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UPGRADING OF EXISTING BRIDGE DECKS USING UHPFRC DENSIFIED BY ETTRINGITE FORMATION (AFT-UHPFRC): PRELIMINARY INVESTIGATION

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Abstract

Bridge deck is one of the structural elements subjected to severe mechanical actions and environmental conditions. Addition of UHPFRC layer on top of bridge decks can take full advantage of UHPFRC's excellent mechanical and transport properties. The paper presents investigation results from the first stage of a project to develop an upgrading method of existing bridge decks using cast-in-situ UHPFRC. The UHPFRC mix used in the research is characterised by its matrix densified by ettringite (AFt) formation; thus, it is called "AFt-UHPFRC". The AFt-UHPFRC was originally developed for fabrication of precast members with thermal curing and hasn't been applied to existing structures by in-situ casting. In order to understand the behaviour of the AFt-UHPFRC as material for upgrading of existing concrete bridge decks, experimental investigation was conducted. The experimental results were analysed and necessity to modify the present AFt-UHPFRC mix composition to be suitable for upgrading of existing concrete bridge decks was identified.

Résumé

Le tablier des ponts est un des éléments structurels sujet à des actions mécaniques et conditions environnementales sévères. L'ajout d'une couche de BFUP sur le dessus du tablier du pont peut tirer le meilleur parti des excellentes propriétés mécaniques et de transport du BFUP. L'article présente les résultats de la première étape d'un projet de recherche pour développer une méthode de réhabilitation de tabliers de pont existants grâce au BFUP coulé en place. Le BFUP utilisé ici est caractérisé par sa matrice densifiée par formation d'ettringite, d'où son nom « E-BFUP ». Originellement, l'E-BFUP a été développé pour la fabrication d'éléments préfabriqués traités thermiquement, et n'a pas été coulé en place au contact de structures existantes. Pour comprendre le comportement de l'E-BFUP en tant que matériau pour réhabiliter des tabliers de ponts en béton existants, une recherche expérimentale a été menée. Les résultats expérimentaux ont été analysés et la nécessité de modifier la composition de l'E-BFUP afin qu'il soit adapté à la réhabilitation de tabliers de ponts en béton a été identifiée.

1. INTRODUCTION

In Japan, the first expressway was put in service in 1963 and about 9,500 km expressways have been constructed so far. Central Nippon Expressway Company Limited (NEXCO Central) operates and manages about 2,000 km expressways in the central part of Japan, 40 % of which have been in service for more than 40 years and average in-service period of the expressways is now approximately 30 years (Fig. 1). In consideration of the fact that recent years have seen growing number of damaged and deteriorated structures in the NEXCO Central's expressways and the number of such damaged and deteriorated structures will be getting larger in the coming decades, extensive renewal project of the expressways was launched in 2015. In the project, replacement and upgrading of bridge decks and girders are mainly conducted and total of approximately one trillion yen will be spent for the renewal of NEXCO Central's expressway structures in the next 15 years.

