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Development and performance of a movable smart vertical connector in a modular roadway slab

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Modular roadway slab;
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Horizontal displacement;
Internal forces.

Abstract. For many years, transportation agencies have been struggling to provide rapid roadway construction and repair work with minimal disruption to traffic and maintenance over the service lifetimes. Precast members provide the characteristics of a controlled roadway quality and rapid construction, while the filler between the slabs can be damaged due to the penetration of water and debris. Also, vertical anchor bolts connecting the slabs and crossbeams are associated with unexpected displacement. In this study, a finite element analysis is conducted to develop a modular roadway slab. Two preliminary analysis models are proposed with varying boundary conditions. A combination of various loads was used to determine the appropriate boundary conditions. The model with pinned supports at both ends was selected after comparing the displacements and stresses. Since the model had high horizontal force, due to the boundary conditions pinned at both end of the slab, a new system was developed to reduce the horizontal force by allowing small horizontal displacements at the supports while still fastening vertically. The results of a detailed model analysis show that the displacement allowance with a horizontal filler material should be about 5 mm and the anchor bolts require horizontal shear force of approximately 80 kN.

1. Introduction

For many years transportation agencies have been struggling to provide rapid roadway construction and repair work with minimal disruption to traffic. They have also pursued satisfactory roadway systems which require minimal maintenance over their service lifetimes. One possible solution to fulfill this concept of ideal maintenance is the use of precast members which can provide high-quality and rapid construction [1]. However, using precast members can also damage the filler used between slabs due to the penetration of water and debris. Also, anchor bolts are associated with unexpected displacement if the force acting on the anchor bolts is relatively large. Thus, a detailed analysis model was developed to identify the required capacity of a vertical connector that can resist high levels of horizontal shear force and allow thermal movement, despite the presence of water and debris. Although there are relevant studies [2,3] and pilot construction projects in Europe and North America [4-8], Asian countries have not yet started to develop conceptual modular roadway systems. The purpose of this study is to develop a roadway joint system as part of the research into Sustainable-Perpetual-Modular (SPM) roadway systems.

The establishment of appropriate roadway boundary conditions to accommodate less displacement and internal force is another goal of the present study. Generally, a modular roadway system is composed of a precast roadway slab, crossbeams, and supporting

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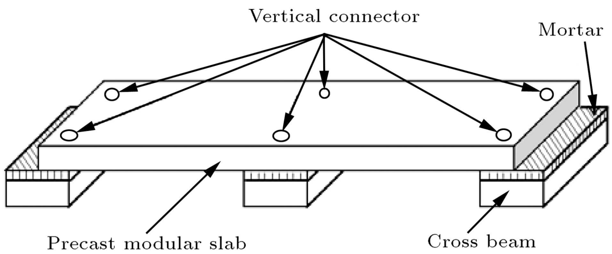


Figure 1. Modular roadway system.

piles, as presented in Figure 1 [9]. The present study was conducted by computer simulations, using ANSYS [10], to establish the internal forces and displacements of these types of slab under various loads. First, the proper boundary conditions were selected in a preliminary analysis with two models. Then, a combination of various loads was used to select the appropriate boundary conditions. Based on the results, a detailed model is developed.

2. Preliminary analysis

2.1. Simplified model

For the preliminary analysis, two different boundary conditions were simulated to determine the appropriate vertical connector boundary conditions for a modular slab. Also, support offsets (d) were considered for use with actual support conditions, as presented in Figure 2. The support offsets were spaced at distances of 0.0 to 0.3 m away from the slab end, after which, the displacements at the top and bottom ends of the roadway slab were investigated under dead, live, and temperature loads. Based on the two boundary conditions and support offset variations, horizontal and vertical displacements and reaction forces were investigated.

2.1.1. Case 1

For Case 1, the proposed boundary conditions are presented in Figure 3. The modular slab has two roller supports at both ends, while a hinge support is located in the middle of the slab. The boundary condition was proposed to allow minimal thermal movement of the slab.

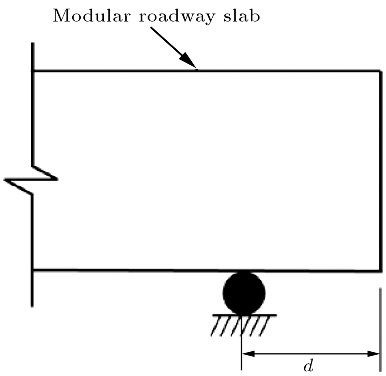


Figure 2. Definitions of parameters.

