論 文 要 旨

Summary of Dissertation

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論文題目 Title	Performance Evaluation of Countermeasures against Rupture and Protrusion of Vertically Tightened PC Bars in PC Girders
和訳または英訳 Translation (J->E, or E->J)	PC 桁の鉛直締め PC 鋼棒に対する破断突出対策の性能評価

In Japan, some existing pre-stressed concrete bridges which were constructed in around 1970 have grout filling shortage and infiltration of water problems. Corrosion is seen as a main cause of rupture of PC bars which have been reported several times in the country. Corrosion due to insufficient grout filling can result in sudden fracture of PC bars. When vertically tightened PC bars in PC girders are ruptured, all the accumulated strain energy is suddenly released. The ruptured PC bar will severely damage cover concrete and asphalt pavement, and PC bars may protrude out of the structure, which may cause severe accidents. Protective measures against eruption of PC bars are necessary to avoid damage to third party.

In 2018 there were 19,657 vertical PC bars in Metropolitan Expressway (MEX) in Japan. In the same year, actual rupture of a vertical PC bar was investigated by the authors. It was concluded that the rupture of the bar was brittle and initiated from corrosion pits, which must have been caused by cyclic drying and wetting due to the ingress of rainy water.

The principal objectives of the present research are (a) performance evaluation of countermeasures against rupture and protrusion of vertically tightened PC bars in PC girders using the Applied Element Method (AEM) simulations, (b) to verify AEM simulation by experimental results, (c) Investigation of failure modes in the countermeasures using the AEM simulations and (d) to propose a safe countermeasure against rupture and protrusion of vertical PC bars in MEX.

Methodology of the present research involves establishing the Applied Element Method (AEM) numerical simulation due to its advantages of simulating structural progressive collapse. The methodology follows three levelled systematic analysis schemes for AEM full scale simulation of performance evaluation of countermeasures. The AEM numerical simulations were verified with the experimental results. In the process of verification, many influential parameters, such as the effects of contact stiffness between separated elements, fracture energy of concrete and asphalt pavement, mesh sensitivity, time interval sensitivity, material properties, temperature effect, and strain rate effect were investigated.

The impact energies were applied on the countermeasures either using a ruptured PC bar or using a drop weight impact test. Performance of asphalt pavements was evaluated using extreme impact energy, 4,408 J, that can cover most of rupture of vertical PC bars in MEX. Performance of asphalt pavements was also evaluated by considering low and high temperatures to simulate winter and summer conditions in Tokyo area. The effect of time dependent deterioration of asphalt pavement by reducing the thickness of asphalt pavement was also investigated. Energy absorption capacity of polyurea and steel fiber reinforced polymer cement mortar (PCM) was investigated using a drop weight impact test.

The effects of 15 mm cover concrete (assuming bottom of a bridge girder) on preventing protrusion of PC bars were investigated. Numerical simulation of rupture and protrusion of PC bars was conducted using the Applied Element Method. The

numerical simulations were verified based on the experimental results. In the process of verification, many influential parameters, such as the effects of contact stiffness between elements, fracture energy of concrete, mesh sensitivity, time interval sensitivity, material properties, and strain rate effect, were investigated. The numerical simulation was required to investigate the protrusion behavior of PC bar and the failure mechanism of cover concrete. The AEM simulation results support, appropriate numerical simulation with the AEM can be conducted with appropriate interface material property between the PC bar and the sheath, considering the fracture energy of concrete, with appropriate mesh discretization, appropriate time interval, appropriate Normal Contact Stiffness Factor (*NF*), and considering strain rate effects in concrete. Cover concrete of 15 mm alone could not prevent the protrusion of a PC bar of 4.5 m rupture length.

A 3D AEM model was developed for simulating asphalt pavement at 0℃, 28℃ and 50℃ under extreme impact energy (4,408 J) generated from a corrosion induced ruptured vertically tightened PC bars in PC bridges. The asphalt pavement material models were calibrated using asphalt pavement bending test results. The bending properties of asphalt pavement at different temperature were numerically investigated. The interface bond material model was calibrated based on the pull-off adhesive test. The effects of temperature on asphalt pavement system on preventing the protrusion of PC bars and concrete spalling were numerically investigated. The *DIF* was employed to accurately capture the dynamic material behavior of the asphalt pavement under high loading rate. The failure mode of the asphalt pavement under 4,408 J impact energy was numerically investigated in detail. In MEX, the asphalt pavement over bridge deck has two layers. In this study, in order to simulate the worst condition in reality (time dependent deterioration), in one specimen, the cover layer was excluded and only the base layer (50 mm thickness) was investigated in terms of its performance in preventing the protrusion PC bars with 4,408 J impact energy at 20℃.

