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16. Abstract

This project focused on developing alternative rail anchorage systems for the T501 and T203 bridge rail systems. The project considered only epoxy adhesive anchoring systems for each of these railings, for use in repair and retrofit situations. Strength data on the existing T501R "bolt-through" retrofit design is not well-defined. A tested retrofit design for the T203 did not exist at the time of starting this project. During this project, documented data on the strength characteristics of the conventionally anchored T501 and T203 bridge rail systems were obtained. These data were analyzed and used to develop alternate rail anchorage systems for both the T501 and T203 bridge rails. Long-term durability of epoxy anchoring systems was also considered based on information provided by the epoxy adhesive manufacturer.

The retrofit/repair strengths from the dynamic and static testing for both the T501 and the T203 compared very closely to the dynamic and static strengths of the conventionally anchored (As-Is) strengths capacities. In summary, the strengths of the retrofit designs were very close and in some tests exceeded the calculated capacities of the bridge rails. The static strengths were very close to the dynamic 50 millisecond average strengths recorded from the dynamic tests.

The new retrofit/repair designs developed and tested for this project are recommended for implementation for use on any new or existing bridge projects. The use of commercial adhesive anchor systems (Hilti RE 500 Adhesive Anchoring System) was very successful in achieving the strengths needed to adequately anchor the retrofit/repair reinforcement for both the T501 and the T203 bridge rails. The information learned from this project can be used to retrofit and repair other bridge rail designs in the future.

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REPAIR/RETROFIT ANCHORAGE DESIGNS FOR BRIDGE RAILS

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CHAPTER 1. INTRODUCTION

INTRODUCTION

Repair of damaged bridge rails due to vehicular impacts is a common occurrence. These repairs are often extensive and require considerable time, manpower, and other resources. These repairs also expose workers to hazardous work zone conditions. Often it is desirable to retrofit existing bridge structures with different railing systems. There is a need to develop alternative anchorage systems for select Texas Department of Transportation (TxDOT) bridge rails that have acceptable structural performance, yet are easily constructed in the field. It is preferable that a common anchorage system be used for both repair and retrofit applications.

This project focused on developing alternative rail anchorage systems for the TxDOT types T501 and T203 bridge rail systems. The project considered only epoxy adhesive anchoring systems for each of these railings, for use in repair and retrofit situations. Strength data on the existing T501R "bolt-through" retrofit design is not well-defined. A tested retrofit design for the T203 did not exist at the time of starting this project. During this project, documented data on the strength characteristics of the conventionally anchored T501 and T203 bridge rail systems were obtained. Researchers analyzed and used these data to develop alternate rail anchorage systems for both the T501 and T203 bridge rails. Long-term durability of epoxy anchoring systems was also considered. Data obtained from this project can be used to retrofit and repair the T501 and T203 bridge rails, as well as better define the required "bolt-through" forces for the T501R bridge rail.

BACKGROUND

Current American Association of State Highway and Transportation Officials (AASHTO) design requires that bridge rails be designed to withstand a transverse impact force of 54 kips for AASHTO Test Levels 3 and 4. All safety appurtenances located along high-speed roadways must, at a minimum, meet the crash requirements of Test Level 3. The design transverse loading of 54 kips has been determined through research to be the required design transverse loading for bridge rails. The load application heights and lengths vary slightly for each of these test levels. It is very possible that impact forces from errant vehicles exceed this limit under some situations. Depending on the geometry and details of the railing systems, forces that exceed this value can and typically do cause concrete failure in the railing members and even the concrete superstructure supporting the railing system.

The geometry and details of the rail system and the location and magnitude of the impact force determine the amount of impact force transmitted to the rail supporting superstructure. Excessive force transmitted to the rail support superstructure (concrete decking or concrete exterior support beams) from the bridge rail can cause failure in the support superstructure. Repairs made to damaged rail anchorage or rail support superstructure should have sufficient strength to resist the applied loading as stated in the current AASHTO rail loading requirements. Before an acceptable repair can be made, the magnitude and distribution of force to the rail support anchorage and superstructure must be determined. This project focused on determining the magnitude and location of force to the rail anchorage members for two current TxDOT bridge rail systems, the T501 and the T203 concrete bridge rails. These rails were studied so that an acceptable structural repair could be made to rails damaged due to impacts.

Another problem similar to repair of rail anchorage members due to impacts is retrofitting new or modified rails onto existing, undamaged bridge support superstructures. Oftentimes, the existing bridge rail anchorage is incompatible or is deficient in strength. In cases such as this, a retrofit anchorage system into the existing superstructure is required. Like the requirements for a repair, the retrofit anchorage must be sufficient to withstand the transmitted forces from the errant vehicles. These transmitted forces vary, depending on bridge rail geometry, rail anchorage details, and magnitude and location of force to the rail anchorage members. As part of this project, retrofit anchorage designs were studied for both the T501 and T203 TxDOT bridge rails. These repair and retrofit designs considered the use of epoxy anchoring systems and the long-term effects on the use of these epoxy systems.

The current AASHTO *Load Resistance Factor Design (LRFD) Bridge Design Specifications* do not address in detail the design of bridge rail anchorage to the concrete bridge superstructure *(1)*. Section 13, A13.1.2 Anchorages of the *AASHTO LRFD* states the following:

> "The yield strength of anchor bolts for steel railing shall be fully developed by bond, hooks, attachment to embedded plates, or any combination. Reinforcing steel for concrete barriers shall have embedment length sufficient to develop the yield strength."

Depending on the railing geometry and details of the bridge superstructure, designing rail anchorage bolts or reinforcing steel to be fully developed for a specific rail design might be difficult to achieve. For a typical rail location near the edge concrete, concrete shear failure near the edge of the deck may govern the strength of the bridge railing. In addition, the distribution of force to rail anchorage from impact loads can influence the overall strength of the bridge rail system. This project focused the actual distribution of force to the rail anchorage systems for both the T501 and T203 bridge rails with the intent to develop suitable repair and/or retrofit designs for these rails.

OBJECTIVES/SCOPE OF RESEARCH

To accomplish the objectives of this project, the following steps were taken:

- Researchers constructed a full-scale test installation of the T501 and T203 bridge rail systems with a simulated deck overhang for static load testing. The conventional rail anchorage reinforcement for both rails was instrumented with strain gages. Strain generated in the rail anchorage was recorded.

- Researchers constructed a minimum of three full-scale test specimens of the T501 and T203 bridge rails for dynamic testing. Like the static testing, the rail anchorage reinforcement for both rails was instrumented with strain gages. Strain generated in the rail anchorage was recorded during the dynamic testing.

- Based on the data obtained from the static and dynamic testing, Texas Transportation Institute (TTI) worked closely with TxDOT personnel to develop a repair and/or retrofit design for the T501 and T203 bridge rails. The use of epoxy anchoring systems was considered in the repair and/or retrofit designs. Information on the long-term strength of the systems considered was provided by the manufacturers. Analyses were performed on the new designs using the data obtained from the static and dynamic testing. Details were developed for each design and submitted to TxDOT for review and approval. Data obtained from the dynamic testing of the conventional anchored systems can be useful in developing other repair and/or retrofit rail anchorage designs.

- A repair and/or retrofit design was constructed using the previously tested samples for the T501 and T203 bridge rails. Researchers tested these new designs to validate that the strengths of the repair and/or retrofit design were acceptable.

- This project provided TxDOT with a repair and/or retrofit design for both the T501 and T203 bridge rails. These designs will be suitable for implementation into TxDOT Bridge Railing Standards. In addition, valuable data that can be used for further bridge rail design research were obtained from the static and dynamic testing. These data can be used to design other anchorage repair or retrofit designs for these same bridge rails and possibly for other rail types. A detailed description of the work for the specific tasks for this project and the data obtained for implementation is presented herein.

This project was divided into four separate tasks, and a detailed explanation of each task along with the data and results are provided herein.

CHAPTER 2. TASK 1 - STATIC LOAD TESTING OF CONVENTIONALLY ANCHORED T501 AND T203 DESIGNS

TEST ARTICLE DESCRIPTION

Prior to performing static testing on full-scale test installation specimens, analytical calculations were performed on the TxDOT Type T501 and Type T203 bridge rails. These analytical calculations were performed to determine the ultimate resistances of these railing systems with respect to the *AASHTO LRFD*. Strengths were calculated within a wall segment (mid-span case) as well as at the end of a wall segment or joint (end/joint case). The strength results obtained from these calculations are presented in Table 1. The rails used in this project were anchored to 8-inch thick concrete deck specimens similar to decks constructed by TxDOT. The reinforcement was Grade 60 and the concrete strength was specified as Class "S" (4000 psi strength) material. Appendix A presents the analytical calculations from both the T501 and T203 bridge rails.

Table 1. Summary of Analytical Strengths in Accordance with AASHTO *LRFD* Bridge Specifications.

No.	Case	Calculated Conventionally Anchored (AS-IS) Strength (kips)
1	T501 Mid-Span Strength Locations A & B	59.7
2	T501 End/Joint Strength Location C	36.4
3	T203 End/Joint Strength Location D	23.2
4	T203 Mid-Span Strength Locations E & F	71.0

TTI constructed approximately 40 ft of standard T501 bridge rail and 60 ft of T203 bridge rail anchored on top of a 30-inch wide by 8-inch thick concrete deck cantilever constructed adjacent to the runway at the TTI testing facility. This construction effectively simulated the typical deck overhang used on Texas bridges. The concrete deck was anchored into the existing runway with top transverse reinforcement doweled into the existing concrete and spaced approximately 24 inches on centers. The transverse reinforcement in the top layer of reinforcing in the deck cantilever consisted of #5 bars spaced at 6 inches on centers. The longitudinal reinforcement in the top of the deck cantilever consisted of #4 bars spaced approximately 9 inches on centers. The transverse reinforcement in the bottom layer of reinforcing consisted of #5 steel bars spaced at 6 inches on centers. The longitudinal reinforcement in the bottom of the deck consisted of two #5 steel bars on the field side of the deck spaced 3 inches on centers with the next adjacent #5 steel bar spaced approximately 12 inches away, toward the traffic face. All steel reinforcement used in the deck cantilever was bare steel (not epoxy-coated) with minimum specified yield strength of 60 ksi. All concrete for this project was provided by Transit Mix Concrete and Materials in Bryan, Texas. The average compressive strength of the deck cantilever concrete on the day the static tests were performed (51 curing days) was 4465 psi.

The TxDOT T501 bridge rail installation was 32 inches in height. Reinforcement in the T501 installation consisted of vertical V-shaped #5 bars ("S" bars) spaced at 10 inches on centers with the three bars located at the end of the rail spaced 6 inches apart. The S bars did not extend into the concrete foundation. Longitudinal reinforcement in the rail consisted of seven #4 bars approximately evenly spaced with a single bar located at the top of the wall immediately beneath the S bars. The T501 installation was anchored to the deck cantilever with #5 U-shaped bars cast in the deck. The concrete used to construct the T501 installation had an average concrete compressive strength of 3914 psi (28 days after construction) at the time of testing.

The TxDOT T203 bridge rail consists of a 1 ft-1.50 inch × 1 ft-2 inch concrete bridge rail supported by 7.50 inch thick × 5 ft-0 inch wide concrete posts spaced every 10 ft-0 inch on centers. Vertical reinforcement in each post consists of 13 #4 L-shaped bars spaced on the front face (traffic side) and five straight #4 bars spaced on the back face (field side). Longitudinal reinforcement in each post consisted of a #4 bar located on the front and back faces. Reinforcement in the rail consisted of three longitudinal #4 bars equally spaced on both the front and back faces of the rail and one bar located in the top center of the rail (seven total). This longitudinal reinforcement was enclosed by #3 stirrups spaced at 6 inches on centers. All the reinforcement used in the bridge rail was bare steel (not epoxy-coated), with a minimum specified yield strength of 60 ksi. All the remaining steel reinforcement in the posts and in the bridge rail was bare steel. Concrete for this project was provided by Transit Mix Concrete and Materials in Bryan, Texas. The average compressive strength of the concrete on the day the static tests were performed (42 curing days) was 4162 psi. Figures 1 through 4 show details of the test installation.

Single-active-arm strain gages were constructed on several U bars in the T501 and several V bars in the T203 posts. These gages were used to measure the amount of strain in the reinforcement from static and dynamic loading on the barrier types. The amount of measured strain was used to compute force in each bar from the static and dynamic testing. Locations of the strain gages are shown on the test installation drawings in Appendix B.

STATIC TEST RESULTS

T203 Static Testing

Three static tests were performed on the T203 bridge rail test installation. Two tests were performed within a wall (or rail) segment, as defined by the AASHTO *LRFD*, and one test was performed near the end of the rail at a wall segment. Eight #4 V bars in each of the three posts tested were instrumented with single-active-arm bridge strain gages (one strain gage per bar). These V bars are used to reinforce the posts. Also, these bars anchor the T203 bridge rail to the concrete deck. The static loading was applied by a hydraulic arm at a rate of approximately 30 kips per minute. The loading was applied near the top of the rail over a length of 3 ft-6 inches. This length is based on the longitudinal length of distribution of impact force as stated in the current AASHTO *LRFD*. This longitudinal length of 3 ft-6 inches of load distribution was used throughout the course of this project, including the dynamic testing. During the loading, the strain in the V bars was recorded for the purpose of determining the forces generated in the #5 V bars.

The first two tests were performed within a wall (post) segment of the T203. During these first two static tests, loads of 73,000 lb and 72,000 lb were achieved just prior to lateral shear and flexural failure in the rail and post in the immediate area of the applied loading. For the third test on the T203, which was performed near the end of the rail, a load of 33,000 lb was achieved. The failure mechanism for this test included failure of the smaller end post in flexure at the post and deck interface as well as flexural failure in the rail at the face of the next adjacent full post. Appendix B presents data from these tests.

T501 Static Testing

Three static tests were performed on the T501 bridge rail test installation. Two tests were performed within a wall segment, as defined by the AASHTO *LRFD*, and one test was performed near the end of a wall segment or joint. Eight #5 U bars closest to the applied loading were instrumented with single-active-arm bridge strain gages (one strain gage per bar). These U bars are used as the rail anchorage reinforcement for the T501 bridge rail. The static loading was applied by a hydraulic arm at a rate of approximately 30 kips per minute. The loading was applied near the top of the rail over a uniform length of 3 ft-6 inches. During the loading, the strain in the U bars in the immediate area of applied loading was recorded for the purpose of determining the forces generated in the anchorage reinforcement.

The first two tests on the T501 were performed within a wall segment. During these first two static tests on the T501, loads of 67,000 lb and 75,000 lb were achieved just prior to lateral shear. Flexural failure occurred in the rail in the immediate area of the applied loading. For the third test on the T501, which was performed near the end of the wall segment, a load of 40,000 lb was achieved. The failure mechanism in the end of the wall segment resulted in a flexural failure (diagonal cracking) extending at the base of the rail near the end upwards to the top of the rail at an approximate angle of 45 degrees. Data from these tests are also presented in Appendix B.

A typical setup of the static testing load frame is presented as Figure 5. A summary of the static testing data obtained for the T203 and T501 bridge rails is presented in Table 2. Photos of the static testing are presented as Figures 6 to 11.

Table 2. Summary of T203 and T501 Static Strengths.

No.	Case	Static Strength Conventionally Anchored Design (kips)
1	T501 Mid-Span Location A	66.0
2	T501 Mid-Span Location B	75.0
3	T501 End/Joint Location C	41.0*
4	T203 End/Joint Location D	33.0*
5	T203 Mid-Span Location E	72.0
6	T203 Mid-Span Location F	73.5

* - Less Than Required Minimum of 54 Kips

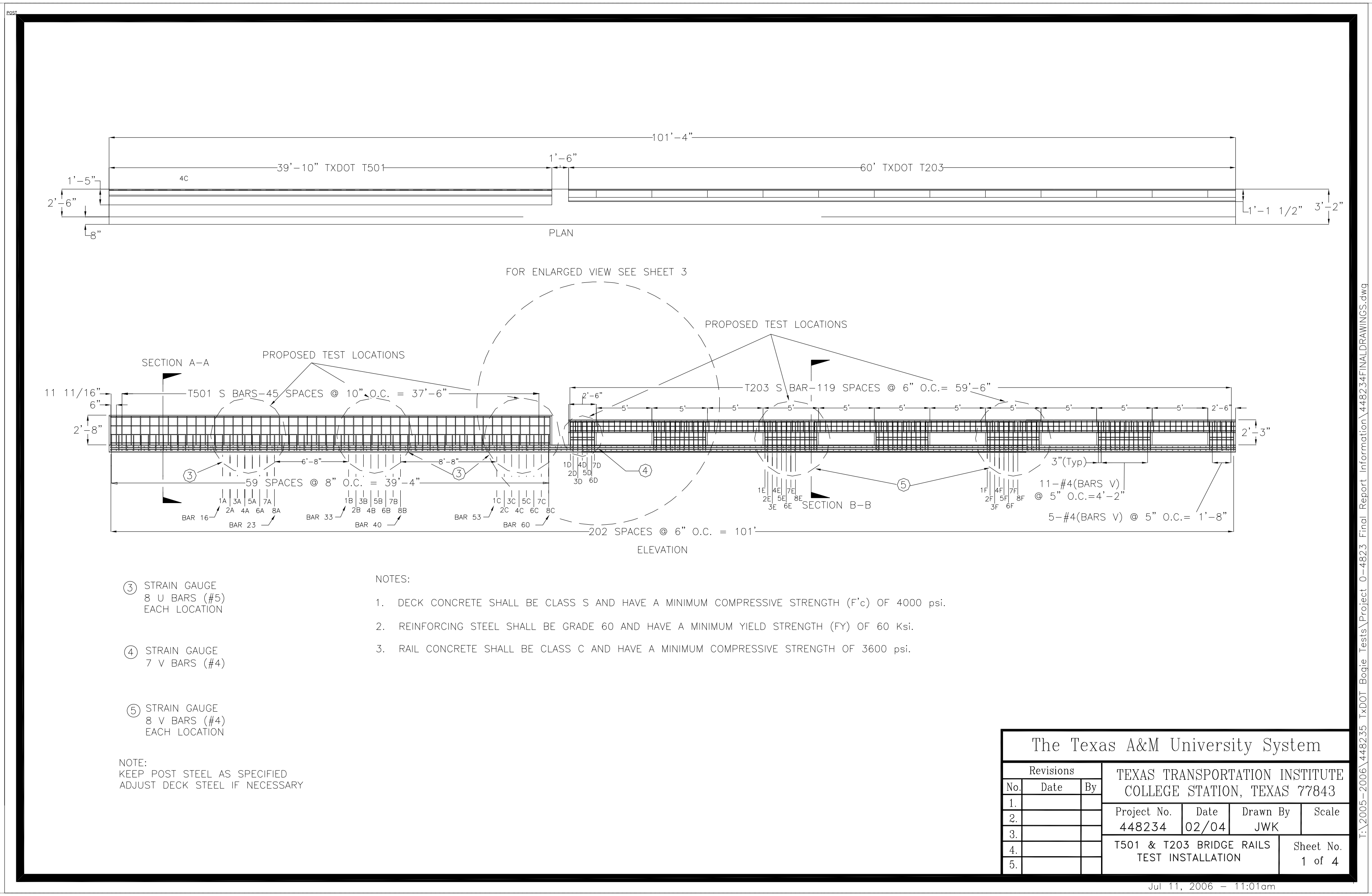


Figure 1. Layout of Test Sections.