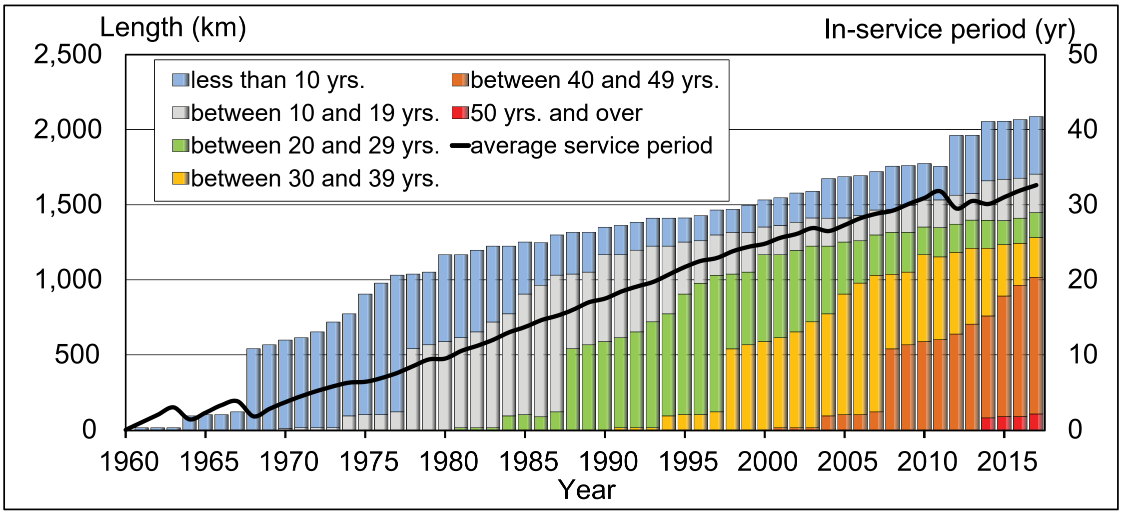

Figure 1: Length and in-service period of NEXCO Central's expressways

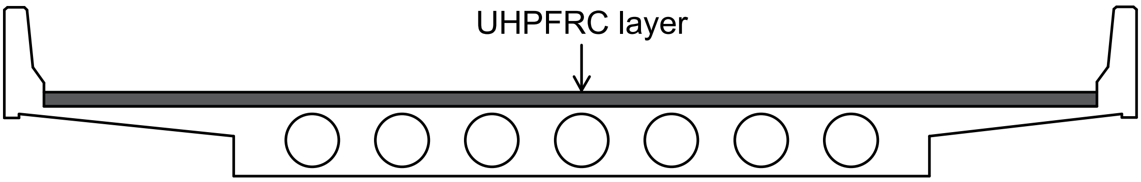

Figure 2: Bridge deck upgraded with UHPFRC

It is planned that upgrading of concrete bridge decks is performed by increasing the load bearing capacity and enhancing the durability which is conventionally achieved by overlaying fibre reinforced concrete (FRC) made of normal strength concrete and 1.3 vol.-% of steel fibres with l = 30 mm and d = 0.5 mm and applying waterproofing membrane on the top surface. However, the FRC overlay thickness could amount to more than 100 mm to attain required load bearing capacity and it is necessary to strengthen other members of bridges to carry increased self-weight of the overlaid bridge decks. By using UHPFRC instead of the FRC, the overlay thickness can be made thinner; increase of the concrete bridge deck thickness can be made even unnecessary by replacing a certain depth of the top concrete with UHPFRC. Moreover, application of waterproofing membrane can be skipped because UHPFRC functions as a protective layer. Thus, application of UHPFRC to concrete bridge decks for upgrading is an efficient and effective method as increase of the load bearing capacity and enhancement of the durability are accomplished simultaneously [1] (Fig. 2).

The paper presents investigation results obtained from the first stage of an ongoing project to develop an upgrading method of existing concrete bridge decks using cast-in-situ UHPFRC.

2. UHPFRC DENSIFIED BY ETTRINGITE FORMATION (AFT-UHPFRC)

The commercially available UHPFRC mix called SUQCEM is used in the project. SUQCEM was developed in 2006 for fabrication of precast UHPFRC members and is characterised by its matrix densified by ettringite (AFt) formation (Fig. 3); thus, it is called AFt-UHPFRC. The microstructure of the AFt-UHPFRC matrix is basically formed by decreasing water/binder ratio using spherical pozzolan particles and superplasticiser and packing ultrafine particles optimally. Numerous needle-shaped ettringite crystals of 1 to 2 μm length fill micropores of hydration structure together with inert and reactive fine fillers. The AFt-UHPFRC mix composition is indicated in Table 1.

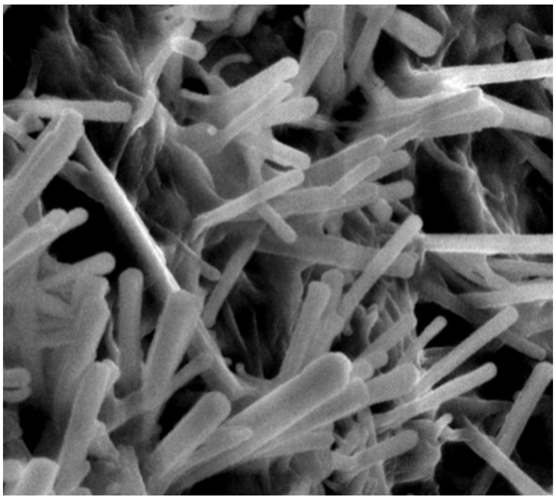

Figure 3: Needle-shaped ettringite crystals

Table 1: Composition of AFt-UHPFRC (SUQCEM)

