Doctoral Dissertation

MULTIPLE PROTECTION DESIGNS FOR DURABLE CONCRETE DECK SLAB ON STEEL GIRDER BRIDGES

(鋼桁橋上のコンクリート床版の耐久性のための多重防護設計)

by

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ABSTRACT

In Japan, a large number of RC structures constructed over the last half-century are suffering severe deterioration due to environmental and loading actions. Several investigations reported that road structures in cold and snowy environment revealed faster and more severe deterioration by cause of the combined actions comprising freezing and thawing, chloride attack from deicing agent, alkali-silica reaction (ASR), cracking, fatigue, and so on. In addition, early-age thermal and shrinkage cracks in RC deck slabs restrained by steel box girder systems exaggerate the penetration of harmful agents leading to severe damages. For such structures, assuring durability performance in design considering aggressive environmental conditions and loading actions during service is necessary.

In order to accelerate recovery from the Great East Japan earthquake in 201, the Japanese government undertook the project named Revival Roads which are allocated in Sanriku area of Tohoku region. Since the Tohoku region experiences cold and snowy weather in the winter, complex degradations involving multiple factors such as those mentioned above are anticipated. Considering the severely cold and harsh environment in Tohoku region, a new durability design initiated by the academics collaborating with government authorities and construction companies was proposed to ensure highly durable RC bridge slabs, and it has been applied to many bridges along the Revival Roads. In the design concept, complex actions were considered for each deterioration type, meanwhile, at least two countermeasures were activated for each deterioration type. Six countermeasures were selected and developed accounting for multiple protection countermeasures. The application of blast furnace slag or fly ash with low water-to-cement ratio was the key countermeasure against frost damage, salt damage and ASR damage. Expansive additive with the dosage of 20 kg/m³ was applied to compensate autogenous and drying shrinkage for cracking mitigation. Also, reinforcing bars were coated by epoxy for anti-corrosion in risky locations. The amount of air content was set as about 5~6% to achieve anti-frost performance. Moreover, additional curing comprising wet curing until around 28 days for the top of the slab and sealed curing for the bottom was proposed.

It was clarified that in the cases of steel box girder bridges with one or two-span no transverse cracking was observed in RC deck slabs until the completion inspection. However, in bridges with three or more spans, noticeable transverse cracks were observed some time after the removal of curing sheets. Especially, the maximum crack width at some locations in the exposed bottom surface of the bridge deck of a 7-span bridge after two years of construction was increased up to 0.2 mm reaching the limitation for repairing during construction in Japanese standard. Additionally, the vertical cracks generated in parapet walls on deck slab have been confirmed to penetrate

into concrete deck slab causing opening of transverse crack width on the top surface.

The principal objectives of the research are (1) To investigate the significant influencing factors affecting early age thermal stress in RC deck slabs utilizing the three leveled systematic FEM structural simulation method for improving the guideline for ensuring durable RC bridge slabs in cold and coastal regions; (2) To evaluate the applicability of the durable material design using GGBS concrete with an increased 25 kg/m³ expansive additive for transverse cracking mitigation considering the adversary effects such as the reduction of compressive strength of concrete, the appearance of microcracking on the surface concrete and the decrease of salt-scaling resistance of highly durable RC slabs; (3) To numerically investigate the principal factors affecting stepwise construction stress comprising time interval, concrete volume and placing sequence for proposing an effective stepwise construction strategy that could effectively reduce or eliminate stepwise construction stress in multiple span continuous steel box girder bridges; (4) To evaluate the potential risk of early age transverse cracking in highly durable RC deck slabs due to the combined effect of thermal and stepwise construction stresses; (5) To verify the effectiveness of a new joint system in parapet walls for controlling the penetration of vertical cracks into RC deck slabs; (6) To propose crack control designs for early age transverse cracking mitigation in highly durable RC deck slabs on multiple span continuous steel box girder bridges.

The study was carried out using numerical simulation tools following FEM and layered models and using reliable site investigation data and laboratory experiments by the author and industrial research laboratories. As for thermal stress analysis, the three leveled systematic analytical scheme for full-scale FEM simulation of bridge RC deck slabs was adopted. As for stepwise construction stress analysis, a commercial software COMPO developed by MHI Plant Engineering Co., Ltd is used as a numerical simulation method for proposing an effective stepwise construction strategy. In the scope of COMPO program, only stepwise construction stress along the bridge axis (longitudinal stress) was calculated without considering the effect of thermal stress and drying shrinkage. In order to evaluate the applicability of the durable material design using GGBS concrete with an increased 25 kg/m³ expansive additive scaling resistance requirement is adopted. In this study, the salt-scaling resistance was investigated by applying varying dosages of EA on small slab specimens to represent the highly durable RC slab of a four-span continuous steel box-girder bridge located along the "Revival Road", Tohoku region, Japan. As for the verification of a new joint system in parapet walls for controlling the penetration of vertical cracks into RC deck slabs, structural cracking investigations were conducted in an actual newly constructed 4-span bridge in Tohoku region where the new joint system was applied.

According to structural investigations, the maximum temperature rise in RC deck slabs was in the location where the low heat conductivity of plywood form was permanently set underneath. The occurrence of maximum longitudinal thermal tensile stress in the RC deck slabs was also observed in this location. Besides, the transverse cracks were mostly initiated on the top surface of the RC slabs after the removal of curing sheets. Furthermore, the new arrangement of joint system in parapets of a 4-span bridge showed its efficiency to prevent cracks at the joints to control cracking propagating into the deck slab.

The full-scale FEM modeling of durable RC deck slabs on multiple span steel box girder bridges considering time-dependent temperature, volumetric strain and stress development was successfully verified throughout three systematic analytical schemes comprising material, member, and structural level utilizing experimental results. Several important factors affecting early-age thermal stress in RC deck slabs are numerically presented comprising the application of expansive additive with different dosages, the effect of concrete thermal expansion coefficient, daily variations of ambient temperature, the initial concrete temperature and curing methods.

According to the results of numerical simulation using COMPO program following layered model, an effective stepwise construction strategy was proposed with appropriate placing sequence, large concrete volume of the interior support lots and longer time interval between steps. According to this strategy, maximum experienced tensile stresses and residual tensile stresses in RC deck slabs can be reduced. Moreover, the efficiency of the proposed stepwise construction strategy was also verified in back analyses of a 7-span and 4-span girder bridges with significant reductions in the maximum residual tensile stresses.

Based on several experimental investigations conducted on highly durable small RC slab specimens utilizing GGBS concrete with expansive additive, the highly durable RC slab specimens with 20 and 25 kg/m^3 expansive additive exhibited acceptable salt-scaling resistance with a cumulative mass loss of less than 0.5 kg/m^2 and a visual rating of level 2 (slight-to-moderate scaling) after 50 F–T cycles.

Finally, the crack control designs including the effective stepwise construction strategy, the application of expansive additive, effective curing methods and the arrangement of joint system in parapet walls are proposed to improve the durability design for highly durable RC deck slabs in Tohoku region