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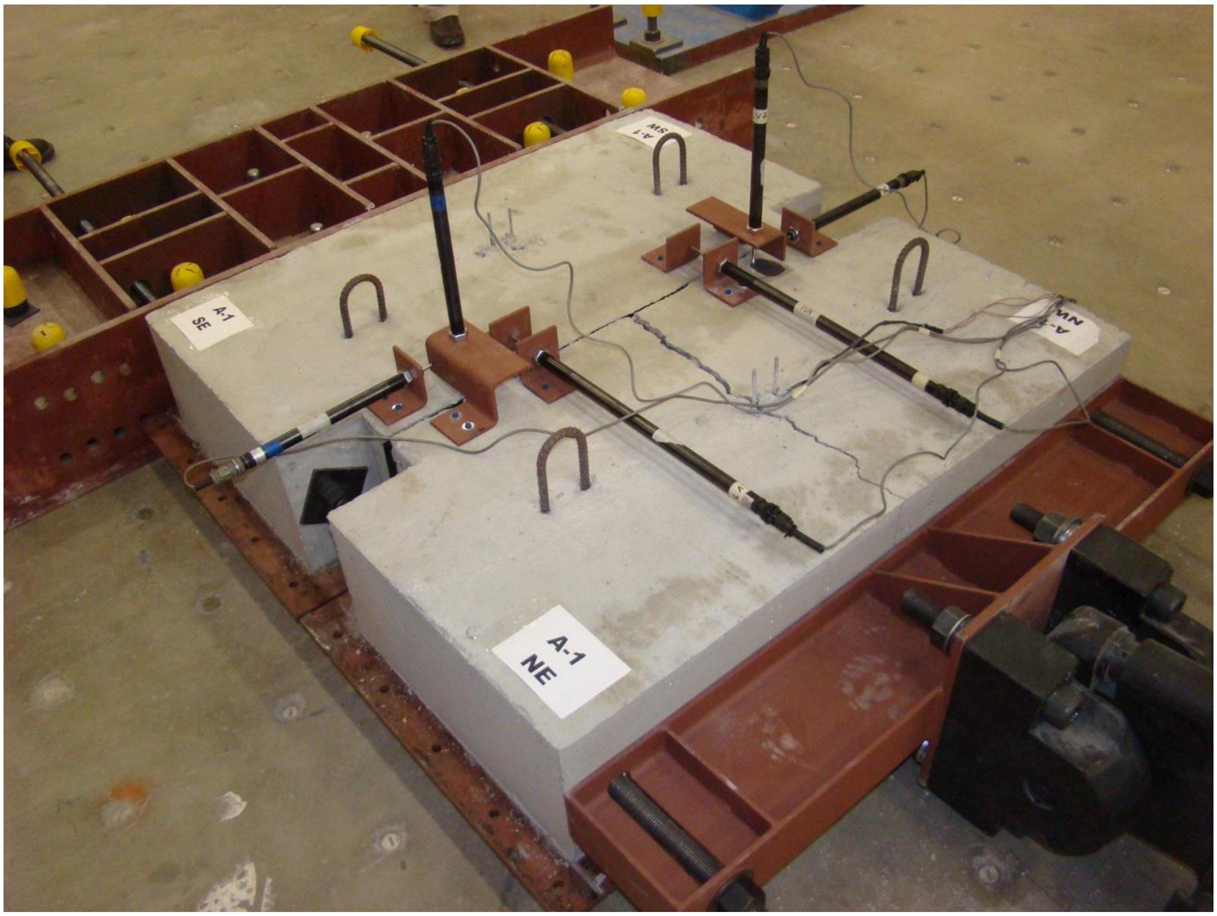

Tolerances for Placement of Tie Bars in Portland Cement Concrete Pavement

Study SD2011-09

Final Report

Prepared by

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May 2017

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16. Abstract

Longitudinal joints are an essential part of Portland Cement Concrete (PCC) pavement slabs. These joints are reinforced with tie bars in order to control joint opening due to thermal stresses. Inspections of PCC pavements by the South Dakota Department of Transportation (SD DOT) using Ground Penetrating Radar (GPR) revealed that it is common for tie bars to be misplaced or missing. It is unclear if these discrepancies would result in additional maintenance costs and reduced pavement life. The tie bar misalignment tolerances that have been established in existing specifications are arbitrary and are not based on any engineering or economic data. Therefore, there is a need for a study to determine the effects of different tie bar misalignments on the tie bar performance in order to establish acceptable placement tolerances. A comprehensive literature review was carried out to look at existing specifications and past studies. The effect of different misalignment configurations and magnitudes on the longitudinal joint performance was examined by conducting laboratory experiments on PCC slabs incorporating four different misalignment configurations and four different misalignment magnitudes. While vertical and longitudinal translation misalignments had no significant effect on the performance of the longitudinal joint, vertical skew misalignment had a mild effect only on joint faulting. Horizontal skew misalignment, however, caused a significant increase in both joint opening and joint faulting. Horizontal skew misalignment also caused a significant decrease in the maximum allowable load. Simplified hand calculations can conservatively estimate the allowable load for horizontal skew misalignments. Based on the results, recommendations are to reduce the horizontal skew tolerance limit from 18 in. to, at most, 16 in.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLE OF ACRONYMS

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AISC	American Institute of Steel Construction
CRCP	Continuously Reinforced Concrete Pavements
DOT	Department of Transportation
DOR	Department of Roads
FE	Finite Element
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GPR	Ground Penetrating Radar
MEPDG	Mechanistic-Empirical Pavement Design Guide
MIT	Magnetic Induction Tomography
MSU	Michigan State University
PCC	Portland Cement Concrete
PVC	Polyvinyl Chloride
SDDOT	South Dakota Department of Transportation
SDSU	South Dakota State University
SDT	Subgrade Drag Theory

1 EXECUTIVE SUMMARY

1.1 Introduction

Concrete pavements are widely used for roadways across the United States. Jointed plain Portland Cement Concrete (PCC) pavement is a common type of concrete pavement that consists of unreinforced concrete slabs with longitudinal and transverse joints. The longitudinal joint runs parallel to the direction of traffic and is reinforced using tie bars. Tie bars are typically deformed, epoxy coated steel bars that control joint openings due to thermal stresses in the concrete slab. The transverse joint runs perpendicular to the direction of traffic and is reinforced using dowel bars. Dowel bars are smooth, round bars that provide load transfer between slabs without restricting expansion and contraction of the pavement due to temperature and moisture changes.

1.2 Problem Description

Inspections of PCC pavements by the South Dakota Department of Transportation (SDDOT) using Ground Penetrating Radar (GPR) revealed that it is common for tie bars to be misplaced or missing. A misplaced tie bar could inhibit the tie bar's ability to provide load transfer across the joint and to prevent excessive joint opening. However, the short- and long-term effects of misplaced or missing tie bars on the performance of the longitudinal joint are not well understood. Missing or misplaced tie bars could cause additional maintenance costs and reduced pavement life.

Placement tolerances for dowel bars have been researched and implemented by most state departments of transportation (DOT's). However, very few states have set requirements on the placement of tie bars in PCC pavements. The tolerances that have been established for tie bar placement are arbitrary and are not based on any engineering or economic data, making it impossible to know if these tolerances are too strict or too relaxed. With millions of dollars spent each year on roads, the financial impacts of missing or misplaced tie bars could be costing the SDDOT a substantial amount of money in the long-term. Therefore, there was a need for a study to determine the effects of various tie bar misalignments on tie bar performance in order to establish acceptable placement tolerances. This report responds to that need.

1.3 Research Work

This research involved two main tasks in order to identify current specifications regarding tie bar misalignment tolerances in PCC pavements and to provide recommendations to improve these specifications. These tasks were: 1) conducting a comprehensive literature review and 2) carrying out experiments involving several tie bar misalignment configurations and magnitudes. The literature review includes sources for existing design practices and specifications, in addition to the most recent studies about longitudinal joints in PCC pavements.

A total of 35 PCC slabs were tested at the Lohr Structures Laboratory at the Civil and Environmental Engineering Department at South Dakota State University (SDSU). All slabs had the same concrete mix design, with the only difference among them being the tie bar misalignment configurations and magnitudes. Three slabs acted as controls, having perfectly aligned tie bars. The other 32 slabs incorporated four different misalignment configurations and four different misalignment magnitudes for each misalignment configuration. The misalignment configurations were vertical and longitudinal translations, and vertical and horizontal skews. A direct mechanical tensile force was applied on each specimen. Allowable load, joint opening, and joint faulting were measured to assess the performance of the longitudinal joint. Simplified hand calculations were also conducted to estimate the maximum allowable load. The results from these experiments were used to recommend adjustments to existing specifications.

1.4 Research Findings

The study presented in this report was conducted to 1) identify current specifications for tie bar placement tolerances in PCC pavements, 2) conduct experimental testing to examine the effect of various tie bar misalignment configurations and magnitudes on the performance of longitudinal joints, and 3) give recommendations to improve current specifications if needed.

The following findings and conclusions are based on the experimental tests that were conducted in this study.

- Vertical and longitudinal translation misalignments had no significant effect on the performance of the longitudinal joint.
- Vertical skew misalignments did not have any significant effect on maximum allowable load or joint opening.
- Vertical skew misalignments resulted in joint faulting that reached as high as 25 times that of aligned specimens (0.152 in. at an offset of 8 in.).
- Horizontal skew misalignments resulted in a decrease in maximum allowable force and an increase in both joint opening and joint faulting.
- The joint opening limit of 1/8 in. was exceeded at 20 in. horizontal skew offset.
- Joint faulting for horizontal skew misaligned specimens reached as much as 35 times that of aligned specimens at an offset of 20 in.
- The maximum allowable force for specimens with horizontal skew misalignment can be conservatively estimated using simplified hand calculations.

1.5 Recommendations

Based on the findings of this study, the research team offers the following recommendations.

- The current SDDOT tie bar tolerance limit for horizontal skew misalignment should be reduced from 18 in. to at most 16 in.
- Further reduction in the horizontal skew tolerance limit might be required if joint faulting is a significant issue.
- The vertical skew tolerance limit is sufficient, but contractors need to strictly abide by it in order to avoid excessive joint faulting.
- For a given design load, the proposed hand calculation can be used to establish maximum allowed horizontal skew, provided it is no more than 16 in.
- For future research, experiments can be conducted on slabs with multiple tie bars that have different horizontal skew magnitudes, examining more real life scenarios.

2 PROBLEM DESCRIPTION

Concrete pavements are widely used for roadways across the United States. Jointed plain Portland Cement Concrete (PCC) pavement is a common type of concrete pavement that consists of unreinforced concrete slabs with longitudinal and transverse joints. Two types of joints are depicted in Figure 2-1. The longitudinal joint runs parallel to the direction of traffic and is reinforced using tie bars. Tie bars are typically deformed, epoxy coated steel bars that control joint opening due to thermal stresses in the concrete slab. The transverse joint runs perpendicular to the direction of traffic and is reinforced using dowel bars. Dowel bars are smooth, round bars that provide load transfer between slabs without restricting expansion and contraction of the pavement due to temperature and moisture changes.

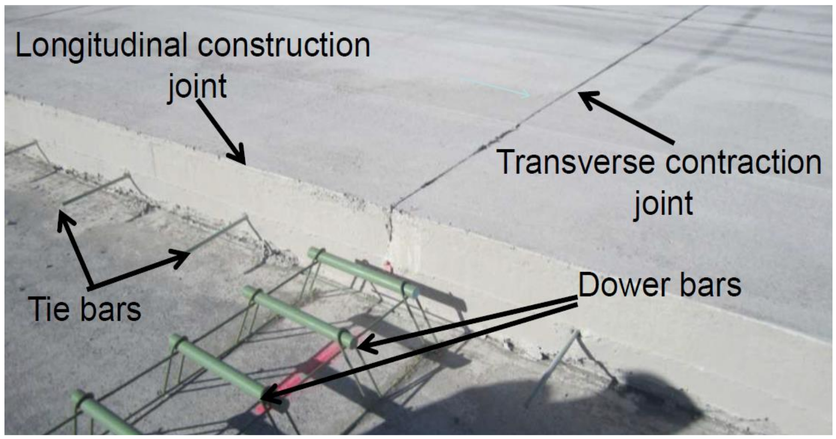


Figure 2-1: Dowel and Tie Bars in PCC Pavement (Khazanovich, 2011)

Inspections of PCC pavements by South Dakota Department of Transportation (SDDOT) using Ground Penetrating Radar (GPR) revealed that it is common for tie bars to be misplaced or missing. A misplaced tie bar could inhibit the tie bar's ability to provide load transfer across the joint and to prevent excessive joint opening. However, the short and long term effects of misplaced or missing tie bars on the performance of the longitudinal joint are not well understood. Missing or misplaced tie bars could be the reason for additional maintenance costs and reduced pavement life.

Placement tolerances for dowel bars have been researched and implemented by most state departments of transportation (DOT's). However, very few states have set requirements on the placement of tie bars in PCC pavements. The tolerances that have been established for tie bar placement are arbitrary and are not based on any engineering or economic data, making it impossible to know if these tolerances are too strict or too relaxed. With millions of dollars spent each year on roads, the financial impacts of missing or misplaced tie bars could be costing the SDDOT a substantial amount of money in the long-term. Therefore, there is a need for a study to determine the effects of various tie bar misalignments on tie bar performance in order to establish acceptable placement tolerances.

3 RESEARCH OBJECTIVES

The three main objectives of this study are listed below.

3.1 Objective 1

Identify and describe specifications currently used for tie bar placement tolerances in PCC pavement.

This objective was accomplished through an extensive literature search, in addition to consultation with the SDDOT. The effort was focused on characterizing available DOT specifications. More details for this objective are presented under Task 2 in this report.

3.2 Objective 2

Develop structural analysis of tie bars that provides a basis for design and placement tolerances.

After identifying the available specifications for tie bar tolerances and looking at previous studies, an experimental plan was devised to examine the effect of various tie bar misalignments on the performance of longitudinal joints. The experiments were carried out at SDSU's Lohr Structures Laboratory. More details on the laboratory testing plan are presented under Tasks 3-6 of this report.

3.3 Objective 3

Develop recommendations for tie bar placement tolerances based on current specifications.

Based on the literature review and the experimental results, recommendations were made to provide guidance for tie bar placement tolerances. More details about the guidelines are presented under Task 7in this report.

4 TASK DESCRIPTIONS

The research work presented in this report is comprised of 10 Tasks, with activities described as follows.

4.1 Meet with Technical Panel

Meet with the technical panel to review the project scope and work plan.

A kick-off meeting with the technical panel was held on December 19, 2013. The researchers gave a presentation on the scope and work plan for the entire project. The presentation also covered an overview of existing specifications and previous studies. Meeting minutes were recorded and feedback from the technical panel was incorporated into the project.

4.2 Review Literature

Review and summarize literature regarding tie bar placement specifications.

A literature review on the design and performance of PCC pavement joints with tie bars was conducted. The main focus was identifying existing specifications and previous studies. The results are presented in Chapter 5 of this report.

4.3 Develop a Testing Plan

Based on the literature review, develop a testing matrix and procedure for individual or group tie bar configurations.

A testing matrix was developed with the aim of examining four different tie bar misalignment configurations. Four different magnitudes were examined for each misalignment configuration. Details about the conducted tests are presented in Chapter 6 of this report.

4.4 Review Testing Plan with Technical Panel

Meet with technical panel to review the testing matrix and the testing procedure.

A meeting with the technical panel was held on February 26, 2014. The researchers gave a presentation on the testing matrix and procedures. Meeting minutes were recorded and feedback from the technical panel was incorporated into the project. Feedback included adjustments of misalignment magnitudes.

4.5 Construct Test Specimens

Construct appropriate specimens.

After approval by the technical panel, specimens were constructed and prepared for testing. Details about the construction procedures and instrumentation are presented in Chapter 6 of this report.

4.6 Perform Load Testing

Perform structural load testing as described in the testing procedure approved by the technical panel.

Structural load testing was performed following the construction of specimens. All specimens were subjected to direct tension as approved by the technical panel. Details about the obtained results are presented in Chapters **Error! Reference source not found.** of this report.

4.7 Recommend Tolerances for Placing Tie Bars

Recommend tolerances for placing tie bars on the basis of literature review and experimental results.

Based on the findings from literature review and experimental results, critical misalignment configurations were identified. The adequacy of tie bar tolerances in SDDOT specifications was then evaluated and necessary adjustments were recommended.

4.8 Discuss Experimental Results with Technical Panel

Meet with technical panel to discuss experimental results and recommend whether any additional testing is needed.

A meeting with the technical panel was held.

4.9 Prepare Final Report

Prepare a final report summarizing the research findings, conclusions, and recommendations.

This task is satisfied through this report.

4.10 Make Executive Presentation

Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project.

A final presentation was given to the SDDOT Research Review Board.

5 LITERATURE REVIEW

This chapter provides a summary of existing literature pertaining to longitudinal PCC joints with tie bars. The literature review focused on identifying common methods for installing tie bars, discussing current tie bar design procedures, and describing tie bar specifications used by various state DOT's. It also summarized findings from previous studies conducted on tie bars.

5.1 Tie Bar Installation Methods

The tie bar installation depends primarily on the longitudinal joint type used. There are two main types of longitudinal joints: sawed joints and construction joints. A sawed longitudinal joint is used when the two sides of the joint are poured monolithically, and the joint is saw cut after the concrete starts to set. A construction longitudinal joint is used if the two sides of the joint are poured at separate times thus creating a cold joint. The type of longitudinal joint used depends on many factors, such as the width of the roadway, capabilities of the paver used, and site restrictions.

For sawed joints, tie bars can be installed either prior to paving using p-stakes or seats or mechanically during paving using automatic inserters. Using p-stakes or seats to place tie bars prior to paving is the most common way to install tie bars in South Dakota. This method involves setting the tie bars in p-stakes or on seats that have been attached to the roadway base prior to paving. Tie bars installed in p-stakes prior to placing concrete is illustrated in Figure 5-1.

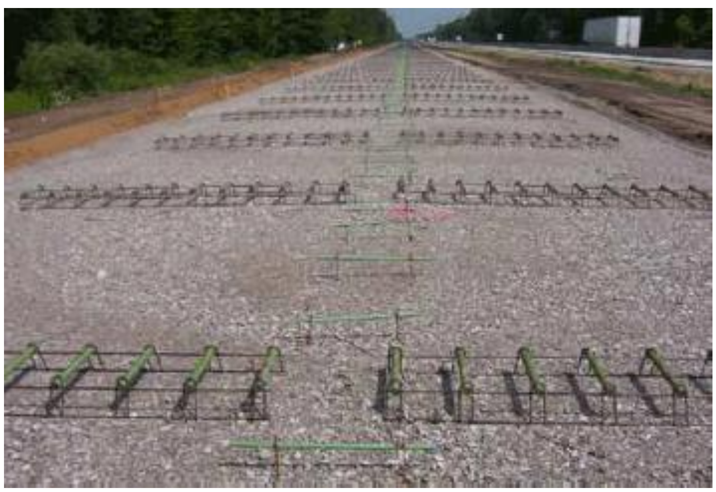


Figure 5-1: Tie Bars prior to Placing Concrete (Perera, Kohn, & Tayabji, 2005)

Mechanically placing tie bars with automatic inserters involves inserting the tie bars in the plastic concrete as it is being placed. However, installing tie bars with automatic inserters is not allowed by many state DOT's, including South Dakota, due to the increased number of missing or misplaced tie bars commonly found with this installation method.

Along construction longitudinal joints, the tie bars can be either installed into the plastic concrete or drilled-in after the concrete has hardened. Installation of tie bars into the plastic concrete can be done either mechanically or by hand. Mechanical placement of tie bars is done by the paving machine prior to final strike off of the paver. The South Dakota DOT (SD DOT) does not allow hand placing tie bars into the plastic concrete. When drilled-in, the tie bars are installed into holes that have been drilled into the face of the hardened concrete (Figure 5-2). An epoxy adhesive is used to form a bond between the tie bar and the hardened concrete.

Figure 5-2: Installation of Drilled-in Tie Bars (South Dakota DOT, 2016)

5.2 Design Methods

There are two main design procedures for determining the required size and spacing for tie bars: 1) the *AASHTO Guide for Design of Pavement Structures* (or AASHTO 1993 design guide) (AASHTO, 1993) and 2) the *AASHTO Mechanistic-Empirical Pavement Design Guide* (or M-E design guide) (AASHTO, 2008).

5.2.1 *AASHTO Guide for Design of Pavement Structures* (AASHTO, 1993)

The AASHTO (1993) design guide procedure is the one most commonly used for selecting tie bar size and spacing. That design procedure provides the following general recommendations for tie bars:

1. Must be made from Grade 40 deformed steel bars or connectors.
2. Shall have a corrosion resistant coating, such as epoxy, in regions were salts are applied to pavements.
3. The minimum length of #4 and #5 tie bars must be 25 in. and 30 in., respectively.
4. The minimum center-to-center spacing must be 48 in.

The AASHTO (1993) design procedure is based on the subgrade drag theory (SDT). The SDT determines the amount of steel required to "drag" the concrete slab across the base material without yielding or pulling out the tie bars. The tie bar spacing using SDT can be found using Equation 1 through Equation 3.

$$F_{drag} = L_{fe} D W_{conc.} F \qquad \text{Equation 1}$$

Where:

$$F_{drag} = Required\ force\ to\ drag\ slab\ accross\ the\ base, lb/in$$

$$L_{fe} = Distance\ from\ longitudinal\ joint\ to\ closest\ free\ edge, ft$$

$$D = Pavement\ slab\ thickness, in$$

$$W_{conc.} = Unit\ weight\ of\ concrete\ \left(Typcally\ use\ 1.0\ \frac{lb}{in^2 ft}\right)$$

$$F = Friction\ factor\ (See\ \text{Table 5-1})$$

$$F_{TB} = f_s A_s \qquad \text{Equation 2}$$

Where:

$$F_{TB} = Allowable\ tie\ bar\ force, lbs$$

$$f_s = Allowable\ steel\ working\ stress, psi\ \left(\frac{3}{4} f_y\right)$$

$$A_s = Tie\ bar\ cross\ sectional\ area, in^2$$

$$J_{TB} = \frac{F_{TB}}{F_{drag}} \leq 48\ in. \qquad \text{Equation 3}$$

Where:

$$J_{TB} = Tie\ bar\ spacing, in$$

$$F_{TB} = Allowable\ tie\ bar\ force, lbs$$

$$F_{drag} = Force\ required\ to\ drag\ slab\ accross\ the\ base, lb/ft$$

The friction factor, F, value used in Equation 2 is given in Table 2.8 of the AASHTO (1993) design procedure for many common base materials. Table 5-1 is a replica of Table 2.8 from the AASHTO (1993) design guide.