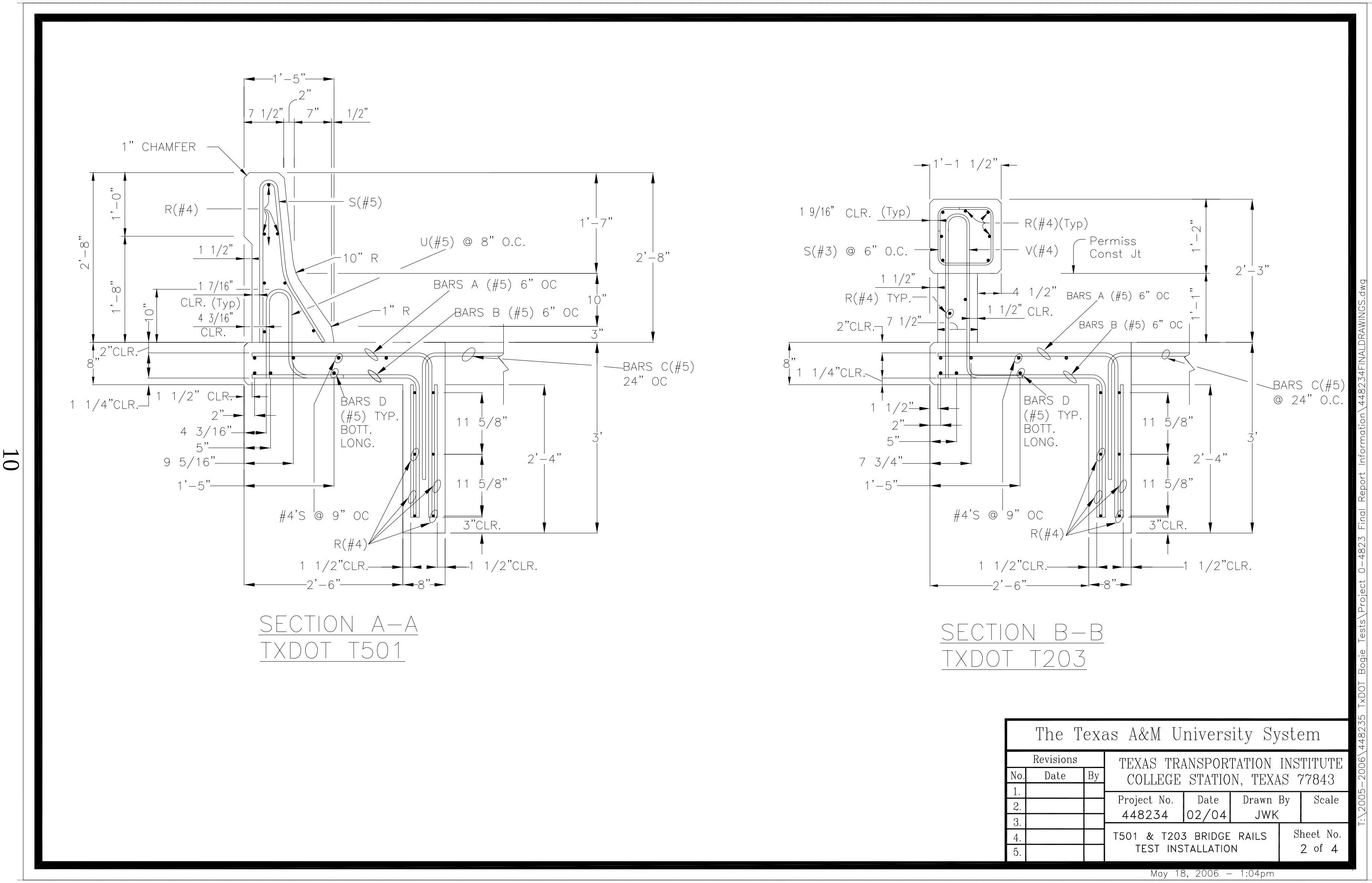


Figure 2. Cross Section of Test Sections.

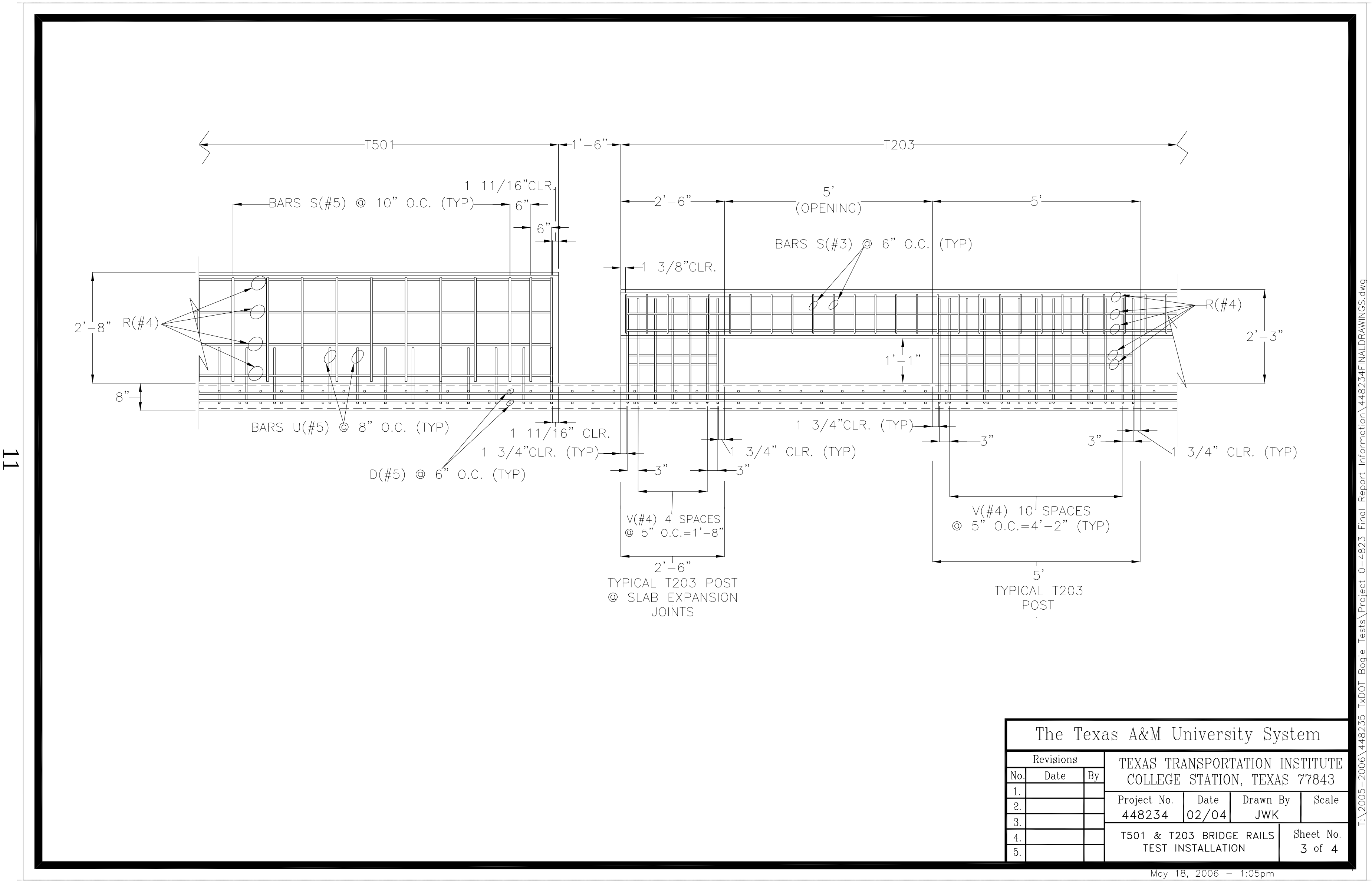


Figure 3. Details of Reinforcement Placement in Test Sections.

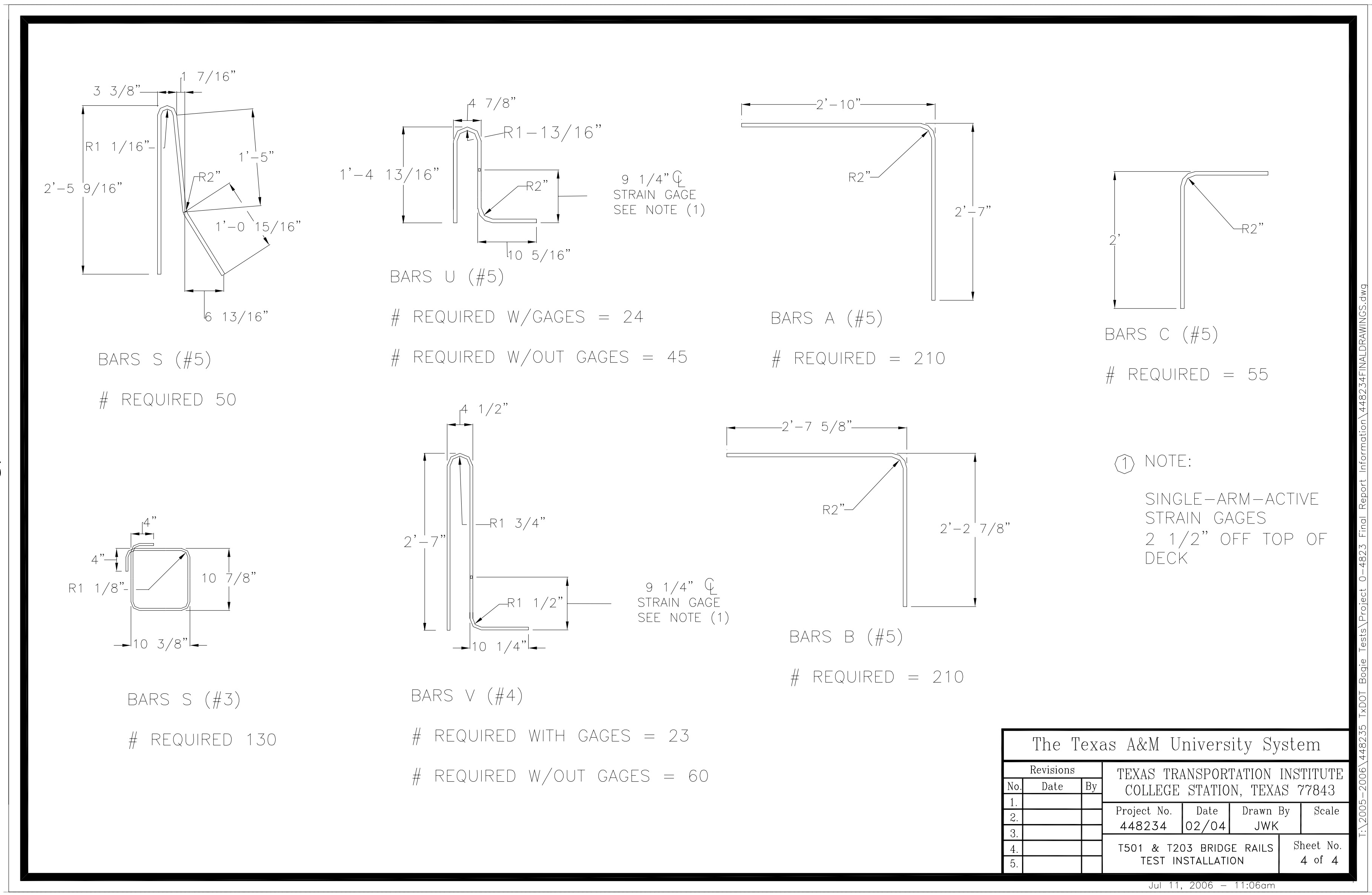


Figure 4. Reinforcement Bending Details.

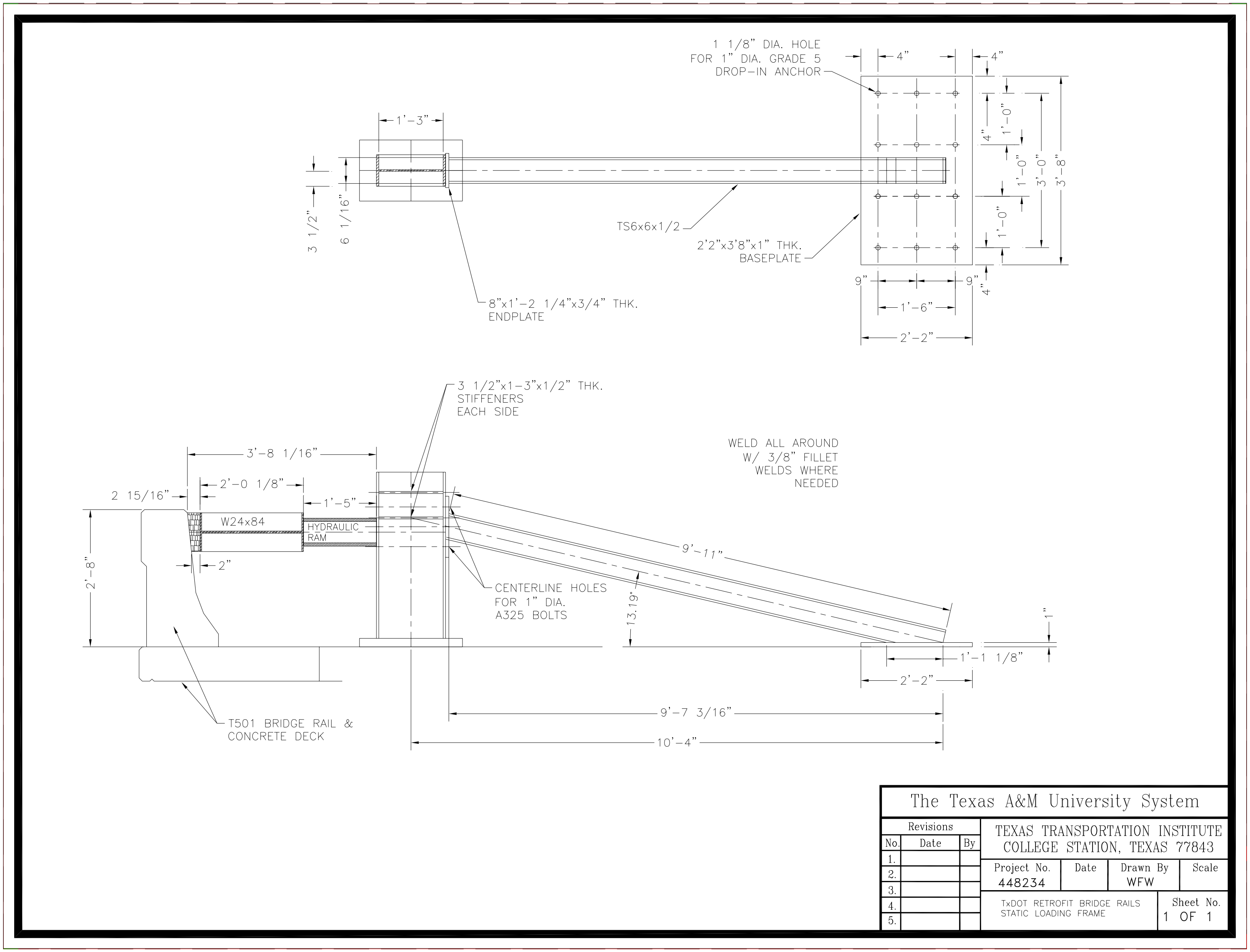


Figure 5. Details of Static Load Frame.

Figure 6. Bridge Rail T203 at Location F after Test S1.

Figure 7. Bridge Rail T203 at Location E after Test S2.

Figure 8. Bridge Rail T203 at Location D after Test S3.

Figure 9. Bridge Rail T501 at Location A after Test S4.

Figure 10. Bridge Rail T501 at Location B after Test S5.

Figure 11. Bridge Rail T501 at Location C after Test S6.

CHAPTER 3. TASK 2 - DYNAMIC LOAD TESTING OF CONVENTIONALLY ANCHORED T501 AND T203 DESIGNS

TEST ARTICLE DESCRIPTION

After the testing in Task 1 was completed, the test installations for both the T203 and the T501 were reconstructed as previously described for Task 1 for dynamic load testing planned for Task 2. This included reconstructing the strain gages on the T203 V bars as well as the T501 U bars. All concrete for this project was provided by Transit Mix Concrete and Materials in Bryan, Texas. The average compressive strength of the deck cantilever concrete on the day the static tests were performed was 4801 psi. The average compressive strength of the T501 and T203 bridge rail concrete was 4380 psi. The average compressive strength of the T203 post concrete was 7033 psi. This strength is considerably higher the targeted strength, however, the influence of this higher post strength was not considered to greatly impact the overall strength of bridge rail. Please refer to Figures 1 through 4 for additional information.

DYNAMIC TESTING USING CRUSHABLE NOSE BOGIE

For this project, a crushable nose for a surrogate vehicle was designed, tested, and implemented. Dynamic testing of bridge rail specimens typically provides more realistic strain rate in the anchoring reinforcement when compared to static testing. The surrogate vehicle (bogie) consisted of a steel frame with a fixed rear axle and a front stirring axle. The crushable nose was designed using three segments of 12-inch diameter, Schedule 40, A53 Pipe, each 8.0 inches in length. The combined crush strength of these three segments was approximately 100 kips when fully crushed. This crush strength and pipe crush combination was selected for the bogie since the adequate crush could be achieved while imparting significant force to cause failure in the bridge rails. Dynamic testing with some energy absorbing crush in the surrogate was necessary to obtain accurate acceleration data from the vehicle. Without some crush in the surrogate vehicle, extremely high acceleration values (spikes) would be obtained from the dynamic testing. In addition, the combined crush of the pipe segments provided energy data to accurately determine the speed of the bogie necessary to impart enough force to fracture the barrier segments. Additional weight was added to the bogie to achieve a final testing weight (with crushable nose mechanism) of 5000 lb. Details of the crushable nose mechanism are presented as Figure 12. Photos of the bogie with crushable nose are presented as Figure 13.

DYNAMIC TEST RESULTS

T203 Dynamic Testing

Three dynamic bogie tests were performed on the T203 bridge rail test specimens. Two tests were performed at post locations within a wall segment (mid-span of a section), as defined by the AASHTO *LRFD*, and one test was performed near the end of the rail at a wall segment. Eight #4 V bars in each of the two posts tested were instrumented with single-active-arm bridge strain gages (one strain gage per bar). These V bars are used to reinforce the posts, as well as anchor the T203 bridge rail to the concrete deck. The impact force was applied near the top of the rail over a length of 3 ft-6 inches. This length is based on the longitudinal length of distribution of impact force as stated in the current AASHTO *LRFD*. The magnitude of the force applied was sufficient to cause failure in the concrete rail. During the dynamic loading, the strain in the V bars was recorded for the purpose of determining the forces generated in these bars which serve to anchor the rail to the concrete deck.

During the first test, the concrete beam cracked to the left of impact, with hairline cracks extending into the deck. The same pattern occurred during the second test; however, it cracked to the right side of impact. During the third test, which was near the end of the rail, the post rotated toward the field side with rupture of the beam on both sides of impact and hairline cracks extending into the deck. Data from the dynamic testing are presented in Appendix C.

T501 Dynamic Testing

Three dynamic bogie tests were performed on the T501 bridge rail test installation. Like the dynamic testing performed on the T203, two tests were performed within a wall segment (mid-span of a segment), as defined by the AASHTO *LRFD*, and one test was performed near the end of a wall segment or joint. Eight #5 U bars closest to the applied loading were instrumented with single-active-arm-bridge strain gages (one strain gage per bar). These U bars are used as the rail anchorage reinforcement for the T501 bridge rail. The dynamic impact loading applied was sufficient to cause failure of the impacted rail element. The loading was applied near the top of the rail over a length of 3 ft-6 inches. During the loading, the strain in the U bars in the immediate area of applied loading was recorded for the purpose of determining the forces generated in the anchorage reinforcement from the dynamic impact force applied to the rail.

During the first two dynamic tests on the T501, the bridge rail fractured fairly uniformly on both sides of impact with hairline cracks extending into the deck. For the third dynamic test on the T501, which was near the end of the rail, the bridge rail ruptured primarily on the left side of impact, with a 33.5-inch section ruptured on the field side of the rail. Some hairline cracks extended into the deck.

Appendix C presents data from the dynamic testing. The dynamic testing strengths compared very closely to the static strengths for both rail types. A summary of the dynamic testing data obtained for the T203 and T501 bridge rails is presented in Table 3. Photos of the dynamic testing are presented in Figures 14 through 19.

Table 3. Summary of T203 and T501 Dynamic Strengths.