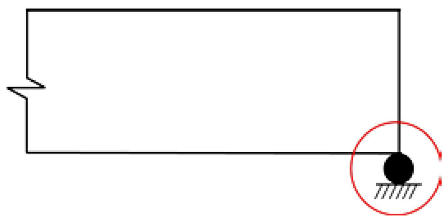


Figure 3. Boundary conditions of Case 1.

Figure 4. Boundary conditions of Case 2.

2.1.2. Case 2

For Case 2, the proposed boundary conditions are presented in Figure 4. The boundary conditions for Case 2 are hinge supports at both ends and in the middle of the slab. The hinge support restricts all displacements except longitudinal bending rotations. Thus, the roadway slab is stable against horizontal and vertical displacements. However, the internal force acting on the ends of the slab is expected to be larger than that of Case 1.

2.2. Loads and material properties

Dead loads, live loads and temperature loads were considered in the analysis. The live loads of KL-510 [11] were based on an influence line analysis to determine truck locations that produce maximum displacements and internal forces. For the temperature load, both a uniform temperature and a temperature gradient were considered, based on actual roadway temperature measurements by KRPSDG [12]. The truck live load (KL-510) location was categorized into two cases: (1) with a convex shape, and (2) with a concave shape of the right-side span of the slab to obtain the maximum displacement at the slab end. Similarly, the temperature loads also considered a convex shape (upper: 46.5°C, lower: 29°C) and a concave shape (upper: −3°C, lower: 2°C). Figure 5 shows the application of live load and temperature load in the numerical model. Table 1 shows the material properties of the modular slab considered in this study.

Table 1. Material properties.

Modulus of elasticity (GPa)	Poisson's ratio	Unit mass (kg/m^3)
37.3	0.18	2500

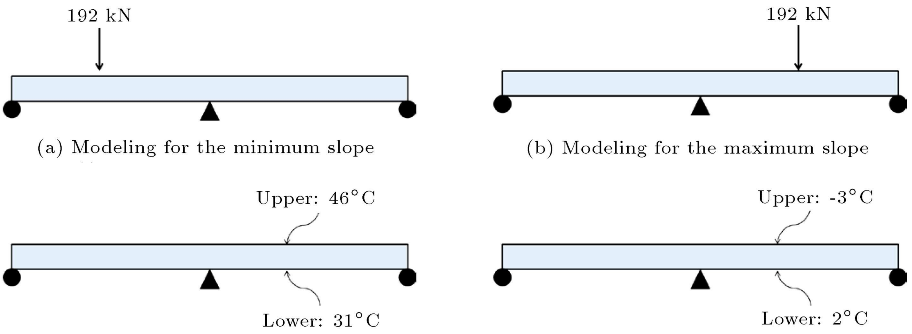


Figure 5. Live load and temperature load modeling.

Table 2. Displacements results.

	d (m)	**Displacements (mm)**	
		Concave	**Convex**
Case 1	0.0	0.69	0.93
	0.1	0.69	0.94
	0.2	0.70	0.96
	0.3	0.71	1.03
Case 2	0.0	0.63	0.83
	0.1	0.66	0.89
	0.2	0.74	1.02
	0.3	0.85	1.18

2.3. Analysis results

2.3.1. Displacements

Table 2 shows the displacement corresponding to the slab deflection shape of each case. The right-side spans of the slab, depending on the load combinations, were investigated with convex and concave shapes. Both the convex and concave shape analysis results demonstrated that both the horizontal and the vertical displacements increased with an increase in the support offset (d) from the tip of the slab end. Also, the convex shape had greater displacement than the concave shape.

2.3.2. Horizontal forces

Table 3 shows the horizontal force of Case 2 under each load. Reaction forces due to self-weight were neglected because the supports of the end tip are fixed after the slab is placed at the construction site and deflection occurs due to self-weight. Significant horizontal forces were observed due to the restraint boundary conditions at both ends of the slab. However, those forces may be reduced if the slab can allow a small amount of displacement. Horizontal forces did not occur due to the roller supports in Case 1.