Table 5-1: Recommended Friction Factor Values (after AASHTO, 1993)

Type of Material Beneath Slab	Subgrade Friction Factor (F)
Surface Treatment	2.2
Lime Stabilization	1.8
Asphalt Stabilization	1.8
Cement Stabilization	1.8
River Gravel	1.5
Crushed Stone	1.5
Sandstone	1.2
Natural Subgrade	0.9

Despite being the most widely used design approach for determining tie bar size and spacing, the AASHTO (1993) design procedure has deficiencies. Some deficiencies discussed in the American Concrete Pavement Association (ACPA) article, "A Mechanistic-Empirical Tie Bar Design Approach for Concrete Pavements" (Mallela, Gotlif, Darter, Ardani, & Littleton, 2009), are presented below:

1. Does not consider the stresses induced from temperature changes or drying shrinkage of the concrete slab.
2. Does not compute the actual stresses in the steel.
3. The distance to a free longitudinal joint is hard to define when more than two lanes are tied together.
4. Is based on a simple friction model and assumes a single parameter to define the behavior at the slab-base interface.
5. Includes a large safety factor by reducing the steel yield stress.
6. Does not account for displacement of the base layer since a rigid base is assumed.

These deficiencies led AASHTO to develop the Mechanistic-Empirical Pavement Design Guide (2008).

5.2.2 AASHTO Mechanistic-Empirical Pavement Design Guide (AASHTO, 2008)

The AASHTO (2008), sometimes called the M-E design guide, is based on engineering mechanics and has been validated by road test performance data. In order to use the M-E design method, the pavement must first be designed according to the AASHTO 1993 design procedure. The pavement design can then be incorporated into the M-E design guide software, along with such conditions as traffic, climate, and subgrade. The M-E design guide software assesses the incremental damage to pavement over time, resulting from the applied stresses. The incremental damaged is used to predict the pavement distresses and smoothness at any given time throughout the pavement's lifespan. The user can then use the predicted pavement distresses and smoothness to determine if the pavement design needs to be improved.

This design method is just used to "fine tune" or "double check" the pavement design developed by the AASHTO 1993 design procedure. Therefore, no changes are made to the allowable tie bar design force. Instead of the SDT, the load experienced by the tie bar, in this method, is a function of the traffic, climate, and subgrade conditions. If the M-E design guide software output shows that the input design performs adequately over the design life of the pavement, no changes need to be made to the tie bar design. However, if the M-E design guide software shows that the design is inadequate, the design procedure recommends iterative changes using engineering judgment until adequate results are obtained.

5.3 Available Standard Specifications

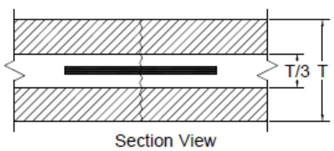
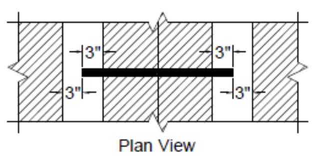
Rather than calculating tie bar spacing for each individual roadway design, most state DOT's have adopted one or several different standard tie bar designs. The standard tie bar designs are determined for various combinations of parameters which may include pavement thicknesses, joint types, tie bar steel grades, tie bar diameters, installation methods, and free edge spacing. The number of parameters considered depends on what each state DOT deems necessary for their specific roads.

5.3.1 South Dakota DOT

The SDDOT publishes standard tie bar design specifications in the annual version of their concrete paving manual (South Dakota DOT, 2016). The concrete paving manual specifies #5, grade 40 or grade 60, epoxy coated, deformed tie bars. The length and spacing of the tie bar depend on the type of longitudinal joint. For tie bars that are not drilled-in, the tie bar length should be 30 in. long with 15 in. embedded on each side of the joint. For drilled-in tie bars, the tie bar should be 24 in. long, with 9 in. embedded in the in-place concrete. Center-to-center spacing of the tie bars is specified to be 48 in. for sawed joints and construction joints with a female keyway. For construction joints with a male keyway or no keyway, the center-to-center tie bar spacing is reduced to 30 in.

The SDDOT provides vertical and transverse placement tolerances for tie bars in their concrete paving manual. Among all of the state DOT specifications, the SDDOT was the only state DOT that provided tie bar placement tolerance specification. However, no explanation is provided on how the placement tolerances were developed. Table 5-2 shows the current tie bar placement tolerances recommended by the SDDOT.

Table 5-2: Current SDDOT Tie Bar Placement Tolerance Limits

Direction	Tolerance Limit
Vertical Placement: 	All parts of the tie bar must be within the middle 1/3 of the pavement depth.
Transverse Placement: 	± 3.0 in. measured perpendicular to the longitudinal joint.

5.3.2 Federal Highway Administration

The Federal Highway Administration (FHWA) recommended a tie bar design in a technical advisory for concrete pavement joints, last updated in November 2011 (Federal Highway Administration, 2011). The technical advisory states that longitudinal joints with tie bars should be used for slabs that have a width exceeding 15 ft. The FHWA recommends that tie bars should be either #4 or #5, epoxy coated, deformed bars. They should be made from either grade 40 or grade 60 steel. The length of the tie bar is a function of the tie bar size and steel grade. The tie bar center-to-center spacing is a function of the pavement thickness, joint type, tie bar size, tie bar material grade, and the distance to the free edge. Table 5-3 and

Table 5-4 show the FHWA's recommended tie bar length and spacing requirements.

Table 5-3: FHWA's Recommended Tie Bar Length

Tie Bar Grade	Tie Bar Length for a #4 Tie Bar	Tie Bar Length for a #5 Tie Bar
Grade 40	24 in.	30 in.
Grade 60	32 in.	40 in.

Table 5-4: FHWA's Recommended Tie Bar Spacing

Pavement Thickness, in.	Joint Type*	Tie Bar Spacing for a #4 Tie Bar, in.									
		Grade 40					Grade 60				
		Distance to Free Edge, ft.					Distance to Free Edge, ft.				
		10	12	16	22	24	10	12	16	22	24
9	Wrap	37	31	23	17	16	48	47	35	25	23
	Butt	26	22	16	12	11	40	34	25	18	16
10	Wrap	34	28	22	16	14	48	42	32	23	20
	Butt	24	20	16	11	10	36	30	23	16	14
11	Wrap	31	25	20	15	13	47	38	29	21	19
	Butt	22	18	14	11	9	34	27	21	15	14
12	Wrap	28	23	18	13	12	42	35	27	19	18
	Butt	20	16	13	9	9	30	25	19	14	13
		Tie Bar Spacing for a #5 Tie Bar, in.									
9	Wrap	48	48	36	25	24	48	48	48	40	36
	Butt	42	35	26	19	17	48	48	39	29	26
10	Wrap	48	44	33	24	22	48	48	48	36	32
	Butt	38	31	24	17	16	48	47	35	26	23
11	Wrap	48	40	30	22	20	48	48	44	32	30
	Butt	34	29	21	15	14	48	43	31	23	21
12	Wrap	44	36	28	20	18	48	48	41	30	28
	Butt	31	26	20	14	13	47	39	29	21	20

* Warp Joint: A sawed or construction joint with a keyway
Butt Joint: A construction joint with no keyway

5.3.3 Minnesota DOT

The *Pavement Design Manual* (Minnesota DOT, 2014) of the Minnesota Department of Transportation (DOT) specifies two tie bar designs based on the pavement thickness. For pavements less than, or equal to, 10 in. thick, the tie bars should be 30 in. long, #4, deformed bars spaced at 30 in. center-to-center. If the pavement thickness is greater than 10 in., the tie bars should be 36 in. long, #5, deformed bars spaced at 30 in. center-to-center. Regardless of the pavement thickness, the pavement design manual recommends grade 60 and epoxy coated tie bars.

5.3.4 Colorado DOT

The Colorado DOT standard tie bar designs are listed in the annual edition of the Colorado DOT's *Pavement Design Manual* (Colorado DOT, 2014). The pavement design manual specifies grade 60, epoxy coated, deformed tie bars that are 30 in. long and placed at 36 in. center-to-center spacing.

When the pavement is placed on an unbound base, the tie bar should be a #5 bar. When the base material is lime treated soil, asphalt treated, cement treated, milled asphalt, or recycled asphalt pavement; the tie bar should be a #6 bar.

5.3.5 Nebraska Department of Roads

The standard concrete pavement details (Nebraska DOR, 2011) for the Nebraska Department of Roads (DOR) specifies different tie bar designs based on the type of longitudinal joint. For a sawed longitudinal joint, the tie bars should be 30 in. long and spaced at 33 in. center-to-center. The tie bar needs to be a #5 bar if the pavement thickness is between 6 in. and 10 in. or a #6 bar if the pavement thickness is greater than 10 in. For a construction longitudinal joint, the pavement thickness must be at least 8 in., so that a keyway can be installed. The tie bars are required to be a #5 bar that is 30 in. long and spaced at 33 in. center-to-center.

5.3.6 Iowa DOT

The Iowa DOT provides their standard tie bar designs in standard concrete pavement drawings (Iowa DOT, 2014). The standard concrete pavement drawings specify the tie bar size, length, and spacing, based on the joint type and pavement thickness. The standard tie bar designs as specified by the Iowa DOT are provided in Table 5-5.

Table 5-5: Iowa DOT's Standard Tie Bar Designs

Joint Type	Pavement Thickness, in.	Bars Number	Bar Length, in.	Tie Bar C-C Spacing, in.
Sawed Joint	< 8	# 4	36	30
	≥ 8	# 5	36	30
Construction without a Keyway	< 8	# 4	36	30
	≥ 8	# 5	36	30
Construction with a Keyway	< 8	# 4	30	30
	≥ 8	# 5	30	30

5.3.7 Indiana DOT

A set of standard concrete pavement design drawings (Indiana DOT, 2011) are used by the Indiana DOT to specify their standard tie bar designs. The standard tie bar designs vary primarily based on the joint type and the pavement thickness. The Indiana DOT standard tie bar designs are provided in Table 5-6.

Table 5-6: Indiana DOT's Standard Tie Bar Designs

Longitudinal Joint Type	Pavement Thickness, in.	Tie bar Length, in.	Tie Bar Size	Tie Bar Center-to-Center Spacing, in.
Sawed	≤ 9	30	# 5	36
	> 9	30	# 6	36
Construction	< 9	30	# 5	36
	9 to 12	30	# 6	36
	> 12	30	# 6	24
		30	# 7	36

5.3.8 Summary

By looking at the tie bar specifications adopted by few state DOTs, upper and lower limits used for each tie bar design parameter were identified. The upper and lower limits for each tie bar design parameter are provided in Table 5-7.

Table 5-7: Upper and Lower Limits for the Tie Bar Design Parameters

Tie Bar Design Parameter	Upper Limit	Lower Limit
Grade	60	40
Size	#7	#4
Length	40 in.	24 in.
Center-to-center Spacing	48 in.	9 in.

5.4 Previous Studies

A rigorous literature review revealed only two previous research studies relating to tie bars placement or PCC pavement joint performance relevant to the testing and development of tie bar placement tolerances. The following are summaries of the work done in each study.

5.4.1 Evaluation of Longitudinal Tie Bar Joint System (Mallela, Gotlif, Littleon, Sadasivam, & Darter, 2011)

Mallela and others evaluated longitudinal joint tie bar systems in a study sponsored by the Colorado DOT (Mallela, Gotlif, Littleon, Sadasivam, & Darter, 2011). The research started with a preliminary field inspection of longitudinal joints. The inspection showed that the condition of the longitudinal joints was highly variable along sections of the roadway for no apparent reason. During the preliminary inspections, three forms of joint distresses were observed at the longitudinal joint: 1) excessive joint opening (most common), 2) joint faulting, and 3) joint slippage (Figure 5-3).

Joint Opening **Joint Faulting** **Joint Slippage**

Figure 5-3: Longitudinal Joint Distresses (Mallela, Gotlif, Littleon, Sadasivam, & Darter, 2011)

The researchers initially suspected the longitudinal joint distresses were caused by one or a combination of the following factors:

- Lane configuration (number/width of lanes, lane to shoulder connection)
- Pavement structure (pavement thickness, base friction and stiffness properties)
- Portland cement concrete properties (compressive strength, modulus of elasticity, thermal expansion, shrinkage, unit weight)
- Weather conditions (changes in temperature/moisture)
- Construction factors (longitudinal joint type, tie bar installation method)
- Other factors (pavement support conditions, slope stability, and road geometry)

To investigate the effects of those six factors, two rounds of field tests were conducted. All of the field tests were performed on sections of roads that had both good and poorly performing longitudinal joints in close proximity to one another with similar tie bar designs, traffic conditions, and base conditions.

The first round of field testing was completed in the fall of 2008 on three sections of a roadway. At each of the three test sections, one lane of the road was closed from morning until early afternoon to collect data on four parameters: longitudinal joint opening, pavement temperature, falling weight deflectometer (FWD), and magnetic induction tomography (MIT) scans. The longitudinal joint opening and the pavement temperature were measured at regular intervals throughout the morning and early afternoon to determine how the joint opening changed as the temperature of the concrete changed. The FWD test was used to measure the load transfer across the longitudinal joint. This test was performed simultaneously with the longitudinal joint opening and concrete temperature measurements to see how the load transfer was affected by the width of the joint opening. The MIT scan testing was performed once during the morning to determine the position of the tie bars in the pavement along the longitudinal joint. The most significant conclusion found during this first round of field tests was that many of the tie bars at the poor longitudinal joints were either missing or severely misaligned. At the good longitudinal joint, the tie bars were found to be very close to their intended position. The MIT scan images are provided (Figure 5-4) for a section of the good and bad longitudinal joints at one of the sites, where the black line on the image represents the longitudinal joint and the orange to red shading indicate the positions of the tie bars.

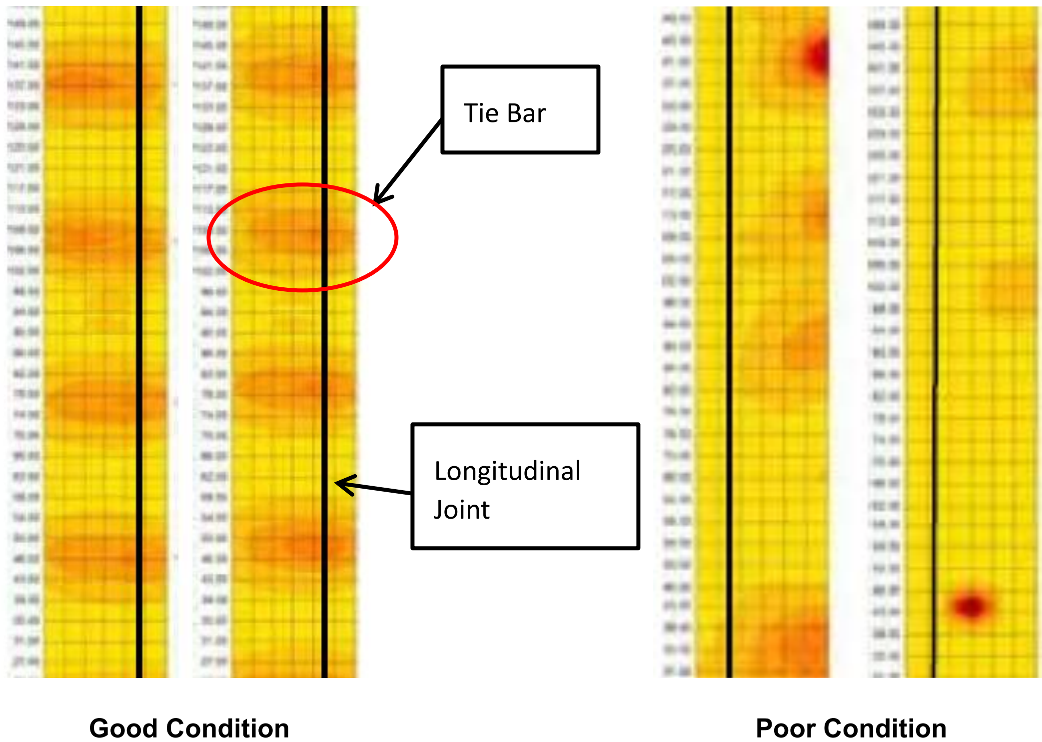


Figure 5-4: MIT Scan Images for a Longitudinal Joint (Mallela, Gotlif, Littleon, Sadasivam, & Darter, 2011)

The second round of field testing was performed in the fall of 2010 to further investigate the impact of tie bar misalignments on the longitudinal joint condition. In this round of testing, at five new sites, the longitudinal joints were scanned with the MIT scanner. Based on the MIT scan images, the longitudinal joints were divided into three groups: category I, category II, and category III. Category I joints showed evenly spaced tie bars across the longitudinal joint and had a joint opening of 0.3 in. to 1.1 in. Category II joints had some missing or misaligned tie bars that were not always crossing the longitudinal joint but still had a joint opening of 0.3 in. to 1.1 in. Category III joints had a number of missing or severely misaligned tie bars and had a joint opening of 0.3 in. to 2.15 in. A sample MIT scan image for each of the three categories is depicted in Figure 5-5.

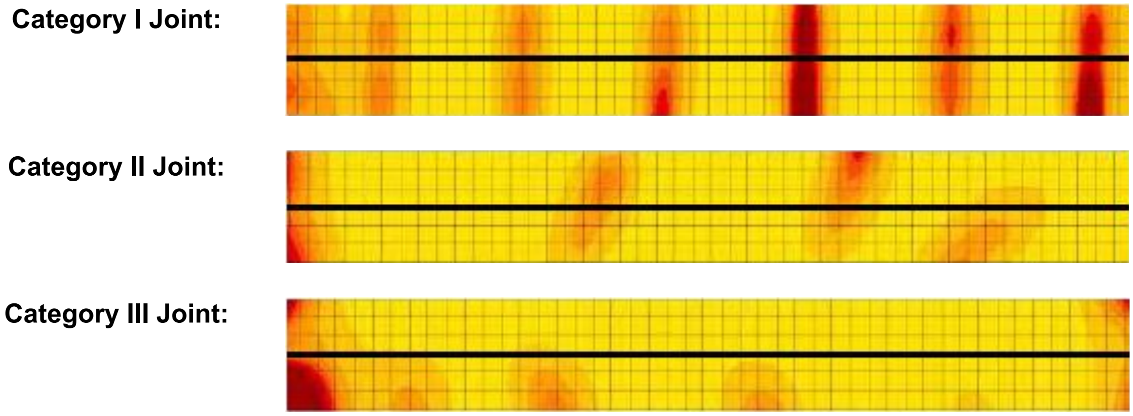


Figure 5-5: MIT Scan Images for Three Joint Categories (Mallela, Gotlif, Littleon, Sadasivam, & Darter, 2011)

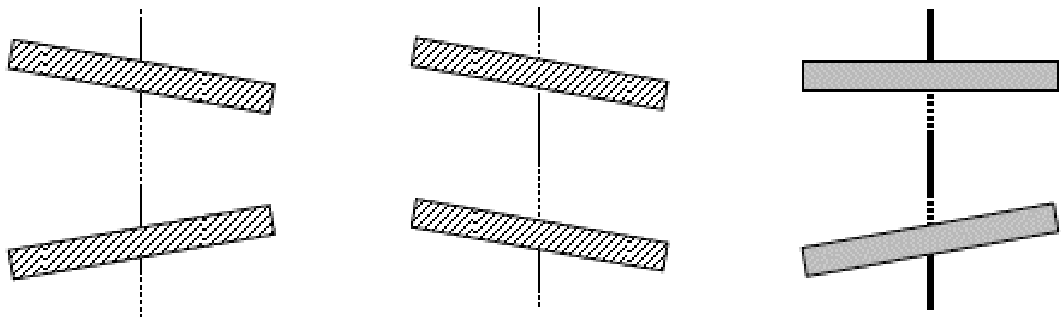
Based on the MIT scan images for the five sites, it was concluded that the largest joint openings were seen when the tie bars were either missing or misaligned in a way that resulted in a reduced embedment length. The vertical placement of the tie bars and misalignments with adequate embedment depths appeared to perform adequately without allowing excessive joint openings.

The results of field tests by Mallela and others (2011) indicate that tie bar placement has a significant impact on the future condition of the longitudinal joints. The investigators conclude that tie bars with "proper embedment" (Mallela, Gotlif, Littleon, Sadasivam, & Darter, 2011) on both sides of the joint appear to be performing adequately. However, the investigators stated that more tests were needed to determine the minimum length for proper embedment.

5.4.2 Laboratory Evaluation of Alignment Tolerances for Dowel Bars and Their Effect on Joint Opening Behavior (Buch et al., 2007)

Buch and others conducted a research study for the Michigan DOT (Buch, Varma, & Prabhu, 2007). The objective of this research was to perform experimental and analytical studies to develop placement tolerances for dowel bars.

Experimental testing was performed on 67 specimens that consisted of 54 different dowel bar configurations. The 54 different configurations were made by varying the number of dowel bars, the alignment configuration, and the dowel bar orientation with respect to the adjacent dowel bar. Specimens were tested with one, two, three and five dowel bars. The specimens with one and two dowel bars were tested while embedded in 48 in. X 48 in. X 10 in. concrete slabs. The three and five dowel bar specimens were tested while embedded in 96 in. X 72 in. X 10 in. concrete slabs. Three alignment configurations were examined with the experimental tests: 1) horizontal skew, 2) vertical skew, and 3) a combination of those two. For each alignment configuration, four misalignment magnitudes were examined. For specimens with more than one dowel bar, the dowel bars were placed in one of three patterns: 1) Non-Uniform, 2) Uniform, and 3) Alternate (Figure 5-6).



Non-Uniform (NU) **Uniform (U)** **Alternate (AM)**

Figure 5-6: Dowel Bar Relative Orientation (Buch, Varma, & Prabhu, 2007)

The experimental test matrix with the dowel bar configurations tested is provided (Table 5-8).