Component	Mass (kg/m^3)	Remarks
Cement	927.0	
Premixed materials	360.0	pozzolanic material, materials to form ettringite
Sand	905.0	manufactured sand, $d_{max} < 2.5$ mm
Steel fibre	137.4	1.75 vol.-%, l = 15 and 22 mm, d = 0.2 mm
Superplasticiser	36.0	
Shrinkage reducing admixture	12.9	
Defoaming agent	6.4	
Water	195.0	including water in superplasticiser, W/B=0.152

The compactness of the AFt-UHPFRC was verified by comparing distributions of porosity measured by mercury intrusion porosimetry between the AFt-UHPFRC and standard UHPFRC exemplified in JSCE Recommendations [2] (Fig. 4). The AFt-UHPFRC was cured at 85 °C for 20 hours, while the standard UHPFRC was cured at 90 °C for 48 hours. Although the ratio of the smallest range of pore radius (3 to 6 nm) of the AFt-UHPFRC is lower than that of the standard UHPFRC, porosity of both UHPFRC is almost the same and approximately half of high strength concrete porosity (≈ 9 %) whose water to cement ratio is 30 % [2]. Moreover, the gas permeability of the AFt-UHPFRC determined with the RILEM-Cembureau method is 4.5×10^{-20} m^2 and much lower than that of normal strength concrete which is between 1.0×10^{-16} and 1.0×10^{-15} m^2 [2].

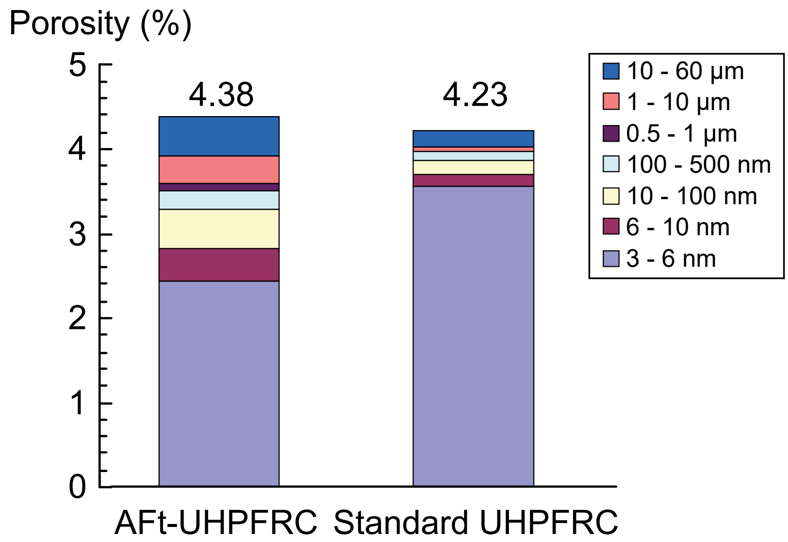

Figure 4: Comparison of porosity distribution [2]

The AFt-UHPFRC mix contains two different lengths of steel fibres with the same diameter of 0.2mm: one fibre is 15 mm long and another is 22 mm long. The total steel fibre content of the AFt-UHPFRC is 1.75 vol.-%. The characteristic values (5 % fractile) of the compressive, elastic limit and tensile strength of the AFt-UHPFRC are determined to be 180 MPa, 8.0 MPa and 8.8 MPa respectively with the methods specified in [2].

3. EXPERIMENTAL TESTS

Although the AFt-UHPFRC was originally developed for fabrication of precast members, recently it was successfully applied in cast in-situ construction of a prestressed UHPFRC girder road bridge without thermal curing [3]. However, it has not been applied to existing concrete members for upgrading by in-situ casting. Assuming conditions to which UHPFRC overlaid on concrete bridge decks is considered to be subjected, experimental investigations were conducted where uniaxial tensile tests and UHPFRC – concrete interfacial bond tests were carried out. The findings from the experimental tests were expected to be utilised for modifying the present AFt-UHPFRC mix to be suitable for upgrading of existing concrete bridge decks. In the following, the two experimental tests are explained respectively.