No.	Case	Dynamic Strength Conventionally Anchored Design 50 millisecond Avg. (kips)
1	T501 Mid-Span Location A	66.0
2	T501 Mid-Span Location B	70.0
3	T501 End/Joint Location C	46.0
4	T203 End/Joint Location D	N/A
5	T203 Mid-Span Location E	72.0
6	T203 Mid-Span Location F	70.0

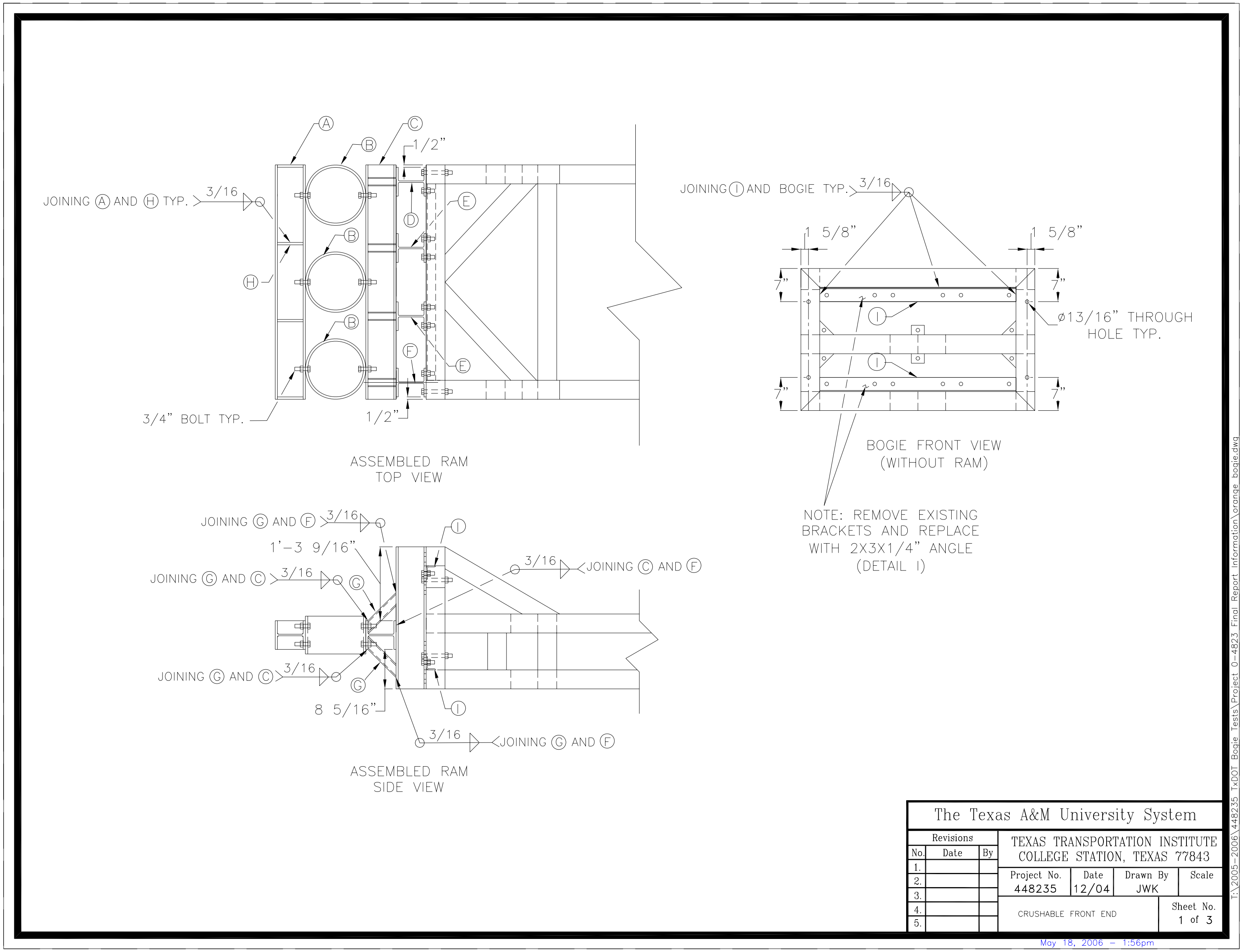


Figure 12. Details of the Crushable Nose Bogie.

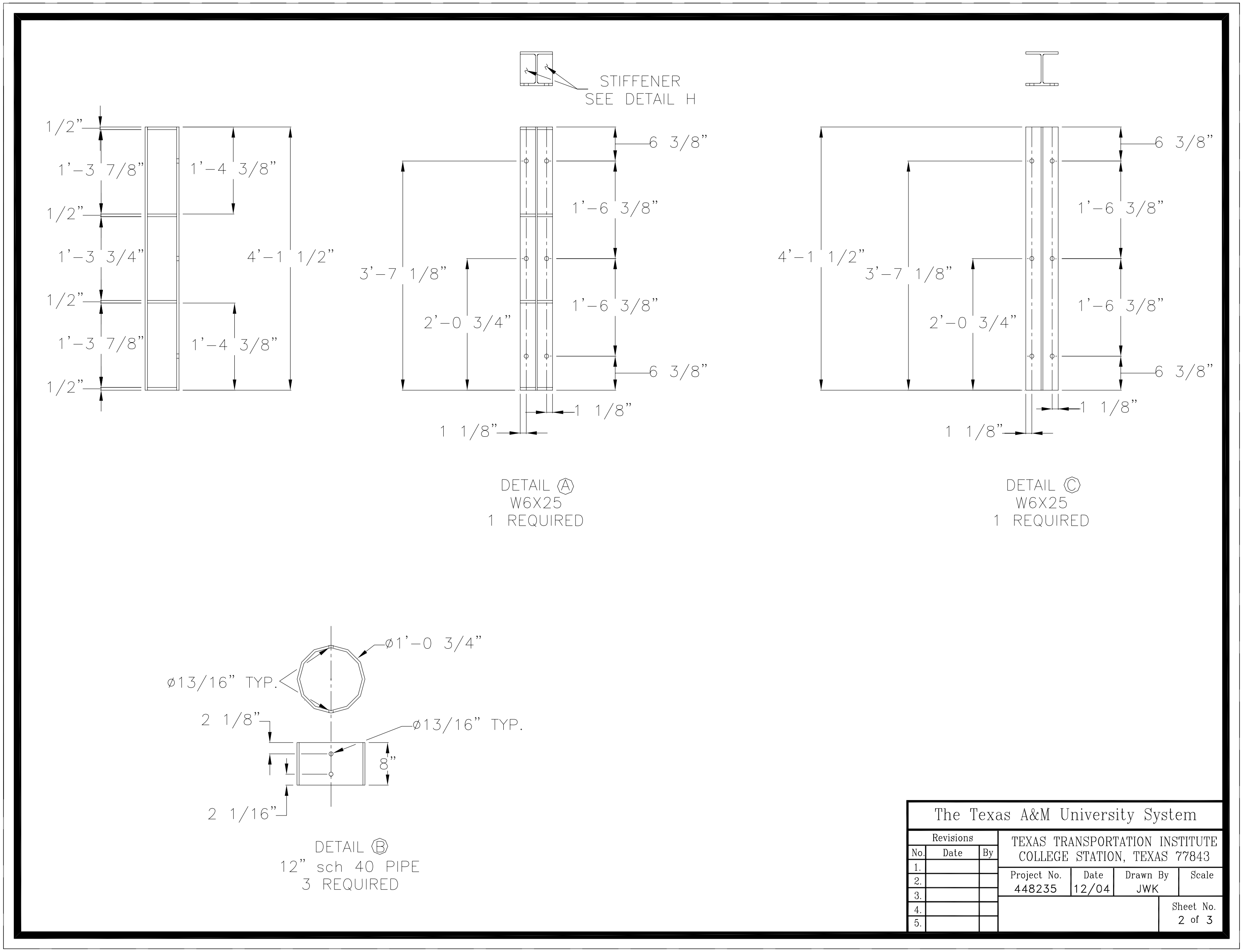


Figure 12. Details of the Crushable Nose Bogie (continued).

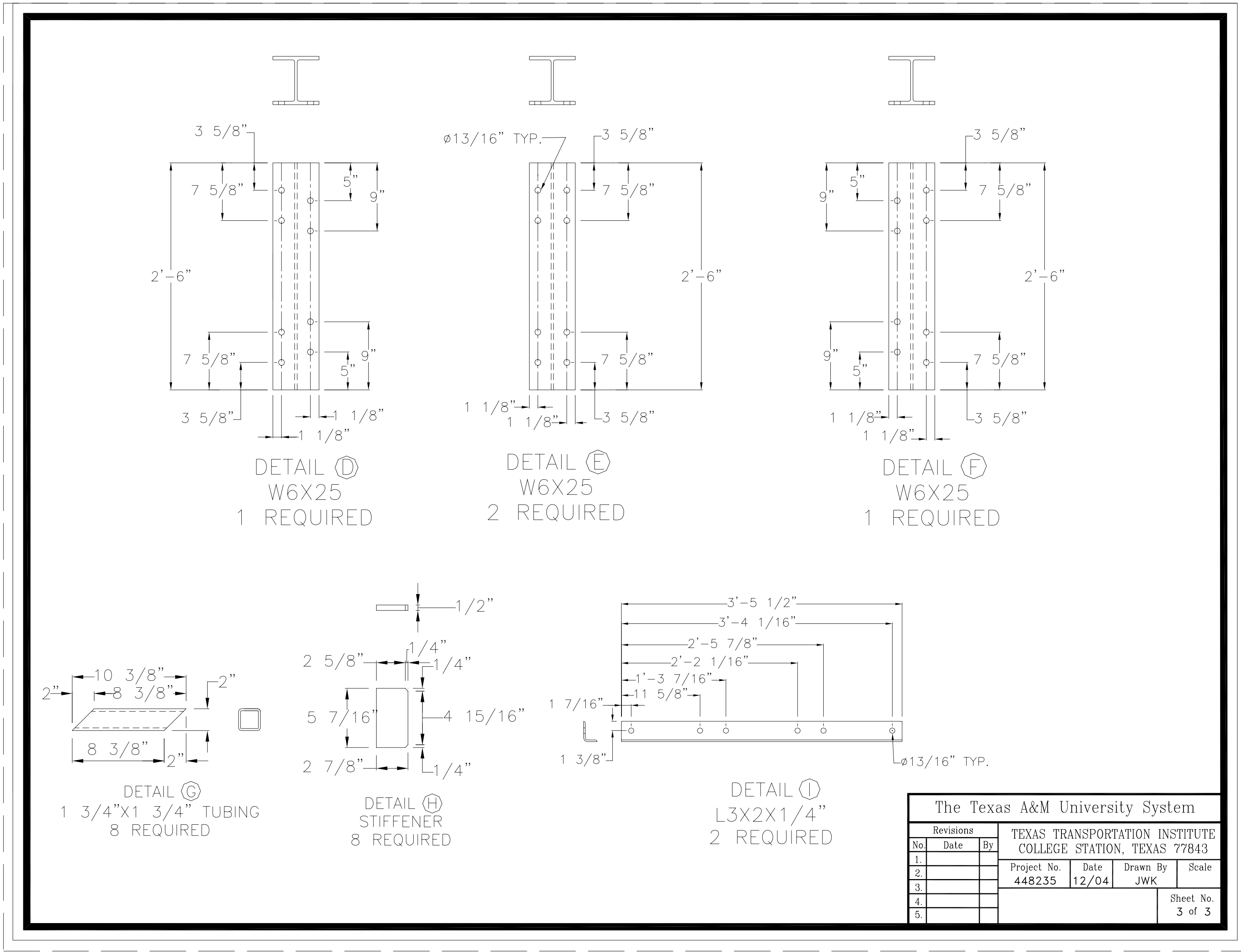


Figure 12. Details of the Crushable Nose Bogie (continued).

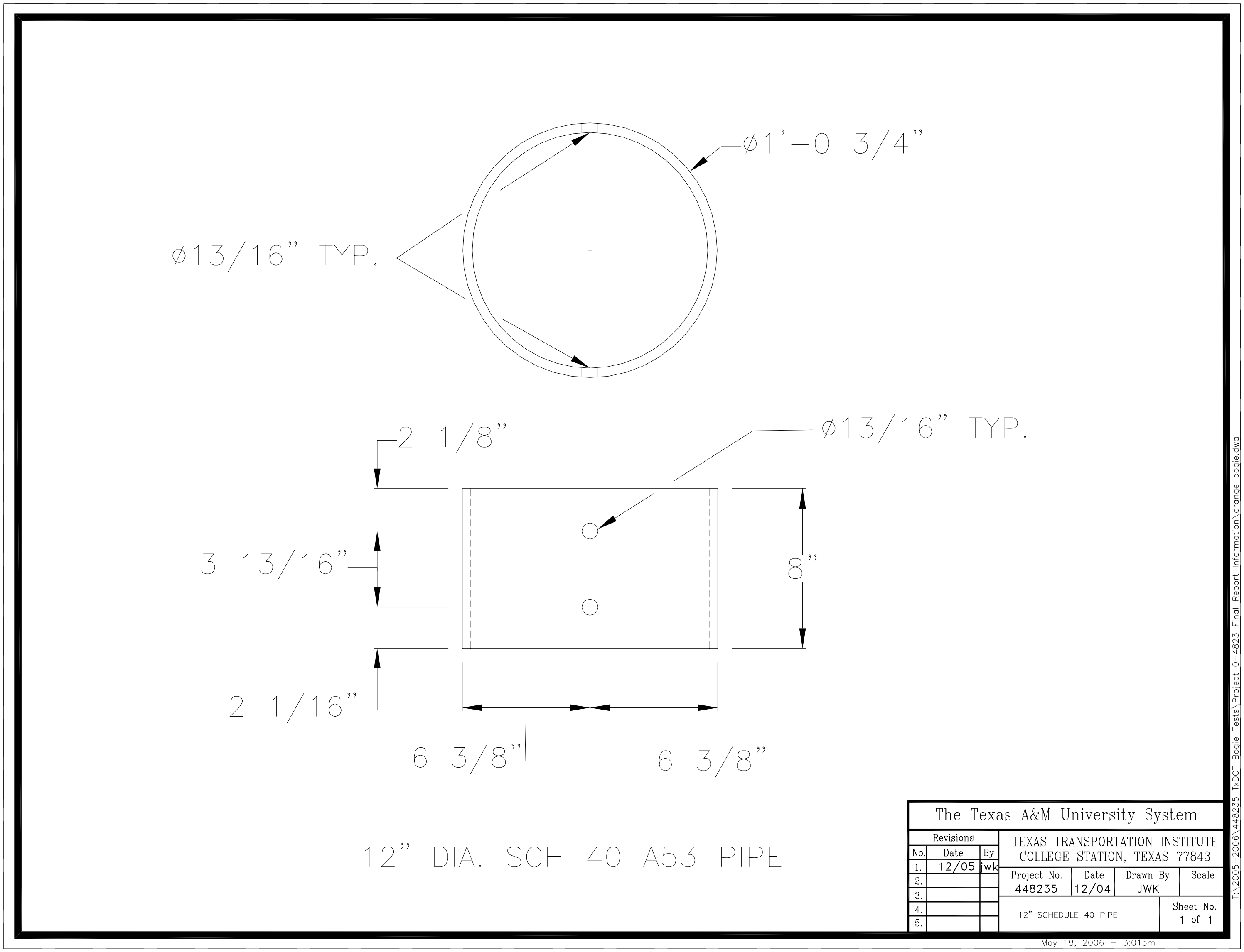


Figure 12. Details of the Crushable Nose Bogie (continued).

Figure 13. Bogie Vehicle Used in Dynamic Load Testing.

Figure 14. Bridge Rail T203 at Location F after Test B1.

Figure 15. Bridge Rail T203 at Location D after Test B2.

Figure 16. Bridge Rail T203 at Location E after Test B3.

Figure 17. Bridge Rail T501 at Location A after Test B4.

Figure 18. Bridge Rail T501 at Location B after Test B5.

Figure 19. Bridge Rail T501 at Location C after Test B6.

CHAPTER 4. TASK 3 - T501 RETROFIT/REPAIR

After completion of the two previous tasks, TTI personnel met with the TxDOT project team to define the retrofitting/repair methodology required for the T501 bridge rail. Several different adhesive anchoring systems were considered for this project. Hilti's RE 500 is typical of epoxy adhesive anchoring systems on the commercial market. The RE 500 epoxy adhesive has very good bond strength and curing time. Hilti's RE 500 Adhesive Anchoring System was selected as the preferred anchoring system for this project. After the methodology was defined and the preferred repair and/or retrofitting design was determined, the project supervisor performed engineering analyses on the preferred design using the data obtained in Tasks 1 and 2 and the design data provided by Hilti for the RE 500 Adhesive Anchoring System. Based on the data obtained from the strain gages in the T501 static and dynamic testing, the average tension obtained in the U bars was approximately 10 kips and 12 kips for the mid-span and end/joint cases, respectively. These average forces were used to design the retrofit/repair anchorage for the T501 bridge rail. The effects of temperature and the long-term effects on this adhesive anchoring system were also considered in the design. After these analyses were completed, the analyses were submitted to TxDOT, along with engineering details for the new repair and/or retrofitting details for the T501 bridge rail for review. For the T501 retrofit design, #6 bent dowel bars widely spaced on 16 inches on centers was selected. A #6 bent dowel bar was selected since this anchor type could be easily fabricated and was more cost effective over a fully threaded bar. The #6 bent bar was designed to maximize the anchoring distance (eccentricity) from the field side edge of the barrier to the centerline of the anchors. These retrofit bars were more closely spaced on the ends to achieve a comparative strength for the barrier end/joint case. Appendix D presents calculations and final design details for the T501 retrofit design for both the mid-span and end/joint cases.

TEST ARTICLE DESCRIPTION

After the details were finalized, TTI reconstructed the specimens used in Task 2. The concrete deck was reconstructed with the U bars cast within the concrete deck. Prior to constructing the T501 retrofit bridge rail, these #5 U bars were removed above the deck surface. An acetylene torch was used to remove the portion of the U bars above the concrete deck. After removing the U bars, the T501 was constructed using the proposed retrofit design shown in Figure 20. The new retrofit anchorage design for the T501 consisted of #6 bent bars anchored approximately 11 inches from the field side edge of the 8-inch thick concrete deck. These bars were anchored approximately 5.25 inches into the concrete deck using the Hilti RE 500 Adhesive Anchoring System. Several days after these #6 anchoring bars were installed, the T501 bridge rail was reconstructed similar to previous installations. Reinforcement was not instrumented in this installation. At the time of testing, the average compressive strength of the T501 bridge rail concrete was 3937 psi. The average compressive strength of the deck concrete was 5305 psi. Calculations and details of the T501 retrofit/repair design are presented in Appendix D. Photos of the T501 retrofit installation are presented as Figure 21.

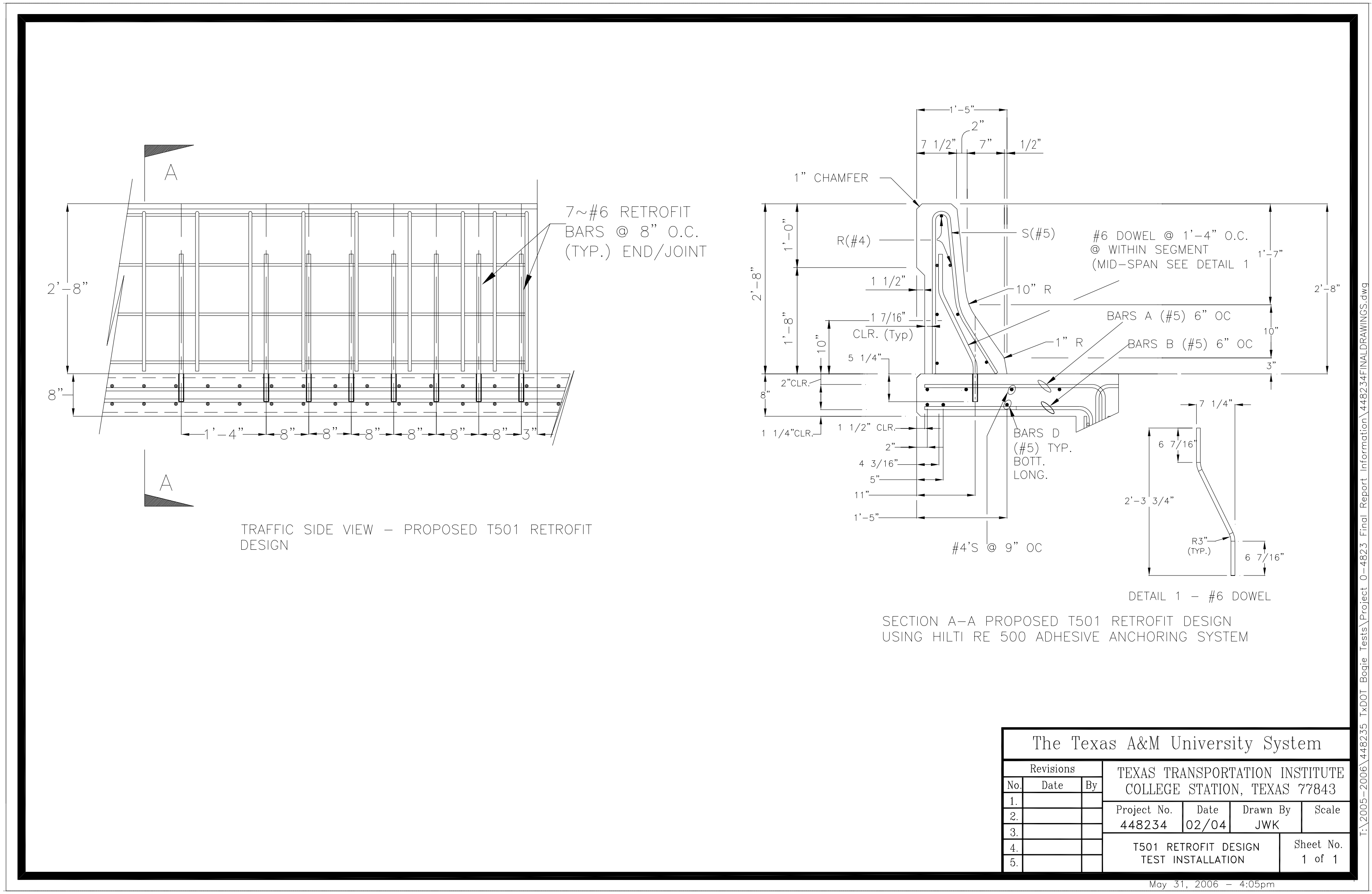


Figure 20. Details of the Retrofit/Repair for the T501 Bridge Rail.