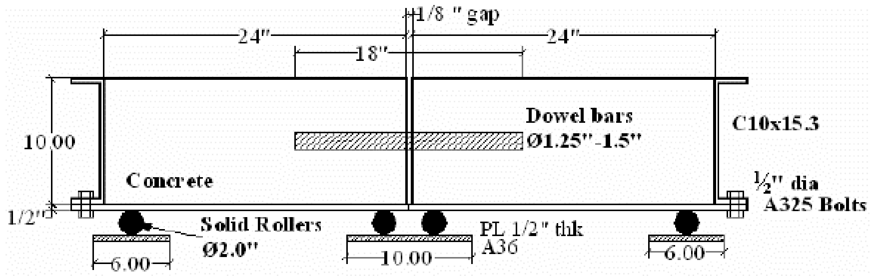
Table 5-8: Experimental Test Matrix for the MSU Dowel Bar Tolerances Study (Buch, Varma, & Prabhu, 2007)

Orientation	Misalignment		1 Bar	2 Bars			3 Bars	5 Bars	
	End Offset (in.)	Bar Rotation (radians)		U[1]	NU	AM	NU	AM	NU
Aligned	0	0	X		X		X	X	
Vertical	1	9	X	X	X				
	3/4	12	X		X	X			
	1/2	18	X	X	X	X	X	X	X
	1/4	36	X	X	X			X	
Horizontal	1	9	X	X	X				
	3/4	12	X		X	X			
	1/2	18	X	X	X	X	X	X	X
	1/4	36	X	X	X			X	
Combined	1	9	X	X	X				
	3/4	12	X		X	X			
	1/2	18	X	X	X	X	X	X	X
	1/4	36	X		X			X	
	Total		13	9	13	6	3	6	4

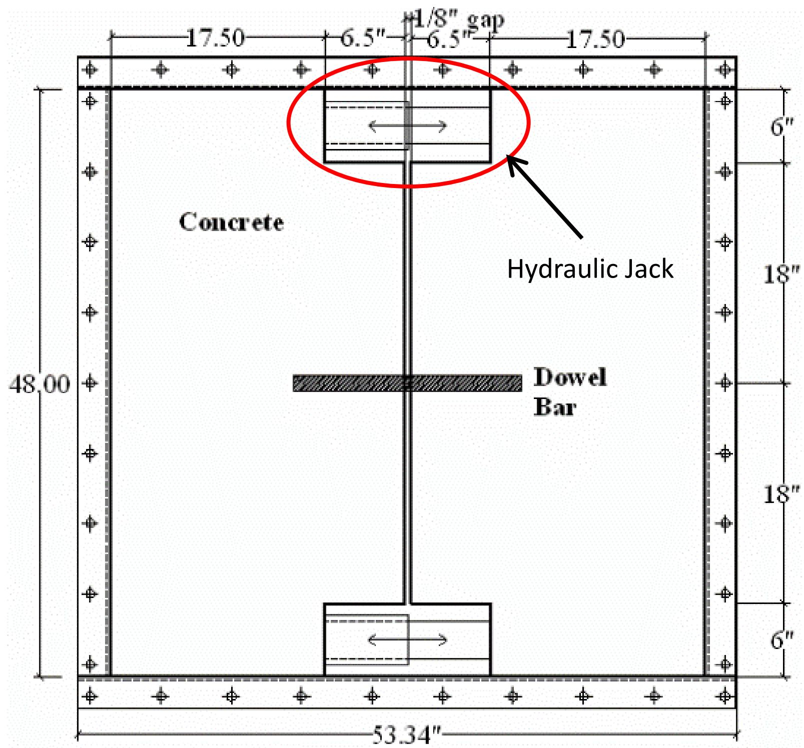
All specimens were cast using custom made steel forms that consisted of a 1/2 in. thick steel plate and C10x15 structural steel channels for the bottom and sides, respectively. The dowel bars were held in place with threaded bars that were bent into a "U" shape and attached to a C3x5 structural steel channel that spanned across the top of the forms. The joint between the two slabs was created with a 1/8 in. thick sheet of aluminum. The aluminum sheet was left in place throughout testing to simulate a completely cracked section of concrete. The 1/8 in. thick aluminum joint was held vertical on either end, by steel forms that attached to the C10x15 structural steel side channels to create box cutouts for the hydraulic cylinders.

After the specimen was poured and cured, it was prepared for testing by first removing the two side channels that were perpendicular to the joint. The hydraulic cylinders were installed into the box cutouts on either end of the joint to apply the tensile force to the specimen during testing. The tensile force was used to simulate the forces imposed on the dowel bars when the concrete contracts. Displacement sensors were attached to the specimen across the crack to measure the relative displacement between the two concrete slabs. The specimen was supported on 2 inch diameter rollers throughout testing to eliminate any friction that would occur between the ground and the steel base.

A dimensioned plan and section views of a 48” X 48” X 10” specimen is shown in Figure 5-7. A 5-dowel bar specimen before testing with the displacement sensors and hydraulic cylinders installed is shown in Figure 5-8.



Section View



Plan View

Figure 5-7: Details of a 48 in. X 48 in. X 10 in. Test Specimen with One Dowel Bar (Buch, Varma, & Prabhu, 2007)

Figure 5-8: A 5-Dowel Bar Specimen (Buch, Varma, & Prabhu, 2007)

In order to better understand the effect of misalignments on the dowel bar-concrete bond and the concrete stresses, a finite element model was created using the finite element software Abaqus. Finite element models were created for each of the 54 different specimens tested in the laboratory so that the results could be compared. In the finite element models of the specimens, the concrete slab and dowel bar were both modeled using 8-node solid elements. The concrete damage plasticity material model in Abaqus was used for the concrete material, while the steel for the dowel bar was modeled using the isotropic elastic multiaxial material model. The contact between the dowel bar and the concrete was modeled in two parts. The first part accounted for the longitudinal interaction, while the second accounted for the transverse interaction. The longitudinal interaction was modeled using spring elements with a nonlinear force-deformation relationship that was calibrated to match the experimental results for the aligned specimen. The transverse interaction was modeled using a hard contact between the dowel bars and concrete that was based on the Coulomb friction model. Using a finite element model with these characteristics, test results for all specimens were closely replicated. The effect of misalignments on the dowel bar-concrete bond and stress propagation through the concrete were observable. The misaligned dowel bars caused areas of high compressive stresses to form in the concrete that were not observed around the aligned dowel bars.

Based on experimental and analytical results, a misalignment tolerance range was determined. The researchers recommended that for a skewed dowel bar, the offset of the dowel bar ends, relative to one another, should not exceed 1/8 in. to ¼ in.

6 METHODOLOGY

The experimental work was performed in the spring of 2014 in the Lohr Structures Laboratory on the SDSU campus in Brookings, SD. This chapter provides an overview of the measurement of material properties, testing matrix, construction, instrumentation, and testing procedures, as well as issues encountered during testing.

6.1 Material Properties

Material properties for the concrete batches and tie bars used to make the specimens were determined in accordance with American Society for Testing and Materials (ASTM) standards. Fresh and hardened concrete properties were measured for each concrete batch. Tension tests were performed to determine the mechanical properties of the tie bar.

The fresh concrete properties were measured prior to casting the specimens. The measured fresh concrete properties were temperature, air content, and slump. Air content and slump measurements are required by the SDDOT to ensure that the concrete meets specifications (see Appendix A: Concrete mix design for the concrete mix design). For the well graded PCC pavement mix used to create the specimens, the SDDOT specifies an air content of 5.0 to 7.5 percent and a slump of 2 in. to 3 in.

The hardened concrete properties were measured by testing 6 in. X 12 in. cylinders and 6 in. X 6 in. X 22 in. beams that were made in conjunction with the specimens according to ASTM 192 (2014). The samples were covered in wet burlap for three days to replicate the curing of the specimens. Compressive strength, modulus of elasticity, split tensile strength, and flexural strength were determined for each batch of concrete. The compressive strength was measured at 3, 7, and 28 days according to ASTM C-39 (2014). The cylinders used for the compressive tests were caped with Tech-Lab Industries HYTECH #9 high strength capping compound according to ASTM C-617 (2012) to provide square and uniform end surfaces for applying the compressive forces. The modulus of elasticity was found by attaching an 8 in. Instron extensometer to the cylinder during the compression tests at 7 and 28 days. The split tensile strength was found by performing a split tensile test on a cylinder according to ASTM C-496 (2004) at 7 and 28 days. The beams were tested at 7 and 28 days according to ASTM C-78 (2010) to find the flexural strength of the concrete. For every test, a minimum of three samples were tested and the average values were reported.

A tensile test was performed according to ASTM E-8 (2013) on a dog-boned sample made from a tie bar. Due to loading capacity limitations of the tensile testing machine the tie bar samples, a middle segment was machined to a diameter of 0.35 in. in order to capture the ultimate strength. A 25 mm. gauge length MTS extensometer was attached to the dog-boned tie bar sample to measure the tie bars extension along the gauge length (Figure 6-1).

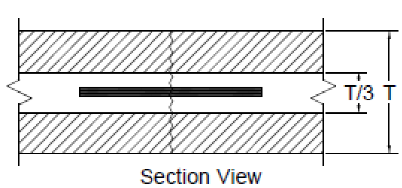
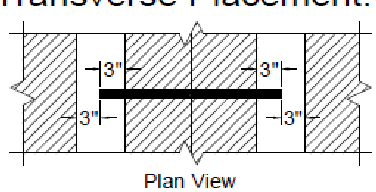
Figure 6-1: Tensile Test of a Dog-Boned Tie Bar Sample

6.2 Testing Matrix

Each specimen consisted of two 48 in. X 24 in. X 10 in. concrete slabs that were connected with a tie bar. The tie bar was 30 in. long, Grade 60, epoxy coated, #5 deformed bar as specified by SDDOT. The purpose of the testing was to investigate the effect of each tie bar alignment configuration on the joint behavior and anchorage strength, when the specimen is subjected to an increasing splitting force, normal to the joint surface.

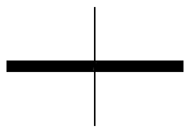
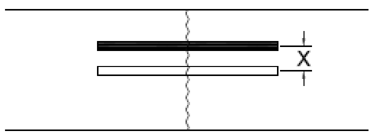
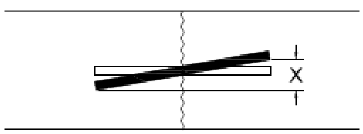
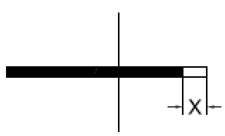
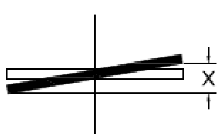
The testing matrix was developed to investigate the behavior of the tie bars and joint under various tie bar alignment configurations. Based on the literature review and discussions with the technical panel, four alignment configurations were selected to be tested: 1) vertical translation, 2) vertical skew, 3) longitudinal translation, and 4) horizontal skew. For each of these alignment configurations, four different misalignment magnitudes were selected. The misalignment magnitudes were based on both current SDDOT tie bar placement tolerances (Table 6-1) and typical as-built conditions as identified by Ground Penetrating Radar (GPR).

Table 6-1: Current SDDOT Tie Bar Placement Tolerances for 10 in. Thick Pavements (South Dakota DOT, 2016)

Vertical Placement: 	Tolerance Limit	All parts of the tie bar must be within the middle 1/3 of the pavement depth.
	Vertical Translation	± 1.25 in.
	Vertical Skew	2.50 in.
Transverse Placement: 	Tolerance Limit	± 3.0 in. measured perpendicular to the longitudinal joint.
	Longitudinal Translation	3.0 in.
	Horizontal Skew	18.0 in.

Two specimens of each misalignment magnitude were constructed, totaling eight samples for each alignment configuration. In addition, three control specimens with aligned tie bars were built. A total of 35 specimens were built and tested in this study (Table 6-2).

Table 6-2: Testing Matrix

ALIGNMENT CONFIGURATION	MISALIGNMENT MAGNITUDE, in.	NUMBER OF SAMPLES
Aligned:  Plan View	0	3
Vertical Translation:  Section View	X = 1	2
	X = 2	2
	X = 3	2
	X = 4	2
Vertical Skew:  Section View	X = 2	2
	X = 4	2
	X = 6	2
	X = 8	2
Longitudinal Translation:  Plan View	X = 3	2
	X = 5	2
	X = 7	2
	X = 9	2
Horizontal Skew:  Plan View	X = 16	2
	X = 20	2
	X = 24	2
	X = 28	2
	TOTAL SAMPLES:	35

The aligned specimens were labeled A-X where X is either 1, 2, or 3 as the specimen number. All other samples were labeled using a series of letters and numerals separated by hyphens (e.g. XX-X-X). The first part represented the misalignment configuration (e.g., VT, VS, LT, and HS for vertical translation, vertical skew, longitudinal translation, and horizontal skew, respectively). The second part represented the misalignment magnitude in inches. The third part represented the sample's serial number when multiple samples were made from the same mix.

6.2.1 Aligned Specimens

Three aligned specimens were poured on April 10, 2014. Each of the specimens contained an ideally placed tie bar. According to the SDDOT's *Concrete Paving Manual* (South Dakota DOT, 2016), an ideally placed tie bar is located at the mid-depth of the slab and aligned perpendicular to the longitudinal joint (Figure 6-2).

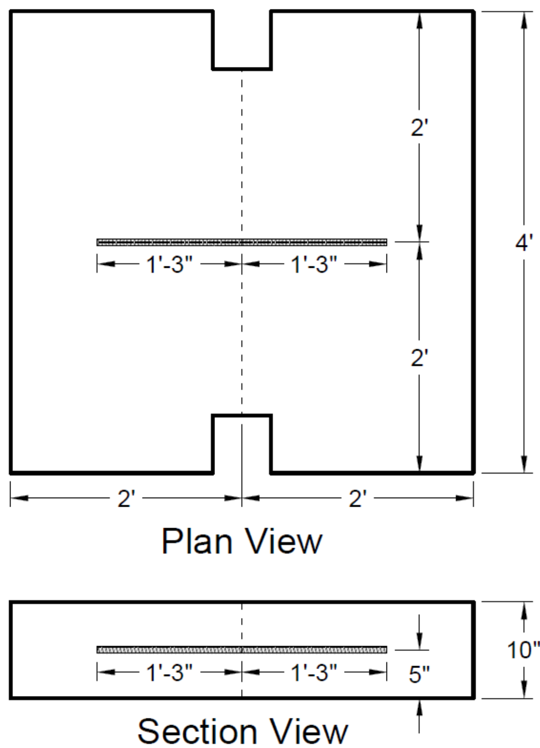


Figure 6-2: Aligned Tie Bar Specimen Details

6.2.2 Vertical Translation

Eight vertical translation specimens were poured on April 24, 2014. The specimens consisted of four different misalignment magnitudes with two samples of each. The four misalignment magnitudes selected for the vertical translation specimens had vertical offsets of 1 in. (VT-1), 2 in. (VT-2), 3 in. (VT-3), and 4 in. (VT-4) upwards from the position of an ideally placed tie bar (Figure 6-3).

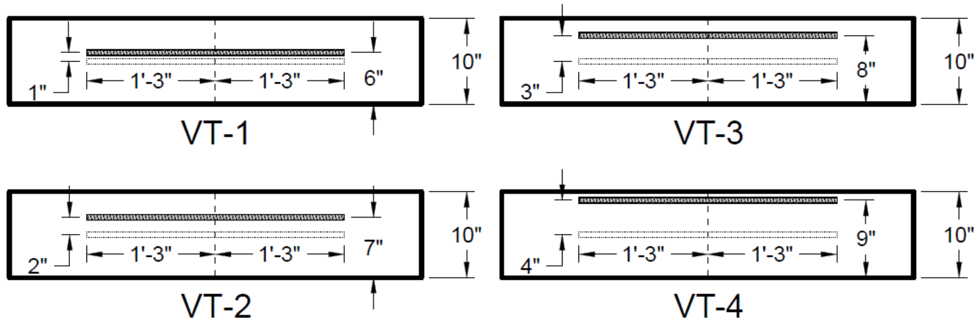


Figure 6-3: Section Views of the Vertical Translation Misalignment Specimens

6.2.3 Vertical Skew

Eight vertical skew specimens were poured on May 13, 2014. The specimens consisted of four different misalignment magnitudes with two samples of each. The four misalignment magnitudes, measured as the vertical offset between the two ends of the tie bar, were 2 in. (VS-2), 4 in. (VS-4), 6 in. (VS-6), and 8 in. (VS-8). Section views of the four vertical skew misalignment magnitudes and how they compare to an ideally placed tie bar are illustrated in Figure 6-4.

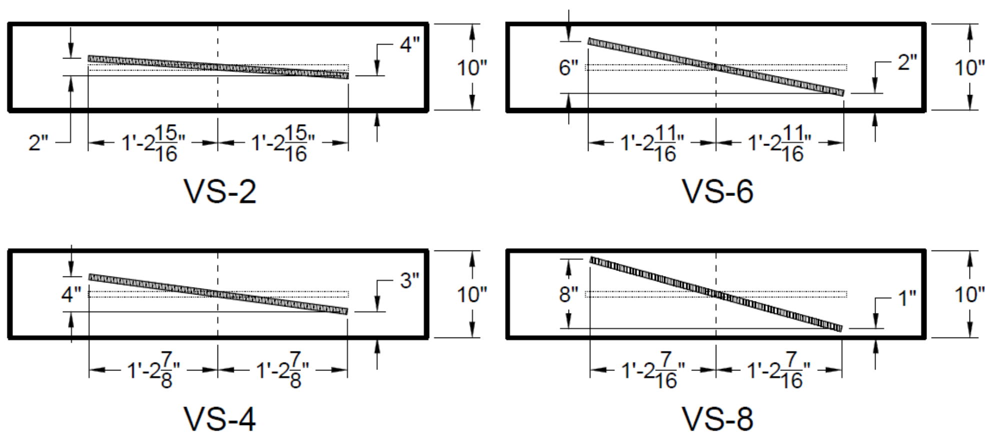


Figure 6-4: Section Views of the Vertical Skew Misalignment Specimens

6.2.4 Longitudinal Translation

Eight longitudinal translation specimens were poured on May 22, 2014. The specimens consisted of four different misalignment magnitudes with two samples of each. The four misalignment magnitudes selected for the longitudinal translation specimens had the tie bar embedment length on the stationary side of the longitudinal joint reduced by 3 in. (LT-3), 5 in. (LT-5), 7 in. (LT-7), and 9 in. (LT-9). Section views of the four longitudinal translation misalignment magnitudes and how they compare to an ideally placed tie bar are illustrated in Figure 6-5.

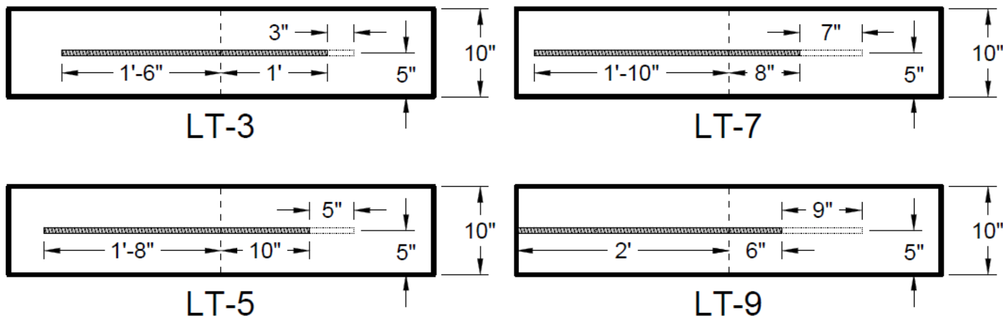


Figure 6-5: Section Views of the Longitudinal Translation Misalignment Specimens

6.2.5 Horizontal Skew

Eight horizontal skew specimens were poured on June 3, 2014. The specimens consisted of four different misalignment magnitudes with two samples of each. The four misalignment magnitudes, measured as the horizontal offset between the tie bar ends, were 16 in. (HS-16), 20 in. (HS-20), 24 in. (HS-24), and 28 in. (HS-28). Plan views of the four horizontal skew misalignment magnitudes and how they relate to an ideally placed tie bar are depicted in Figure 6-6.

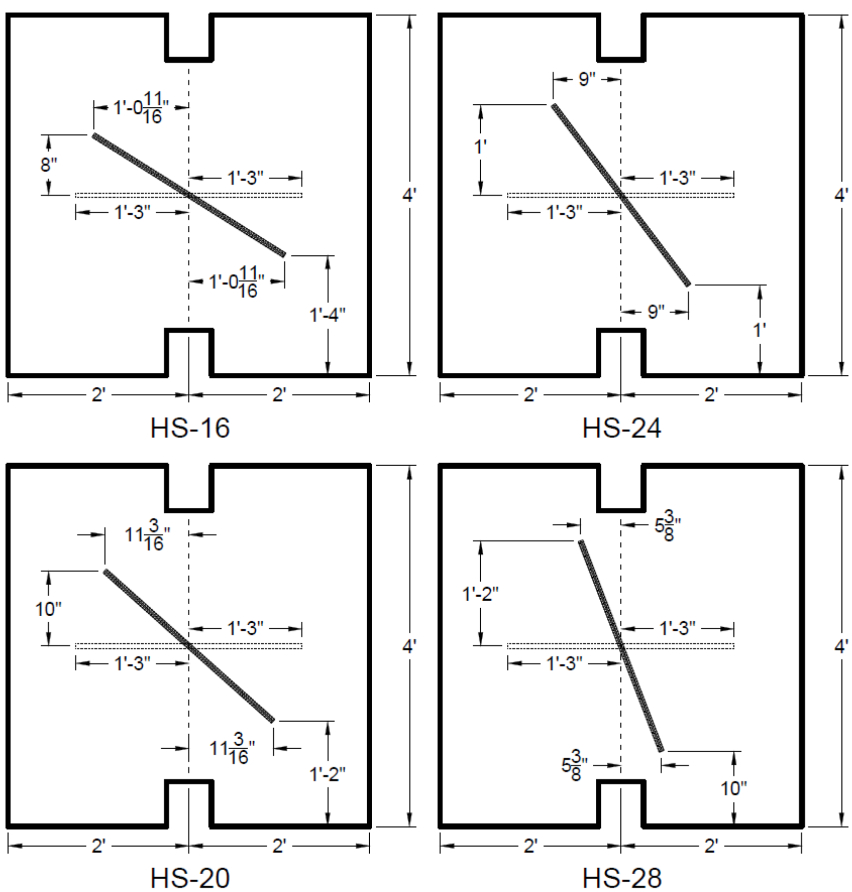


Figure 6-6: Plan Views of the Horizontal Skew Misalignment Specimens

6.3 Construction of Specimens

The specimens were cast inside steel forms. Eight forms were fabricated to allow using the same concrete batch for the casting of all specimens of the same alignment configuration. Each steel form consisted of 1/2 in. thick A36 steel plate bottom and C10x15 structural steel channel sides. The joint between the two concrete slabs was created by a 1/8 in. thick acrylic sheet. The acrylic sheet had a hole to allow for the passage of the tie bar. The acrylic sheet, which was left in place throughout the testing, provided a completely cracked section condition. The acrylic sheet was held in place by means of two 6 in. X 6 in. X 10 in. wooden boxes placed on either end of the sheet. The two wooden boxes were also used to hold polyvinyl chloride (PVC) sleeves in place and to create block outs. The PVC sleeves and block outs were needed to facilitate the testing setup. The tie bar was held in place using a tie bar support assembly. The tie bar support assembly consisted of a C3x5 structural steel channel and a 1/4 in. diameter threaded steel rod that was bent into a “U” shape. The threaded steel rod was fastened to the C3x5 structural steel channel which spanned across the top of the forms. The tie bar was then secured to the “U” of the threaded steel rod in its required position using zip ties. Figure 6-7 and Figure 6-8 show a dimensioned top view and a picture of the steel forms prior to placing concrete, respectively.