This study found that appropriate AEM numerical simulation of rupture and protrusion of PC bar with asphalt pavement can be conducted with appropriate interface material property between the slab concrete and the asphalt pavement layers, considering the fracture energy of concrete and asphalt pavement, with appropriate mesh discretization, appropriate time interval, appropriate Normal Contact Stiffness Factor (*NF*), and considering strain rate effects both in concrete and in asphalt pavement. The asphalt pavement system used in this study, without using a steel plate and FRP sheet, with appropriate material and thickness could prevent the protrusion of the PC bar of 4.5 m rupture length. The AEM simulation results proved that the two layers of asphalt pavement with 80 mm thick at 0℃, 28℃ and 50℃ was effective against 4,408 J impact energy and effective against PC bar protrusion and concrete spalling. Moreover, a single layer of guss asphalt pavement with 50 mm thick at 20℃ was effective against PC bar protrusion which was around 22 mm in the AEM simulation. However, asphalt pavement fracture was observed near the anchorage area. Based on the analysis results, the effectiveness of the asphalt pavement system depends on impact energy of ruptured PC bars, material properties of asphalt pavements, material properties of interface bond materials, fracture energy, mesh discretization, strain rate and temperature.

In the two layers of asphalt pavement system at 28℃, the PC bar protrusion was prevented by ductile deformation of asphalt pavement delaminated from slab concrete. The strain energy of the PC bar was dissipated by a simultaneous action of asphalt pavement deformation, cone-shaped crack in the mortar, and interface delamination between the slab concrete and the asphalt pavement. In the two layers of asphalt pavement system at 50℃, the strain energy of the PC bar (4,408 J) was dissipated by a synchronized action of a shear-cone shaped fracture in the concrete and in the non-shrinking mortar, deformation and cracks in the asphalt pavement. In the two layers

of asphalt pavement system at 0℃, the strain energy of the PC bar (4,408 J) was dissipated by a synchronized action of a shear-cone shaped fracture in the base layer and in the non-shrinking mortar, deformation and cracks in the asphalt pavement and delamination of tack coat. In the single layer (50 mm tick) of guss asphalt pavement system at 20℃, the strain energy of the PC bar (4,408 J) was dissipated by a simultaneous action of a shear-cone shaped fracture in the asphalt pavement and in the non-shrinking mortar, interface bond delamination between the concrete slab and the asphalt pavement, and cracks in the asphalt pavement. The results of the numerical simulation had a good agreement with the experimental data.

Punching tests for polyurea sheet with thickness of 3 mm, 5 mm and 10 mm under different impact loads were investigated. This study numerically investigates the effects of polyurea coating on impact resistance and on preventing concrete spalling. The results obtained are used to assess the extent of energy absorption and to identify the mode of failure of the polyurea as a function of the imposed impact conditions. The numerical simulations were verified with the experiments.

Both numerical simulations and high-speed photography measurements indicated that the polyurea sheet significantly reduced impulsive loads. Effectiveness of the polyurea sheet depends on impact energy, polyurea thickness, bond strength, primer and quality of surface concrete, etc. The constitutive model using a bi-linear material for polyurea in the drop weight AEM simulation showed good agreement with the experimental results in terms of impact resistance and failure mode. A polyurea (500 mm × 500 mm) sheet with 5 mm thickness was effective in resisting against 758 J impact energy. However, 3 mm and 10 mm thick polyurea sheets with 500 mm × 500 mm were not effective in resisting against 758 J and 3,983 J impact energy respectively.

The impact resistance of a steel fiber reinforced polymer cement mortar (PCM) against drop weight impact were investigated numerically and experimentally. Effectiveness of the PCM depended on impact energy, depth of core, material properties of the PCM and boundary conditions. The modeling of PCM in the drop weight AEM simulation showed good agreement with the experimental results in terms failure mode. The drop weight impact energy was dissipated by damages in the PCM, deflection of boundary and strain in the reinforcing bars. Both numerical simulations and high-speed photography indicated that the drop weight impact test were significantly affected by boundary conditions. The proposed boundary condition in this study greatly reduced deflection at the boundary and hence eliminate the energy absorbed by flexure.

Basic information of vertical PC bars in Metropolitan Expressway (MEX) including the recent situations and onsite inspection of rupture of vertical PC bars were discussed briefly. The strategy for risk assessment of rupture of vertical PC bars was also addressed in detail. Moreover, risk reduction (control) interventions were explained.