Figure 21. Retrofit/Repair for the T501 Bridge Rail before Testing.

TEST RESULTS

Researchers performed three dynamic bogie tests on the T501 bridge rail test specimens incorporating the proposed repair/retrofit design. Two tests were performed within a wall segment (mid-span case), as defined by the AASHTO *LRFD*, and one test was performed near the end of a wall segment (end/joint case). Like the testing performed in Task 2, the dynamic impacting force was sufficient to cause failure in the impacted rail element. The dynamic loading was applied over a length of 3 ft-6 inches. The results for the T501 repair/retrofit design were compared with the dynamic testing results for the conventionally anchored T501 design tested in Task 1. Dynamic testing on the T501 end consisted of anchoring reinforcement spaced at 1 ft-4 inches on centers similar to the spacing in the middle of the rail segment. The dynamic testing on the T501 end/joint with the #6 bent retrofit bars spaced on 16-inch centers yielded undesirable results. The T501 was reconstructed after the dynamic testing and additional reinforcement was added to improve the performance. The final design consisted of the reinforcement as shown in the preceding details. A static test was performed on the new design for the T501 end/joint anchoring design. The failure modes for the mid-span and end/joint cases using the retrofit designs were very similar to failure modes observed for the static and dynamic testing of conventionally anchored T501 design. Data obtained from the dynamic testing is presented in Appendix E. Photos of the dynamic testing are presented in Figures 22 through 24.

Figure 22. Bridge Rail T501 Retrofit/Repair at Location A after Test B7.

Figure 23. Bridge Rail T501 Retrofit/Repair at Location B after Test B8.

Figure 24. Bridge Rail T501 Retrofit/Repair at Location C.

CHAPTER 5. TASK 4 - T203 RETROFIT/REPAIR

After completion of the three previous tasks, TTI personnel met with the TxDOT project team to define the retrofitting/repair methodology required for the T203 bridge rail. After the methodology was defined and the preferred repair and/or retrofitting design was determined, the project supervisor performed engineering analyses on the preferred design using the data obtained in Tasks 1 and 2 and the design data provided by Hilti for the RE 500 Adhesive Anchoring System. For the T203 static and dynamic testing, the average tension obtained from the strain gages in the #4 V bars was approximately 8 kips and 10 kips, for the mid-span posts and end/joint post, respectively. These average forces were used to design the retrofit/repair anchorage for the T203 bridge rail. The use of epoxy anchoring systems and the long-term effects on these systems was considered in this task. After these analyses were completed, the analyses were submitted to TxDOT, along with engineering details for the new repair and/or retrofitting details for the T203 bridge rail for review. After review of all available data, analyses, and details, TTI worked closely with the TxDOT project team to develop a repair and/or retrofit design for the T203 bridge rail. Calculations and final design details for the T203 retrofit design for both the mid-span posts and end/joint posts are presented in Appendix F.

TEST ARTICLE DESCRIPTION

After the details were finalized, TTI reconstructed/repaired the specimens used in Task 2. Reinforcement was not instrumented in these specimens. The concrete deck was reconstructed with the #4 V bars cast within the concrete deck. Prior to constructing the T203 retrofit bridge rail, these V bars were removed above the deck surface. An acetylene torch was used to remove the portion of the V bars above the concrete deck. After removing the V bars, the T203 was constructed using the proposed retrofit design shown in Figures 25 and 26. The new retrofit anchorage design for the T203 consisted of #5 straight dowel bars anchored approximately 7 inches from the field side edge of the 8-inch thick concrete deck. These #5 retrofit bars were more widely spaced in the retrofit design when compared to the bar size and spacing used in the conventionally anchored design to maximize the pull-out strength using the Hilti RE 500 epoxy adhesive anchoring system. These bars were anchored approximately 5.25 inches into the concrete deck using the Hilti RE 500 Adhesive Anchoring System. After these #5 dowel bars were installed, several days later the T203 posts and bridge rail were reconstructed similar to previous installations. Reinforcement was not instrumented in this installation. At the time of testing, the average compressive strength of the T203 bridge rail concrete was 3937 psi. The average compressive strength of the T203 post concrete was 4887 psi. The average compressive strength of the deck concrete was 5305 psi. Calculations and details of the T203 retrofit/repair design are presented as Appendix F. Photos of the T203 retrofit installation are presented in Figure 27.

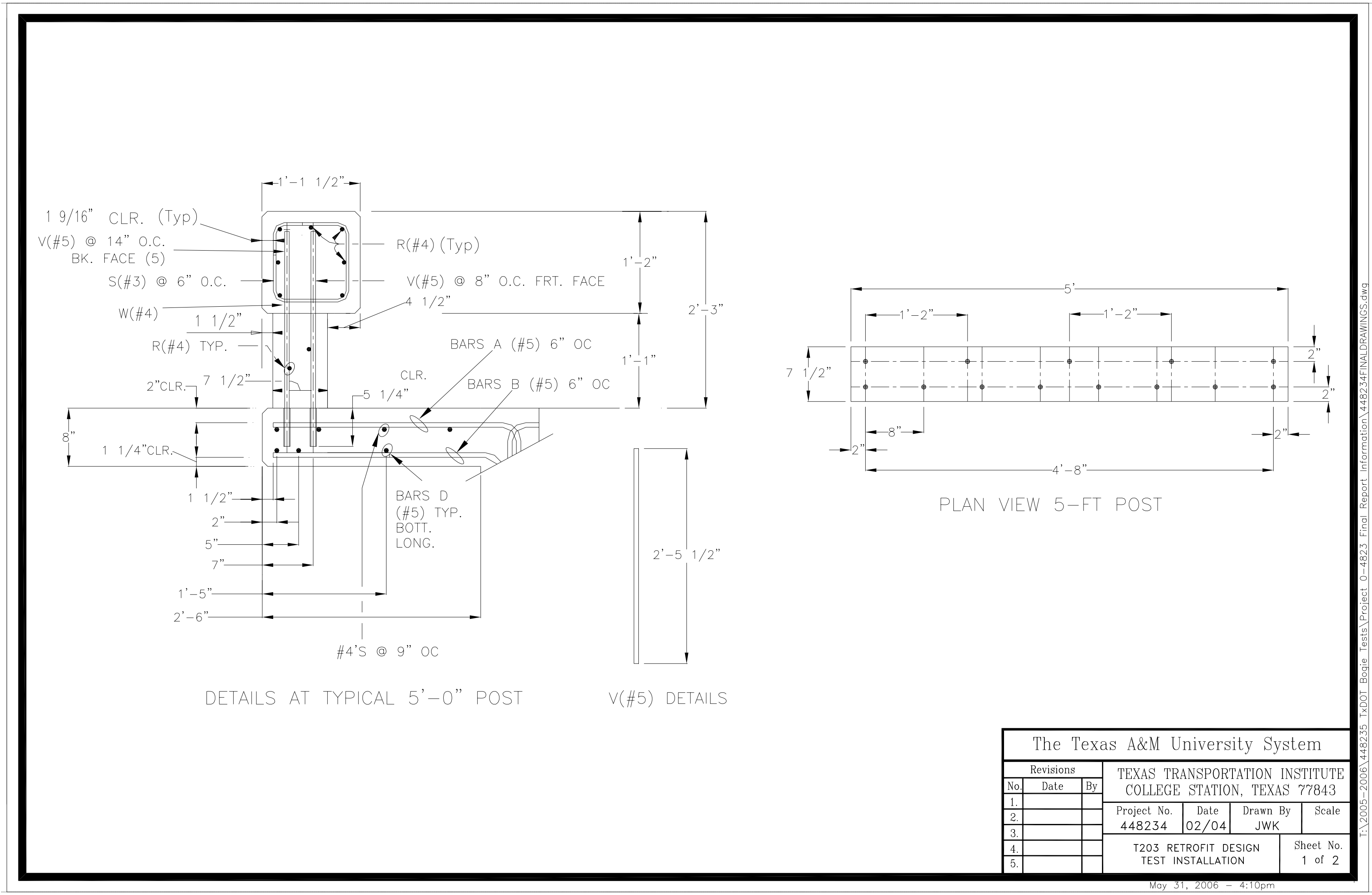


Figure 25. Details of the Retrofit/Repair for the T203 Bridge Rail – 5 ft Post.

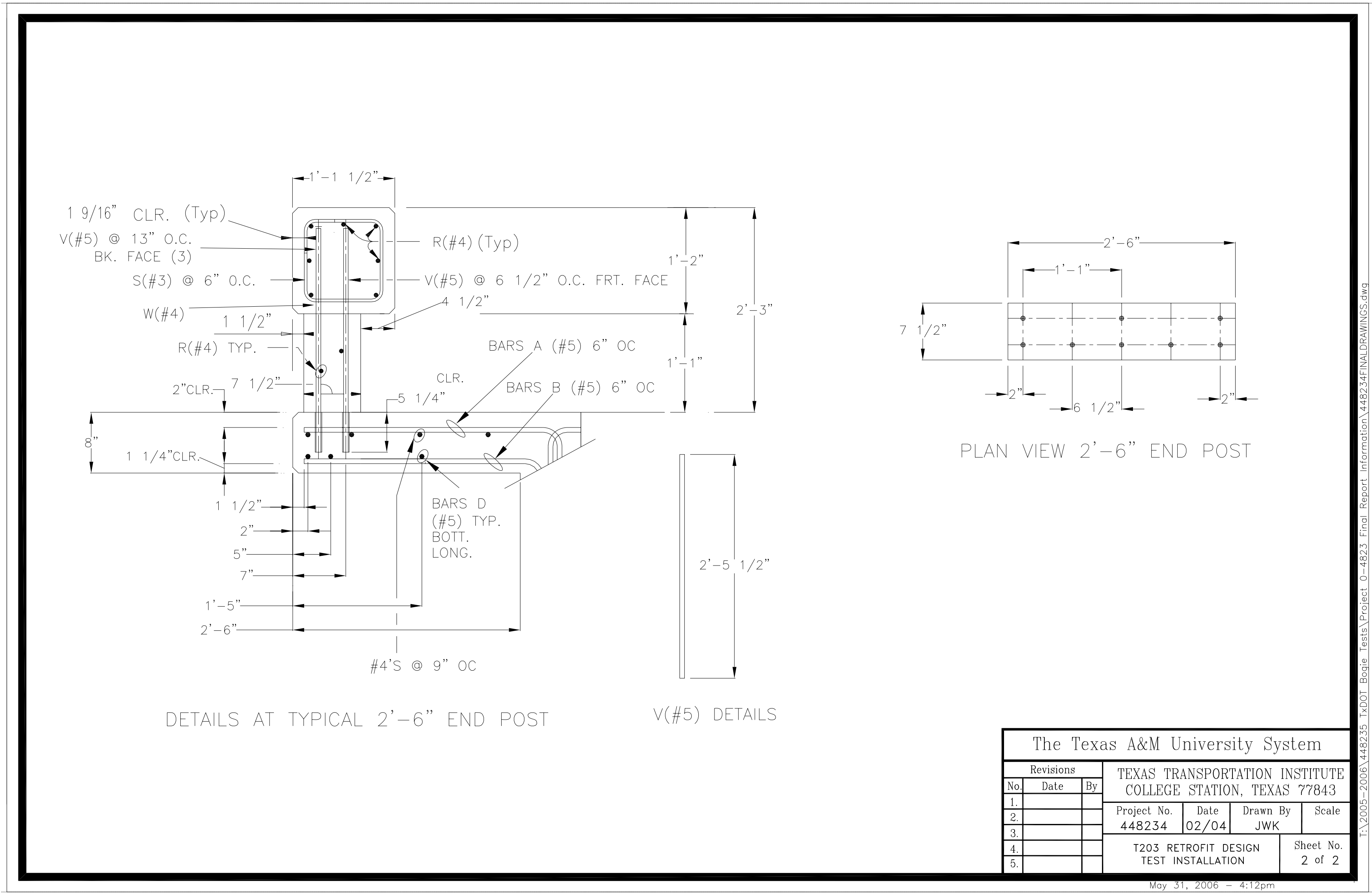


Figure 26. Details of the Retrofit/Repair for the T203 Bridge Rail – End Post.

Figure 27. Retrofit/Repair for the T203 Bridge Rail before Testing.

TEST RESULTS

Three dynamic bogie tests were performed on the T203 bridge rail test specimens incorporating the proposed repair/retrofit design. Two tests were performed within a wall segment, as defined by the AASHTO *LRFD*, and one test was performed near the end of a wall segment. Like the testing performed in Task 2, the dynamic impacting force was sufficient to cause failure in the impacted rail element. The dynamic loading was applied over a length of 3 ft-6 inches. The results for the T203 repair/retrofit design were compared with the dynamic testing results for the current T203 design tested in Task 2. The failure modes for the mid-span and end/joint cases using the T203 retrofit designs were very similar to failure modes observed for the static and dynamic testing of conventionally anchored T203 design. However, the T203 End/Joint strength (39.5 kips) using the 2'-6" wide post was still below the desired strength of 54 kips. Table 4 presents a summary of the dynamic testing data obtained for the T501 and T203 retrofit/repair designs. Data obtained from the dynamic testing are presented in Appendix G. Photos of the dynamic testing are presented in Figures 28 through 30.

Table 4. Summary of T501 Retrofit Design (Dynamic) Strengths.

No.	Case	Retrofit Design Strength (Dynamic) 50-ms Avg. (kips)
1	T501 Mid-Span Location A	64.5
2	T501 Mid-Span Location B	61.0
3	T501 End/Joint Location C	50*
4	T203 End/Joint Location D	39.5
5	T203 Mid-Span Location E	67.0
6	T203 Mid-Span Location F	69.5

* Denotes Result Obtained From Static Testing on 5-12-06

Figure 28. Bridge Rail T203 Retrofit/Repair at Location F after Test B10.

Figure 29. Bridge Rail T203 Retrofit/Repair at Location E after Test B11.

Figure 30. Bridge Rail T203 Retrofit/Repair at Location D after Test B12.

CHAPTER 6. CONCLUSIONS

SUMMARY OF FINDINGS

Table 5 presents a summary of the static and dynamic testing data.

Table 5. Summary of Analytical and Full-Scale Testing.

No.	Case	Calculated Convent. Anchored Strength (kips)	Static Strength Convent. Anchored (kips)	Dynamic Strength Convent. Anchored 50-ms Avg. (kips)	Retrofit Design Strength (Dynamic) 50-ms Avg. (kips)
1	T501 Mid-Span Location A	59.7	66.0	66.0	64.5
2	T501 Mid-Span Location B	59.7	75.0	70.0	61.0
3	T501 End/Joint Location C	36.4	41.0	46.0	50*
4	T203 End/Joint Location D	23.2	33.0	N/A	39.5
5	T203 Mid-Span Location E	71.0	72.0	72.0	67.0
6	T203 Mid-Span Location F	71.0	73.5	70.0	69.5

* Denotes Result Obtained From Static Testing on 5-12-06

The retrofit/repair strengths from the dynamic and static testing for both the T501 and the T203 compared very closely to the dynamic and static strengths of the conventionally anchored strengths. However, the T203 End/Joint strength (39.5 kips) using the 2'-6" wide post was still below the desired strength of 54 kips. The static strengths were very close to the dynamic 50 millisecond average strengths recorded from the bogie testing.

CONCLUSIONS

The new retrofit/repair designs developed and tested for this project are recommended for implementation for use on any new or existing bridge projects. The use of epoxy adhesive anchors were very successful in achieving the strengths needed to adequately anchor the retrofit/repair reinforcement for both the T501 and the T203 bridge rails. The information learned from this project can be used to retrofit and repair other bridge rail designs in the future. The T501 conventional anchorage in the end/joint regions is deficient and needs improvements. Additional (more closely spaced) anchorage is needed to improve the strength of the barrier in the end/joint regions. The T203 conventional and retrofit anchorage is deficient in the end/joint regions and also needs improvements. Additional (more closely spaced) anchorage for both the conventional and retrofit designs is needed in the smaller post (2 ft-6 inch length) to improve the strength of the barrier in the end/joint regions. One option would be to eliminate the use of the smaller 2 ft-6 inch length T203 posts altogether in new bridge construction. Additional longitudinal reinforcement in the T203 Bridge Rail in the end/joint regions would also improve the strength capacity of this rail in the end/joint regions. Based on the results of this study, retrofit/repair anchorage to thinner decks is not recommended. In addition, retrofit/repair anchorage installed at shallower depths of embedment (less than 5 ¼" depth) is also not recommended.

REFERENCES

1. *AASHTO LRFD Bridge Design Specifications, U.S. Units, 2001 Interim Revisions*, American Association of State Highway and Transportation Officials, May 2001.