Table 3. Horizontal forces of Case 2.

d (m)	**Temperature load (kN)**	**Live load (kN)**	**Sum (kN)**
0.0	-4252	-376	-4628
0.1	-4330	-372	-4702
0.2	-4342	-365	-4707
0.3	-4353	-357	-4710

2.3.3. Preliminary analysis results

The analysis results for Case 1 and Case 2 show the smallest displacements with a support offset condition of $d = 0.0$ m. Although the minimum displacement occurred in Case 1 when $d = 0.0$ m, Case 2 was considered to be a more stable configuration for actual modular roadway slabs. Also, Case 2 produced high horizontal forces. Therefore, detailed models of the proposed vertical connector that allowed horizontal displacement at the slab ends were investigated.

3. Detailed analysis

3.1. Detailed model

Section 2 of this study is to determine the boundary conditions and optimal parameter 'd'. Based on the results, an analysis was conducted to develop a detailed model. The analysis results for both Case 1 and Case 2 show the smallest displacements when the support offset condition had d equal to 0.0 m, as noted above. Although minimum displacement occurred in Case 1, Case 2 was considered to be a more stable configuration for actual modular roadway slabs. However, Case 2 produced high horizontal forces. Therefore, detailed models for the proposed vertical connector that allowed horizontal displacement at the slab ends were investigated. The detailed model is a two-span continuous beam and is reinforced with cross beams under the slab. Between the slab and cross beam, a steel anchor is proposed, as shown in Figure 6, with a debonding treatment around the anchor in the slab.

3.2. Loads and material properties

The same loads and material properties were used in the preliminary model. In addition, the long-term behavior of the concrete creep and shrinkage

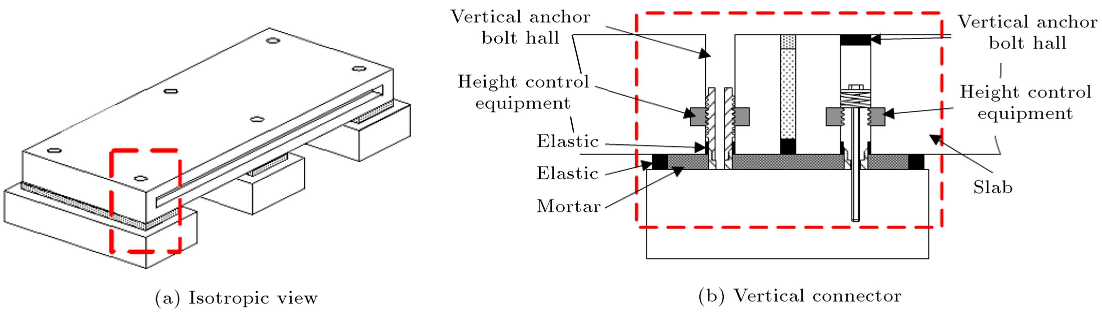


Figure 6. Detailed model.

Table 4. Material properties.

	Modulus of elasticity (GPa)	Poisson's ratio	Unit mass (kg/m^3)
Anchor bolt	200	0.3	7850
Slab	36.6	0.18	2500
Mortar	18.5	0.18	2150
Cross beam	36.6	0.18	2500

were considered. The preliminary analysis models showed that the temperature loads induced the greatest displacements and horizontal forces compared to the other loads. Thus, only the temperature loads were considered in the parametric study. Table 4 shows the material properties of the components of the detailed models assessed in this study.

3.3. Parameters

In detailed model, (i) the distance to the anchor bolts in the slab (a), (ii) the distance to the anchor bolts in the cross beam (b), and (iii) the height of the mortar (h) were considered as parameters. Table 5 shows the possible ranges.

Also, in the parametric study, the displacements of the slab and the internal forces of the anchor bolts were analyzed. Figure 7 shows the definitions of the parameters. Here, A denotes the upper slab, B is the lower slab, C is the upper anchor bolt, and D denotes the middle anchor bolt.

Table 5. Case ID and name for a parametric study.

Case ID	Case name
1	$a150b100h30$
2	$a150b100h50$
3	$a150b200h30$
4	$a150b200h50$
5	$a200b100h30$
6	$a200b100h50$
7	$a200b200h30$
8	$a200b200h50$

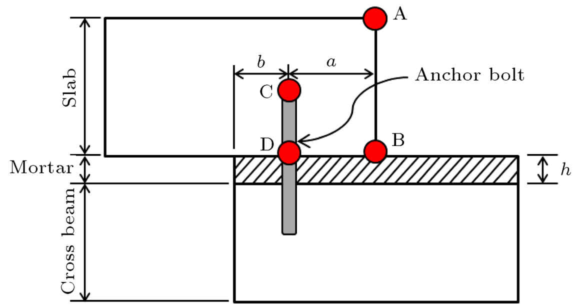


Figure 7. Cross-section of the model.