3.1 Static tensile tests

Tensile behaviour of UHPFRC needs to be understood in detail because restrained shrinkage induces tensile stresses in UHPFRC cast on top of concrete bridge decks and tensile stresses are predominantly imposed on the UHPFRC layer at overhangs and close to intermediate supports. In light of this, uniaxial static tensile tests were performed using relatively large specimens to examine the tensile behaviour of the AFt-UHPFRC. Although quasi-static tensile tests were conducted on the AFt-UHPFRC previously, the specimens used in the tests were small (300 mm long, 50 mm wide and 10 mm thick with double edge notches) and fibres in the specimens might be almost uniformly orientated to force direction, resulting in overestimation of the tensile behaviour. Because fibre distribution and orientation influence to a very large extent the tensile behaviour of UHPFRC [4], a certain size of specimens allowing for three-dimensional fibre distribution and orientation should be used in uniaxial tensile tests. Static tensile tests were conducted using not only the basic AFt-UHPFRC indicated in Table 1, but also a modified AFt-UHPFRC in which manufactured sand was replaced with quartz sand ($d_{max} < 0.85$ mm) and a single type of steel fibre ($l = 15$ mm, $d = 0.2$ mm) was used with increased content of 3 vol.-%. The specimens were 400 mm long and 100 mm wide with varying thickness (dog-bone shaped) to make fracture occur within the 100 mm long tapered central part of the specimens. The thickness of the central and end parts of the specimens were 40mm and 100 mm respectively and there were 90 mm long transitional zones between the central and end parts (Fig. 5). The specimens were cast in steel moulds and cured at 20 °C for 12 hours; then, demoulded and cured at 85 °C for 24 hours.