APPENDIX A. ANALYTICAL CALCULATIONS FOR BOTH THE T501 AND T203 BRIDGE RAILINGS

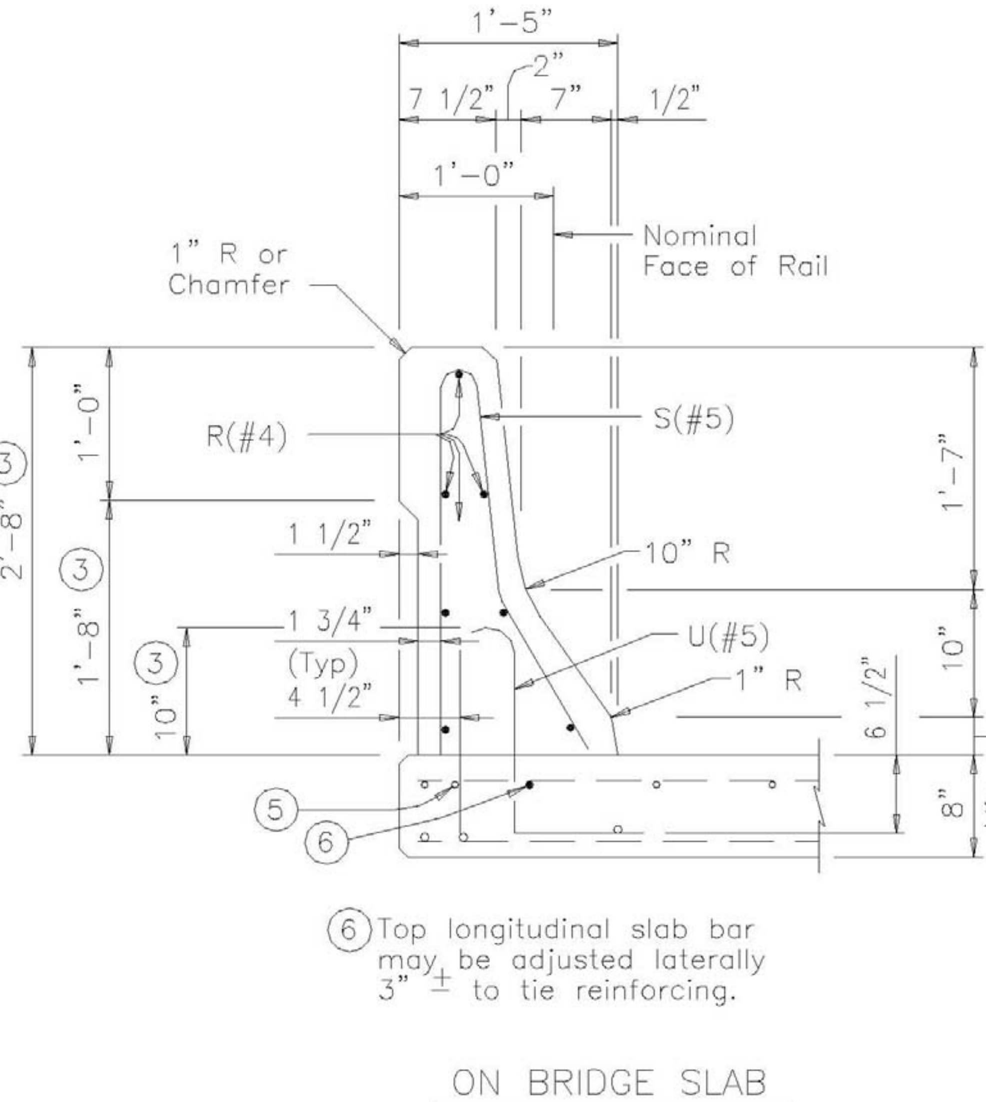
Texas Transportation Institute

SUBJECT **T501 Yield Line Analysis**

Conventional Design

CLIENT **TxDOT**

1.) Given the Following Details & Design Data for the T501 Parapet:



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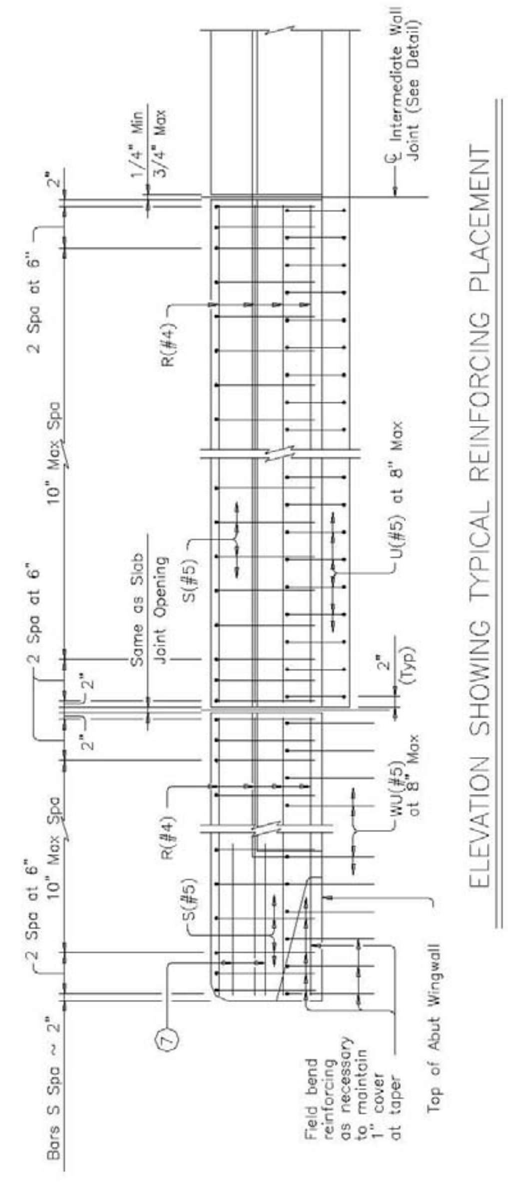

Material Properties:

28 day compressive strength of the wall concrete:	$f'c := 3600 \cdot psi$
Yield Strength of the Reinforcing Steel (F_y):	$F_y := 60 \cdot ksi$
Concrete Factor for 3600 *psi Concrete	$\beta_1 := 0.85$
	$kips \equiv kip$

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2.) Design Information from AASHTO LRFD, Section 13, 2000 Interim Specifications, for TL-4 Loading Conditions:

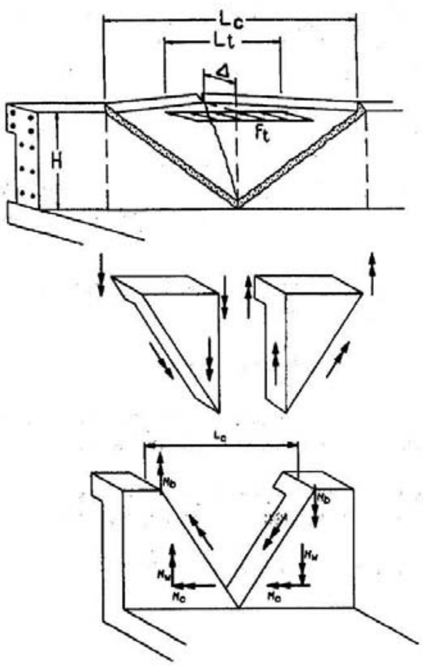

Figure 1: Failure Mechanism @ Mid-Span

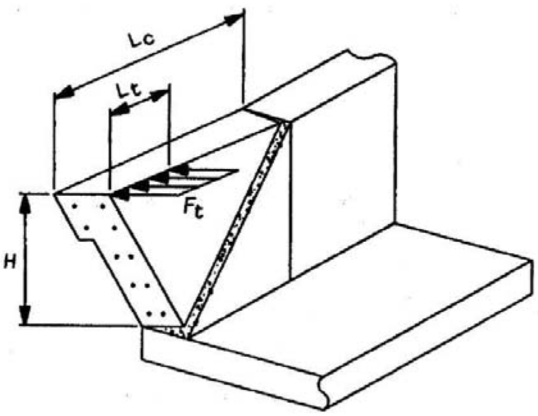

Figure 2: Failure Mechanism @ End Of Parapet or at a Joint

$H_e := 32in$ Height of Parapet/Load Application (inches).

$F_t := 54kips$ ...... Transverse Force on the Rail

$L_t := 3.5ft$ ...... Length of Transverse Force (F_t) Distributed on the Rail

$F_L := 18kips$ .... Longitudinal Force on the Rail

$L_L := 3.5ft$ .... Length of Longitudinal Force (F_L) Distributed on the Rail

$F_v := 18kips$ ...... Vertical (Downward) Force on the Rail

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3.) Calculate the flexural Resistance (M_w) of the wall about the vertical axis per foot of parapet:

$$d_w := 8.0in - 1.75in - \frac{5}{16}in - \frac{1}{4}in \qquad d_w = 5.69\,in$$ ..... bending about the vertical axis @ critical section

$$H_e = 2.67\,ft \qquad d_w = 5.69\,in$$

.... amount of longitudinal steel per foot
4~ #4's spaced over the 32 inches

$$A_{stw} := .20in^2 \cdot 4$$

$$a_{w1} := \frac{A_{stw} \cdot F_y}{0.85 \cdot f'c \cdot H_e}$$

$$M_w := \frac{0.85 \cdot A_{stw} \cdot F_y \cdot \left(d_w - \frac{a_{w1}}{2}\right)}{H_e} \qquad M_w = 6.94\,ft^{-1}\,kip \cdot ft$$

4.) Calculate the flexural Resistance (M_c) of the wall about the longitudinal axis per foot of parapet at two locations: 1.) 13" Above Base, 2.) At Base:

$$d_{c1} := 8.0in - 1.75in \qquad d_{c1} = 6.25\,in$$ .... bending about the longitudinal axis **@ Section 13" Above the Base**

$$d_{c1} = 6.25\,in$$ Distance from compression face of the field side to center of "S" Bars

$$A_{stc1} := .31in^2 \cdot \frac{12}{10}$$ .... amount of Vertical steel per foot
#5"s @ 10" o.c.

$$a_{c1} := \frac{A_{stc1} \cdot F_y}{0.85 \cdot f'c \cdot 12in} \qquad a_{c1} = 0.61\,in$$

$$M_{c1} := \frac{0.85 \cdot A_{stc1} \cdot F_y \cdot \left(d_{c1} - \frac{a_{c1}}{2}\right)}{ft}$$

$$M_{c1} = 9.4\frac{kip \cdot ft}{ft}$$ Strength @ 13" Above the Base

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$d_{c2} := 3in + 4.25in$ $\quad d_{c2} = 7.25in$ .... bending about the longitudinal axis
@ Section At the Base

$d_{c2} = 7.25in$ This is the distance from field side compression face to center of "U" bar

$A_{stc2} := .31in^2 \cdot \frac{12}{8}$ .... "U" Bars Spaced on 8-inch centers therefore #5"s @ 8" o.c.

$$a_{c2} := \frac{A_{stc2} \cdot F_y}{0.85 \cdot f'c \cdot 12in} \qquad a_{c2} = 0.76in$$

$$M_{c2} := \frac{0.85 \cdot A_{stc2} \cdot F_y \cdot \left(d_{c2} - \frac{a_{c2}}{2}\right)}{ft}$$

$M_{c2} = 13.58 \frac{kip \cdot ft}{ft}$ Strength @ Base of Barrier

Strength @ Base is greater than Strength @ 13 inches above base, therefore use Mc at 13 inches above base.

$$M_c := M_{c1}$$

5.) Calculate the flexural Resistance (M_b) of any additional resistance of beam in addition to M_w, if any, at the top of wall (K-FT/FT):

$M_b := 0kip \cdot ft$ ...... no additional strength about the vertical axis of the rail at the top of the T501 Rail.

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6.) Calculate the Total Transverse Resistance of the T501 Parapet at Mid-Span:

$$L_t = 3.5\,ft$$

$$M_b = 0$$

$$M_w = 6.94\,\frac{kip \cdot ft}{ft}$$

$$M_c = 9.4\,\frac{kip \cdot ft}{ft}$$

$H := 32in$ ..... Total Height of T501 Wall

$$L_c := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H \cdot (M_b + M_w \cdot H)}{M_c}}$$

$$L_c = 8.46\,ft$$

Calculate R_w:

$$R_w := \left(\frac{2}{2 \cdot L_c - L_t}\right) \cdot \left(8 \cdot M_b + 8 \cdot M_w \cdot H + \frac{M_c \cdot L_c^2}{H}\right)$$

$$R_w = 59.66\,kips$$

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Conventional Design

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7.) Check conditions for impacts at the end of the Parapet or at a joint:

$d_c := 8.0in - 1.75in$ $\quad d_c = 6.25in$ .... bending about the longitudinal axis @ critical section

$d_c = 6.25in$

$A_{stc} := .31in^2 \cdot \frac{12}{8.667}$

.... amount of Vertical steel per foot #5"s @ 10" o.c. w/ 2 Spaces @ 6 in o.c. @ the end. Average last 4 feet of barrier

$$a_{c1} := \frac{A_{stc} \cdot F_y}{0.85 \cdot f'c \cdot 12in}$$

$$M_c := \frac{0.85 \cdot A_{stc} \cdot F_y \cdot \left(d_c - \frac{a_{c1}}{2}\right)}{ft}$$

$$M_c = 10.76 \frac{kip \cdot ft}{ft}$$

$$L_c := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + H \cdot \left(\frac{M_b + M_w \cdot H}{M_c}\right)}$$

$$L_c = 4.52 ft$$

$$R_w := \left(\frac{2}{2 \cdot L_c - L_t}\right) \cdot \left(M_b + M_w \cdot H + \frac{M_c \cdot L_c^{\,2}}{H}\right)$$

$$R_w = 36.44 kips$$

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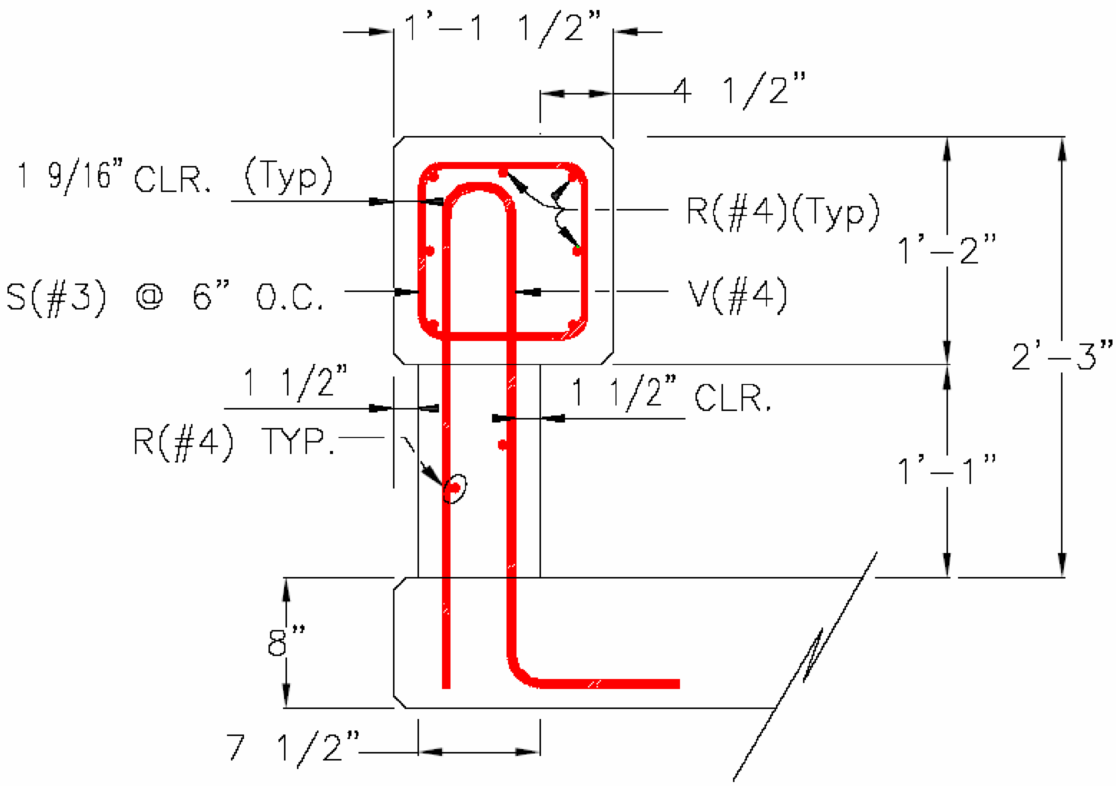
SUBJECT **TxDOT T203 Bridge Rail**

LRFD Section 13 Analysis

SPONSOR **TxDOT**

1.) Given Details:

1.) Given the Following T203 Bridge Rail Details.
2.) Find the Ultimate Resistance (R) for the Bridge Rail for Mid-Span & End/Joint Conditions in Accordance with AASHTO LRFD Section 13, 1998, Second Edition.



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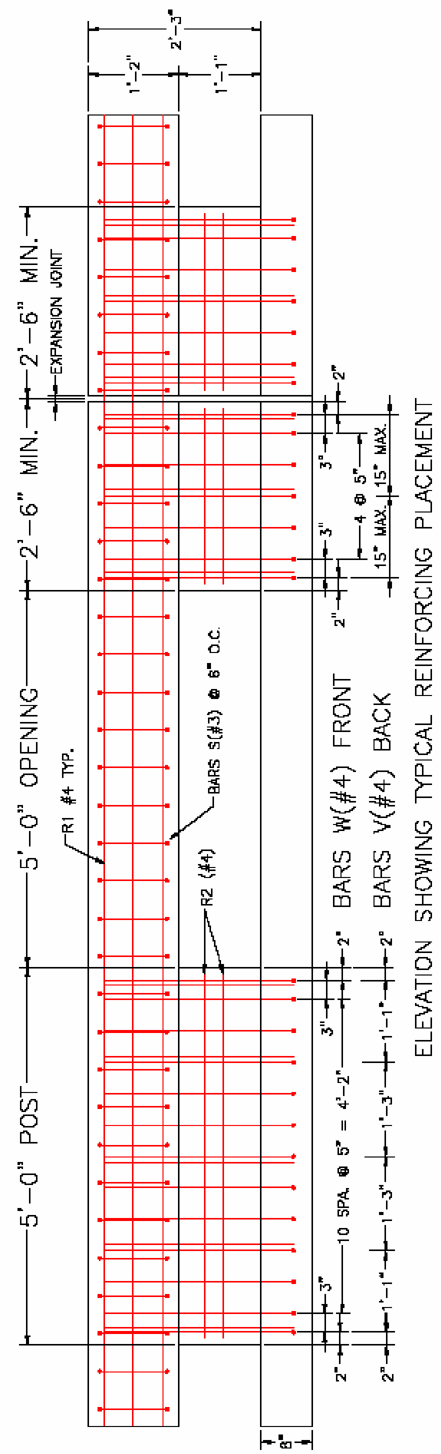

2.) Given Design Information: $\phi := 0.9$

Concrete Strength: $f'c := 3600psi$ $\quad \beta_1 := 0.85$

Reinforcing Yield Strength: $f_y := 60ksi$

$b_{rail} := 14in$ .... depth of rail

$H_{rail} := 13.5in$ ... height rail (lateral direction)

$$d_1 := H_{rail} - 1.75in - \frac{3}{16}in - \frac{4}{16}in$$

$d_1 = 11.31\,in$ $\quad d_2 := 13.5in \cdot 0.5$ $\quad A_{s2} := 0.2in^2$

$A_{s1} := 3 \cdot .20in^2$ (3 ~ #4's Long. in tension)

$$A_{slateral} := A_{s1} + A_{s2} \qquad d_{rail} := \frac{A_{s1} \cdot d_1 + A_{s2} \cdot d_2}{A_{slateral}}$$

Calculate ρ: $\quad A_{slateral} = 0.8\,in^2$

$$\rho_{rail} := \frac{A_{slateral} \cdot 2}{b_{rail} \cdot d_{rail}} \qquad \rho_{rail} = 0.01124$$

calculate ρ_{min}:

$$\rho_{min1} := \frac{3 \cdot \sqrt{f'c \cdot psi}}{f_y} \qquad \rho_{min1} = 0.003$$

or

$$\rho_{min2} := \frac{200 \cdot psi}{f_y} \qquad \rho_{min2} = 0.00333$$

Calculate ρ_{bal}:

$$\rho_{bal} := \beta_1 \cdot \left(\frac{0.85 \cdot f'c}{f_y}\right) \cdot \left(\frac{87000psi}{87000psi + f_y}\right)$$

$$\rho_{bal} = 0.0257$$

$$\rho_{max} := 0.75 \cdot \rho_{bal} \qquad \rho_{max} = 0.0192$$

.......Steel Ratio is O.K. .... steel yields!!

calculate "a":

$$a_{railhor} := \frac{A_{slateral} \cdot f_y}{0.85 \cdot f'c \cdot b_{rail}} \qquad a_{railhor} = 1.12\,in$$

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3.) Calculate the Strength of the Rail due to Lateral Impact Force (CONTINUED):

Calculate Nominal Strength of Rail (Horizontal):

$A_{slateral} = 0.8\,in^2$ (Area of 3 ~ #4 Bars)

$f_y = 60\,ksi$

$d_{rail} = 10.17\,in$

$a_{railhor} = 1.12\,in$ depth of the compression block

$$M_{ulateral} := \phi \cdot A_{slateral} \cdot f_y \cdot \left(d_{rail} - \frac{a_{railhor}}{2}\right)$$

$M_{ulateral} = 34.6\,kip \cdot ft$ $\quad M_{nlateral} := \dfrac{M_{ulateral}}{\phi}$ $\quad M_{nlateral} = 38.45\,kip \cdot ft$

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SUBJECT **TxDOT T203 Bridge Rail**

LRFD Section 13 Analysis

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4.) Calculate the Strength of the Posts for the Entire 5-foot Width:

$Post_{width} := 7.5in$ $\quad b_{post} := 5ft$

$d_{post} := Post_{width} - 1.75in$

$A_{spost} := 13 \cdot 0.2in^2$ $\quad A_{spost} = 2.6\,in^2$ $\quad$ 13 ~ #4 bars total on the tension face

Calculate ρ_{post}:

$$\rho_{post} := \frac{A_{spost}}{d_{post} \cdot b_{post}} \qquad \rho_{post} = 0.00754$$

$\rho_{min2} = 0.00333$

$\rho_{max} = 0.01924$ $\quad$ Steel Ratio O.K. ..... steel yields

Calculate Compression Block "a" for post:

$$a_{post} := \frac{A_{spost} \cdot f_y}{0.85 \cdot f'c \cdot b_{post}}$$

$a_{post} = 0.85\,in$

Calculate Nominal Strength M_n of Post section:

$A_{spost} = 2.6\,in^2$ $\quad f_y = 60\,ksi$ $\quad d_{post} = 5.75\,in$ $\quad a_{post} = 0.85\,in$

$$M_{upost} := \phi \cdot A_{spost} \cdot f_y \cdot \left(d_{post} - \frac{a_{post}}{2} \right)$$

$M_{upost} = 62.3\,kip \cdot ft$ $\quad M_{npost} := \frac{M_{upost}}{\phi}$ $\quad M_{npost} = 69.23\,kip \cdot ft$

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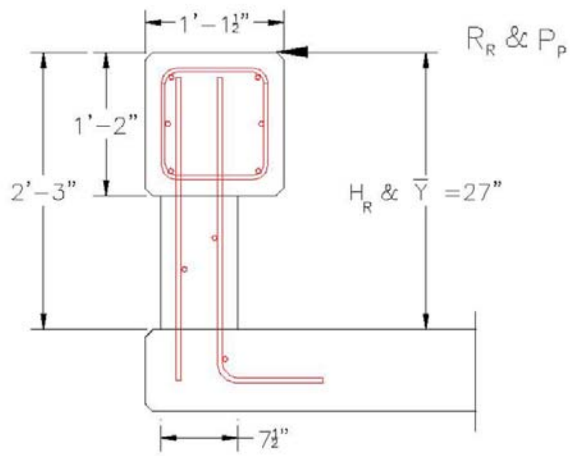
SUBJECT **TxDOT T203 Bridgerail**

LRFD Section 13 Analysis

SPONSOR **TxDOT**

5.) Check T203 Rail Strength at Mid-Span in accordance with AASHTO LRFD Section 13 Specifications:



RAIL EVALUATION – IMPACT AT POST

(LAYOUT 4)

$\mathbf{H := 27in}$ Height of Rail

$\mathbf{L_t := 4.0ft}$ Longitudinal length of distribution of impact force (feet).