3.4. Parametric study results

3.4.1. Slab displacements

Figure 8 shows that the horizontal displacements of the convex shape are greater than the vertical displacements of the concave shape. Moreover, the resulting values are constant in accordance with the parameters.

3.4.2. Anchor bolts displacements

Figure 9 shows the displacements of C and D. The horizontal displacement of C is greater than the other displacements at C. Also, the figure shows that the displacements of C are greater than the displacements of D.

3.4.3. Anchor bolts internal forces

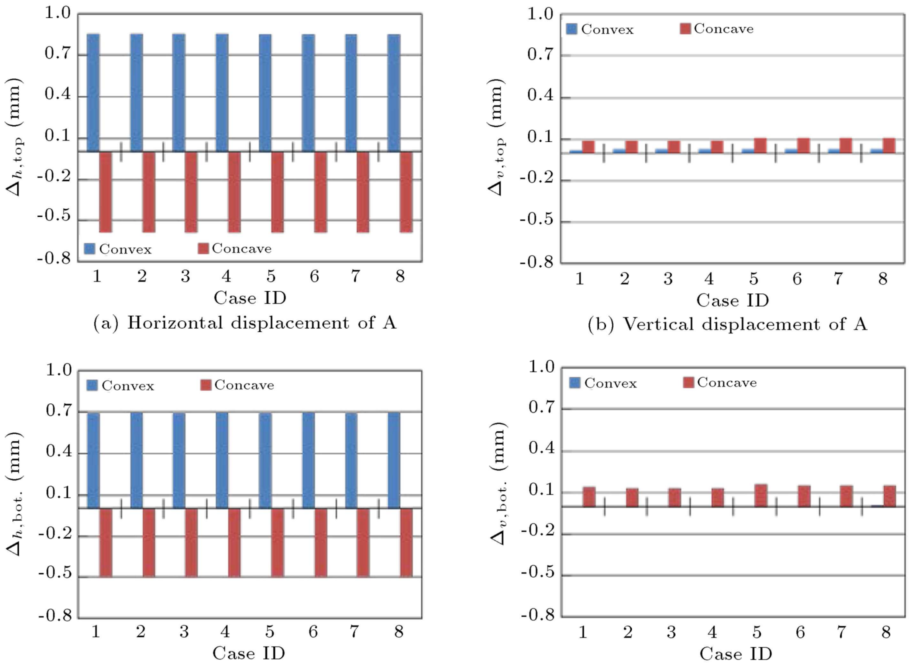
Figure 10 show that the tensile forces were greater than the shear forces. Similarly, the resulting values are constant, in accordance with the parameters.

3.5. Comparison with Case 2 and detailed model

The internal forces of case 2 showed that restrained and large horizontal reaction forces were induced. For the detailed model, the internal force is significantly reduced, due to the displacement, to allow for the anchor bolts. Table 6 shows the internal forces of both Case 2 and the detailed model.