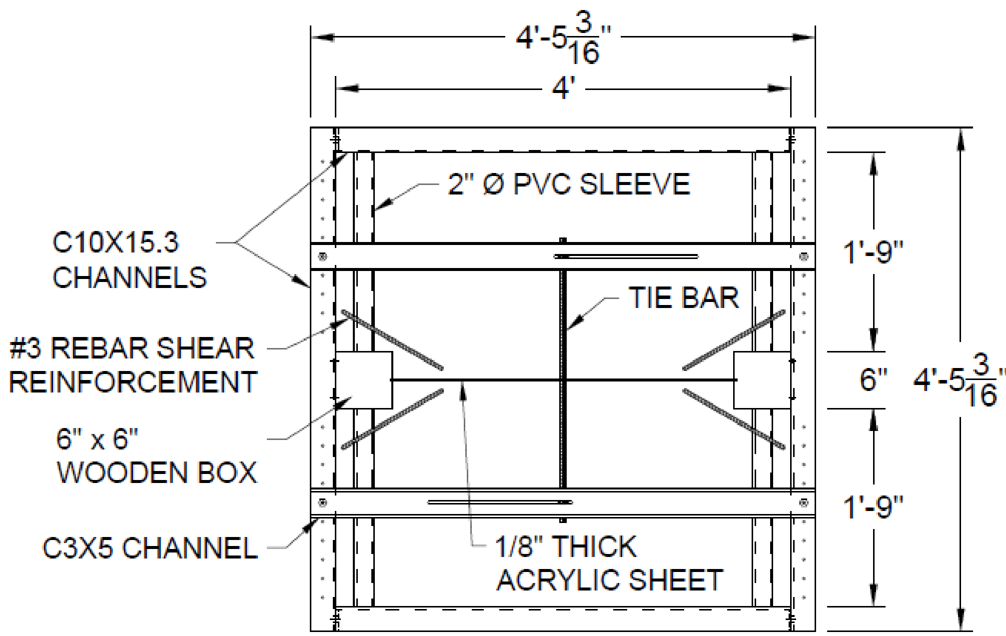


Figure 6-7: Plan View of the Casting Form

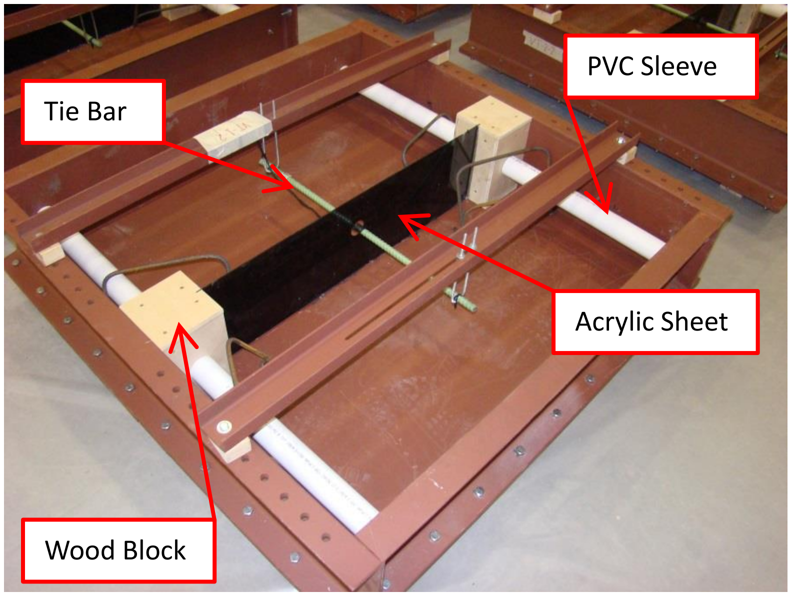


Figure 6-8: Steel Casting Forms

The specimens for each alignment configuration were constructed and tested in two-week cycles. In the week prior to casting, the eight steel forms were assembled and the tie bars were secured in the positions defined by the testing matrix. On the day of the concrete pour, the fresh concrete properties (temperature, air content, and slump) were checked to ensure that the concrete was within the specified ranges for the well-graded PCC pavement mix. Following the measurement of fresh properties, all eight specimens along with eighteen 6 in. X 12 in. concrete cylinders and eight 6 in. X 6 in. X 22 in. concrete beams were cast (Figure 6-9).

Figure 6-9: Concrete Casting

The specimens, cylinders, and beams were all cured for three days while covered with wet burlap and plastic sheets. The forms were stripped one day after concrete casting. On the fifth day after casting, the custom steel LVDT brackets were installed on the specimens using a hammer drill and masonry screws. The two C10x15 structural steel side channels were reinstalled, on the sixth day after casting, to allow the samples to be moved over to the testing position without being damaged.

6.4 Instrumentation

Each of the 35 specimens were instrumented with strain gauges and linear variable displacement transducers (LVDT) to measure strain in the tie bar and the relative displacement between the two sides of the concrete slab across the joint.

Three Vishay CEA-06-250UN-350 strain gauges were installed on the tie bar at the location where the tie bar crosses the joint. The three strain gauges were attached to the surface of the tie bar, 120 degrees apart around the circumference of the tie bar. The strain gauges arrangement allowed for identification of the location on the circumference where yielding initiates. The orientation of the strain gauges on the tie bar circumference is shown in Figure 6-10.

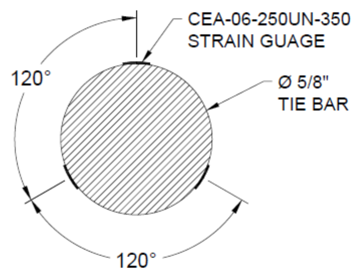


Figure 6-10: Placement of the Strain Gauges

Six LVDTs were mounted to the top of each specimen using custom steel brackets (Figure 6-11). Three LVDTs were mounted on each end of the joint, to allow for measuring the relative displacement of the two slab segments across the joint in three orthogonal directions and to calculate rotations and twisting about the joint.

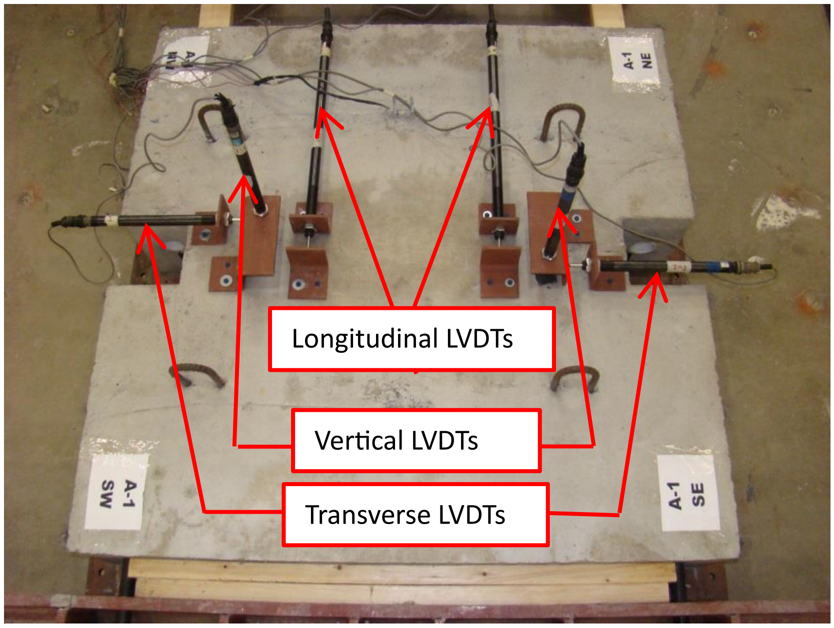


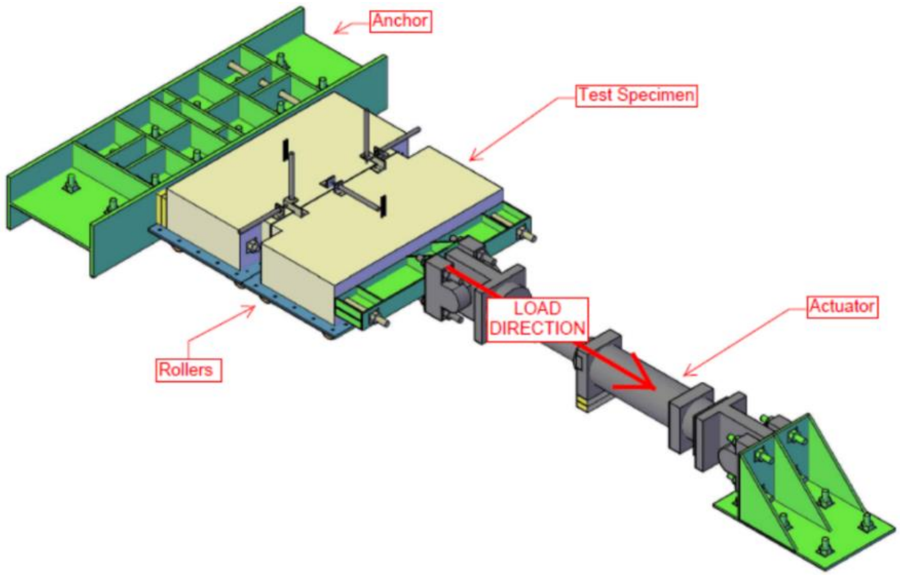
Figure 6-11: LVDT Arrangement

The longitudinal LVDTs measure the relative joint opening between the two concrete slab segments parallel to the direction of the applied tensile force. The transverse LVDT's measure the relative joint slippage between the two concrete slabs perpendicular to the direction of the applied force. The vertical LVDT's measure the relative joint faulting that occurs between the two concrete slabs in the vertical direction. In the following chapters, the relative displacement readings from the longitudinal, transverse, and vertical LVDT's will be referred to as the joint opening, joint slippage, and joint faulting, respectively.

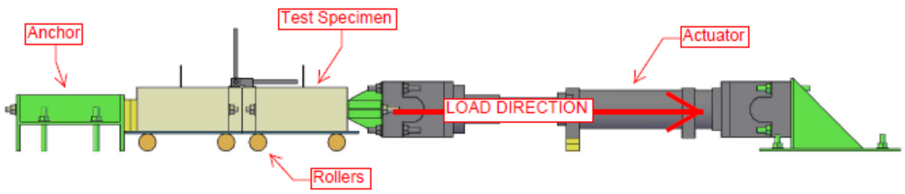
The data measured by the strain gauges and LVDT's was collected using the Vishay Micro-Measurements System 7000. It allowed for measurements to be recorded at a rate of 10 hertz throughout testing.

6.5 Testing Procedure

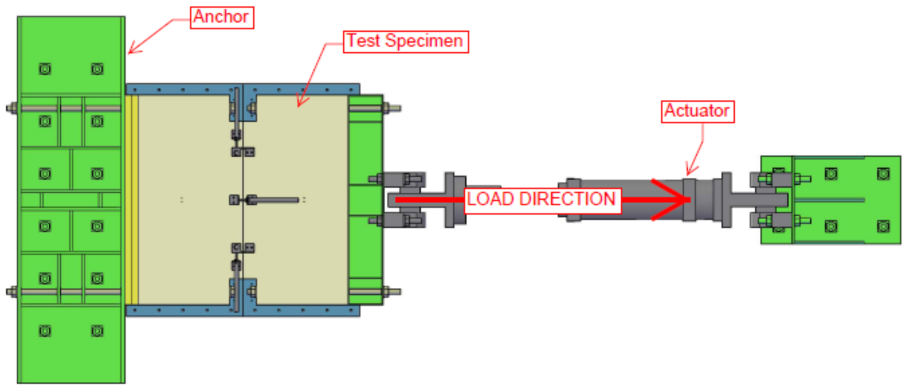
All specimens were tested seven days after pouring. The specimens were tested by securing one end to an anchor and the other end to a hydraulic actuator. The hydraulic actuator then applied a splitting force normal to the face of the joint until failure occurred. Figure 6-12 presents AutoCAD drawings of the testing setup.



Isometric View



Side View



Top View

Figure 6-12: Schematic Views of the Testing Setup

On testing day, a specimen was moved into the testing position and placed on a set of rollers. Once the specimen was in position, the stationary side of the specimen was secured to the anchor beam using two threaded rods. The two C10x15 structural steel side channels were then removed, and the six LVDT's were installed at their respective brackets. The connection to the anchor beam is shown in Figure 6-13.

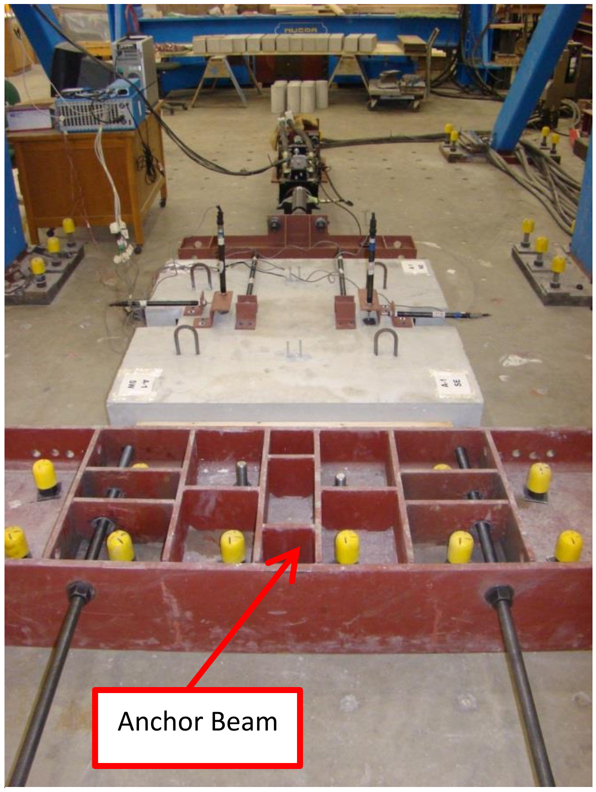


Figure 6-13: Attachment of a Test Specimen to the Anchor Beam

The LVDT and strain gauge wires were then connected to the Micro-Measurement Data Acquisition System and an initial reading was taken for all of the strain gauges and LVDT's. With the initial reading taken, the hydraulic actuator could then be seated and connected to the specimen with two threaded rods (Figure 6-14).

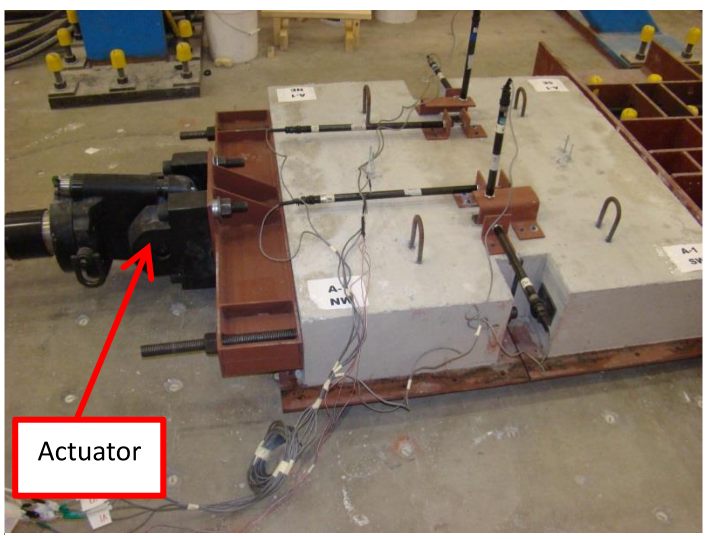


Figure 6-14: Attachment of a Test Specimen to the Actuator

The specimen was tested by applying a splitting force normal to the face of the joint using the hydraulic actuator. The hydraulic actuator was operated in displacement control mode with intervals of 0.005 in. until the yielding of the tie bar. When the incremental displacement was being applied to the specimen, the data acquisition system was activated to record the strain and relative displacement data at a frequency of 10 Hz. All of the specimens were tested until bond failure occurred between the concrete and the tie bar. The typical mode of failure for the specimens was splitting of the concrete along the length of the tie bar.

The longitudinal joint width was evaluated when the measured strain in the tie bar reached $0.75\varepsilon_y$, where ε_y is the yield strain corresponding to the tie bar yield stress, f_y. The $0.75\varepsilon_y$ threshold was established based on the allowable tie bar design force for a single tie bar given in AASHTO (AASHTO, 1993). According to AASHTO (1993), the allowable tie bar design force, F_{TB}, is calculated using Equation 4.

$$F_{TB} = f_s A_s = 0.75 f_y A_s \qquad \text{Equation 4}$$

The tie bars used in the experimental testing were Grade 60 ($f_y = 60\ \text{ksi}$), #5 ($A_s = 0.31\ \text{in}^2$) bars. Therefore, the allowable tie bar design force, F_{TB}, for a single tie bar is 13.95 kips.

The joint opening performance limit was based on the typical SDDOT sawed joint detail for longitudinal joints which calls for a 1/4 in. wide sawed joint, filled with a hot poured elastic joint sealer. This elastic joint sealer allows the joint to expand while remaining water tight. Based on the manufacturer's specifications for the hot poured elastic joint sealers, the hot poured elastic joint sealers should be able to elongate at least 50 percent of their original lengths before bond failure occurs. This specification is approved by the SDDOT (South Dakota DOT, 2016). The hot poured elastic joint sealers approved by the SDDOT include 3405 Sealtight – Type II, Beram 195 – Type II, Roadsaver 221 – Type II, and Hi-Spec – Type II. The 50 percent elongations means that 1/8 in. would be an acceptable performance limit for the joint opening to ensure that the hot poured elastic joint sealer is still able to keep the joint water tight.

Joint faulting and joint slippage were outside the scope of this study; therefore, no allowable limits were established for joint faulting and joint slippage. However, the measured data for the joint faulting and joint slippage was compared between the specimens, with aligned and misaligned tie bars.

Some issues were encountered during the testing of specimens with vertical translation misalignment. During testing of these specimens, the actuator load at the slab mid-height and the eccentric resisting force in the tie bar, created a force couple about the horizontal axis of the joint plane Figure 6-15 depicts a free body diagram of the initial forces acting on the joint plane.

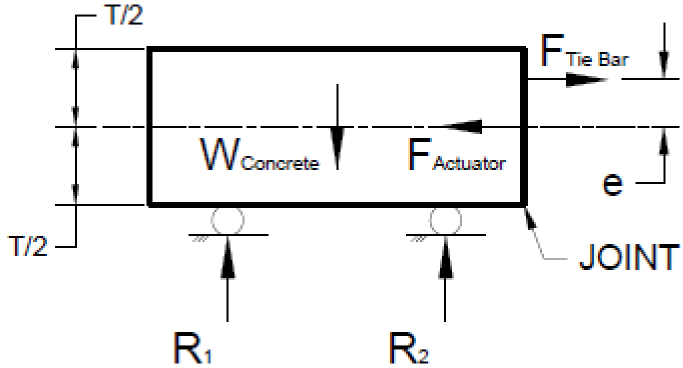


Figure 6-15: Free Body Diagram of One Side of the Test Specimen

The couple created by the eccentric loading caused the joint plane to rotate, thus inducing compressive stresses in the concrete at the top of the joint. Figure 6-16 shows the rotation resulting from the eccentric loading. The couple tends to increase the tension force in the tie bar for a given applied actuator load.

Figure 6-16: Slab Rotation During Testing of Specimen VT-4-1

Increasing the actuator load caused the joint rotation and compressive concrete stresses to increase to a level that induced concrete crushing and spalling at the top of the joint (Figure 6-17).

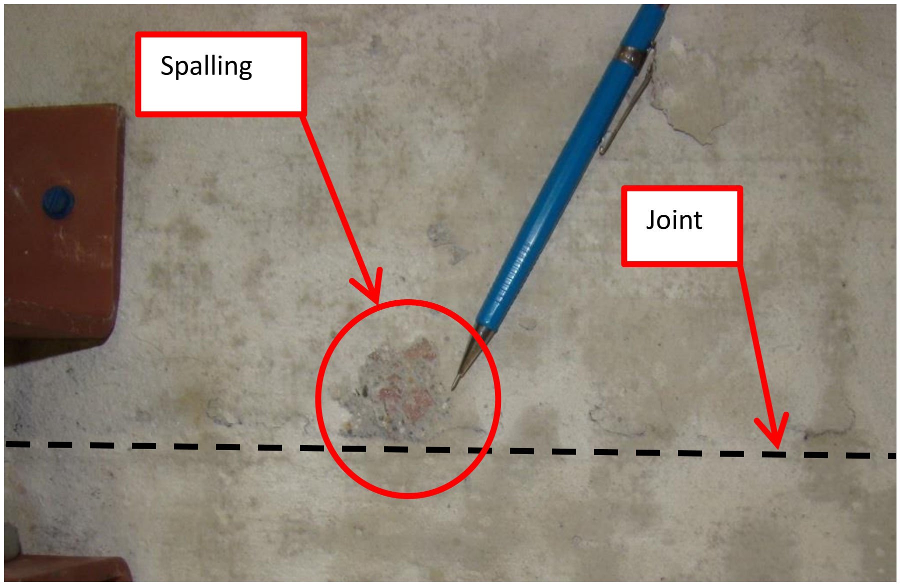


Figure 6-17: Spalling of Compression Concrete at the Joint

As a result, only one specimen of each misalignment magnitude of the vertical translation specimens was tested under eccentric loading with unrestricted rotation. The specimens tested under unrestricted rotation were VT-1-1, VT-2-1, VT-3-1, and VT-4-1. Since in actual pavements, the weight of the slab will restrain rotation about the joint, it was decided to test the remaining four specimens (VT-1-2, VT-2-2, VT-3-2, and VT-4-2) under restrained rotation conditions.

Rotational restraint was achieved by installing two C10×15 side forms and two C3×5 top braces (Figure 6-18). The C10×15 provided resistance to the horizontal sliding of one side of the joint relative to the other. The C3×5 top braces provided resistance to slab uplift and, thus to joint rotation. The sides of the steel channels in contact with the concrete were greased prior to installation in order to reduce the frictional stresses. The LVDT's measuring relative transverse displacement were removed from this test setup to allow for the installation of the C10×15 side forms.

