Unit
13	BS-CX	Opening & Closing	Before	0.014	-0.095	0.109	mm
			After	0.014	-0.054	0.068	mm
			Ratio	100%	57%	62%	



No	Item	Location	Repairing	Max	Min	Amplitude	Unit
14	BS-CY	Gap	Before	0.024	-0.023	0.047	mm
			After	0.011	-0.010	0.021	mm
			Ratio	46%	43%	45%	



No	Item	Location	Repairing	Max	Min	Amplitude	Unit
15	BS-CY	Step	Before	0.008	-0.006	0.014	mm
			After	0.007	-0.005	0.012	mm
			Ratio	88%	83%	86%	

Figure 16 Behavior of crack 2 before and after repairing

6 Conclusion

In this study, J-THIFCOM was introduced and applied on a deteriorated bridge. Through the verification plan, the dynamic and static loading tests were conducted before and after repairing to examine the efficiency and performance of J-THIFCOM on a rehabilitation project. The main results and conclusions drawn from this study are summarized below.

1. Considering the repaired performance in the lab-test results, it confirmed that the use of J-THIFCOM as a thin-bonded overlay for large-scale deteriorated specimens created a promising repaired mechanism. This is, this novel material could reach higher compressive strength (130 MPa) at a shorter time. It has an excellent low permeability and good resistance to freeze thaw damage, and chloride salt attack. Moreover, a 20 mm thick layer of material provides the superiority over conventional concrete overlays in both structural strengthening and waterproofing. Thus, the use of J-THIFCOM is appropriate to apply on the concrete structures which offers a number of advantages over conventional concretes, including enhanced strength and stiffness of structures, improved durability properties, and blocked deterioration factors.
2. The magnificent mechanical properties of J-THIFCOM, which includes very high strength, early hardening, high flowability and excellent permeability, as well as great durability, allows the Matsushima Bridge to be repaired with this novel material with limited time and limited spacing.
3. The conspicuous performance of Matsushima Bridge can be achieved by the use of J-THIFCOM and proved by experiments in practice. Through the dynamic and static loading test evaluation, the field evidence verified that J-THIFCOM deck were able to reduce the deflection of deck, improve the main girder stains and restrain the crack occurrence after repairing.
4. In the future, more applications of J-THIFCOM will be introduced in a variety of bridge construction and rehabilitation applications, including prefabricated structural bridge elements, retrofit and repair of bridge decks, girders, and substructures.

7 Acknowledgements

The authors gratefully acknowledge the friendly support of Prof. emer. Dr. Shigeyuki Matsui of Osaka University, and Prof. Dr. Eugen Bruehwiler of the Swiss Federal Institute of Technology in Lausanne (EPFL) for the J-THIFCOM development.

8 References

[1] Garboczi, E. J., and D. P. Bentz,Digital Simulation of the Aggregate–cement Paste Interfacial Zone in Concrete. Journal of Materials Research, 6;1:196–201, 1991.

[2] I.H. Yang, C. Joh, B.-S. Kim, Structural behavior of ultra high performance concrete beams subjected to bending, Engineering Structructures. 32, 3478–3487, 2010.

[3] V. Mechtcherine, O. Millon, M. Butler, K. Thoma, Mechanical behaviour of strain hardening cement-based composites under impact loading, Cement- Concrrete Composites. 33, 1–11, 2011.

[4] D.-Y. Yoo, S.-T. Kang, Y.-S. Yoon, Effect of fiber length and placement method on flexural behavior, tension-softening curve, and fiber distribution characteristics of UHPFRC, Construction and Building Matererials. 64,67–81, 2014.

[5] Report: verification of repair effect of Matsushima Bridge. July. 2017.