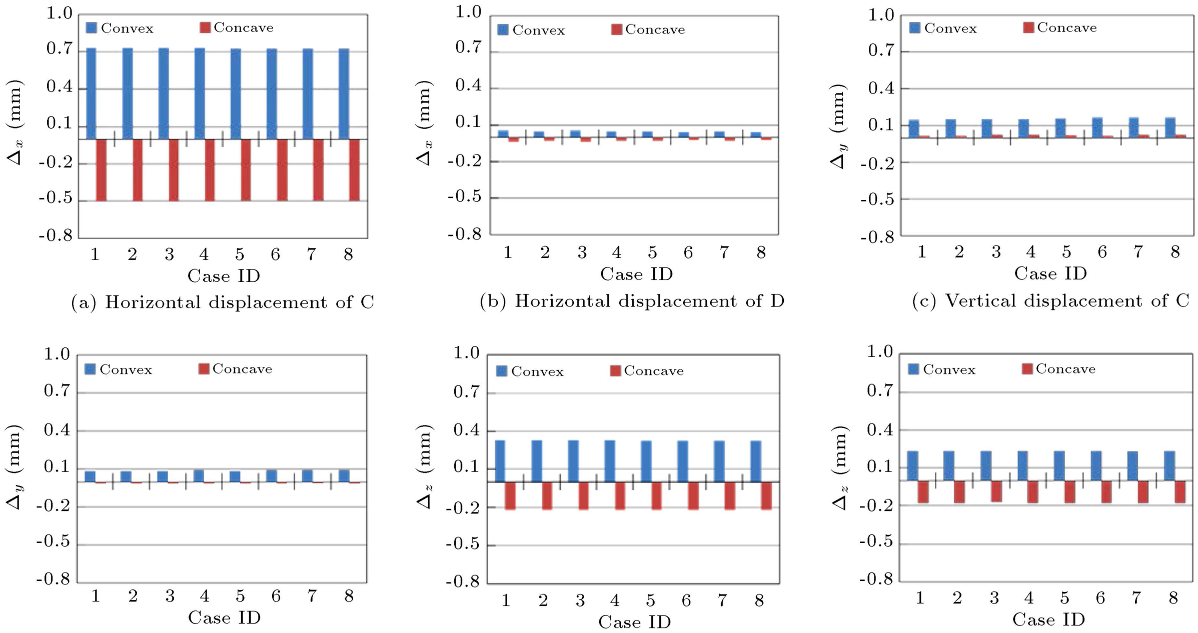
Table 6. Internal force comparison.

	F_x (kN)	F_y (kN)	F_z (kN)
Case 2	275	3872	0
Detail model	52.1	19.4	2.2



(a) Horizontal displacement of A
(b) Vertical displacement of A
(c) Horizontal displacement of B
(d) Vertical displacement of B

Figure 8. Slab displacement results.



(a) Horizontal displacement of C
(b) Horizontal displacement of D
(c) Vertical displacement of C
(d) Vertical displacement of D
(e) Transverse displacement of C
(f) Transverse displacement of D

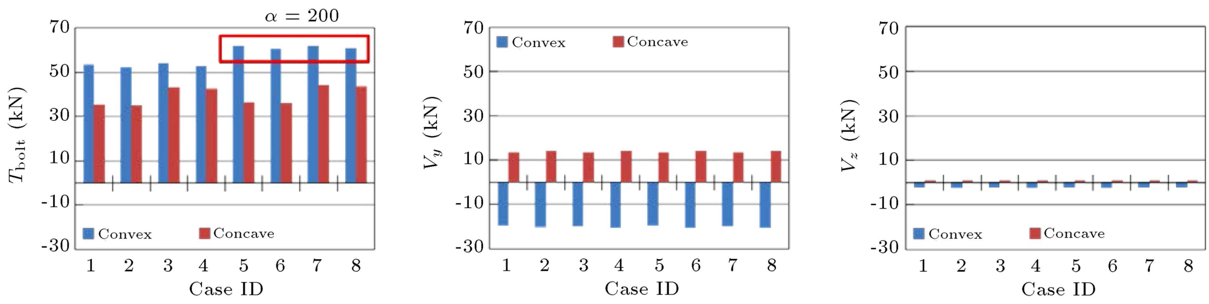
Figure 9. Anchor bolt displacements.

3.6. Additional parametric study

In the parametric study results, the displacements values were found to be constant in accordance with the parameters. However, the internal force of the anchor bolts affects the parameter 'a'. As a result, $a150b100h30$ was deemed suitable in terms of economic efficiency, constructability, and usability. Additionally, a parametric study was conducted to assess only parameter 'a'. Parameters 'b' and 'h' were fixed and parameter 'a' was changed from 100 to 300. Figure 11 shows the internal force results. Shearing forces (longitudinal and transverse) show no response. In contrast, the axial force showed a response.

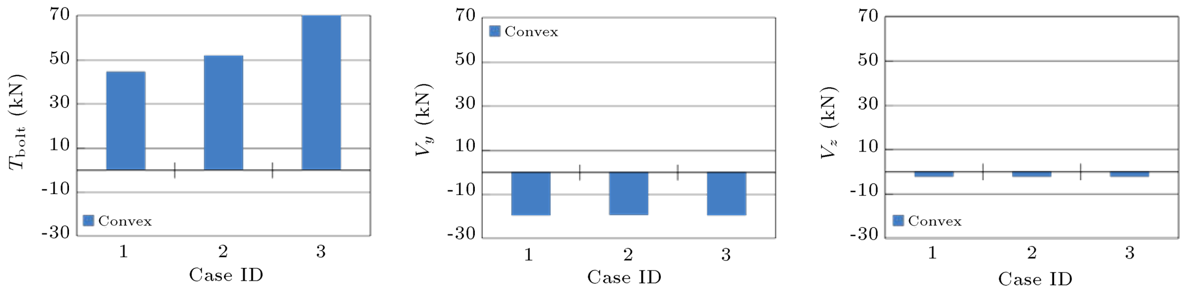
3.7. Load combination results

The case with the parameter $a150b100h30$ showed the smallest displacements and internal forces. Thus, this case was selected to represent the appropriate parame-