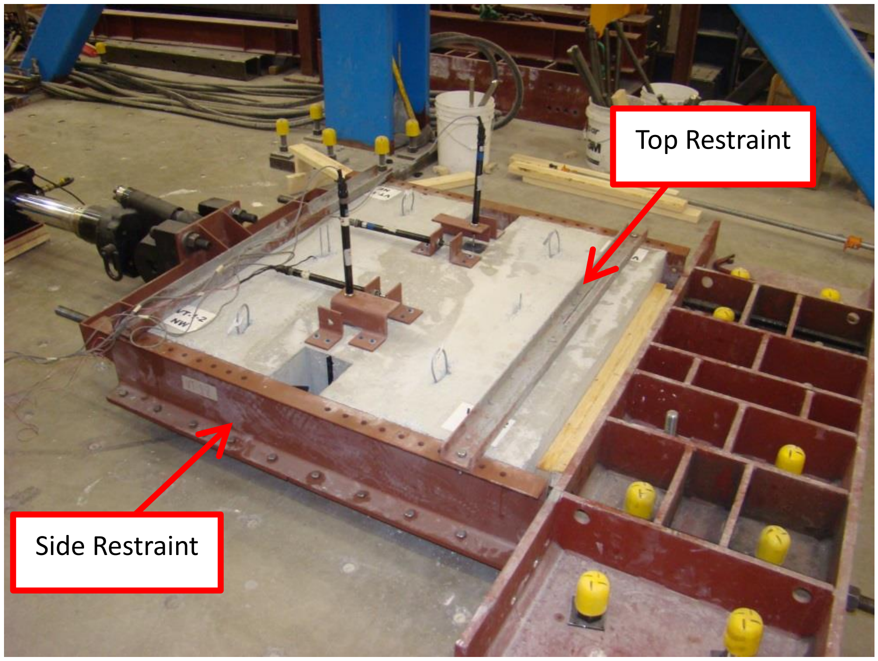


Figure 6-18: Testing Setup of a Specimen Restrained against Joint Sliding and Rotation

The restrained joint against sliding and rotation test setup was adopted for the remainder of the specimens with the vertical skew, longitudinal translation, and horizontal skew alignment configurations.

7 EXPERIMENTAL RESULTS AND ANALYSIS

7.1 Material Properties

Table 7-1 shows the measured fresh concrete properties for all five batches of concrete used to make specimens. The measured air content and slump for all five batches were within the SDDOT specified limits.

Table 7-1: Fresh Concrete Properties

Alignment Configuration	Date Tested	Temperature, °F	Air Content, %	Slump, in.
Aligned	April 10, 2014	85	7.5	2.50
Vertical Translation	April 24, 2014	62	6.2	2.50
Vertical Skew	May 13, 2014	63	5.0	2.75
Longitudinal Translation	May 22, 2014	81	5.7	2.75
Horizontal Skew	June 3, 2014	80	6.7	2.75

Table 7-2 shows a summary of the hardened concrete properties (see Appendix B: fresh and hardened concrete properties for the complete fresh and hardened concrete properties for each concrete batch).

Table 7-2: Hardened Concrete Properties

Alignment Configuration	Concrete Cure Time	Compressive Strength, psi	Modulus of Elasticity, psi	Flexural Strength, psi	Split Tensile Strength, psi
Aligned	3 Day	2740	-	-	-
	7 Day *	3973	3.78E+06	435	482
	28 Day	4785	4.01E+06	647	434
Vertical Translation	3 Day	4562	-	-	-
	7 Day *	5357	4.60E+06	460	565
	28 Day	6635	4.81E+06	699	629
Vertical Skew	3 Day	4383	-	-	-
	7 Day *	5261	4.59E+06	644	478
	28 Day	6216	4.89E+06	738	567
Longitudinal Translation	3 Day	4297	-	-	-
	7 Day *	5241	4.79E+06	502	490
	28 Day	6320	4.32E+06	608	553
Horizontal Skew	3 Day	4103	-	-	-
	7 Day *	5297	4.44E+06	486	488
	28 Day	6384	4.51E+06	776	563

*All specimens were tested after seven days of cure time.

A stress-strain graph (Figure 7-1) was produced from the tensile test data for the tie bar. The measured ultimate strength and the modulus of elasticity were 124 ksi and 29000 ksi, respectively. The yield strength was found to be 74 ksi, using the 0.2 percent offset method (2013).

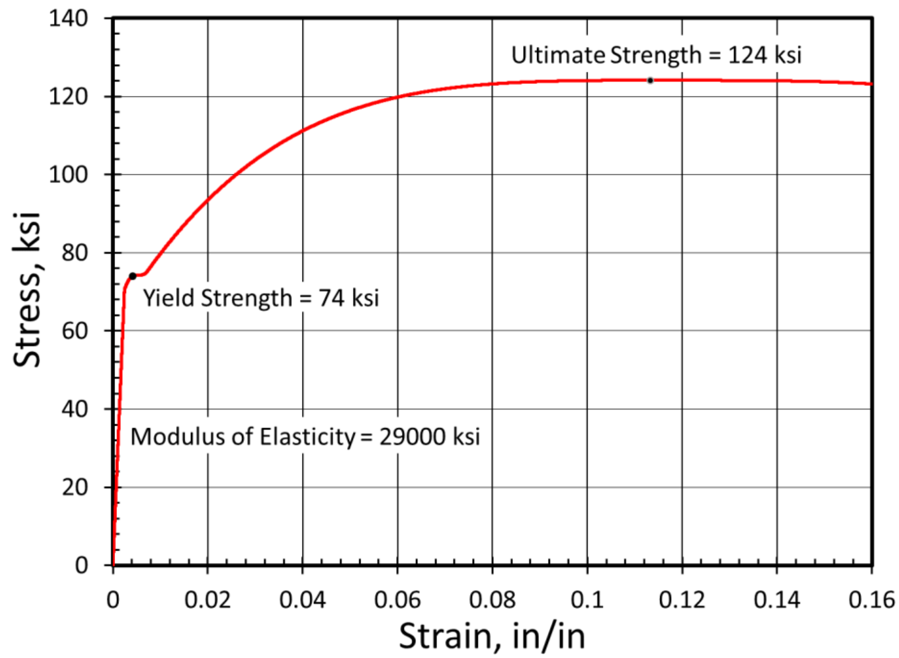


Figure 7-1: Stress versus Strain Curve for Tie Bar Material

7.2 Testing Results

7.2.1 Aligned Specimens

In all three aligned specimens the tie bar yielded prior to bond failure. Bond failure occurred by splitting of the concrete along the length of the tie bar. The longitudinal crack and bond failure of specimen A-1 are shown in Figure 7-2 and Figure 7-3, respectively.

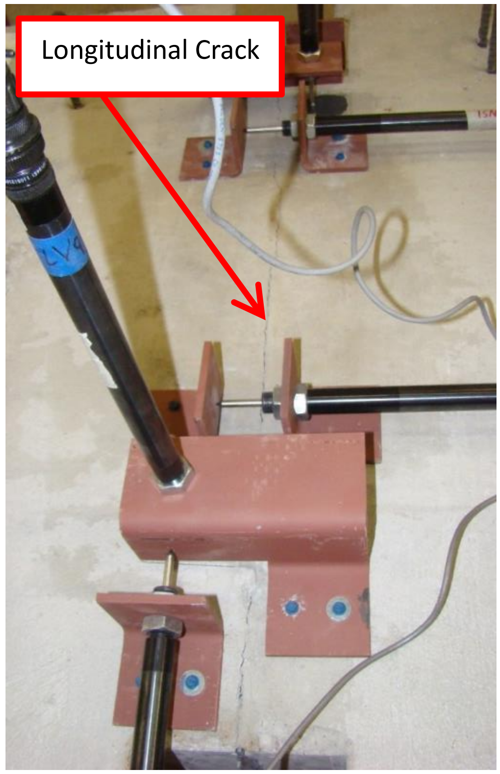


Figure 7-2: Longitudinal Crack on Specimen A-1 at a Tie Bar Strain of 0.75ε_y

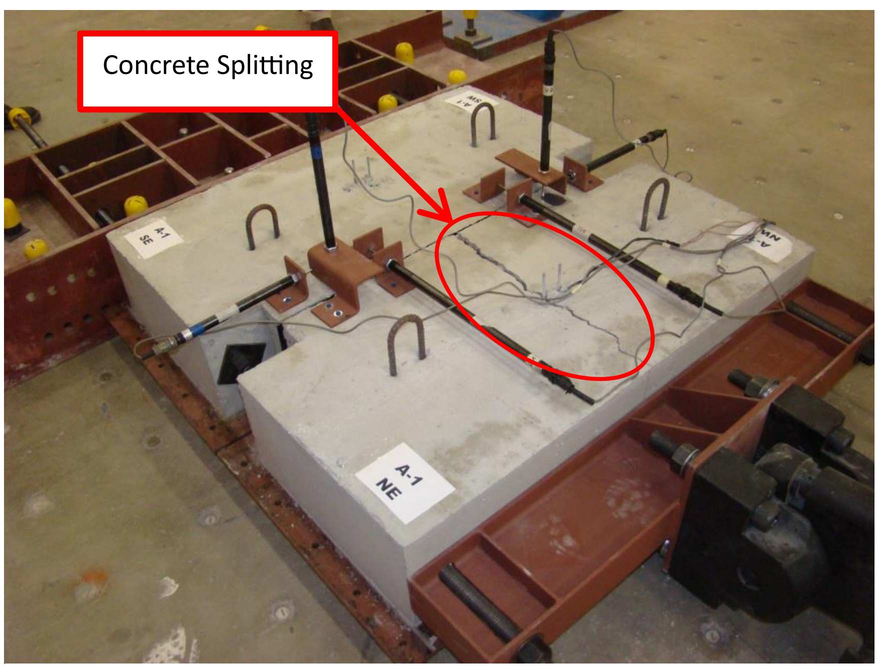
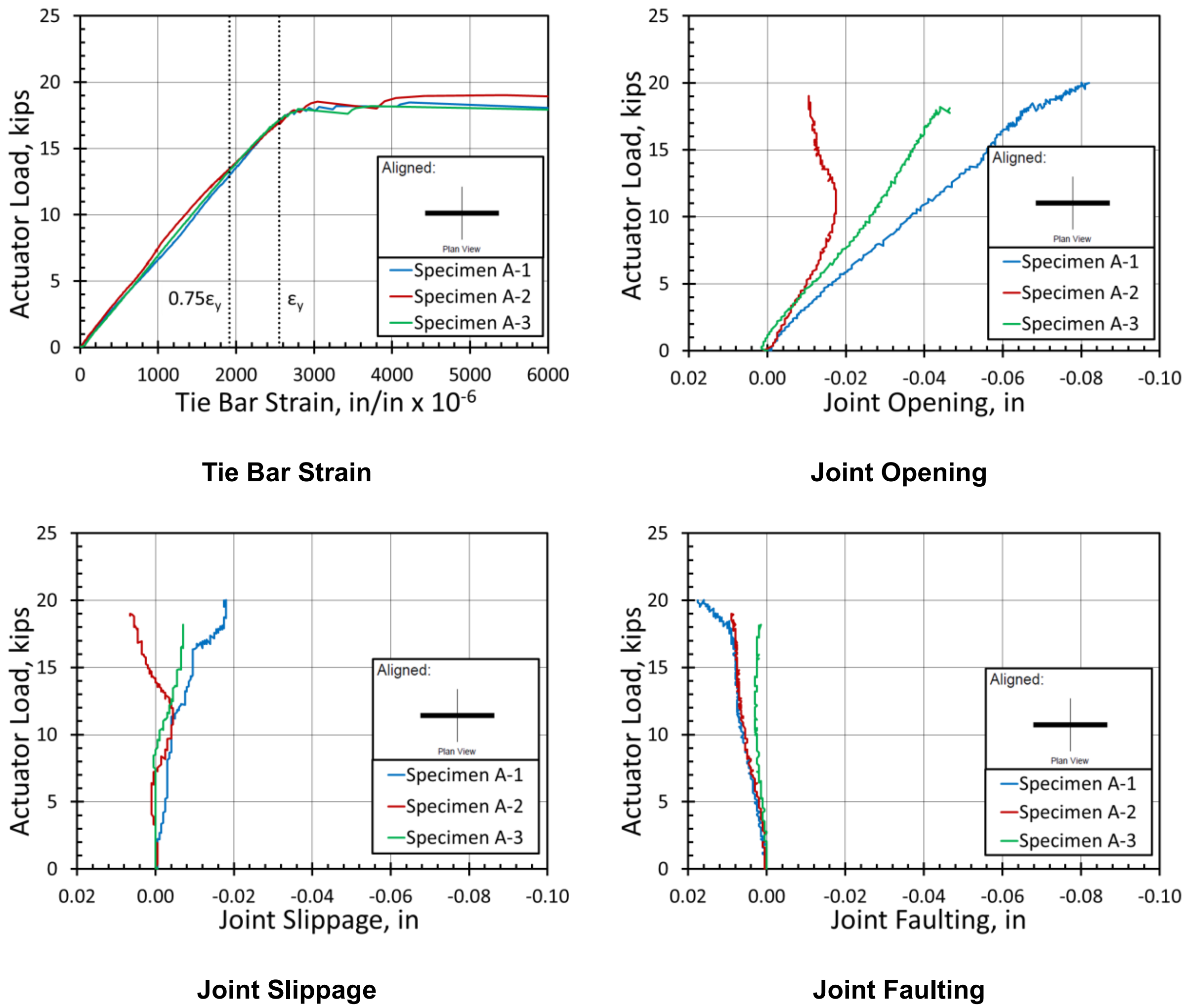


Figure 7-3: Bond Failure of Specimen A-1

Plots of the measured tie bar strain, joint opening, joint slippage, and joint faulting, versus applied actuator load are documented (Figure 7-4). The actuator load-tie bar strain relationships for the three aligned specimens were almost identical. The joint opening increased as the actuator load increased, with the exception of specimen A-2. The joint opening values for specimen A-2 increased initially with the actuator load until a load of 12 kips was reached, after which the joint opening values began decreasing. The probable explanation is that some rotation about the joint must have occurred causing the joint at the top of the slab to begin closing. There was no significant joint slippage and faulting for any of the three aligned specimens.



Tie Bar Strain

Joint Opening

Joint Slippage

Joint Faulting

Figure 7-4: Testing Results for the Aligned Specimens

A summary is provided of the actuator load and relative displacement testing results at the point when the first measured tie bar strain reached $0.75\varepsilon_y$ (Table 7-3).

Table 7-3: Actuator Load and Joint Opening, Slippage, and Faulting for the Aligned Specimens

Specimen	At First Measured Tie Bar Strain Equal to $0.75\varepsilon_y$			
	Actuator Load, kips	Joint Opening, in.	Joint Slippage, in.	Joint Faulting, in.
A – 1	12.8	-0.048	-0.008	0.008
A – 2	13.5	-0.016	-0.002	0.007
A – 3	13.2	-0.033	-0.005	0.003
AVERAGE	13.2	-0.032	-0.005	0.006

The average actuator load required to cause a tie bar strain of $0.75\varepsilon_y$ for the aligned specimens is 13.2 kips. In addition, the 13.2 kips is slightly less than the allowable 13.95 kip tie bar design force for a single tie bar. The slight difference between the values is likely due to the fact that the actuator load is recorded when the first strain gauge reading reaches $0.75\varepsilon_y$. The actuator load of 13.2 kips will be used as the baseline for comparison with other alignment configurations.

The joint movements in all three dimensions at $0.75\varepsilon_y$ were extremely small. The average joint opening for the three aligned specimens was well below the 1/8 in. performance limit. The joint slippage and joint faulting values were nearly negligible.

7.2.2 Vertical Translation

Specimens VT-1-1, VT-2-1, VT-3-1, and VT-4-1 were not restrained against joint rotation resulting in an eccentric loading condition. Joint rotation of specimen VT-4-1 and bond failure of specimen VT-3-1 are shown in Figure 7-5 and Figure 7-6.

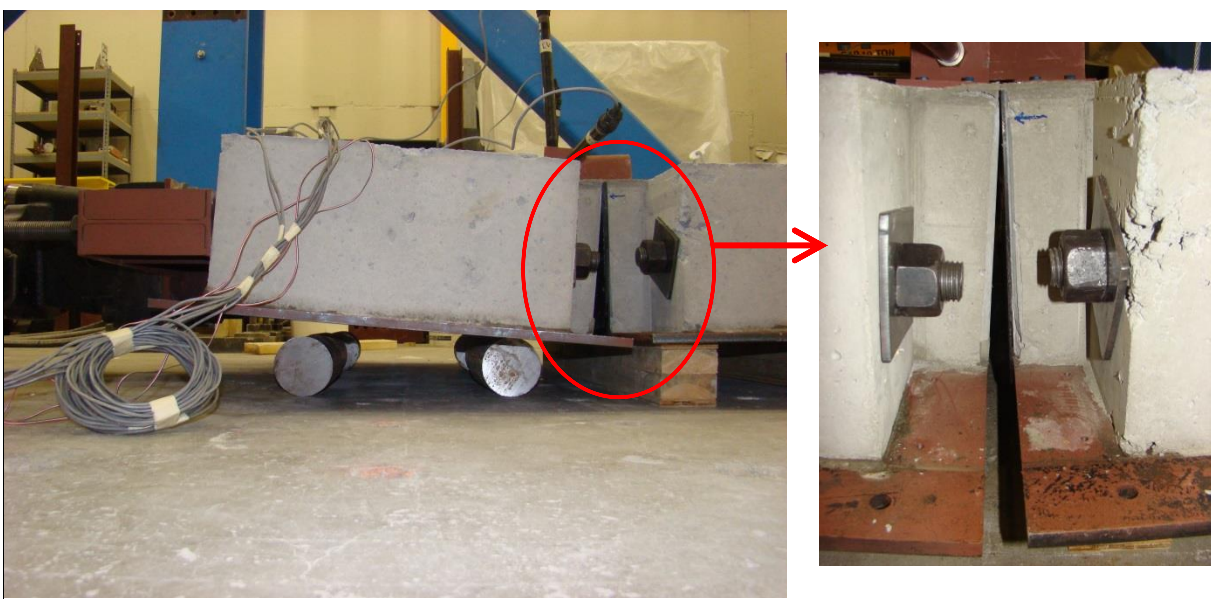


Figure 7-5: Joint Rotation of Specimen VT-4-1

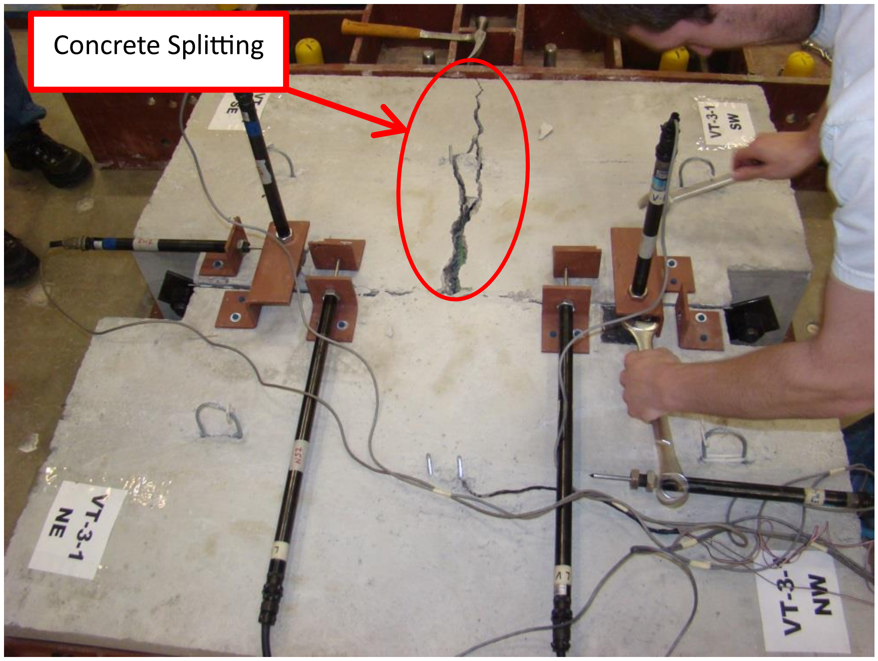


Figure 7-6: Bond Failure of Specimen VT-3-1

The remaining four specimens VT-1-2, VT-2-2, VT-3-2, and VT-4-2 were restrained to prevent joint rotation. Restrained specimens during testing were documented through photography (Figure 7-7 and Figure 7-8).

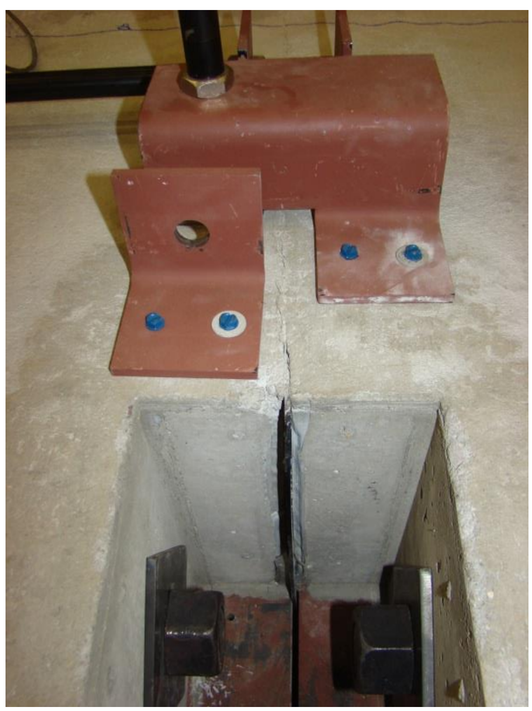


Figure 7-7: Reduced Joint Rotation of Specimen VT-4-2

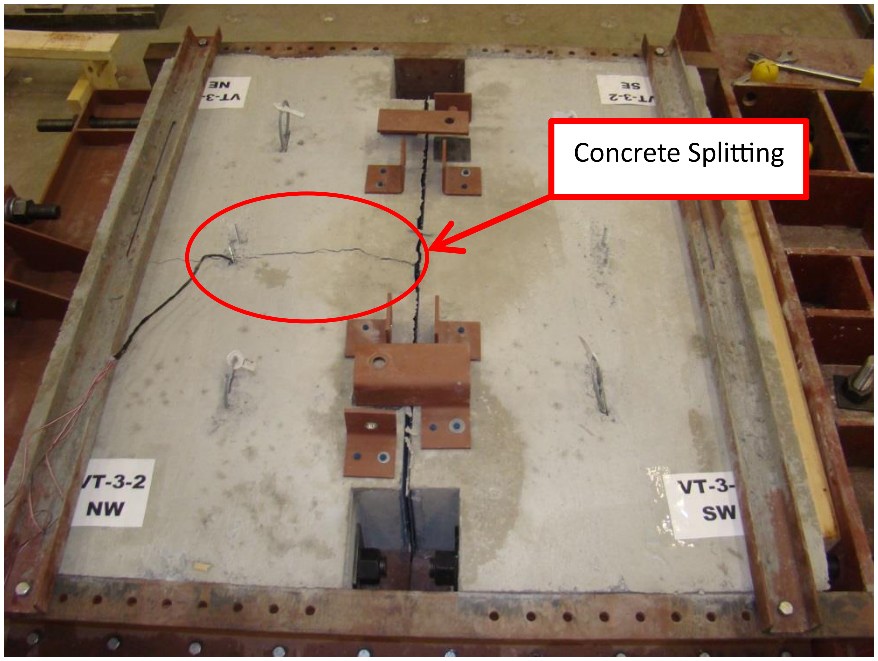


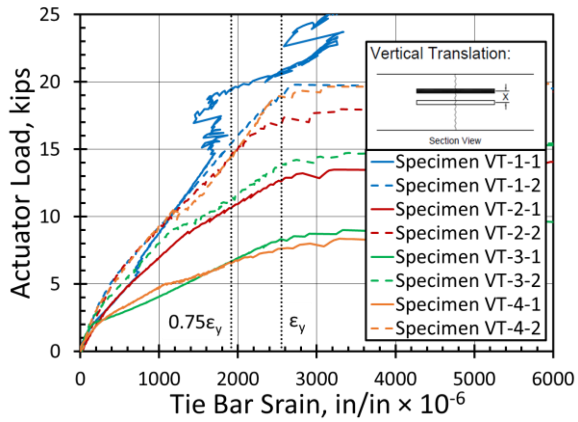
Figure 7-8: Bond Failure of Specimen VT-3-2

The LVDT's measuring the joint slippage were removed from the restrained specimen setups since slippage was restricted. A comparison between Figure 7-5 and Figure 7-7 indicate a significant reduction in joint rotation in the restrained specimens.