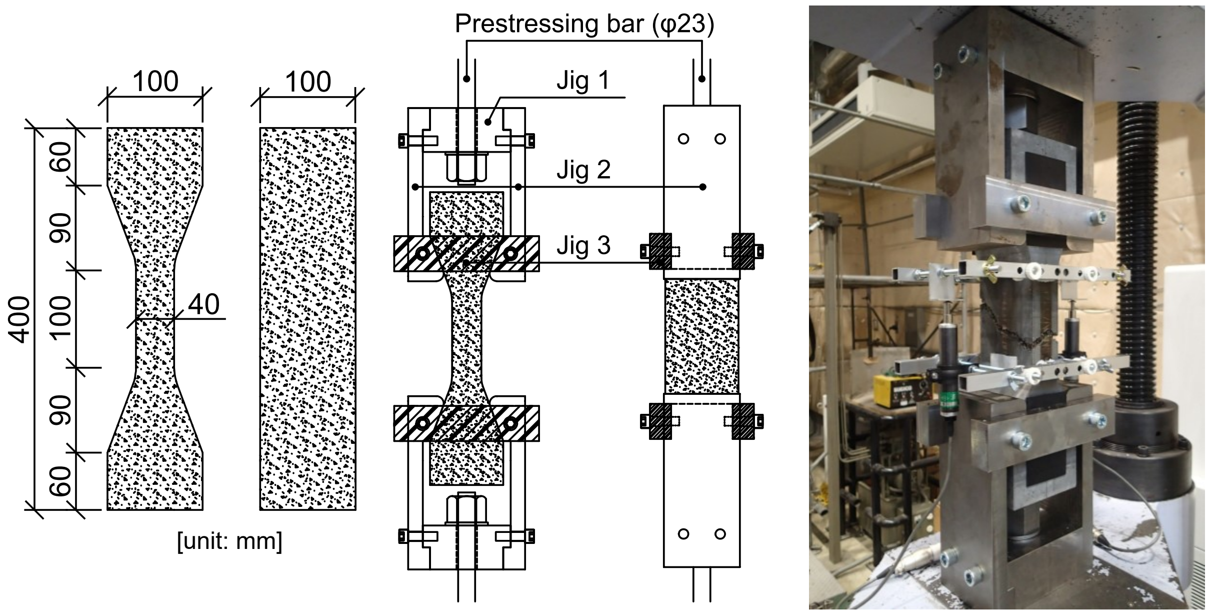

Figure 5: Specimen geometry and test set-up of static tensile tests

A new uniaxial tensile test set-up was developed for the present investigation (Fig. 5). A prismatic steel jig (Jig 1 in Fig. 5) was fixed to the testing machine at the top and the bottom respectively with a prestressing bar. The top prestressing bar was connected to the testing machine with a pivot to allow for rotation, while the bottom prestressing bar was connected rigidly to the testing machine. On the both side of the Jig 1, plate-like steel jigs (Jig 2 in

Fig. 5) were fixed with two bolts for each jig. Thickness of the free end of the Jig 2 was gradually enlarged to grip the specimen at the tapering locations. Another plate-like steel jigs (Jig 3 in Fig. 5) were bolted at both side of the Jig 2 to ensure rigid gripping of the specimen.

Two 100 mm-long Linear Variable Differential Transducers (LVDTs) were installed on both of specimen sides through aluminium jigs to measure the specimen deformation. In this paper the average of deformation as measured by the two LVDTs are always referred to as deformation. Force was measured by the load cell installed in the actuator of the 500 kN servo-hydraulic testing machine. The tensile tests were performed in a displacement-controlled mode with a displacement rate of 0.02 mm/min.

3.2 UHPFRC – concrete interfacial bond tests

Built-in tensile stresses in the UHPFRC layer due to restrained shrinkage and repeated wheel loading may hinder interfacial bonding of the UHPFRC with concrete bridge decks which must be ensured for long-term monolithic behaviour of UHPFRC – concrete composite members. In order to understand the bond behaviour of the AFt-UHPFRC with concrete, static tensile bond tests were performed using a standard test method published by NEXCO Central [5]. The basic AFt-UHPFRC and the basic AFt-UHPFRC with expansive admixture of 10 kg/m^3 ("expansive AFt-UHPFRC" hereafter) were used in the tests.

The specimen was cylinder with equal height and diameter of 100 mm and the top and bottom halves of the specimens were made of UHPFRC and concrete respectively (Fig. 6). Three types of cylinder specimens were fabricated: the basic AFt-UHPFRC – concrete composite cylinder with and without epoxy adhesive on the interface (specimen B and BA respectively) and the expansive AFt-UHPFRC – concrete composite cylinder without epoxy adhesive on the interface (specimen E). It was intended the influence of adhesive on the interfacial bond strength is understood by comparing the test results of specimen B and BA. Shrinkage of the expansive AFt-UHPFRC is smaller than that of the basic AFt-UHPFRC and lower tensile stresses are supposed to be induced in the expansive AFt-UHPFRC than the basic AFt-UHPFRC by restrained shrinkage; the influence of UHPFRC shrinkage on the interface was intended to be understood by comparing the test results of specimen B and E.

All the cylinder specimens were taken out from the slab specimens that were 4,000 mm long, 2,000 mm wide and 280 mm high, comprising an 80-mm thick reinforced UHPFRC (RU) layer and a 200-mm high RC element. The RC slabs were first fabricated, and eight days later UHPFRC was cast on top of the RC slabs whose surfaces were roughened by high pressure water jetting (epoxy adhesive was applied to one of the roughened RC slab surface). Fabrication and curing of the slab specimens were conducted outdoors.

The average tested cylinder compressive strength and elastic modulus of the basic AFt-UHPFRC and the expansive AFt-UHPFRC were 190.7 MPa/45.8 GPa and 172.2 MPa/42.8 GPa after 100 days, respectively. Concrete in the RC part was made of high early strength cement with water-to-cement ratio of 43 % and maximum size of the aggregate was 20 mm. The average tested cylinder compressive strength and elastic modulus of the concrete were 42.0 MPa and 29.0 GPa after 100 days, respectively.

Two series of static tensile bond tests were carried out. In the first test series static tensile bond tests were simply conducted on intact specimens. In the second test series, before static tensile bond testing, 4.8 million cycle tensile fatigue stresses were imposed on specimens immersed in water of room temperature where maximum and minimum stress were 0.7 MPa and 0.1 MPa respectively (Fig. 7). Three tests were performed for each specimen in the first test series, while one test was performed for each specimen in the second test series.