(a) Axial force (b) Shearing force (longitudinal) (c) Shearing force (transverse)

Figure 10. Anchor bolt internal forces.



(a) Axial force (b) Shearing force (longitudinal) (c) Shearing force (transverse)

Figure 11. Internal forces with respect to a.

ters. The combination of the load when the span on the right side of the slab has a convex shape is as follows: Dead load + Live load (convex) + Temperature load (summer) + Creep and shrinkage. On the other hand, the combination of the load when the span of the right side of slab has a concave shape is as follows: Dead load + live load (concave) + Temperature load (winter) + creep and shrinkage. Table 7 shows the displacement results of the slab. Tables 8 and 9 show the anchor bolt displacement at the top and midpoint, respectively, and Table 10 shows the internal forces of the anchor bolt.

4. Conclusion

A preliminary analysis based on two boundary conditions investigated the influence of boundary conditions

Table 7. Slab displacements.

Loads		Δ_{ht}	Δ_{vt}	Δ_{hb}	Δ_{vb}
DL		-0.01	0.01	0.01	0.01
LL (concave)		-0.04	0.06	0.04	0.06
LL (convex)		0.01	0.00	-0.01	0.00
TU+TG (winter)		-0.58	0.09	-0.51	0.14
TU+TG (summer)		0.87	0.01	0.69	-0.02
Creep		-0.50	-0.02	-1.40	0.10
Shrinkage		-1.40	-0.02	-1.40	0.10
Sum	Concave	-2.53	0.12	-2.42	0.36
	Convex	-1.03	-0.01	-1.28	0.14

Table 8. Displacements of the anchor bolt at the top.

Loads		Δ_x	Δ_y	Δ_z
DL		0.00	0.00	0.00
LL (concave)		0.02	0.01	0.00
LL (convex)		0.01	-0.01	0.00
TU+TG (winter)		0.02	-0.51	-0.22
TU+TG (summer)		0.15	0.73	0.33
Creep		0.08	-0.52	0.17
Shrinkage		0.04	-1.40	-0.59
Sum	Concave	0.16	-2.42	-0.64
	Convex	0.29	-1.19	-0.09

Table 9. Displacements of the anchor bolt at the midpoint.

Loads		Δ_x	Δ_y	Δ_z
DL		0.00	0.00	0.00
LL (concave)		0.01	0.00	0.00
LL (convex)		0.01	0.00	0.00
TU+TG (winter)		-0.01	0.03	-0.18
TU+TG (summer)		0.08	0.06	0.23
Creep		0.06	0.08	-0.23
Shrinkage		0.04	-0.16	0.13
Sum	Concave	0.19	-0.02	0.13
	Convex	0.10	-0.05	-0.28

Table 10. Internal forces of the anchor bolt.

Loads		T_{bolt} (kN)	V_y (long.) (kN)	V_z (trans.) (kN)
DL		0.00	0.00	0.00
LL (concave)		0.01	0.00	0.00
LL (convex)		0.01	0.00	0.00
TU+TG (summer)		0.08	0.06	0.23
TU+TG (winter)		-0.01	0.03	-0.18
Creep		0.06	0.08	-0.23
Shrinkage		0.04	-0.16	0.13
Sum	Concave	0.19	-0.02	0.13
	Convex	0.10	-0.05	-0.28

on slab and anchor bolt responses. Detailed analytical models were then developed, leading to the following conclusions.

1. For a convex shape, a horizontal filler material set between two slabs needs to allow a distance of at least 2 mm. Similarly, for a concave shape, the horizontal filler between the two slabs needs to allow at least 5 mm;
2. Anchor bolts can be subjected to a maximum of 80 kN horizontal shear force;
3. The vertical displacement is 0.12 mm. This was not considered large enough to cause any rideability problems.

Acknowledgment

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