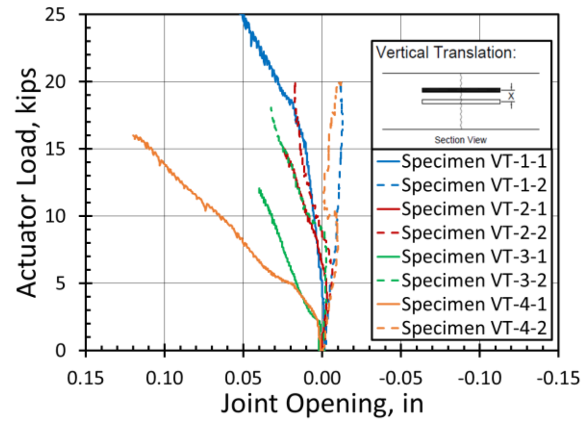
Measured tie bar strain, joint opening, and joint faulting, versus applied actuator load were plotted (Figure 7-9). With the exception of the 1 in. offset case (VT-1-1 and VT-1-2), the strain in the tie bars of the unrestrained specimens (VT-2-1, VT-3-1, VT-4-1) were much higher than the tie bar strains in the respective restrained specimen (VT-2-2, VT-3-2, VT-4-2) for a given actuator load. Those results indicate that the eccentric loading condition and the resulting moment, increase the tensile stress in the tie bar for a given actuator load. Since the unrestrained condition is not representative of real pavement conditions, the unrestrained test should not be used to draw conclusions regarding the effect of the vertical translation alignment configuration. The presence of a moment resulting from eccentric loading conditions is also apparent. The unrestrained specimens with 3 in. and 4 in. offsets show high positive joint opening values. Positive joint opening values indicate that the longitudinal joint is closing.

With the exception of specimen VT-3-2, the restrained specimens showed almost identical tie bar strain development up to $0.75\varepsilon_y$ (Figure 7-9). Specimen VT-3-2 exhibited higher tie bar strain values than the other three specimens. Moreover, the tie bar strain in specimen VT-2-2 past $0.75\varepsilon_y$ increased at a higher rate than the strain in specimens VT-1-2 and VT-4-2. The inconsistency in the tie bar strain results in specimen VT-3-2 and VT-2-2 can be explained by examining Figure 7-9. That Figure shows that specimens VT-1-2 and VT-4-2 exhibited negligible joint opening throughout the test, while specimens VT3-2 and VT-2-2 exhibited joint closing at the top of the joint past an actuator load of approximately 10 kips. That indicates that specimens VT-3-2 and VT-2-2 were not properly restrained. Excluding the results from specimen VT-1-2, that had the lowest bar offset, it seems probable that the vertical translation has little to no effect on the actuator load required to induce given tie bar strain. The joint openings for the restrained specimens appear to be small and unaffected by vertical translation.

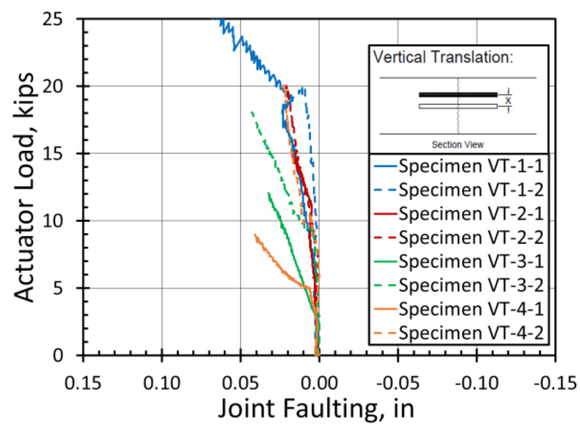
The joint faulting values for the vertical translation specimens (Figure 7-9), indicate that the joint faulting was minimal until after the tie bar strain had exceeded 0.75ε_y, regardless of the restraining conditions.



Tie Bar Strain



Joint Opening



Joint Faulting

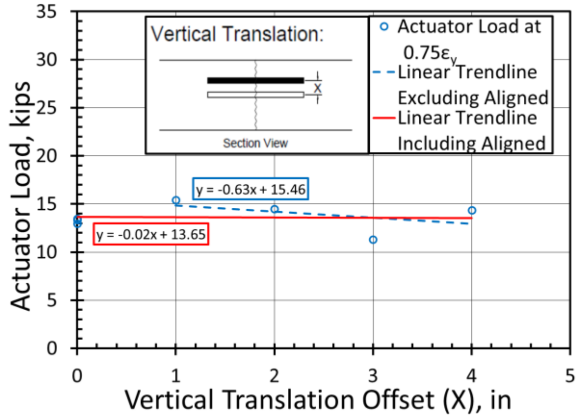
Figure 7-9: Testing Results for the Vertical Translation Specimens

The actuator load and relative displacement testing results at the point when the first measured tie bar strain reaches 0.75ε_y are summarized (Table 7-4).

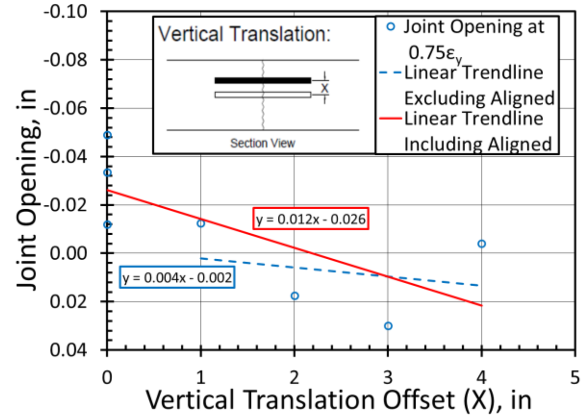
Table 7-4: Actuator load and joint opening, slippage and faulting for the vertical translation specimens

Specimen	At First Measured Tie Bar Strain Equal to 0.75εy			
	Actuator Load, kips	Joint Opening, in.	Joint Slippage, in.	Joint Faulting, in.
VT – 1 – 1	19.3	0.027	-0.002	0.021
VT – 1 – 2	15.4	-0.013	-	0.006
VT – 2 – 1	10.6	0.011	-0.001	0.005
VT – 2 – 2	14.5	0.018	-	0.014
VT – 3 – 1	6.6	0.022	0.001	0.014
VT – 3 – 2	11.3	0.030	-	0.018
VT – 4 – 1	6.5	0.040	0.040	0.026
VT – 4 – 2	14.4	-0.004	-	0.017

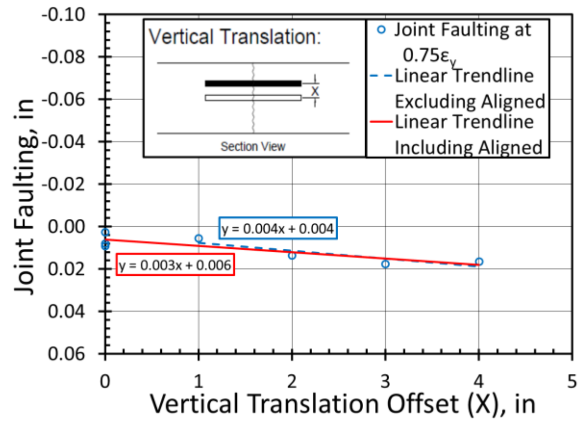
The effect of vertical translation on the actuator load, joint opening, and joint faulting at $0.75\varepsilon_y$ is documented (Figure 7-10). These figures exclude the data from the unrestrained specimens. It is clear that the vertical translation does not induce significant performance variation from the ideally placed tie bar (aligned). The average actuator load at $0.75\varepsilon_y$ for the vertical translation specimens is 13.9 kips, which is 1.05 times that for the aligned specimens. The change in joint opening/closing and faulting is negligible. The joint opening remains well below the 1/8 in. performance limit.



Actuator Load



Joint Opening



Joint Faulting

Figure 7-10: Effect of Vertical Translation Offset on Joint Parameters

7.2.3 Vertical Skew

The eight vertical skew specimens were tested while restrained against rotation. In all specimens, the tie bar yielded prior to bond failure. Bond failure occurred by splitting of the concrete along the length of the tie bar. The process of testing was documented throughout with photography (Figure 7-11 and Figure 7-12).

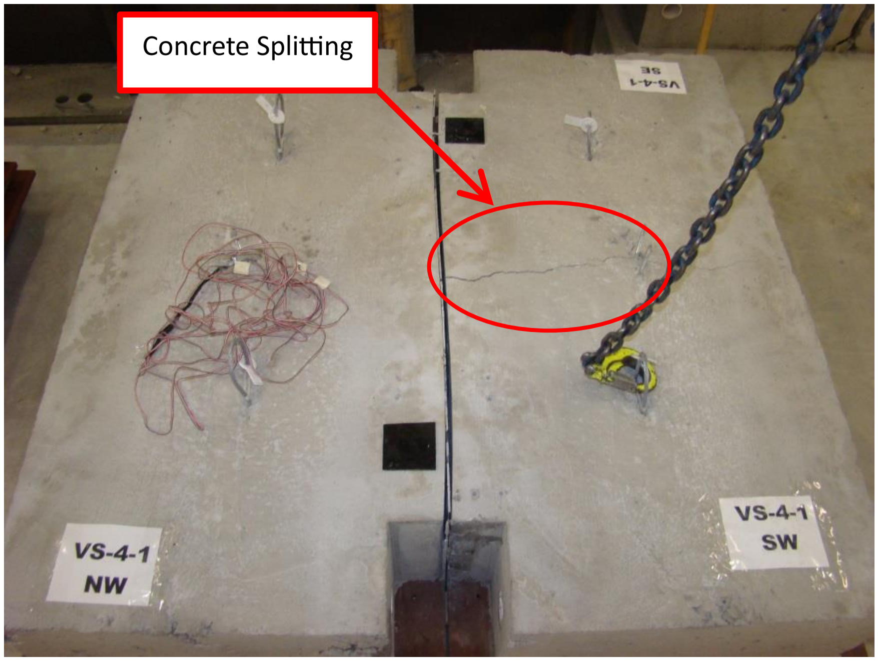
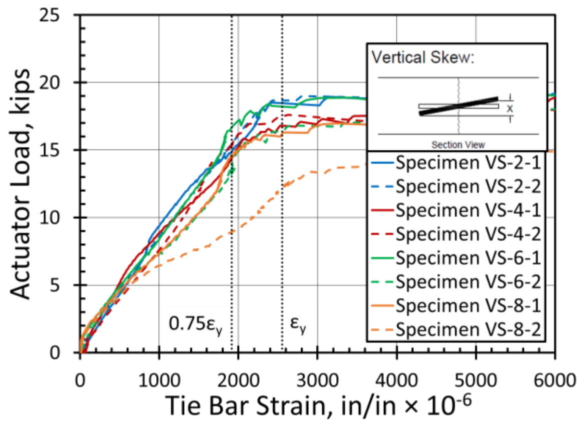


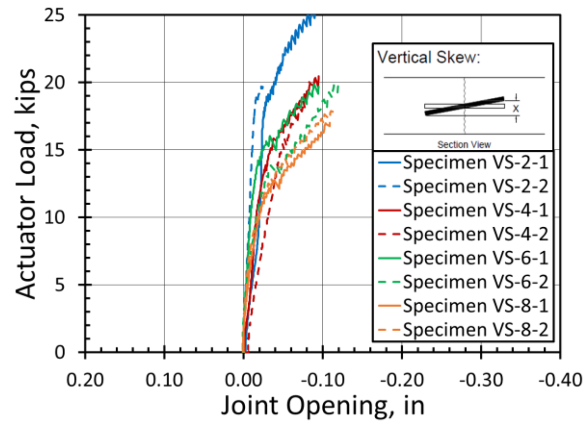
Figure 7-11: Bond Failure of Specimen VS-4-1

Figure 7-12: Specimen VS-4-1 Failure Plane

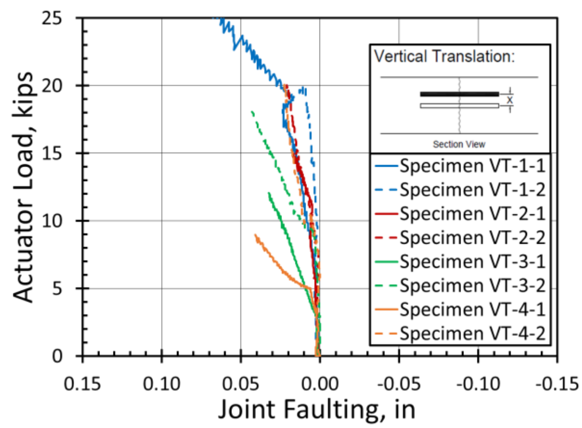
The measured tie bar strain, joint opening, and joint faulting are plotted, versus applied actuator load (Figure 7-13). Excluding specimen VS-4-2, the development of tensile tie bar strain in the tie bar was not significantly affected by the magnitude of the vertical skew. Results indicated, however, an increase in joint slippage and faulting with an increase in misalignment magnitude.



Tie Bar Strain



Joint Opening



Joint Faulting

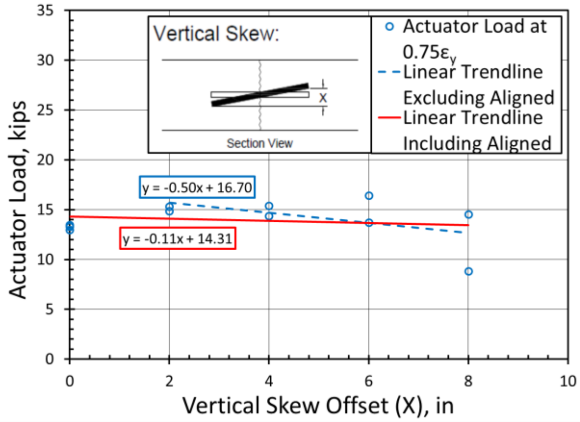
Figure 7-13: Testing Results for the Vertical Skew Specimens

The actuator load and relative displacement testing results at the point when the first measured tie bar strain reached $0.75\varepsilon_y$ are summarized (Table 7-5).

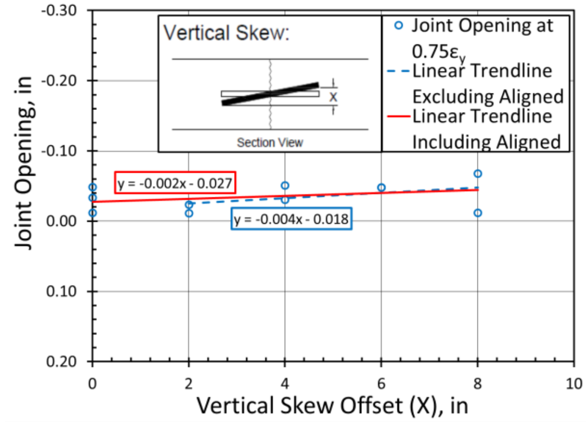
Table 7-5: Actuator Load and Joint Opening and Faulting for the Vertical Skew Specimens

Specimen	At First Measured Tie Bar Strain Equal to $0.75\varepsilon_y$		
	Actuator Load, kips	Joint Opening, in.	Joint Faulting, in.
VS – 2 – 1	14.9	-0.024	0.058
VS – 2 – 2	15.3	-0.012	0.017
VS – 4 – 1	14.4	-0.031	0.138
VS – 4 – 2	15.4	-0.051	0.065
VS – 6 – 1	16.4	-0.048	0.127
VS – 6 – 2	13.7	-0.048	0.115
VS – 8 – 1	14.5	-0.068	0.132
VS – 8 – 2	8.8	-0.012	0.171

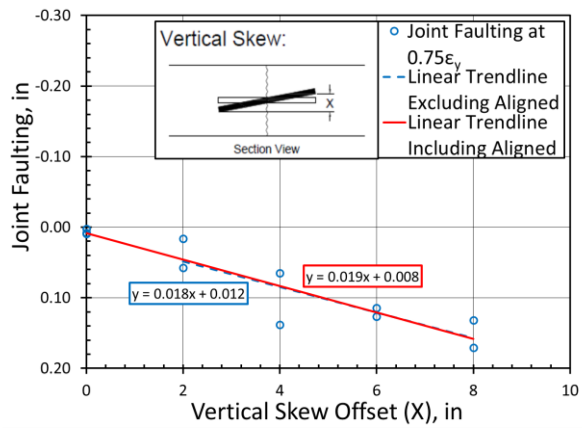
The effect of vertical skew on the actuator load, joint opening and joint faulting at $0.75\varepsilon_y$ is presented (Figure 7-14). With the exception of one of the VS-8 specimens, the magnitude of the vertical skew had no significant effect on the actuator load at a tie bar strain of $0.75\varepsilon_y$. The average actuator load at $0.75\varepsilon_y$ for the misaligned specimens is 14.2 kips, which is 1.08 times that for the aligned specimens. The joint opening increased slightly as the misalignment magnitude increased, but the maximum measured joint opening was 0.068 in. (VS-8-1) which is still well below the allowable joint opening limit of 1/8 in. As the vertical skew increased, the joint faulting also increased. At a vertical skew magnitude of 8 in., the average measured joint faulting was 0.151 in., which is 25 times the average joint faulting experienced by the aligned specimens.



Actuator Load



Joint Opening



Joint Faulting

Figure 7-14: Effect of Vertical Skew Offset on Joint Parameters

7.2.4 Longitudinal Translation

The eight longitudinal translation specimens were tested while restrained against rotation, as shown in Figure 7-15. All specimens failed due to bond failure after the tie bar had yielded. Bond failure occurred by splitting of the concrete along the length of the tie bar. Pictures taken during testing are shown in Figure 7-15 and Figure 7-16.

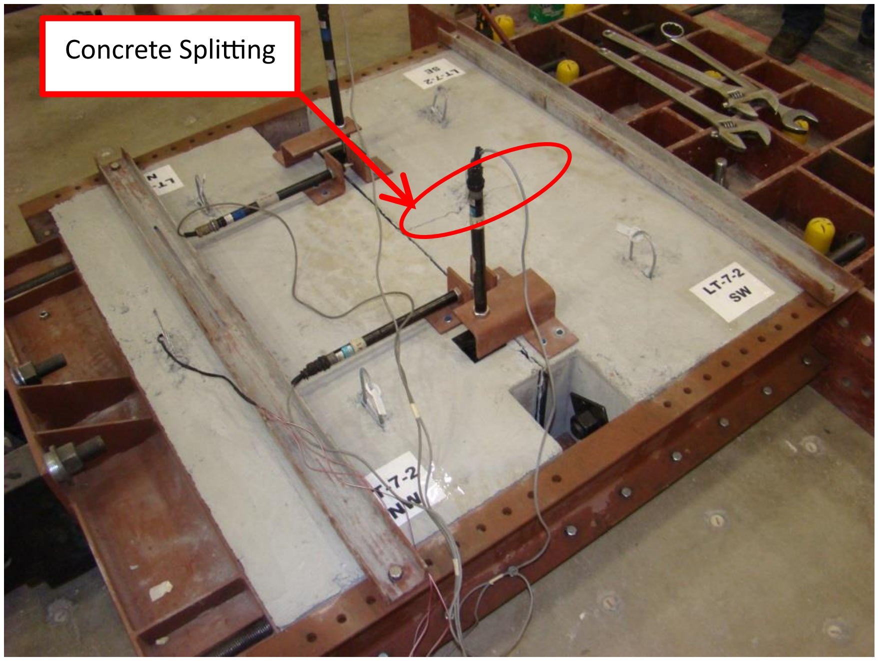
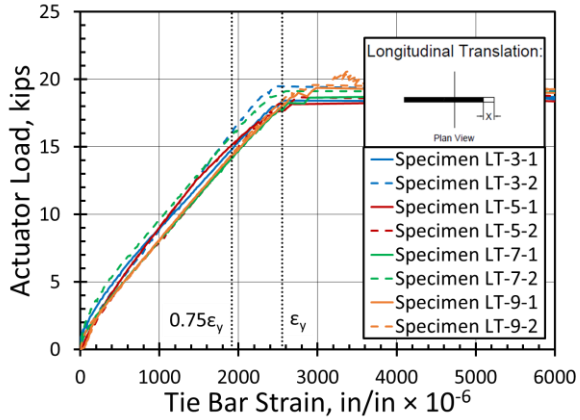


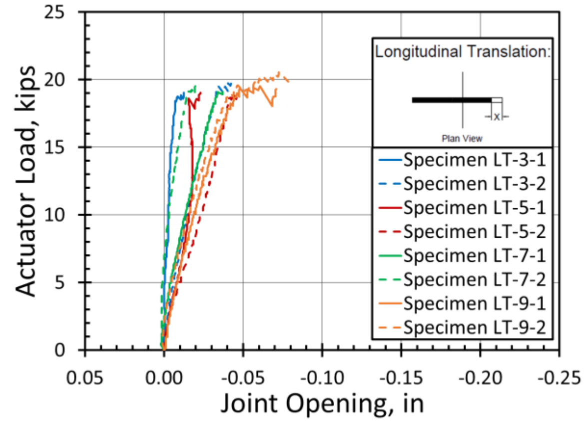
Figure 7-15: Bond Failure Specimen LT-7-2

Figure 7-16: Specimen LT-7-2 Failure Plane

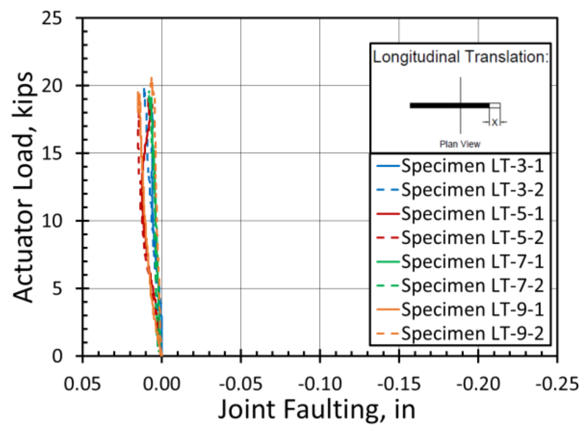
The measured tie bar strain, joint opening, and joint faulting versus applied actuator load were plotted (Figure 7-17). The development of tensile strain in the tie bar and the joint faulting were not significantly affected by the magnitude of the longitudinal translation. The joint opening was slightly affected as the magnitude of the longitudinal translation misalignment increased.