Static tensile bond tests were force-controlled with a stress rate of 0.06 MPa. 500 kN hydraulic testing machine was used and only force was measured by the load cell installed in the actuator of the testing machine.

Figure 6: Application of tensile fatigue force to specimen immersed in water

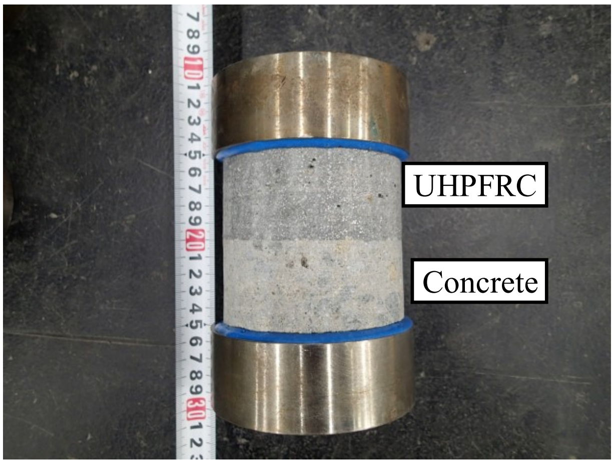

Figure 7: UHPFRC – concrete composite cylinder specimen

4. RESULTS AND DISCUSSION OF EXPERIMENTAL TESTS

4.1 Static tensile tests

Stress deformation relationships obtained from the static tensile tests are shown in Figure 8. Five tests were conducted per each UHPFRC mix and the average curves were plotted using all the test results (one specimen of the modified mix fractured outside the gauge length and the test result wasn't considered in the average curve). Averages of elastic limit strength, ultimate tensile strength and strain corresponding to the ultimate tensile strength were 11.3 MPa/13.3 MPa/5.7 ‰ for the basic AFt-UHPFRC and 11.7 MPa/14.4 MPa/4.1 ‰ for the modified AFt-UHPFRC, respectively. Although different type and size of sand was used as a component of mortar-based matrix which predominantly determines the elastic behaviour, the elastic limit strength of both mixes was almost the same. The replacement of manufactured sand with a maximum size of 2.5 mm with an equal volume of quartz sand with a maximum size of 0.85 mm did not change the elastic limit strength at the same water-binder ratio with the same binder components. From this it follows that mortar-based matrix components of the basic AFt-UHPFRC mix don't need to be modified in terms of improvement in the mechanical property. However, moisture control of manufactured sand could be demanding where the Aft-UHPFRC is made on site and appropriateness of using manufactured sand needs to be examined from the viewpoint of cost-effectiveness.

In the average stress-deformation curve of the basic AFt-UHPFRC peak is not clear and strain-hardening is small, while the modified AFt-UHPFRC exhibits good strain-hardening behaviour. The difference is considered to be attributed to fibre content. Because strain-hardening behaviour is key in resisting tensile stresses induced by restrained shrinkage and thermal deformation in UHPFRC overlaid on concrete substrates [6], increase of the fibre content of the AFt-UHPFRC may be necessary for being used for upgrading of existing concrete bridge decks by overlaying. Comparing to the modified AFt-UHPFRC, strain of the basic AFt-UHPFRC corresponding to the ultimate tensile strength is larger and the strain-softening curve is shallower. This is considered to be attributed to the performance of the 22 mm long steel fibres. In the 40 mm thick specimens the 22 mm long steel fibres might be more favourably orientated than the 15 mm long steel fibres, which also probably explains the better ductility of the basic AFt-UHPFRC. Although excellent tensile properties are conferred by the 22 mm long steel fibre, some difficulties are identified concerning workability. Besides, the excellent tensile properties may not necessarily be fully exploited in upgrading of existing concrete bridge decks. The necessity of the 22 mm long steel fibre needs to be investigated a little further.

