Field Instrumentation for Load-Induced Fatigue Damage of Concrete Pavement Systems Under Superloads

Yongsung Koh(1), Halil Ceylan(2), Sunghwan Kim(3), and In Ho Cho(4)

(1) Department of Civil, Construction and Environmental Engineering, Iowa State University; Email: yskho27@iastate.edu
(2) Department of Civil, Construction and Environmental Engineering, Iowa State University; Email: hceylan@iastate.edu
(3) Department of Civil, Construction and Environmental Engineering, Iowa State University; Email: sunghwan@iastate.edu
(4) Department of Civil, Construction and Environmental Engineering, Iowa State University; Email: icho@iastate.edu

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  - Many Research Team Members from ISU PROSPER and CCEE/InTrans/ISU
Background

What is the problem with the superload?

> High Gross Vehicle Weights (GVWs) or axle weights exceeding the United State’s permit limit
> Non-standardized configurations of tires and axles representing a wide range of dimensions
> Slow moving behavior and wide vehicle width likely to exceed the lane-width of concrete pavements
> Unexpected fatigue damages on concrete pavement systems when subjected to superloads, including Implement of Husbandry (IoH) and Superheavy Loads (SHL), especially in the Midwestern region of the U.S.

Objectives

(i) Computational determination of structural fatigue damages of Jointed Plain Concrete Pavements (JPCPs) when subjected to various types of superloads and the (ii) field instrumentation
Classification of Critical Loading Locations

<table>
<thead>
<tr>
<th>Type of IoTs</th>
<th>Grain Cart</th>
<th>Manure Tanker</th>
<th>Agricultural Trailer</th>
<th>Agricultural Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IoTs</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Gross Vehicle Weight (GVW) (kg)</td>
<td>35,000 ~ 85,000</td>
<td>42,000 ~ 70,000</td>
<td>20,000 ~ 44,000</td>
<td>24,000 ~ 35,000</td>
</tr>
<tr>
<td>Number of axles</td>
<td>1 ~ 3</td>
<td>2 ~ 4</td>
<td>2 ~ 3</td>
<td>2 ~ 3</td>
</tr>
<tr>
<td>Number of tires per axle</td>
<td>2 (single tire), 4 (dual tire)</td>
<td>2 (single tire)</td>
<td>2 (single tire)</td>
<td>2 (single tire)</td>
</tr>
</tbody>
</table>

Classification of superloads

- **7 classes** for IoTs classified by different axle types
- **4 classes** for SHLs classified by different trailer types

Note: Details of superload classification can be found in Koh et al. 2022
### Classification of Critical Loading Locations

#### Classification of IoHs according to the critical loading locations

<table>
<thead>
<tr>
<th>Case</th>
<th>Type</th>
<th>Critical loading location</th>
<th>Relevant IoHs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>single, single single-axle located near the mid-axle</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>2</td>
<td>tandem, tandem tandem-axle located symmetrically within a PCC slab</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>3</td>
<td>tandem, tandem tandem-axle located symmetrically within a PCC slab</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>4</td>
<td>quad, quad two all axles located symmetrically within a PCC slab</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>5</td>
<td>quad, quad two all axles located symmetrically within a PCC slab</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>6</td>
<td>combined single, tandem, tandem, or quad one axle located on or near the transverse joint</td>
<td> </td>
<td> </td>
</tr>
</tbody>
</table>

#### Classification of SHLs according to the critical loading locations

<table>
<thead>
<tr>
<th>Case</th>
<th>Type</th>
<th>Critical loading location</th>
<th>Relevant SHLs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>modular modular load of up to two modules</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>2</td>
<td>drop-deck drop-deck load of up to two modules</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>3</td>
<td>modular modular load of up to two modules</td>
<td> </td>
<td> </td>
</tr>
<tr>
<td>4</td>
<td>drop-deck drop-deck load of up to two modules</td>
<td> </td>
<td> </td>
</tr>
</tbody>
</table>

Note: Details of sub-load classification can be found in Kohl et al. 2022.
Mechanistic-based Damage Ratio Calculation

### Finite Element Method (FEM)-based JPCP analysis (software: ISLAB2005)

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness of PCC layer (mm)</th>
<th>Composite modulus of subgrade reaction (MPa/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>180, 230</td>
<td>Transverse joint spacing (m): 4.5</td>
</tr>
<tr>
<td>Highway</td>
<td>260, 330</td>
<td>Transverse joint spacing (m): 5.2, 6.0</td>
</tr>
</tbody>
</table>

#### Elastic modulus of PCC layer (MPa)

<table>
<thead>
<tr>
<th>Type</th>
<th>Elastic modulus of PCC layer (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>2,700</td>
</tr>
<tr>
<td>Highway</td>
<td>2,700</td>
</tr>
</tbody>
</table>

#### Traffic loadings

<table>
<thead>
<tr>
<th>Type</th>
<th>Traffic loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td>IoH</td>
<td>18 types x 4 payload levels + 72 types</td>
</tr>
<tr>
<td>SHL</td>
<td>16 types x 4 payload levels + 64 types</td>
</tr>
<tr>
<td>FHWA class 9 truck (reference)</td>
<td>1 type</td>
</tr>
</tbody>
</table>

#### Total analysis cases:

- General: 10,960 cases
- Total analysis cases: 21,920 cases

#### Damage ratio for bottom-up transverse cracking

\[
\text{Damage ratio for bottom-up transverse cracking} = \frac{N_{\text{bottom-up}}}{N_{\text{top-down}}} \times \frac{N_{\text{bottom-up}}}{N_{\text{top-down}}}
\]