Tie Bar Strain



Joint Opening



Joint Faulting

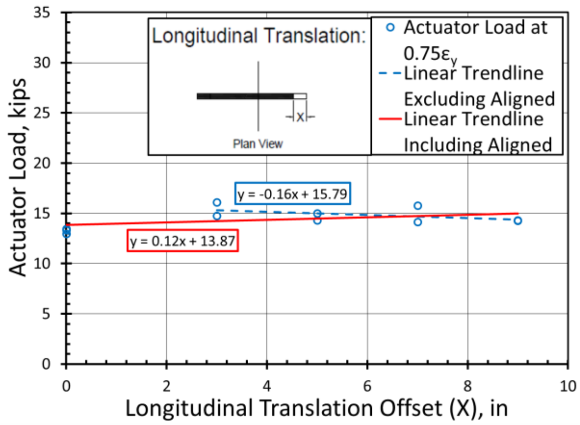
Figure 7-17: Testing Results for the Longitudinal Translation Specimens

The actuator load and relative displacement testing results at the point when the first measured strain tie bar reached $0.75\varepsilon_y$ are summarized in Table 7-6.

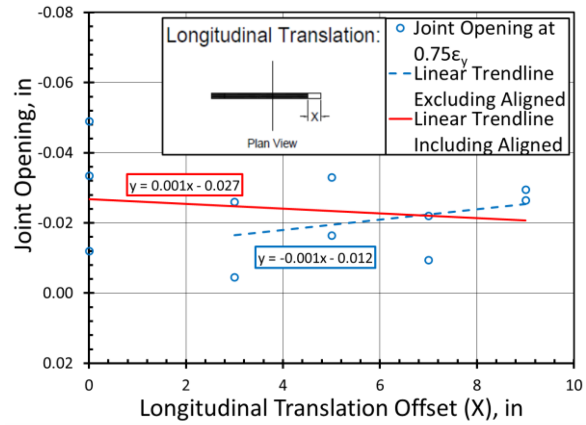
Table 7-6: Actuator Load, Joint Opening and Joint Faulting for the Longitudinal Translation Specimens

Specimen	At First Measured Tie Bar Strain Equal to 0.75ε_y		
	Actuator Load, kips	Joint Opening, inches	Joint Faulting, inches
LT – 3 – 1	14.8	-0.005	0.008
LT – 3 – 2	16.1	-0.026	0.010
LT – 5 – 1	15.0	-0.017	0.011
LT – 5 – 2	14.3	-0.033	0.015
LT – 7 – 1	14.1	-0.022	0.006
LT – 7 – 2	15.8	-0.010	0.008
LT – 9 – 1	14.3	-0.030	0.013
LT – 9 – 2	14.3	-0.027	0.004

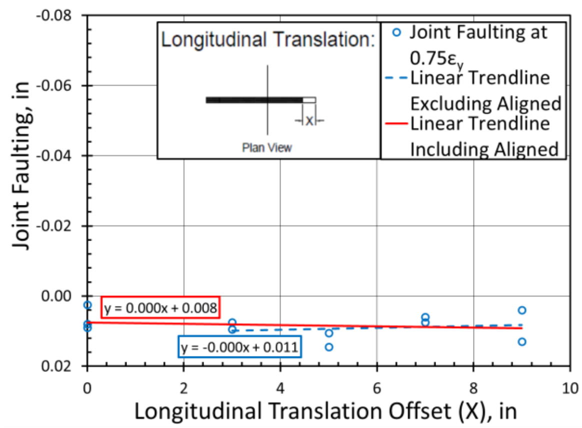
The effect of the longitudinal translation on the actuator load, joint opening and joint faulting at 0.75ε_y is presented in Figure 7-18. Longitudinal translation does not induce a performance variation from the ideally placed tie bar (aligned). The average actuator load at 0.75ε_y for the longitudinal translation specimens is 14.73, which is 1.12 times that for the aligned specimens. The changes in the joint opening and joint faulting are negligible and the joint opening is well below the 1/8 inch performance limit.



Actuator Load



Joint Opening



Joint Faulting

Figure 7-18: Effect of Longitudinal Translation on Joint Parameters

7.2.5 Horizontal Skew

The eight vertical skew specimens were tested while restrained against rotation. In all eight of the horizontal skew specimens, the tie bar yielded prior to bond failure. Bond failure occurred by the splitting of the concrete along the length of the tie bar. There was photo documentation throughout the process of testing (Figure 7-19 and Figure 7-20).

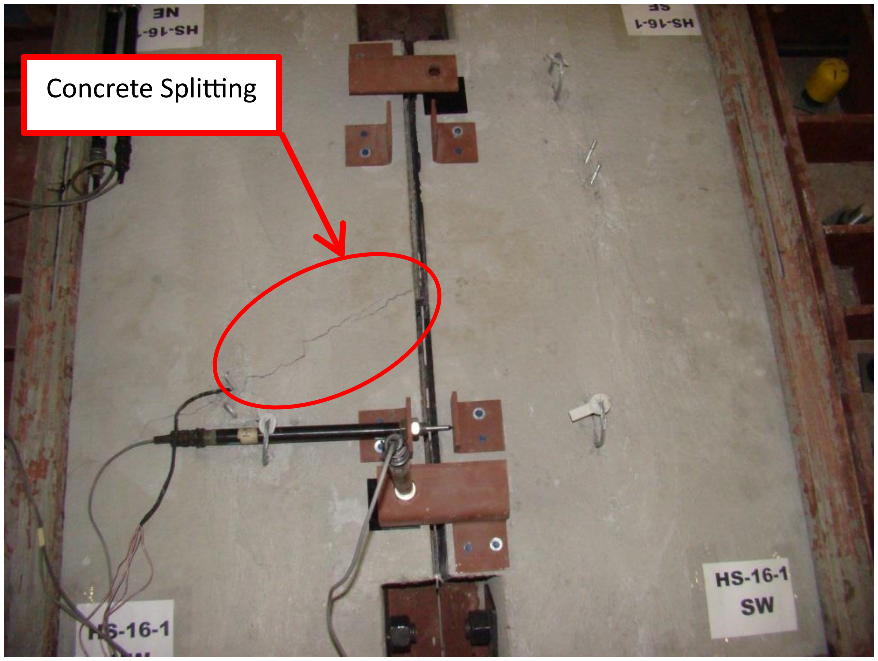


Figure 7-19: Bond Failure of Specimen HS-16-1

Figure 7-20: Specimen HS-16-1 Failure Plane

The measured tie bar strain, joint opening, and joint faulting versus applied actuator load were plotted (Figure 7-21). The actuator load, joint opening, and joint faulting, respectively, were all significantly affected by the magnitude of the horizontal skew. An increase in the horizontal skew misalignment results in a faster increase in the tie bar's tensile strain. An increase in misalignment magnitude also increases the joint slippage and joint faulting.

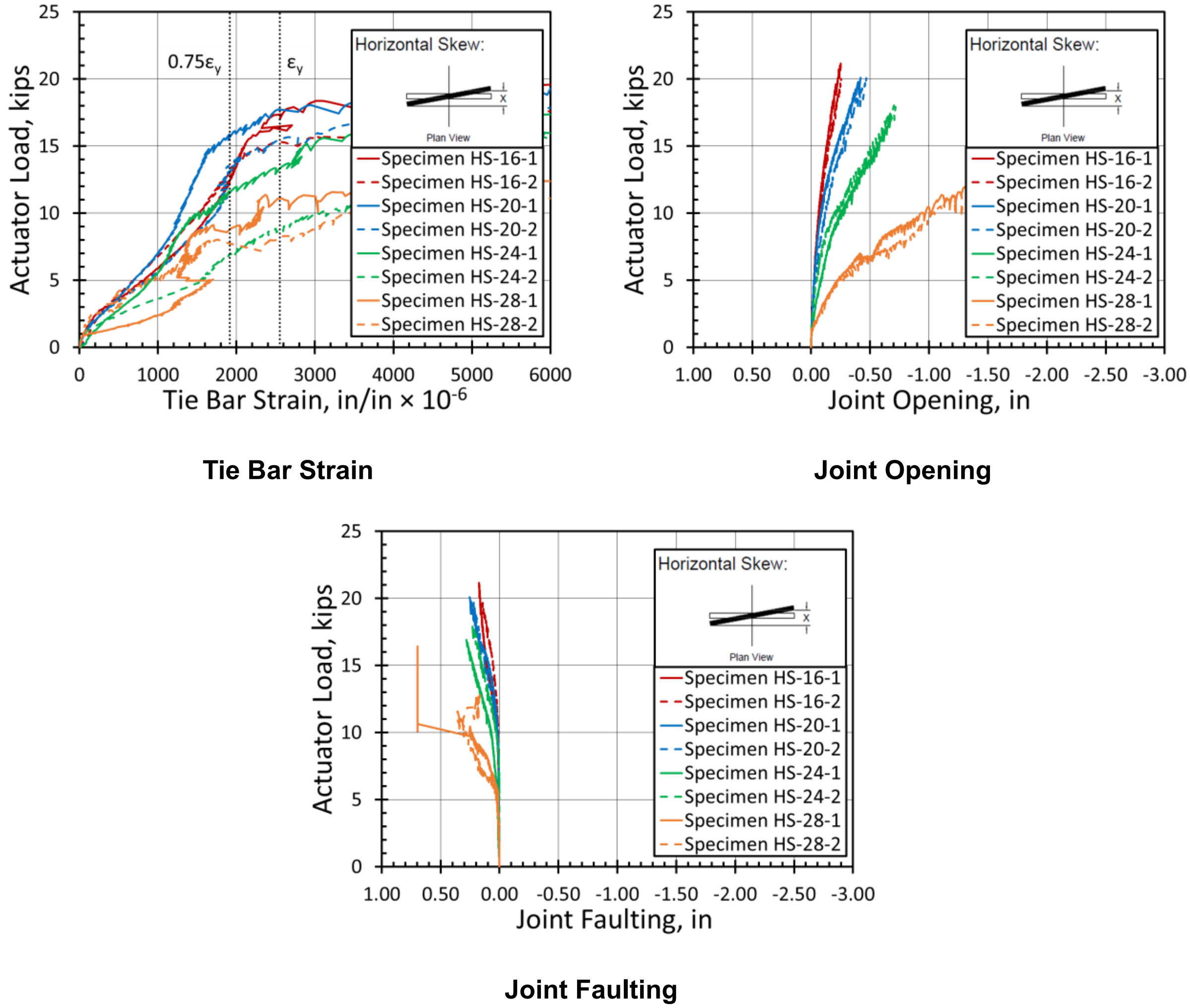


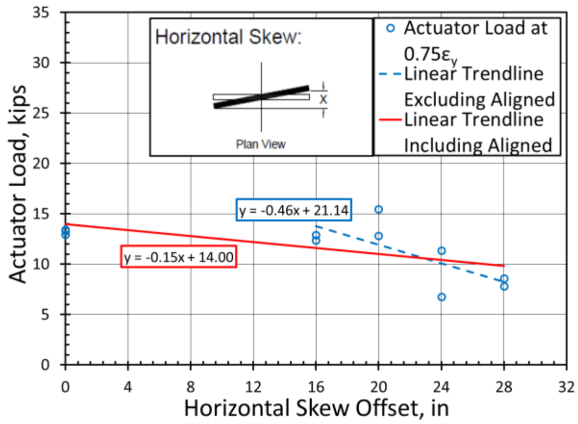
Figure 7-21: Testing Results for the Horizontal Skew Specimens

The actuator load and relative displacement testing results at the point when the first measured tie bar strain reached $0.75\varepsilon_y$ are summarized in Table 7-7.

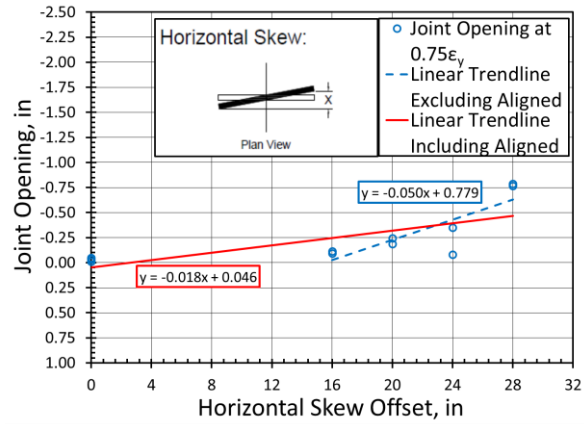
Table 7-7: Actuator Load, Joint Opening, and Joint Faulting for the Horizontal Skew Specimens

Specimen	At First Measured Tie Bar Strain Equal to $0.75\varepsilon_y$		
	Actuator Load, kips	Joint Opening, inches	Joint Faulting, inches
HS – 16 – 1	12.4	-0.095	0.170
HS – 16 – 2	12.9	-0.115	0.134
HS – 20 – 1	15.5	-0.246	0.230
HS – 20 – 2	12.8	-0.188	0.194
HS – 24 – 1	11.4	-0.350	0.216
HS – 24 – 2	6.8	-0.082	0.215
HS – 28 – 1	8.6	-0.768	0.697
HS – 28 – 2	7.8	-0.786	0.343

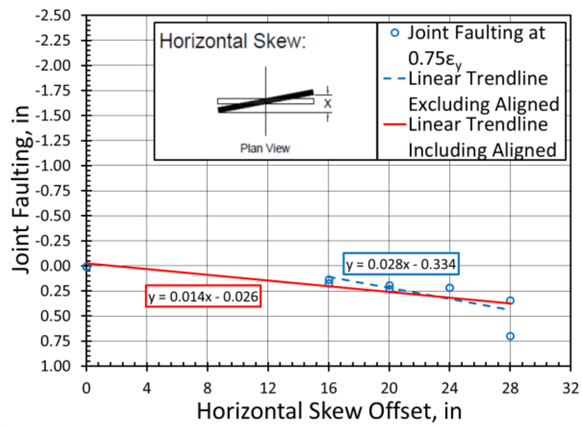
The effect of horizontal skew on the actuator load, joint opening, and joint faulting at $0.75\varepsilon_y$ is presented (Figure 7-22). The magnitude of the horizontal skew causes the actuator load at a tie bar strain of $0.75\varepsilon_y$ to decrease. The average actuator load at $0.75\varepsilon_y$ for the 16 inch and 20 inch misaligned specimens is 12.65 kips and 14.15 kips, respectively; both are approximately equal to the 13.2 kip experienced by the aligned specimens. The 24 in. misaligned specimen, however, resulted in an average actuator load at $0.75\varepsilon_y$ of 9.1 kips, 0.65 times that of the aligned specimen. With the exception of one of the HS-24 specimens, the horizontal skew caused the magnitude of the joint opening to increase at a tie bar design strain of $0.75\varepsilon_y$. The average joint opening at $0.75\varepsilon_y$ for the 16 in. misaligned specimen is 0.105 in., over 3 times that of the aligned specimen but less than the 1/8 in. performance limit. However, the 1/8 in. performance limit was exceeded by the 20 in. misaligned specimen, where the average joint opening at $0.75\varepsilon_y$ was 0.217 in. The horizontal skew increased the magnitude of the joint faulting at a tie bar design strain of $0.75\varepsilon_y$. At a horizontal skew magnitude of 20 in., the average measured joint faulting was 0.212 in., 35 times the average joint faulting experienced by the aligned specimens.



Actuator Load



Joint Opening



Joint Faulting

Figure 7-22: Effect of Horizontal Skew on Joint Parameters

7.3 Simple Analytical Tool

Since the results showed that the horizontal skew was the only misalignment that caused significant drop in performance of longitudinal joints, the research team decided that finite element modeling was not needed to examine the effect of combined misalignments on the bond strength. However, a conservative simplified hand calculation, which can be used to estimate the load at $0.75\varepsilon_y$ for any given horizontal skew offset, is presented here. If the pavement specimen is cut at the longitudinal joint and the concrete is assumed to be fully cracked, the only force resisting the applied tension would be the tie bar force. To illustrate, the free body diagram of the right half of the specimen is presented (Figure 7-23).

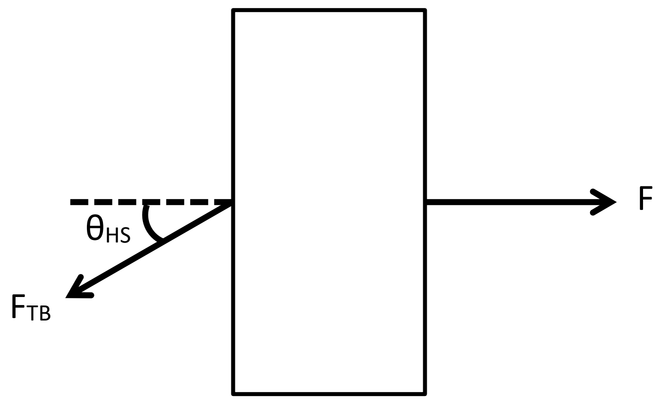


Figure 7-23: Free Body Diagram of the Right Half of the Specimen (Top View)

The horizontal skew angle can be obtained from the horizontal skew offset using Equation 5.

$$\theta_{HS} = sin^{-1}\frac{HSO}{L_{TB}} \qquad \text{Equation 5}$$

Where:

$\theta_{HS} = Horizontal\ skew\ angle, rad$

$HSO = Horizontal\ skew\ offset, in$

$L_{TB} = Tie\ bar\ length, in$

The load when the strain of the tie bar reaches 0.75εy can then be obtained using Equation 6.

$$F = F_{TB}\cos\theta_{HS} = 0.75 f_y A_s \cos\theta_{HS} \qquad \text{Equation 6}$$

Where:

$F = The\ applied\ load\ at\ 0.75\varepsilon_y, kip$

A comparison between the hand calculation and the actual loads for the tested horizontal skew offsets are presented (Table 7-8). It can be observed that the estimated loads are close to the actual loads for some cases, while they are very conservative in others.

Table 7-8: Estimated versus Actual Load for Tested Horizontal Skew Offsets

HSO, in.	Estimated F, kips	Actual F, kips	Error, %
16	11.80	12.65	6.72
20	10.40	14.15	26.52
24	8.37	9.1	8.02
28	5.01	8.2	38.92

8 FINDINGS AND CONCLUSIONS

The study presented in this report was conducted to 1) identify current specifications for tie bar placement tolerances in PCC pavements, 2) conduct experimental testing to examine the effect of different tie bar misalignment configurations and magnitudes on the performance of longitudinal joints, and 3) give recommendations to improve current specifications if needed.

The following findings and conclusions are based on the experimental tests carried out in this study.

- Vertical and longitudinal translation misalignments had no significant effect on the performance of the longitudinal joint.
- Vertical skew misalignment had no significant effect on the applied load or joint opening at a tie bar strain of $0.75\varepsilon_y$.
- Vertical skew misalignment resulted in joint faulting at $0.75\varepsilon_y$ that reached as high as 25 times that of the aligned specimens (0.152 in. at an offset of 8 in.).
- Horizontal skew misalignment resulted in a decrease in applied load and an increase in both joint opening and joint faulting when the strain in the tie bar reached $0.75\varepsilon_y$.
- The joint opening limit of 1/8 in. was exceeded at the 20 in. horizontal skew offset.
- Through interpolation, results show that the joint opening limit of 1/8 in. would also be exceeded at a horizontal skew offset of 18 in.
- Joint faulting at $0.75\varepsilon_y$ for horizontal skew misaligned specimens reached as much as 35 times that of aligned specimens at an offset of 20 in.
- The applied load at a tie bar strain of $0.75\varepsilon_y$ for specimens with horizontal skew misalignment can be conservatively estimated using simplified hand calculations.

9 RECOMMENDATIONS

Based on the findings of this study, the research team offers the following recommendations.

- The current SDDOT tie bar tolerance limit for horizontal skew misalignment should be reduced from 18 in. to, at most, 16 in. This would correspond to a reduction in the transverse placement tolerance limit from ±3.0 in. to, at most, ±2.25 in. measured perpendicular to the longitudinal joint.
- Further reduction in the horizontal skew tolerance limit might be required if joint faulting is a significant issue.
- The vertical skew tolerance limit is sufficient, but contractors need to strictly abide by that limit in order to avoid excessive joint faulting.
- For a given design load, the proposed hand calculation can be used to establish maximum allowed horizontal skew, provided it is no more than 16 in.
- For future research, experiments on slabs with multiple tie bars that have various horizontal skew magnitudes can help examine more real life scenarios.

10 RESEARCH BENEFITS

Tie bars are routinely used in jointed PCC pavements to provide load transfer between longitudinal slabs and to prevent lane separation. Inspection of South Dakota pavements after construction using GPR revealed that many bars were misaligned or missing. The long-term effect on pavement performance from misaligned or missing bars was unknown. Before the current research was conducted, there was no experimental and quantitative estimation to determine how profound that impact might be. While tie bars are considered necessary for long-lasting pavements, only a few states have set requirements on their placement tolerances. When specifications have been established, they may have included arbitrary tolerance requirements that lacked an engineering or economic basis, making it impossible to know whether they are too lax or too stringent. In the absence of an engineering or economic basis for the specifications, it is difficult to judge what corrective actions are warranted when violations are detected.

With millions of dollars spent each year on roads, the financial impacts of missing or misplaced tie bars could be costing the SDDOT substantial amount of money in the long-term. Therefore, there was a need for a study to determine the effects of various tie bar misalignments on tie bar performance in order to set acceptable placement tolerances. This research produced experimental results that were able to quantitatively evaluate the effect of these tie bar misalignments on the performance of longitudinal joints. Consequently, recommendations were made for tolerances for placement of tie bars in PCC pavement in order to avoid undesirable long-term maintenance costs.