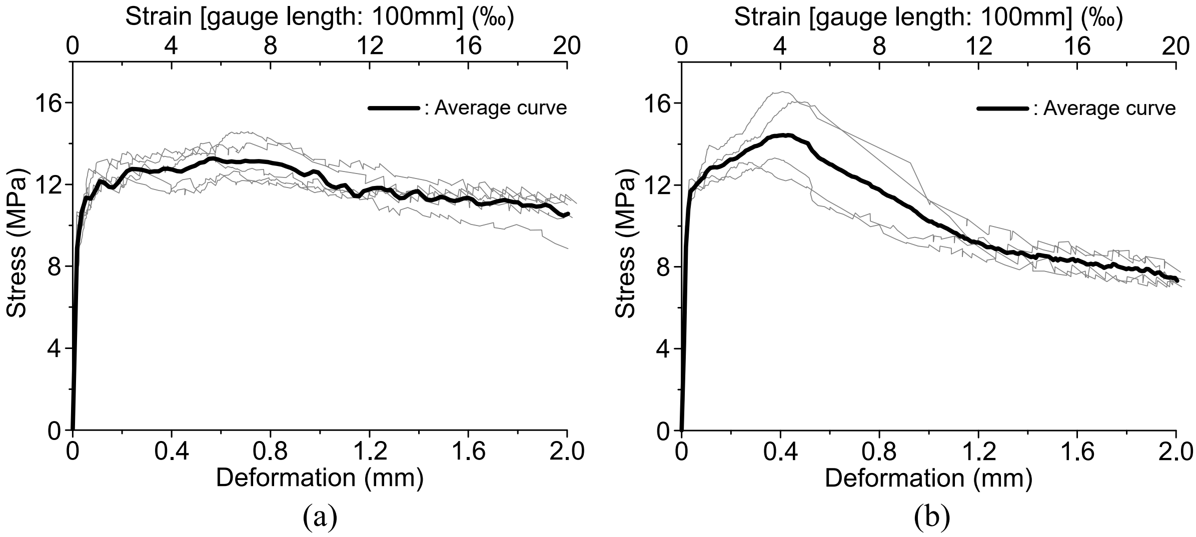

Figure 7: Stress deformation relationships obtained from the static tensile tests of (a) basic Aft-UHPFRC and (b) modified Aft-UHPFRC

4.2 UHPFRC – concrete interfacial bond tests

Table 2 shows the results of the tensile bond tests. All the specimens except specimen BA1 of the first series fractured in concrete close to the UHPFRC – concrete interface. Bonding of the AFt-UHPFRC with concrete could be said to be robust. Specimen BA1 of the first series fractured at the interface (Fig. 9), which may indicate there is a possibility that application of epoxy adhesive to the UHPFRC – concrete interface may hinder the interfacial bonding. The influence of reduced shrinkage and possibly lowered built-in tensile stresses on the UHPFRC – concrete interface wasn't clearly comprehended from the test results.

Although the tensile bond strength between the AFt-UHPFRC and concrete wasn't determined from the present testing program, it was inferred that about five million cycle tensile fatigue stress may not deteriorate the tensile bond strength, which, however, is deduced from the results of a limited number of tests. Considering the fact fatigue loading is one of the most detrimental actions on bridge decks and can damage the interface between overlaid UHPFRC and concrete bridge decks, the behaviour of the UHPFRC – concrete interface subjected to tensile and shear fatigue stress will be investigated in more detail.

Table 2: Results of the tensile bond tests [unit: MPa]

Specimen	1st series	2nd series
B1	2.46	2.68
B2	2.59	-
B3	3.11	
Avg.	2.72	2.68
BA1	2.98	3.09
BA2	4.31	-
BA3	3.86	
Avg.	3.72	3.09
E1	3.63	2.29
E2	3.14	-
E3	3.03	
Avg.	3.27	2.29

Figure 8: Specimen BA1 fractured at the UHPFRC – concrete interface

5. CONCLUSION

The present paper describes results of experimental tests conducted as preliminary investigation concerning the development of upgrading method of existing concrete bridge decks using AFt-UHPFRC. Necessity to increase the fibre content of the present AFt-UHPFRC mix was understood for in-situ cast on top of concrete bridge decks. Bonding between the AFt-UHPFRC and concrete was confirmed to be firm even without adhesives or mechanical connectors on the AFt-UHPFRC – concrete interface.

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