#### Damage ratio for top-down transverse cracking

\[
\text{Damage ratio for top-down transverse cracking} = \frac{N_{\text{top-down}}}{N_{\text{bottom-up}}} \times \frac{N_{\text{top-down}}}{N_{\text{bottom-up}}}
\]

### S-N curve from previous experimental tests by ISU

Note: ISU experimental results for fatigue testing of PCC slabs from Klaiber et al. 1979
Field Instrumentation - Data Acquisition System

Field instrumentation site – K45 road (full-depth PCC pavement reconstruction)

- Determination of Critical Loading Locations
- FEM-based Mechanistic Analysis for Damage Rate Calculation
- Field Instrumentation and Monitoring
- Remaining Tasks of Study: FEA Result Calibration Using the Field Data

Field Instrumentation site - K45 road (full-depth PCC pavement reconstruction)

- Excavation of existing pavement
- Removal
- JCPs construction
- Gradation

Monona County (K45 road)

Potential enclosure spot (external power supply)

130th St (eastbound)

Semi-trailer spot (northbound)

K45 (HMA overlay pavement → PCC reconstruction)

K45 (HMA overlay pavement)
Field Instrumentation - Data Acquisition System

Determination of Critical Loading Locations

FEM-based Mechanistic Analysis for Damage Rate Calculation

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

Pre-Instrumentation activities

LWD test
DCP test
Sand cone test

Drilling the holes to install the sensor trees

Remaining Tasks of Study:
FEA Result Calibration Using the Field Data

Conceptual configuration of data acquisition system

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

IOWA STATE UNIVERSITY

Civil, Construction and Environmental Engineering (CCEE)
Program for Sustainable Pavement Engineering & Research (PROSPER) at InTrans

Field Instrumentation - Data Acquisition System

Pre-Instrumentation activities

Determination of Critical Loading Locations

FEM-based Mechanistic Analysis for Damage Rate Calculation

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

IOWA STATE UNIVERSITY

Civil, Construction and Environmental Engineering (CCEE)
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Field Instrumentation - Data Acquisition System

Pre-Instrumentation activities

Determination of Critical Loading Locations

FEM-based Mechanistic Analysis for Damage Ratio Calculation

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

Field Instrumentation and Monitoring

Remainder Tasks of Study: Pre-instrumentation activities

Pre-testing in laboratory

Wooden supports for fixing the enclosure

Pre-instrumentation activities

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Civil, Construction and Environmental Engineering (CCEE)
Program for Sustainable Pavement Engineering & Research (PROSPER) at InTrans
Field Instrumentation - Data Acquisition System

Determination of Critical Loading Locations

FEM-based Mechanistic Analysis for Damage Ratio Calculation

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

Concrete paving and sensor protection

Field Instrumentation - Data Acquisition System

Sensor installation and cable protection

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

Civil, Construction and Environmental Engineering (CCEE)
Program for Sustainable Pavement Engineering & Research (PROSPER) at InTrans
Field Instrumentation - Data Acquisition System

Post-instrumentation activities

External power supply for data acquisition system

Field Instrumentation and Monitoring

Remaining Tasks of Study: FEA Result Calibration Using the Field Data

Field data analysis

Braces data of PCC slab (12/19/2021)

Temperature data of PCC slab (12/19/2021)

- Compressive thermal strains are induced at the top of the PCC slab and tensile thermal strains at the bottom of the PCC slab during the daytime due to temperature gradients
- Tensile thermal strains are induced at the top of the PCC slab and compressive thermal strains at the bottom of the PCC slab during the nighttime due to temperature gradients
Field Instrumentation - Data Acquisition System

- Tensile strain at the bottom of the PCC slab when subjected to traffic loadings
- Compressive strain at the top of the PCC slab when subjected to traffic loadings
- Strain data of PCC slab (6-axles traffic)
- Strain data of PCC slab (4-axles traffic)
- Strain data of PCC slab (3-axles traffic)
- Strain data of PCC slab (2-axles traffic)

Remaining Tasks of Study - FEA Result Calibration

- Field data analysis
- Portable Weight-in-Motion (P-WIM) system
- 8 ft (recommended)
- 1st axle weight
- 2nd axle weight
- GVW
- 1st axle weight
Summary and Discussions

- A total of 34 types of superload can be classified into seven categories of IoHs and four categories of SHLs, depending on their critical loading locations.
- Grain cart type IoHs and dual-row modular type SHLs show much higher damage ratios regarding the bottom-up and top-down transverse cracking of JPCPs.
- Decreasing the payload levels of all the superload types from 100% to 50% significantly reduced the fatigue cracking damage ratios reaching to one.
- Field instrumentation was conducted at K45 road in Monona county to monitor and evaluate the fatigue damages of JPCP when subjected to the superload traffic.
- Concrete strain gauges and thermistors on the top and bottom of the PCC layer at various critical pavement response positions were installed in the field and connected to the data loggers having consistent external power supply.
- Long-term field data monitoring is being performed to evaluate the fatigue damages according to different types of traffic with various payload levels.
- The FEA results will be calibrated shortly using the field data from the data acquisition system and P-WIM system installed in the field.
Author Information

Yongsung Koh
Ph.D. student
Research Assistant
yskho27@iastate.edu

Dr. Halil Ceylan, Dist.M.ASCE
Pitt-Des Moines, Inc. Professor in CCEE
Director, Program for Sustainable Pavement Engineering and Research (PROSPER)

Dr. Sunghwan Kim, P.E.
Associate Director of PROSPER
sunghwan@iastate.edu

Dr. In Ho Cho
Associate Professor of CCEE department in Iowa State University
icho@iastate.edu

Thank you