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APPENDIX A: CONCRETE MIX DESIGN

Contractor Concrete Mix Design — DOT-24 (10-10)

Project:	Tie Bar Tolerance	County:	PCN:
Concrete Supplier	GCC Brookings	Class of Concrete:	Well Graded PCCP
Supplier Signature		Mix # (DOT use):	
Prepared by/ Title:		Approved by (DOT):	
Date Prepared:		Approval Date (DOT):	

MATERIALS:

				Sp. Gr.	Absorption	F.M.
Fine Aggregate	(source, type):	LG Everist Washed Sand	*	2.66	1.1	2.99
	(pit name, county):	Brookings				
	(Section-Township-Range):					
Coarse Aggr.	(source, type):	LG Everist 1" Quartzite	*	2.63	0.3	
	(pit name, county):	Dell Rapids				
	(Section-Township-Range):					
Additional Aggr.	(source, type):	LG Everist 3/8" Chips	*	2.63	0.5	
	(pit name, county):	Dell Rapids	* Saturated Surface Dry Basis			
	(Section-Township-Range):					
Cement	(brand, type, source):	GCC Type I/II Rapid City		3.15		
Fly Ash	(brand, type, source):	Headwaters Coal Creek ND		2.50		
Water	(source, location):	Brookings		1.00		
					oz/yd^3, oz/cwt, lb/yd^3	
Admixture(s), etc	(brand, type):	Air Entrainment			(5.0%-7.5% Air)	
		Water Reducer			(2"-3" Slump)	

DESIGN MIX PROPORTIONS:

			lb/yd^3	Abs. Vol. (ft^3) - †	
W/C Ratio:	0.41	(field max.)			
Cement			460	2.34	
Fly Ash			115	0.74	
Fine Aggr. %	40.0		1222	7.36	
Coarse Aggr. %	44.0		1344	8.19	
Addit. Aggr. %	16.0		490	2.99	
Water			235	3.77	
Air Content (structural, paving- 6.5%)			6.5%	1.76	
TOTAL			3866	27.15	(≈27.0 ft^3)

%- Percent of Total Aggregate *† - Absolute Volume= (lb. of product)÷[(Sp. Gr.)×(62.4)]*

TRIAL MIX TEST DATA: Attach Supporting Lab Test Documents - Aggregate: {sieve analysis, coarse % particles passing 200, absorption, fineness modulus, specific gravity, % particles less than 1.95 sp. gr., soundness, LA abrasion, flat and elongated, colormetric} Trial Batch: {batch weights, slump, air content, unit weight, actual aggregate moisture, actual w/c ratio, cylinder compressive strengths, strength gain curve}

Concrete Purpose:

Comments:

Distribution: Conc. Engr. - Area Engr. - Reg. Matl's Engr.

APPENDIX B: FRESH AND HARDENED CONCRETE PROPERTIES

Tolerances for Placement of Tie Bars in Portland Cement Concrete Pavement

Project SD2011-09

Tie Bar Misalignment Type: Aligned Specimen's (3 poured)

Testing by: SDSU, Walker Olson

Concrete:

Supplier:	GCC Ready Mix
Mix Design:	Well Graded PCCP
Quantity (yd^3):	2
W/C Ratio:	0.398
Pouring Date:	Thursday, April 10, 2014
Pouring Time:	3:00:00 PM
Curing Method:	Wet burlap

FRESH CONCRETE PROPERTIES:		
	Measured	Allowable
Air Temp. (°F)	45	-
Concrete Temp. (°F)	85	-
Unit Weight (lb/ft^3)	-	143 .1 lb/ft^3
Slump (in)	2.5	2" to 3"
% Air Content	7.5	5.0 to 7.5%

Cylinders:

Group Number:	WO - A
Number of Cylinders:	18
Cylinder Diameter (in):	6.0
Cylinder Length (in):	12.0

Beams:

Group Number:	WO - A
Number of Beams:	8
Beam width/height (in):	6.0
Span Length (in):	18.0

HARDENED CONCRETE PROPERTIES:			
Compressive Strength	3 - Day	2740	psi
	7 - Day	3973	psi
	28 - Day	4785	psi
Tensile Strength	3 - Day	-	psi
	7 - Day	482	psi
	28 - Day	434	psi
Flexural Strength	3 - Day	-	psi
	7 - Day	435	psi
	28 - Day	647	psi
Modulus of Elasticity	3 - Day	-	psi
	7 - Day	3.78E+06	psi
	28 - Day	4.01E+06	psi
Average Concrete Unit Weight		142.3	pcf

Compressive Strength (ASTM C39-14):

Loading Rate: 35 psi/sec (35 ± 7 psi/sec = 989.6 ± 197.9 lb/sec)

3 - Day: Sunday, April 13, 2014

Sample number	Modulus of Elasticity (ksi)		Compressive Strength (psi)
WO - A -1			2307
WO - A -2			2486
WO - A -3			3427
AVERAGE			2740

7 - Day: Thursday, April 17, 2014

Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - A -4	3.83E+06		3939
WO - A -5	3.84E+06		3721
WO - A -6	3.75E+06		4145
WO - A -8	3.70E+06		4111
WO - A -9	3.78E+06		3948
AVERAGE	3.78E+06		3973

28 - Day: Thursday, May 08, 2014

Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - A -16	~~8.29E+06~~		4956
WO - A -17	4.01E+06		4803
WO - A -18	~~7.63E+06~~		4596
AVERAGE	4.01E+06		4785

Split Tensile Strength (ASTM C496):

Loading Rate: 150 psi/min (100 to 200 psi/min)

3 - Day: Sunday, April 13, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)

7 - Day: Thursday, April 17, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)
WO - A -7	55640		492
WO - A -10	54110		478
WO - A -11	53800		476
	AVERAGE		482

28 - Day: Thursday, May 08, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)
WO - A -12	41670		368
WO - A -13	53380		472
WO - A -14	45220		400
WO - A -15	56000		495
	AVERAGE		434

Flexural Strength (ASTM C78):

Loading Rate: 1800 lb/min (1500 - 2100 lb/min)

3 - Day: Sunday, April 13, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)

7 - Day: Thursday, April 17, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
WO - A -1	6430	1	536
WO - A -2	5090	1	424
WO - A -3	5450	1	454
WO - A -4	4970	1	414
WO - A -5	4150	1	346
	AVERAGE		435

28 - Day: Thursday, May 08, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
WO - A -6	7680	1	640
WO - A -7	8200	1	683
WO - A -8	7400	1	617
	AVERAGE		647

* See ASTM C76. If failure initiates in the tension face of the Middle 1/3 **enter 1.** If failure initaites in the tension face outside of the middle 1/3 by more than 0.9" **enter 2.** If failure initiates in the tension face within 0.9" of the middle 1/3 **enter value of "a" in inches.** (a = average distance between line of fracture and the nearest support)

Tolerances for Placement of Tie Bars in Portland Cement Concrete Pavement

Project SD2011-09

Tie Bar Misalignment Type: Vertical Translation (8 Specimens)

Testing by: SDSU, Walker Olson

Concrete:

Supplier:	GCC Ready Mix
Mix Design:	Well Graded PCCP
Quantity (yd^3):	4.5
W/C Ratio:	0.409
Pouring Date:	Thursday, April 24, 2014
Pouring Time:	10:00
Curing Method:	Wet burlap

FRESH CONCRETE PROPERTIES:

	Measured	Allowable
Air Temp. (°F)	50	-
Concrete Temp. (°F)	62	-
Unit Weight (lb/ft^3)	-	143 .1 lb/ft^3
Slump (in)	2.5	2" to 3"
% Air Content	6.2	5.0 to 7.5%

Cylinders:

Group Number:	WO - VT
Number of Cylinders:	18
Cylinder Diameter (in):	6.0
Cylinder Length (in):	12.0

Beams:

Group Number:	WO - VT
Number of Beams:	8
Beam width/height (in):	6.0
Span Length (in):	18.0

HARDENED CONCRETE PROPERTIES:

Compressive Strength	3 - Day	4562	psi
	7 - Day	5357	psi
	28 - Day	6635	psi
Tensile Strength	3 - Day	-	psi
	7 - Day	565	psi
	28 - Day	629	psi
Flexural Strength	3 - Day	-	psi
	7 - Day	460	psi
	28 - Day	699	psi
Modulus of Elasticity	3 - Day	-	psi
	7 - Day	4.60E+06	psi
	28 - Day	4.81E+06	psi
Average Concrete Unit Weight		146.0	pcf

Compressive Strength (ASTM C39-14):

Loading Rate: 35 psi/sec (35 ± 7 psi/sec = 989.6 ± 197.9 lb/sec)

3 - Day: Sunday, April 27, 2014				7 - Day: Thursday, May 01, 2014				28 - Day: Thursday, May 22, 2014			
Sample number	Modulus of Elasticity (ksi)		Compressive Strength (psi)	Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)	Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - VT -1			4624	WO - VT -5	4.72E+06		5489	WO - VT -11	4.53E+06		~~5076~~
WO - VT -2			4409	WO - VT -9	4.41E+06		4966	WO - VT -7	~~7.11E+06~~		6526
WO - VT -3			4654	WO - VT -8	~~9.31E+06~~		5406	WO - VT -12	5.00E+06		6663
				WO - VT -6	4.67E+06		5568	WO - VT -4	4.91E+06		6717
AVERAGE			4562	AVERAGE	4.60E+06		5357	AVERAGE	4.81E+06		6635

Split Tensile Strength (ASTM C496):

Loading Rate: 150 psi/min (100 to 200 psi/min)

3 - Day: Sunday, April 27, 2014				7 - Day: Thursday, May 01, 2014				28 - Day: Thursday, May 22, 2014			
Sample number	Ultimate Load (lb)		Tensile Strength (psi)	Sample number	Ultimate Load (lb)		Tensile Strength (psi)	Sample number	Ultimate Load (lb)		Tensile Strength (psi)
				WO - VT -18	65680		581	WO - VT -16	72300		639
				WO - VT -13	63230		559	WO - VT -17	70650		625
				WO - VT -10	62730		555	WO - VT -14	71480		632
								WO - VT -15	70270		621
					AVERAGE		565		AVERAGE		629

Flexural Strength (ASTM C78):

Loading Rate: 1800 lb/min (1500 - 2100 lb/min)

3 - Day: Sunday, April 27, 2014				7 - Day: Thursday, May 01, 2014				28 - Day: Thursday, May 22, 2014			
Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)	Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)	Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
				WO - VT -4	6020	1	502	WO - VT -6	9450	1	788
				WO - VT -3	5120	1	427	WO - VT -7	7500	1	625
				WO - VT -1	~~3450~~	1	~~288~~	WO - VT -8	8210	1	684
				WO - VT -5	5410	1	451				
					AVERAGE		460		AVERAGE		699

* See ASTM C76. If failure initiates in the tension face of the Middle 1/3 **enter 1.** If failure initaites in the tension face outside of the middle 1/3 by more than 0.9" **enter 2**. If failure initiates in the tension face within 0.9" of the middle 1/3 **enter value of "a" in inches**. (a = average distance between line of fracture and the nearest support)

Tolerances for Placement of Tie Bars in Portland Cement Concrete Pavement

Project SD2011-09

Tie Bar Misalignment Type: Vertical Skew (8 Specimens) Testing by: SDSU, Walker Olson

Concrete:

Supplier:	GCC Ready Mix
Mix Design:	Well Graded PCCP
Quantity (yd^3):	4.5
W/C Ratio:	0.39
Pouring Date:	Tuesday, May 13, 2014
Pouring Time:	3:00
Curing Method:	Wet burlap

FRESH CONCRETE PROPERTIES:

	Measured	Allowable
Air Temp. (°F)	50	-
Concrete Temp. (°F)	63	-
Unit Weight (lb/ft^3)	-	143 .1 lb/ft^3
Slump (in)	2.75	2" to 3"
% Air Content	5	5.0 to 7.5%

Cylinders:

Group Number:	WO - VS
Number of Cylinders:	18
Cylinder Diameter (in):	6.0
Cylinder Length (in):	12.0

Beams:

Group Number:	WO - VS
Number of Beams:	8
Beam width/height (in):	6.0
Span Length (in):	18.0

HARDENED CONCRETE PROPERTIES:

Compressive Strength	3 - Day	4383	psi
	7 - Day	5261	psi
	28 - Day	6216	psi
Tensile Strength	3 - Day	-	psi
	7 - Day	478	psi
	28 - Day	567	psi
Flexural Strength	3 - Day	-	psi
	7 - Day	644	psi
	28 - Day	738	psi
Modulus of Elasticity	3 - Day	-	psi
	7 - Day	4.59E+06	psi
	28 - Day	4.89E+06	psi
Average Concrete Unit Weight		147.0	pcf

Compressive Strength (ASTM C39-14):

Loading Rate: 35 psi/sec (35 ± 7 psi/sec = 989.6 ± 197.9 lb/sec)

3 - Day: Friday, May 16, 2014			7 - Day: Tuesday, May 20, 2014			28 - Day: Tuesday, June 10, 2014		
Sample number	Modulus of Elasticity (ksi)	Compressive Strength (psi)	Sample number	Modulus of Elasticity (psi)	Compressive Strength (psi)	Sample number	Modulus of Elasticity (psi)	Compressive Strength (psi)
WO - VS -1		4268	WO - VS -7	4.71E+06	5453	WO - VS -14	4.84E+06	6201
WO - VS -2		4552	WO - VS -5	4.53E+06	5420	WO - VS -15	5.02E+06	6324
WO - VS -3		4328	WO - VS -6	~~9.42E+06~~	5146	WO - VS -13	4.82E+06	6124
			WO - VS -8	4.54E+06	5026			
AVERAGE		4383	AVERAGE	4.59E+06	5261	AVERAGE	4.89E+06	6216

Split Tensile Strength (ASTM C496):

Loading Rate: 150 psi/min (100 to 200 psi/min)

3 - Day: Friday, May 16, 2014			7 - Day: Tuesday, May 20, 2014			28 - Day: Tuesday, June 10, 2014		
Sample number	Ultimate Load (lb)	Tensile Strength (psi)	Sample number	Ultimate Load (lb)	Tensile Strength (psi)	Sample number	Ultimate Load (lb)	Tensile Strength (psi)
			WO - VS -10	53340	472	WO - VS -17	61910	547
			WO - VS -9	51630	457	WO - VS -16	63340	560
			WO - VS -11	61210	541	WO - VS -18	67040	593
			WO - VS -12	50250	444			
				AVERAGE	478		AVERAGE	567

Flexural Strength (ASTM C78):

Loading Rate: 1800 lb/min (1500 - 2100 lb/min)

3 - Day: Friday, May 16, 2014				7 - Day: Tuesday, May 20, 2014				28 - Day: Tuesday, June 10, 2014			
Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)	Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)	Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
				WO - VS -4	7490	1	624	WO - VS -3	8420.00	1	702
				WO - VS -1	8130	1	678	WO - VS -5	9370.00	1	781
				WO - VS -2	7560	1	630	WO - VS -6	8790.00	1	733
					AVERAGE		644		AVERAGE		738

* See ASTM C76. If failure initiates in the tension face of the Middle 1/3 **enter 1.** If failure initaites in the tension face outside of the middle 1/3 by more than 0.9" **enter 2**. If failure initiates in the tension face within 0.9" of the middle 1/3 **enter value of "a" in inches**. (a = average distance between line of fracture and the nearest support)

Tolerances for Placement of Tie Bars in Portland Cement Concrete Pavement

Project SD2011-09

Tie Bar Misalignment Type: Lateral Translation (8 Specimens)

Testing by: SDSU, Walker Olson

Concrete:

Supplier:	GCC Ready Mix
Mix Design:	Well Graded PCCP
Quantity (yd^3):	4.5
W/C Ratio:	0.399
Pouring Date:	Thursday, May 22, 2014
Pouring Time:	3:00
Curing Method:	Wet burlap

FRESH CONCRETE PROPERTIES:

	Measured	Allowable
Air Temp. (°F)	72	-
Concrete Temp. (°F)	81	-
Unit Weight (lb/ft^3)	-	143 .1 lb/ft^3
Slump (in)	2.75	2" to 3"
% Air Content	5.7	5.0 to 7.5%

Cylinders:

Group Number:	WO - LT
Number of Cylinders:	18
Cylinder Diameter (in):	6.0
Cylinder Length (in):	12.0

Beams:

Group Number:	WO - LT
Number of Beams:	8
Beam width/height (in):	6.0
Span Length (in):	18.0

HARDENED CONCRETE PROPERTIES:

Compressive Strength	3 - Day	4297	psi
	7 - Day	5241	psi
	28 - Day	6320	psi
Tensile Strength	3 - Day	-	psi
	7 - Day	490	psi
	28 - Day	553	psi
Flexural Strength	3 - Day	-	psi
	7 - Day	502	psi
	28 - Day	608	psi
Modulus of Elasticity	3 - Day	-	psi
	7 - Day	4.79E+06	psi
	28 - Day	4.32E+06	psi
Average Concrete Unit Weight		145.3	pcf

Compressive Strength (ASTM C39-14):

Loading Rate: 35 psi/sec (35 ± 7 psi/sec = 989.6 ± 197.9 lb/sec)

3 - Day: Sunday, May 25, 2014

Sample number	Modulus of Elasticity (ksi)		Compressive Strength (psi)
WO - LT -1			4373
WO - LT -2			4247
WO - LT -3			4271
AVERAGE			4297

7 - Day: Thursday, May 29, 2014

Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - LT -6	4.65E+06		5237
WO - LT -8	4.74E+06		5243
WO - LT -4	4.99E+06		5243
AVERAGE	4.79E+06		5241

28 - Day: Thursday, June 19, 2014

Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - LT -5	4.49E+06		6190
WO - LT -9	4.72E+06		6460
WO - LT -11	3.38E+06		6426
WO - LT -12	4.70E+06		6204
AVERAGE	4.32E+06		6320

Split Tensile Strength (ASTM C496):

Loading Rate: 150 psi/min (100 to 200 psi/min)

3 - Day: Sunday, May 25, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)

7 - Day: Thursday, May 29, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)
WO - LT -17	55530		491
WO - LT -16	62560		553
WO - LT -15	48290		427
WO - LT -18	55180		488
	AVERAGE		490

28 - Day: Thursday, June 19, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)
WO - LT -7	62690		554
WO - LT -13	61660		545
WO - LT -10	60930		539
WO - LT -14	64960		574
	AVERAGE		553

Flexural Strength (ASTM C78):

Loading Rate: 1800 lb/min (1500 - 2100 lb/min)

3 - Day: Sunday, May 25, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)

7 - Day: Thursday, May 29, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
WO - LT -4	6640	1	553
WO - LT -3	5340	1	445
WO - LT -2	6100	1	508
	AVERAGE		502

28 - Day: Thursday, June 19, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
WO - LT -1	7030	1	586
WO - LT -5	7540	1	628
WO - LT -6	6860	1	572
WO - LT -7	6800	1	567
WO - LT -8	8260	1	688
	AVERAGE		608

* See ASTM C76. If failure initiates in the tension face of the Middle 1/3 **enter 1.** If failure initaites in the tension face outside of the middle 1/3 by more than 0.9" **enter 2**. If failure initiates in the tension face within 0.9" of the middle 1/3 **enter value of "a" in inches**. (a = average distance between line of fracture and the nearest support)

Tolerances for Placement of Tie Bars in Portland Cement Concrete Pavement

Project SD2011-09

Tie Bar Misalignment Type: Horizontal Skew (8 Specimens)

Testing by: SDSU, Walker Olson

Concrete:

Supplier:	GCC Ready Mix
Mix Design:	Well Graded PCCP
Quantity (yd^3):	4.5
W/C Ratio:	0.402
Pouring Date:	Tuesday, June 03, 2014
Pouring Time:	1:00
Curing Method:	Wet burlap

FRESH CONCRETE PROPERTIES:

	Measured	Allowable
Air Temp. (°F)	67	-
Concrete Temp. (°F)	80	-
Unit Weight (lb/ft^3)	-	143 .1 lb/ft^3
Slump (in)	2.75	2" to 3"
% Air Content	6.7	5.0 to 7.5%

Cylinders:

Group Number:	WO - HS
Number of Cylinders:	18
Cylinder Diameter (in):	6.0
Cylinder Length (in):	12.0

Beams:

Group Number:	WO - HS
Number of Beams:	8
Beam width/height (in):	6.0
Span Length (in):	18.0

HARDENED CONCRETE PROPERTIES:

Compressive Strength	3 - Day	4103	psi
	7 - Day	5297	psi
	28 - Day	6384	psi
Tensile Strength	3 - Day	-	psi
	7 - Day	488	psi
	28 - Day	563	psi
Flexural Strength	3 - Day	-	psi
	7 - Day	486	psi
	28 - Day	766	psi
Modulus of Elasticity	3 - Day	-	psi
	7 - Day	4.44E+06	psi
	28 - Day	4.51E+06	psi
Average Concrete Unit Weight		83.7	pcf

Compressive Strength (ASTM C39-14):

Loading Rate: 35 psi/sec (35 ± 7 psi/sec = 989.6 ± 197.9 lb/sec)

3 - Day: Friday, June 06, 2014

Sample number	Modulus of Elasticity (ksi)		Compressive Strength (psi)
WO - HS -1			4044
WO - HS -2			4053
WO - HS -3			4213
AVERAGE			4103

7 - Day: Tuesday, June 10, 2014

Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - HS -4	4.59E+06		5453
WO - HS -6	4.34E+06		5097
WO - HS -5	4.40E+06		5341
AVERAGE	4.44E+06		5297

28 - Day: Tuesday, July 01, 2014

Sample number	Modulus of Elasticity (psi)		Compressive Strength (psi)
WO - HS	4.56E+06		6570
WO - HS	4.68E+06		6627
WO - HS	4.50E+06		6293
WO - HS	4.28E+06		6046
AVERAGE	4.51E+06		6384

* See ASTM C39 for the 6 typical failure types.

Split Tensile Strength (ASTM C496):

Loading Rate: 150 psi/min (100 to 200 psi/min)

3 - Day: Friday, June 06, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)

7 - Day: Tuesday, June 10, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)
WO - HS -13	51960		459
WO - HS -12	58270		515
WO - HS -15	55480		491
	AVERAGE		488

28 - Day: Tuesday, July 01, 2014

Sample number	Ultimate Load (lb)		Tensile Strength (psi)
WO - HS	63100		558
WO - HS	63230		559
WO - HS	64610		571
	AVERAGE		563

Flexural Strength (ASTM C78):

Loading Rate: 1800 lb/min (1500 - 2100 lb/min)

3 - Day: Friday, June 06, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)

7 - Day: Tuesday, June 10, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
WO - HS -1	5690	1	474
WO - HS -2	5580	1	465
WO - HS -3	6220	1	518
	AVERAGE		486

28 - Day: Tuesday, July 01, 2014

Sample number	Ultimate Load (lb)	Failure Type*	Modulus of Rupture (psi)
WO - HS	9230.00	1	769
WO - HS	9010.00	1	751
WO - HS	9330.00	1	778
	AVERAGE		766

* See ASTM C76. If failure initiates in the tension face of the Middle 1/3 **enter 1.** If failure initaites in the tension face outside of the middle 1/3 by more than 0.9" **enter 2**. If failure initiates in the tension face within 0.9" of the middle 1/3 **enter value of "a" in inches.** (a = average distance between line of fracture and the nearest support)