$\mathbf{L := 5ft}$ ..... Post Spacing (feet)

$\mathbf{width_{post} := 5ft}$ .... Post Width (feet)

$\mathbf{H_R := 27in}$ ...... Height of Rail (inches)

5a.) Calculate Pp for the Post @ 27 inches:

$\mathbf{M_{npost} = 69.23 kip \cdot ft}$ $\quad$ $\mathbf{H = 27 in}$

$$\mathbf{P_p := \frac{M_{npost}}{H}}$$

$\mathbf{P_p = 30.77 kips}$

5b.) Calculate Mp of the Rail:

$\mathbf{M_p := M_{nlateral}}$

$\mathbf{M_p = 38.45 kip \cdot ft}$

AASHTO TL-3 SECTION 13 REQUIREMENTS:

F_t = 54 kips

F_L = 18 kips

F_v = 4.5 kips

L_t and L_L = 4.0 feet

L_v = 18 feet

H_e = 24 inches (min.)

Min. Height = 27 inches

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SUBJECT **TxDOT T203 Bridgerail**

LRFD Section 13 Analysis

SPONSOR **TxDOT**

5c.) Calculate the The total ultimate resistance "R", i.e., nominal resistance of the railing in kips for a single span:

$N_1 := 1$ ...... number of spans

$M_p = 38.45\,\mathrm{kip \cdot ft}$ $P_p = 30.77\,\mathrm{kips}$ $L_t = 4\,\mathrm{ft}$

$$R_1 := \frac{16 \cdot M_p + (N_1 - 1) \cdot (N_1 + 1) \cdot P_p \cdot L}{2 \cdot N_1 \cdot L - L_t}$$

Post Spa. $L = 5\,\mathrm{ft}$

$R_1 = 102.52\,\mathrm{kips}$ (O.K. .... R_1 > 54kips min)

5d.) Calculate the The total ultimate resistance "R", i.e., nominal resistance of the railing in Kips for two spans:

$N_2 := 2$ ...... number of spans

$M_p = 38.45\,\mathrm{kip \cdot ft}$ $P_p = 30.77\,\mathrm{kips}$ $L_t = 4\,\mathrm{ft}$

$$R_2 := \frac{16 \cdot M_p + N_2^{\,2} \cdot P_p \cdot L}{2 \cdot N_2 \cdot L - L_t}$$

Post Spa. $L = 5\,\mathrm{ft}$

$R_2 = 76.91\,\mathrm{kips}$ (O.K. .... R_2 > 54 kips min)

5e.) Calculate the The total ultimate resistance "R", i.e., nominal resistance of the railing in Kips for three spans:

$N_3 := 3$ .... number of spans

$M_p = 38.45\,\mathrm{kip \cdot ft}$ $P_p = 30.77\,\mathrm{kips}$ $L_t = 4\,\mathrm{ft}$

$$R_3 := \frac{16 \cdot M_p + (N_3 - 1) \cdot (N_3 + 1) \cdot P_p \cdot L}{2 \cdot N_3 \cdot L - L_t}$$

Post Spa. $L = 5\,\mathrm{ft}$

$R_3 = 70.99\,\mathrm{kips}$ (O.K. .... R_3 > 54 kips min)

5f.) Calculate the The total ultimate resistance "R", i.e., nominal resistance of the railing in Kips for four spans:

$M_p = 38.45\,\mathrm{kip \cdot ft}$ $P_p = 30.77\,\mathrm{kips}$ $L_t = 4\,\mathrm{ft}$

Post Spa. $L = 5\,\mathrm{ft}$

$N_4 := 4$ .... number of spans

$$R_4 := \frac{16 \cdot M_p + N_4^{\,2} \cdot P_p \cdot L}{2 \cdot N_4 \cdot L - L_t}$$

$R_4 = 85.46\,\mathrm{kips}$

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SUBJECT **T501 Yield Line Analysis**

Conventional Design

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7.) Check conditions for impacts at the end of the Parapet or at a joint:

$d_c := 8.0in - 1.75in \qquad d_c = 6.25in$

.... bending about the longitudinal axis @ critical section

$d_c = 6.25in$

.... amount of Vertical steel per foot #5"s @ 10" o.c. w/ 2 Spaces @ 6 in o.c. @ the end. Average last 4 feet of barrier

$$A_{stc} := .31in^2 \cdot \frac{12}{8.667}$$

$$a_{c1} := \frac{A_{stc} \cdot F_y}{0.85 \cdot f'c \cdot 12in}$$

$$M_c := \frac{0.85 \cdot A_{stc} \cdot F_y \cdot \left(d_c - \frac{a_{c1}}{2}\right)}{ft}$$

$$M_c = 10.76 \frac{kip \cdot ft}{ft}$$

$$L_c := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + H \cdot \left(\frac{M_b + M_w \cdot H}{M_c}\right)}$$

$$L_c = 4.52\,ft$$

$$R_w := \left(\frac{2}{2 \cdot L_c - L_t}\right) \cdot \left(M_b + M_w \cdot H + \frac{M_c \cdot L_c^2}{H}\right)$$

$$R_w = 36.44\,kips$$

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APPENDIX B. DATA FROM STATIC TESTING

TEST S1 - T203 – LOCATION F

Texas Transportation Institute

Page: 1 of 4

Job #: 448234

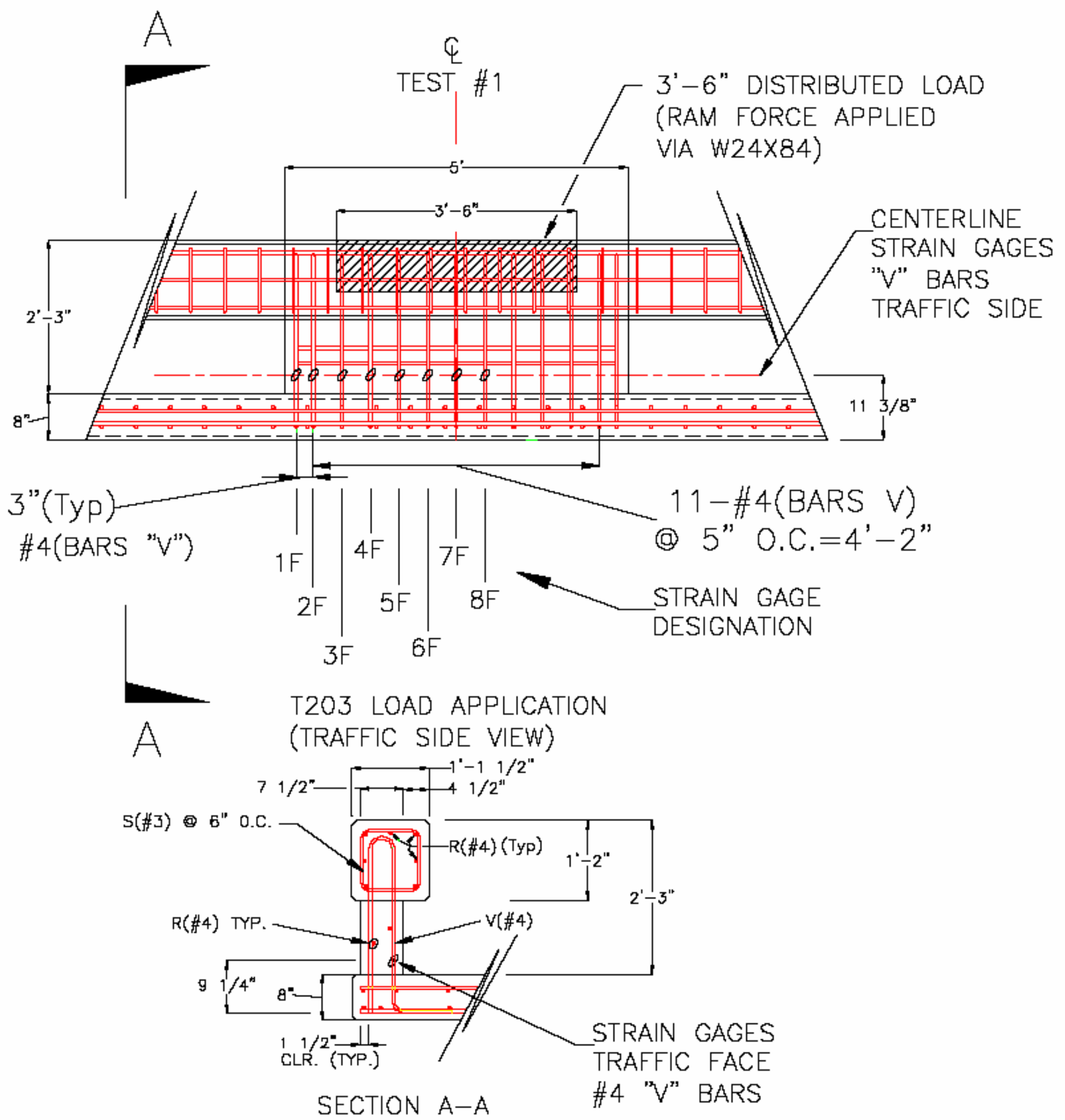
Subject: T203 Rail Static Load Test 1 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 1 - Location F

By: William Williams

Checked: ______

Sponsor: TxDOT



448234FData(S).xmcd
5/16/2006

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PAGE 1

Texas Transportation Institute

Job #: 448234

Subject: T203 Rail Static Load Test 1 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 1 - Location F

Checked: ______

Sponsor: TxDOT

Strain Data in Excel Format from Static Testing Performed 7-16-04:

$E_s := 29000000\text{psi}$ Modulus of Steel (psi)

$A_{st} := 0.20\text{in}^2$ Area of rebar (in^2)

$Fdata :=$ T203FData(S).xls

$Time := Fdata^{\langle 1 \rangle} \times sec$

$Force := Fdata^{\langle 2 \rangle} \times lbf$

$Strain1F := Fdata^{\langle 3 \rangle}$

$Strain2F := Fdata^{\langle 4 \rangle}$

$Strain3F := Fdata^{\langle 5 \rangle}$

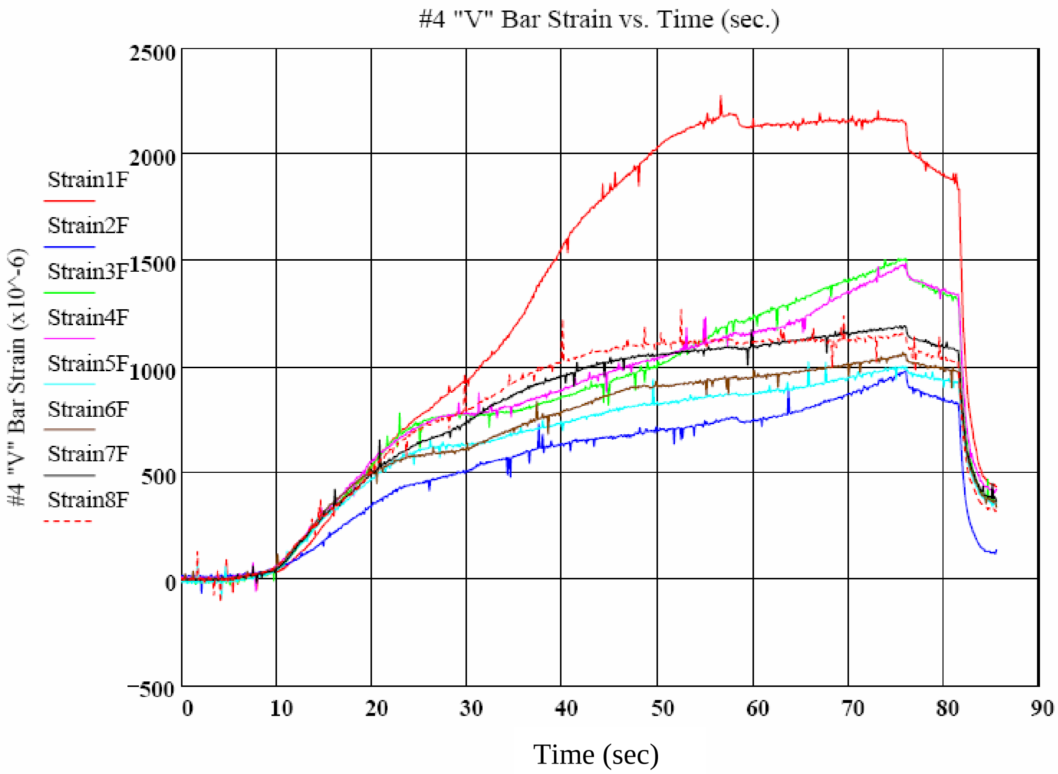
$Strain4F := Fdata^{\langle 6 \rangle}$

$Strain5F := Fdata^{\langle 7 \rangle}$

$Strain6F := Fdata^{\langle 8 \rangle}$

$Strain7F := Fdata^{\langle 9 \rangle}$

$Strain8F := Fdata^{\langle 10 \rangle}$



448234FData(S).xmcd
5/16/2006

William Williams, P.E.
Ph. # (979) 862-2297

Job #: 448234

Subject: T203 Rail Static Load Test 1 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 1 - Location F

Checked:

$Force1F := Strain1F \times E_s \times A_{st} \times 0.000001$

$Force2F := Strain2F \times E_s \times A_{st} \times 0.000001$

$Force3F := Strain3F \times E_s \times A_{st} \times 0.000001$

$Force4F := Strain4F \times E_s \times A_{st} \times 0.000001$

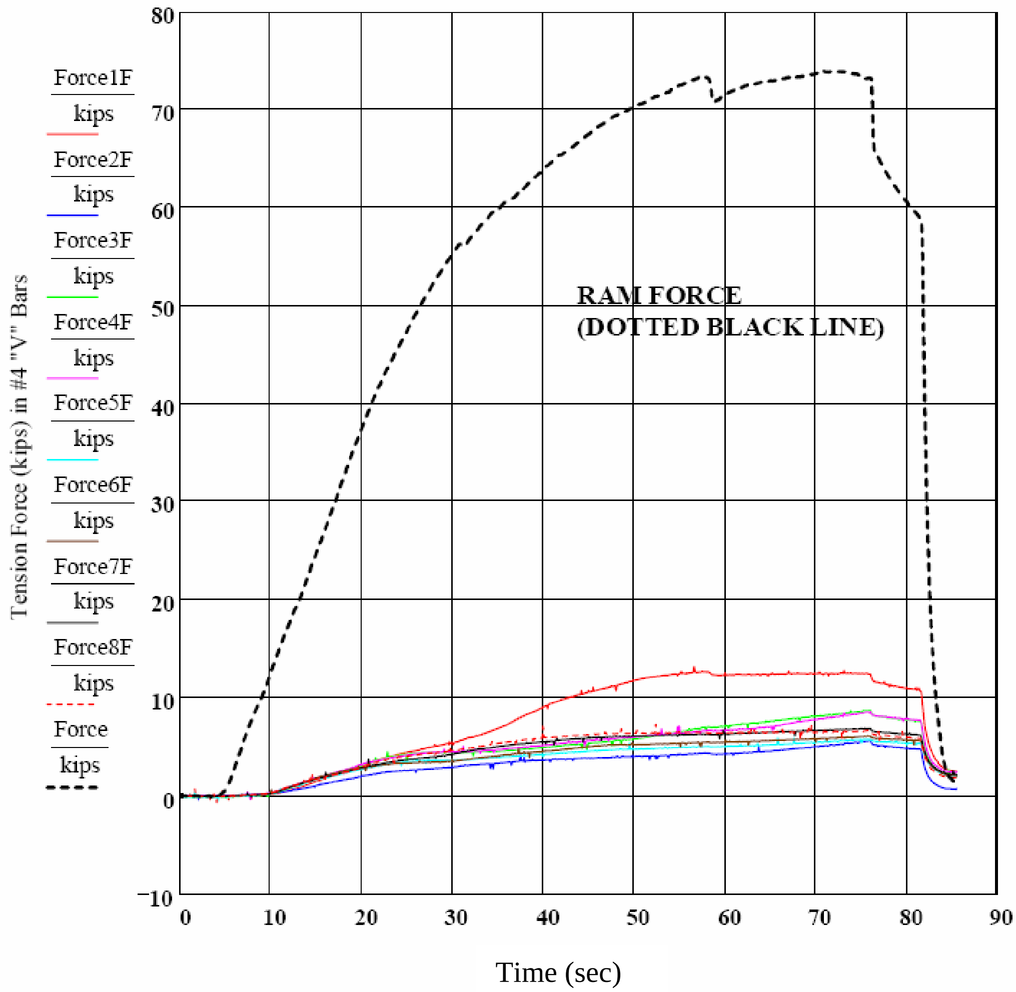
$Force5F := Strain5F \times E_s \times A_{st} \times 0.000001$

$Force6F := Strain6F \times E_s \times A_{st} \times 0.000001$

$Force7F := Strain7F \times E_s \times A_{st} \times 0.000001$

$Force8F := Strain8F \times E_s \times A_{st} \times 0.000001$

Tension Force in #4 ~ "V" Bars



Texas Transportation Institute

Job #: 448234

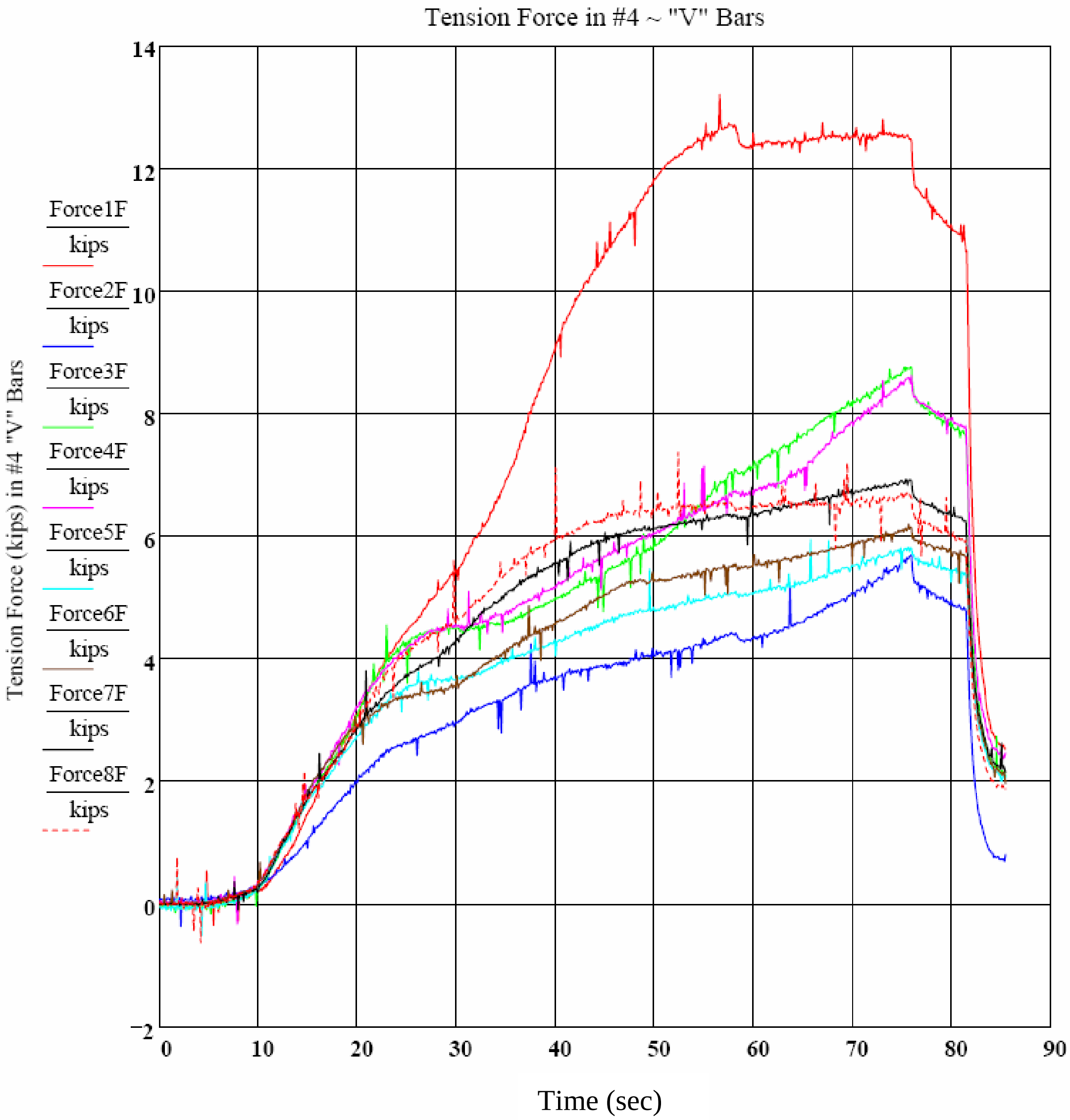
By: William Williams

Checked:

Subject: T203 Rail Static Load Test 1 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 1 - Location F

Sponsor: TxDOT



TEST S2 - T203 – LOCATION E

Texas Transportation Institute

Page: 1 of 4

Job #: 448234

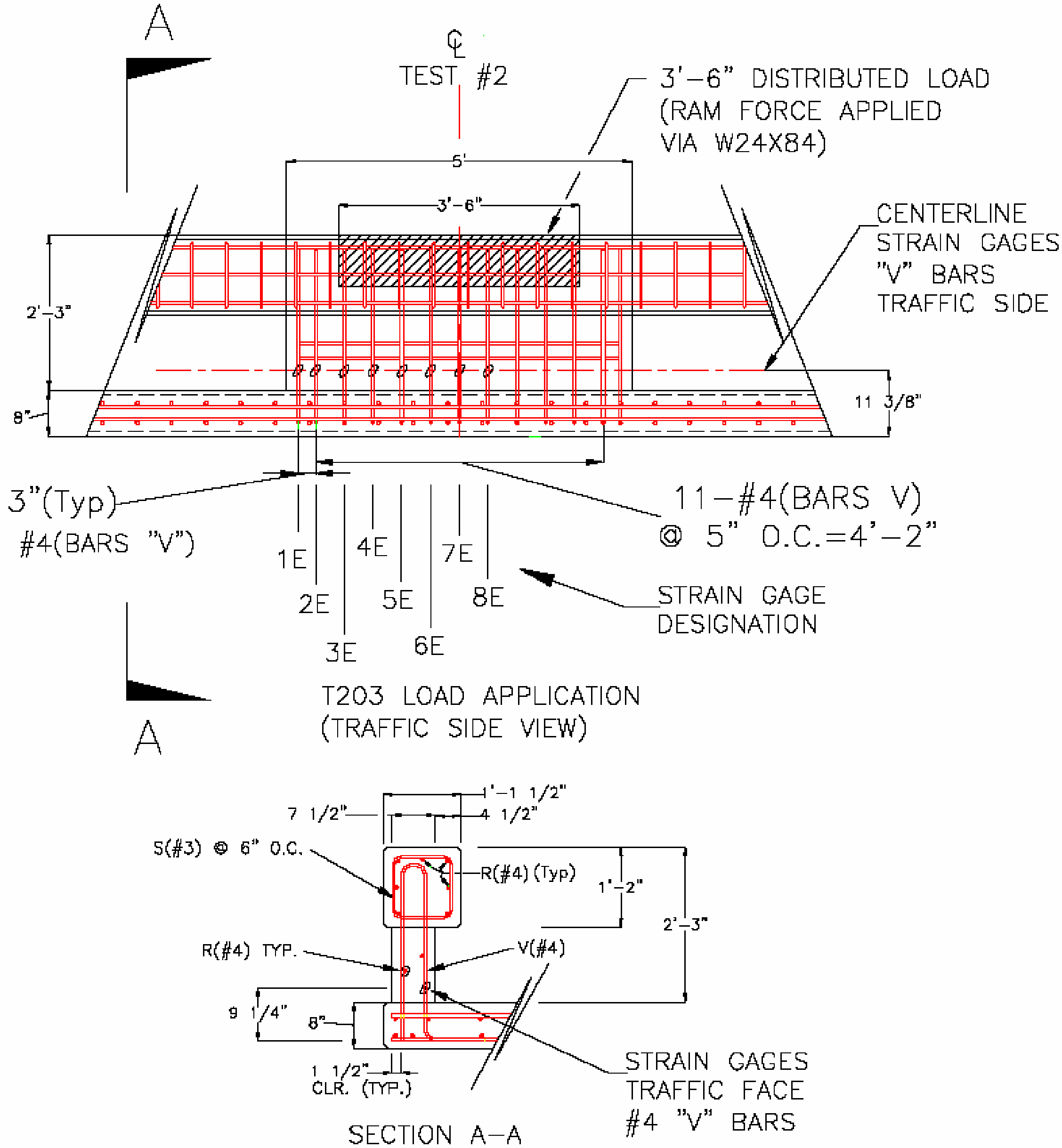
By: William Williams

Checked: ______

Subject: T203 Rail Static Load Test 2 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 2 - Location E

Sponsor: TxDOT



Subject: T203 Rail Static Load Test 2 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 2 - Location E

Sponsor: TxDOT

$E_s := 29000000psi$ Modulus of Steel (psi)

$A_{st} := 0.20in^2$ Area of rebar (in^2)

Strain Data in Excel Format from Static Testing Performed 7-16-04:

Edata := T203EData(s).xls

$Time := Edata^{\langle 1 \rangle} \times sec$

$Force := Edata^{\langle 2 \rangle} \times lbf$

$Strain1E := Edata^{\langle 3 \rangle}$

$Strain2E := Edata^{\langle 4 \rangle}$

$Strain3E := Edata^{\langle 5 \rangle}$

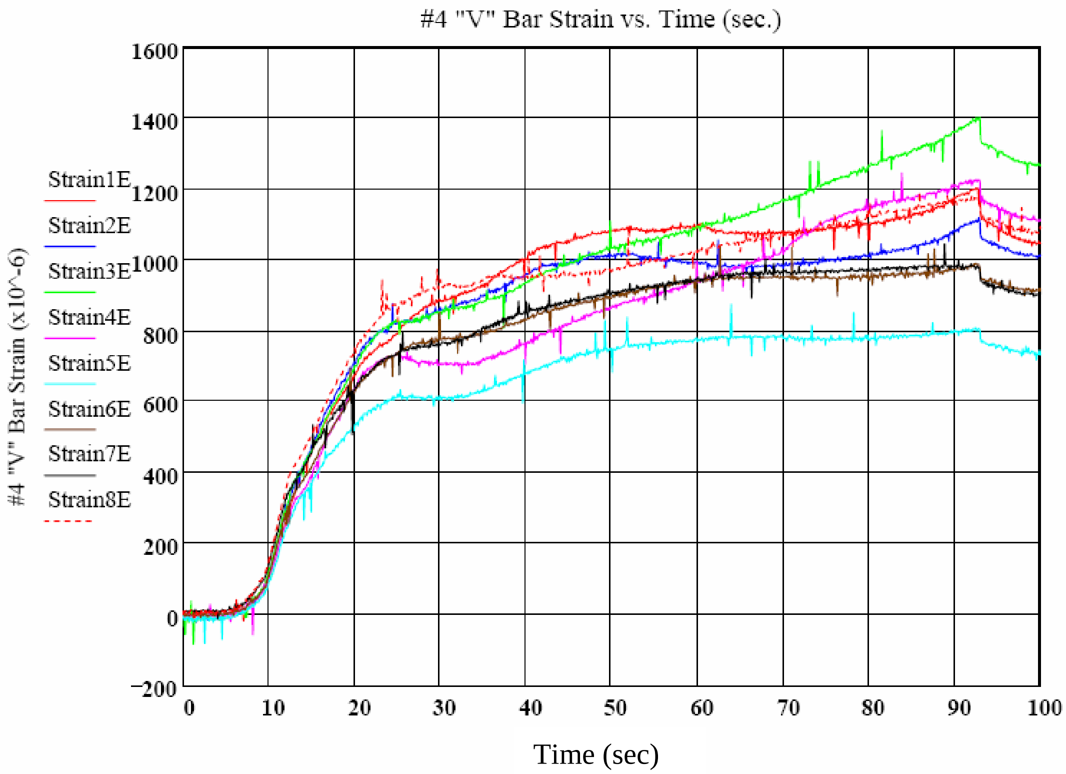
$Strain4E := Edata^{\langle 6 \rangle}$

$Strain5E := Edata^{\langle 7 \rangle}$

$Strain6E := Edata^{\langle 8 \rangle}$

$Strain7E := Edata^{\langle 9 \rangle}$

$Strain8E := Edata^{\langle 10 \rangle}$



Job #: 448234

Subject: T203 Rail Static Load Test 2 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 2 - Location E

Checked: ____

$Force1E := Strain1E \times E_s \times A_{st} \times 0.000001$

$Force2E := Strain2E \times E_s \times A_{st} \times 0.000001$

$Force3E := Strain3E \times E_s \times A_{st} \times 0.000001$

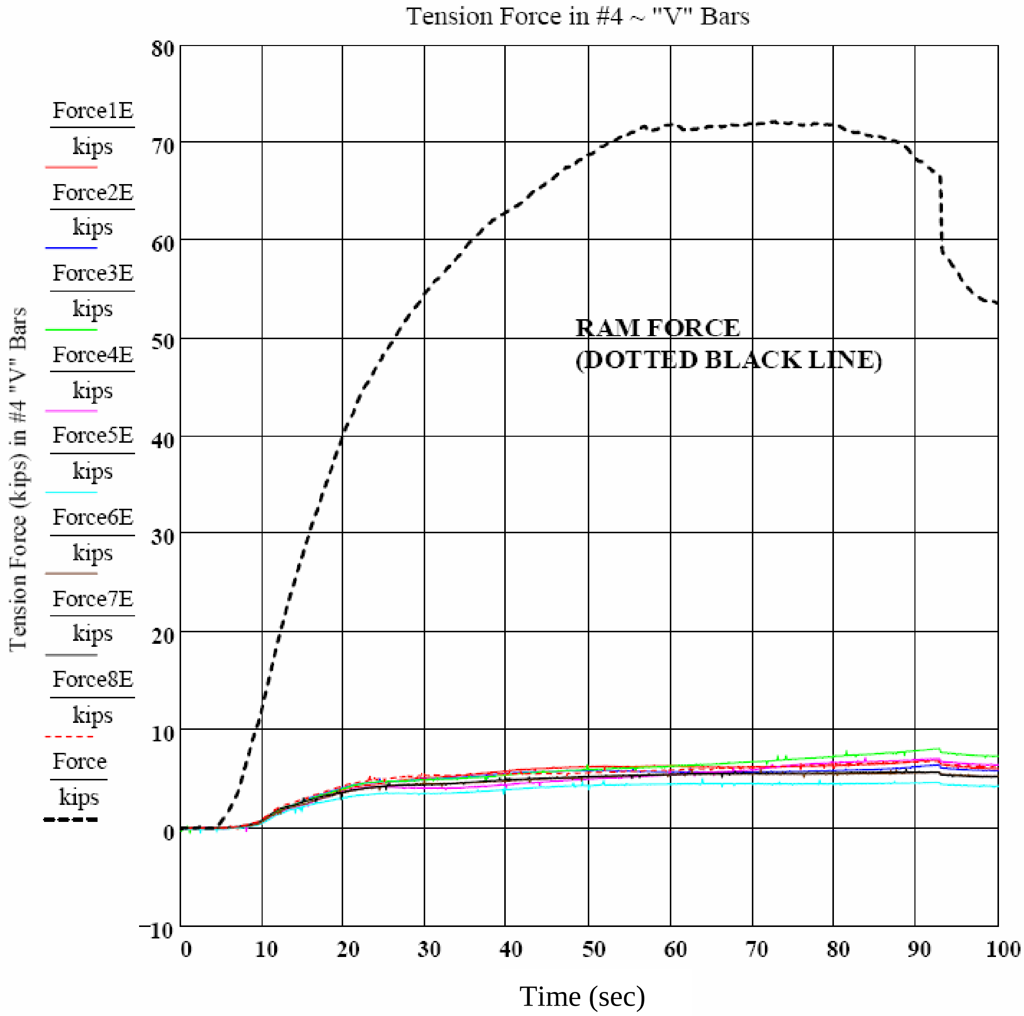
$Force4E := Strain4E \times E_s \times A_{st} \times 0.000001$

$Force5E := Strain5E \times E_s \times A_{st} \times 0.000001$

$Force6E := Strain6E \times E_s \times A_{st} \times 0.000001$

$Force7E := Strain7E \times E_s \times A_{st} \times 0.000001$

$Force8E := Strain8E \times E_s \times A_{st} \times 0.000001$



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Subject: **T203 Rail Static Load Test 2 ~ Mid-Span Case**

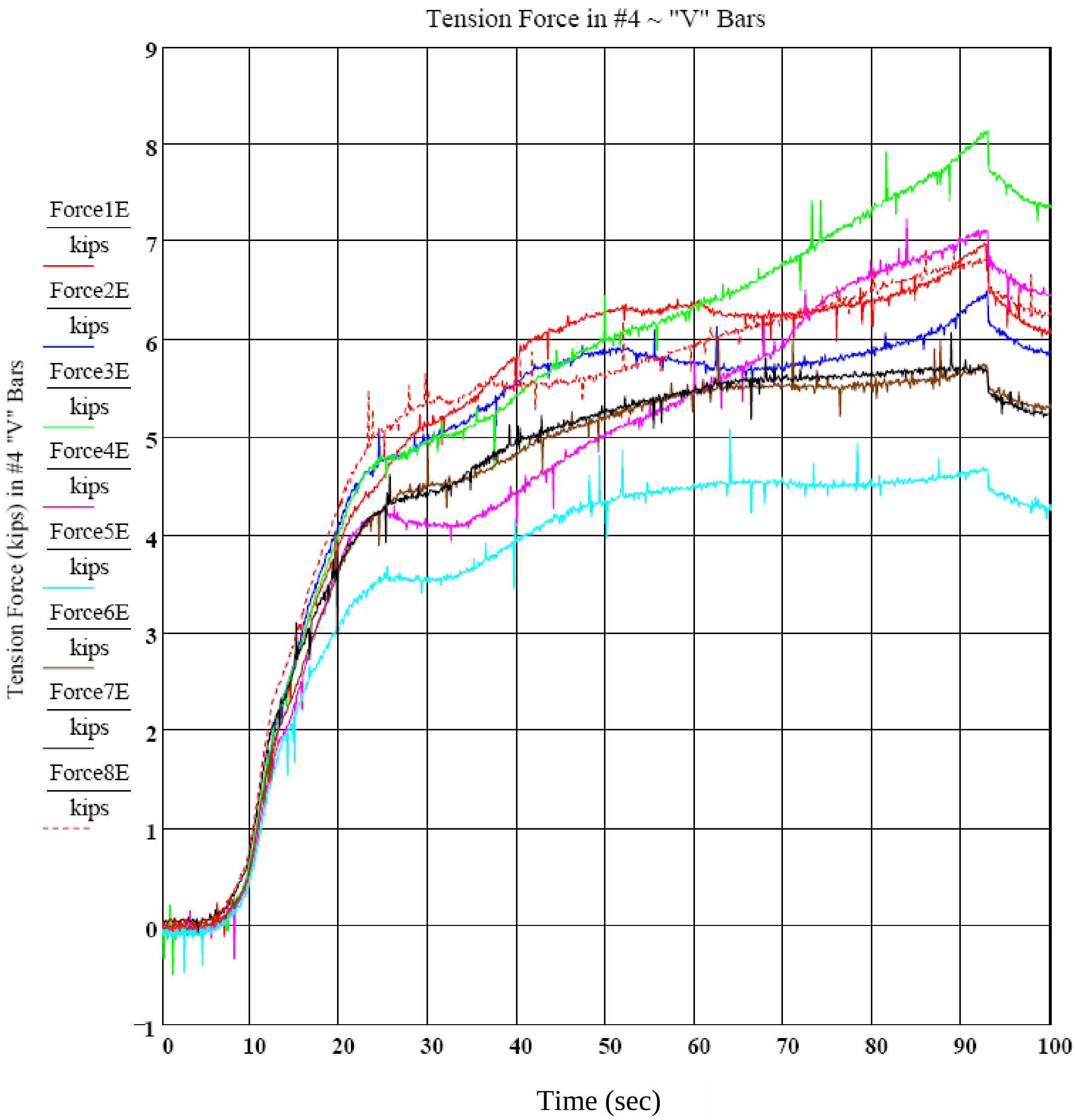
Strain Gage Data Analysis ~ Test 2 - Location E

Sponsor: **TxDOT**

Job #: **448234**

By: **William Williams**

Checked: ______



TEST S3 - T203 – LOCATION D

Texas Transportation Institute

Page: 1 of 4

Job #: 448234

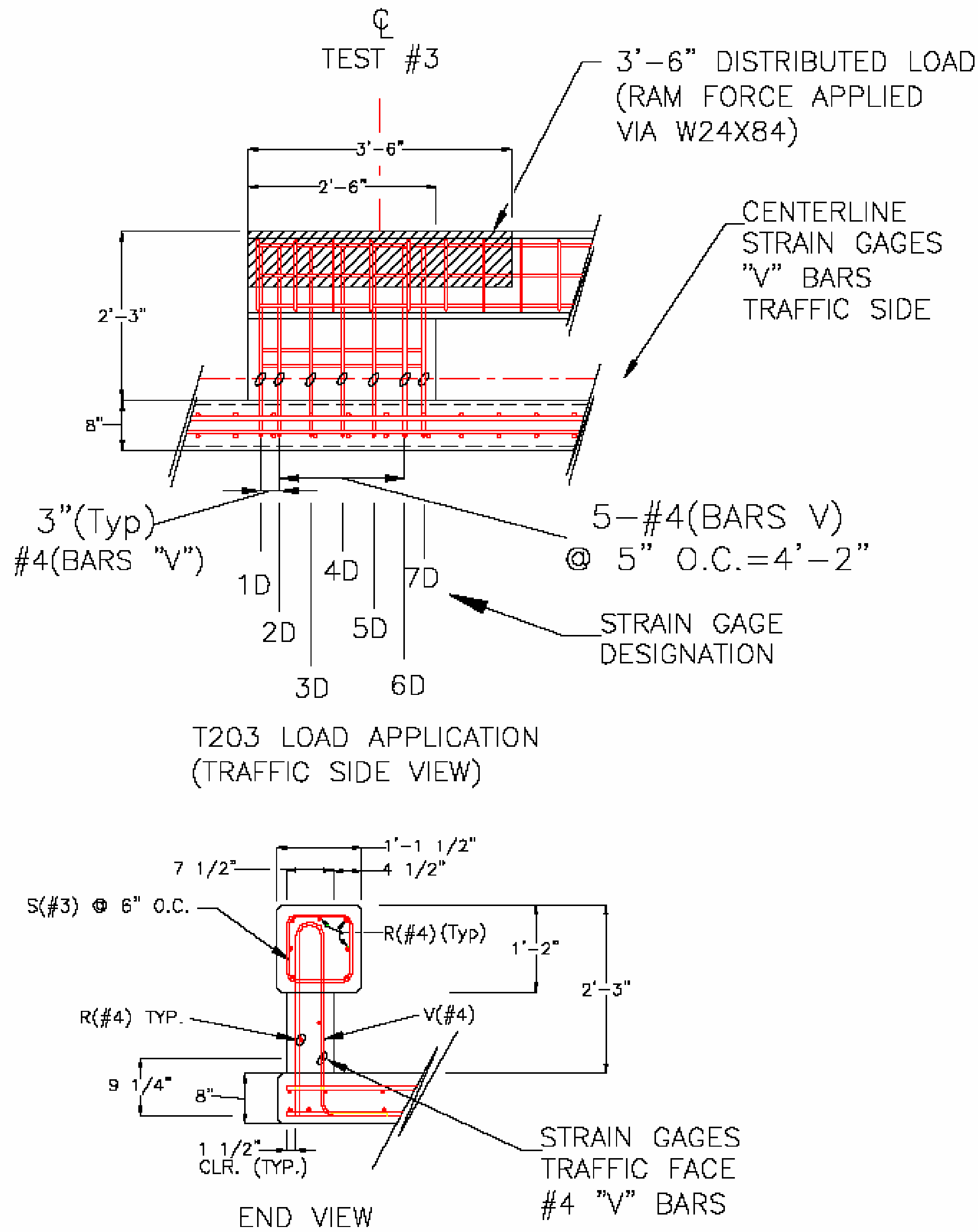
By: William Williams

Checked: ______

Subject: T203 Rail Static Load Test 3 ~ End Case

Strain Gage Data Analysis ~ Test 3 - Location D

Sponsor: TxDOT



Texas Transportation Institute

Job #: 448234

Subject: T203 Rail Static Load Test 3 ~ End Case

By: William Williams

Strain Gage Data Analysis ~ Test 3 - Location D

Checked: ______

Sponsor: TxDOT

Strain Data in Excel Format from Static Testing Performed 7-16-04:

$E_s := 29000000\text{psi}$ Modulus of Steel (psi)

Ddata :=

'203DData(S).xl

$A_{st} := 0.20\text{in}^2$ Area of rebar (in^2)

$\text{Time} := \text{Ddata}^{\langle 1 \rangle} \times \text{sec}$

$\text{Strain1D} := \text{Ddata}^{\langle 3 \rangle}$

$\text{Force} := \text{Ddata}^{\langle 2 \rangle} \times \text{lbf}$

$\text{Strain6D} := \text{Ddata}^{\langle 8 \rangle}$

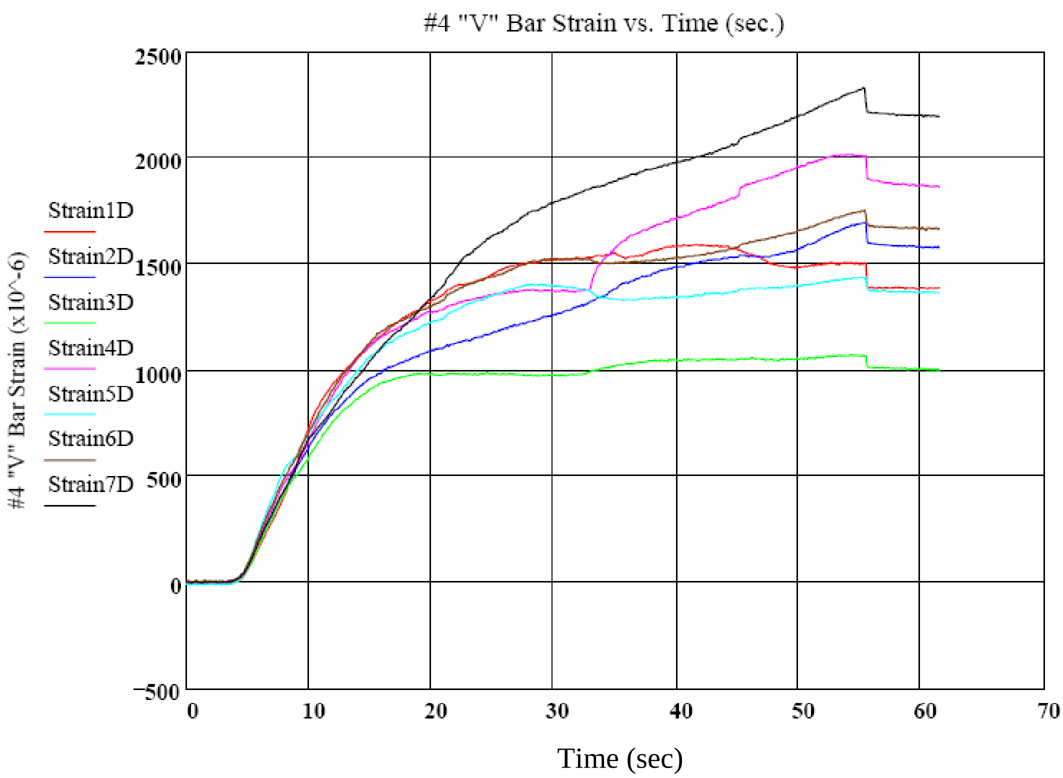
$\text{Strain2D} := \text{Ddata}^{\langle 4 \rangle}$

$\text{Strain4D} := \text{Ddata}^{\langle 6 \rangle}$

$\text{Strain7D} := \text{Ddata}^{\langle 9 \rangle}$

$\text{Strain3D} := \text{Ddata}^{\langle 5 \rangle}$

$\text{Strain5D} := \text{Ddata}^{\langle 7 \rangle}$



Texas Transportation Institute

Job #: 448234

By: William Williams

Checked: ______

Subject: T203 Rail Static Load Test 3 ~ End Case

Strain Gage Data Analysis ~ Test 3 - Location D

$Force1D := Strain1D \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force2D := Strain2D \times E_s \times A_{st} \times \mathbf{0.000001}$

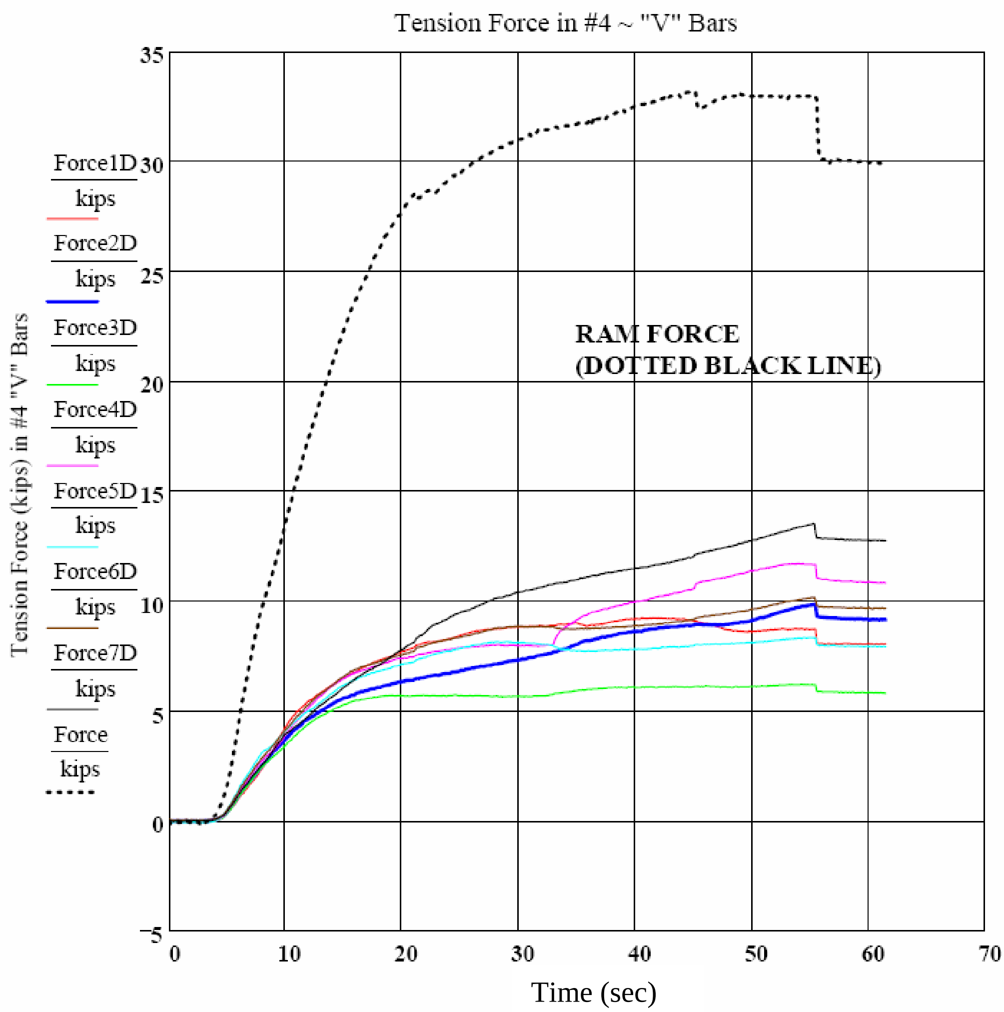
$Force3D := Strain3D \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force4D := Strain4D \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force5D := Strain5D \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force6D := Strain6D \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force7D := Strain7D \times E_s \times A_{st} \times \mathbf{0.000001}$



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Texas Transportation Institute

Subject: T203 Rail Static Load Test 3 ~ End Case

Strain Gage Data Analysis ~ Test 3 - Location D

Sponsor: TxDOT

Page: 4 of 4

Job #: 448234

By: William Williams

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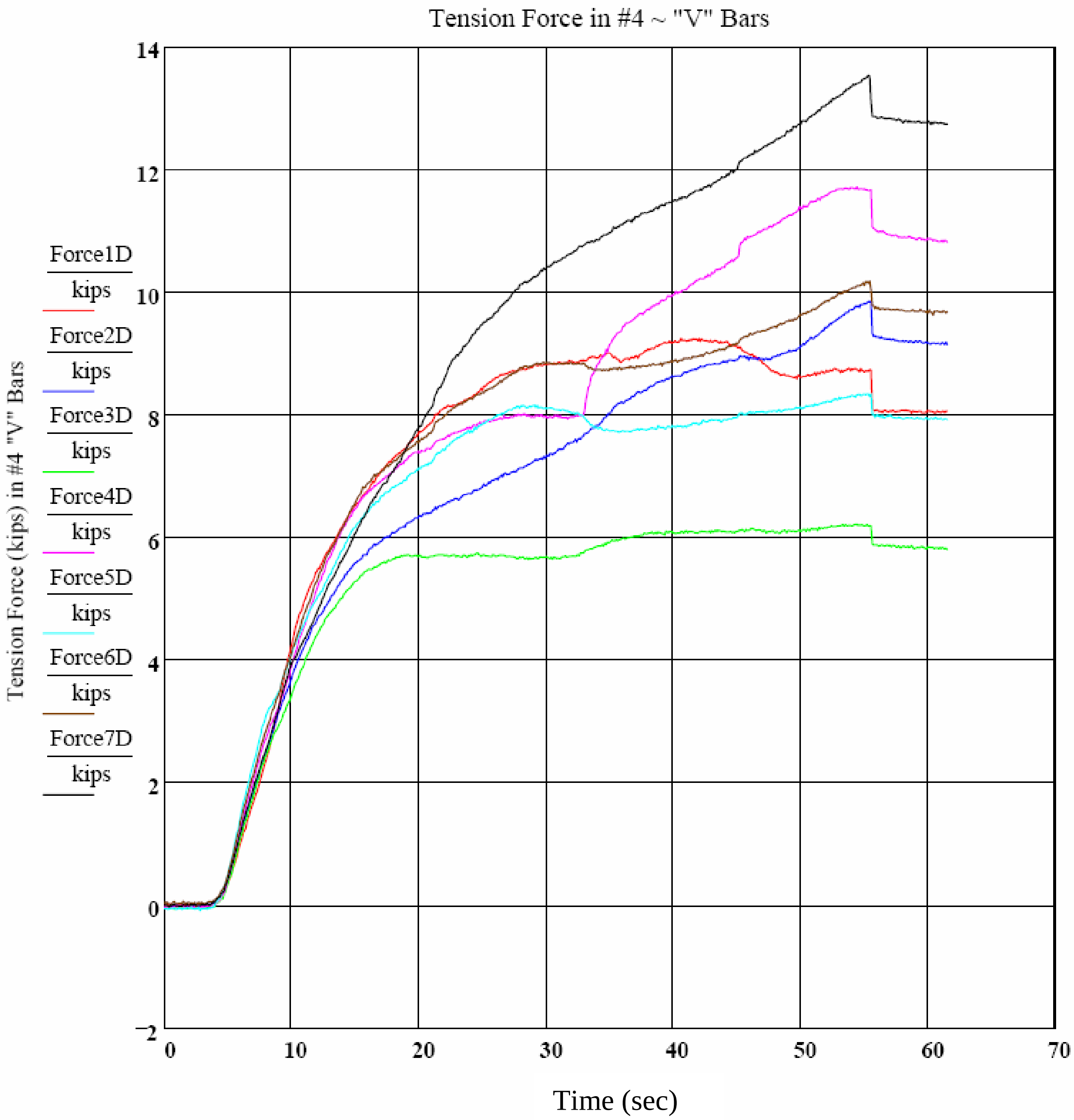


TEST S4 - T501 – LOCATION A

Texas Transportation Institute

Page: 1 of 4

Job #: 448234

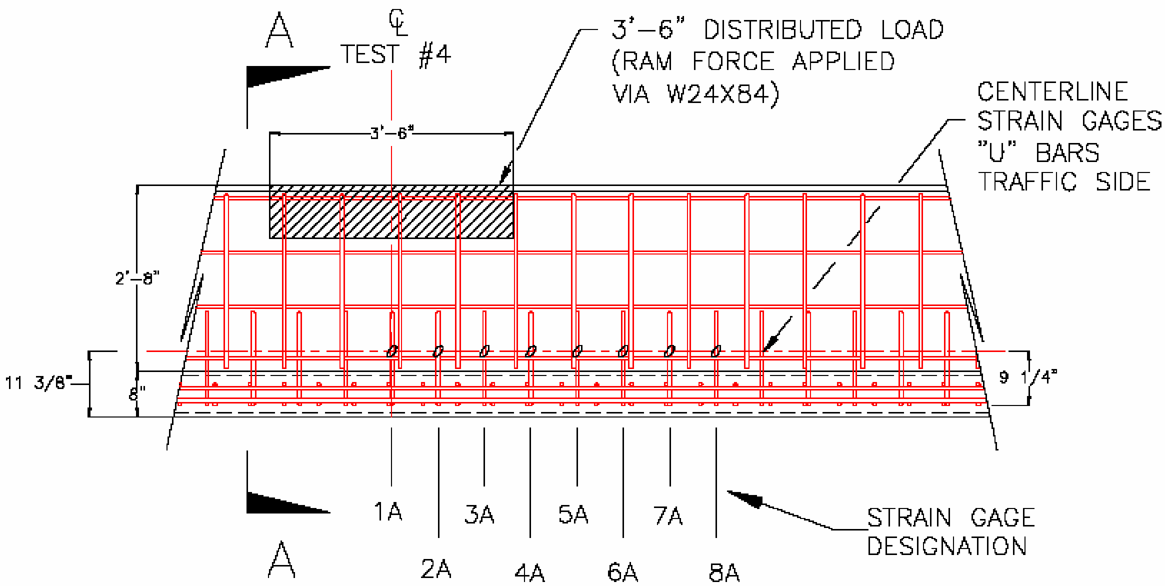
Subject: T501 Rail Static Load Test 4 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 4 - Location A

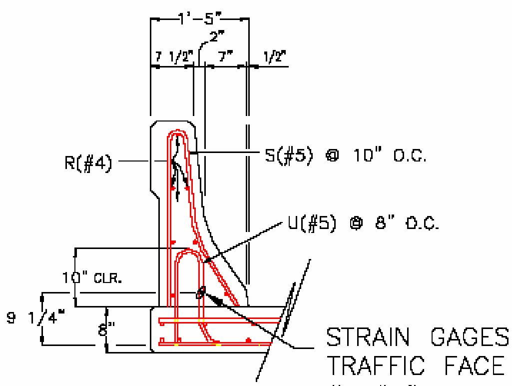
By: William Williams

Checked: ______

Sponsor: TxDOT



T501 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



SECTION A–A

448234AData(S).xmcd
5/16/2006

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PAGE 1

Texas Transportation Institute

Page: 2 of 4

Job #: 448234

Subject: **T501 Rail Static Load Test 4 ~ Mid-Span Case**

Strain Gage Data Analysis ~ Test 4 - Location A

By: **William Williams**

Checked: ______

Sponsor: **TxDOT**

Strain Data in Excel Format from Static Testing Performed 7-16-04:

$E_s := 29000000psi$ Modulus of Steel (psi)

$A_{st} := 0.31in^2$ Area of rebar (in^2)

Adata := T501AData(S).xls

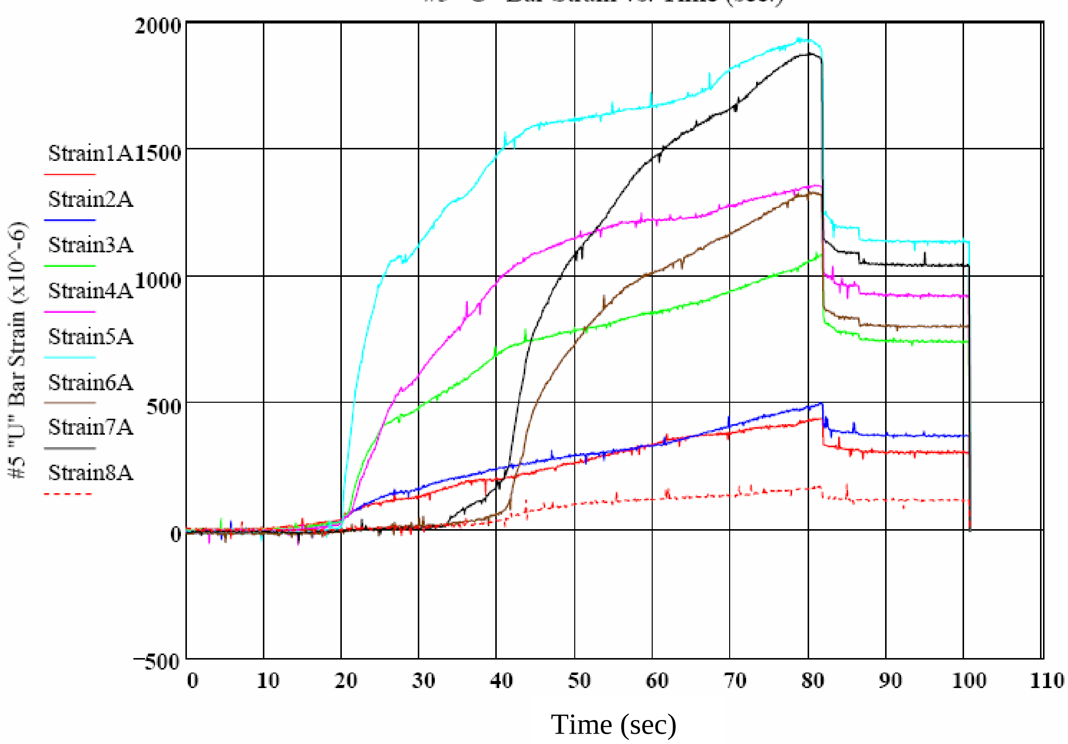
$Time := Adata^{\langle 1 \rangle} \times sec$

$Strain1A := Adata^{\langle 3 \rangle}$ $Force := Adata^{\langle 2 \rangle} \times lbf$ $Strain6A := Adata^{\langle 8 \rangle}$

$Strain2A := Adata^{\langle 4 \rangle}$ $Strain4A := Adata^{\langle 6 \rangle}$ $Strain7A := Adata^{\langle 9 \rangle}$

$Strain3A := Adata^{\langle 5 \rangle}$ $Strain5A := Adata^{\langle 7 \rangle}$ $Strain8A := Adata^{\langle 10 \rangle}$

#5 "U" Bar Strain vs. Time (sec.)



448234AData(S).xmcd
5/16/2006

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Texas Transportation Institute

Page: 3 of 4

Job #: 448234

By: William Williams

Checked: ______

Subject: T501 Rail Static Load Test 4 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 4 - Location A

$Force1A := Strain1A \times E_s \times A_{st} \times 0.000001$

$Force2A := Strain2A \times E_s \times A_{st} \times 0.000001$

$Force3A := Strain3A \times E_s \times A_{st} \times 0.000001$

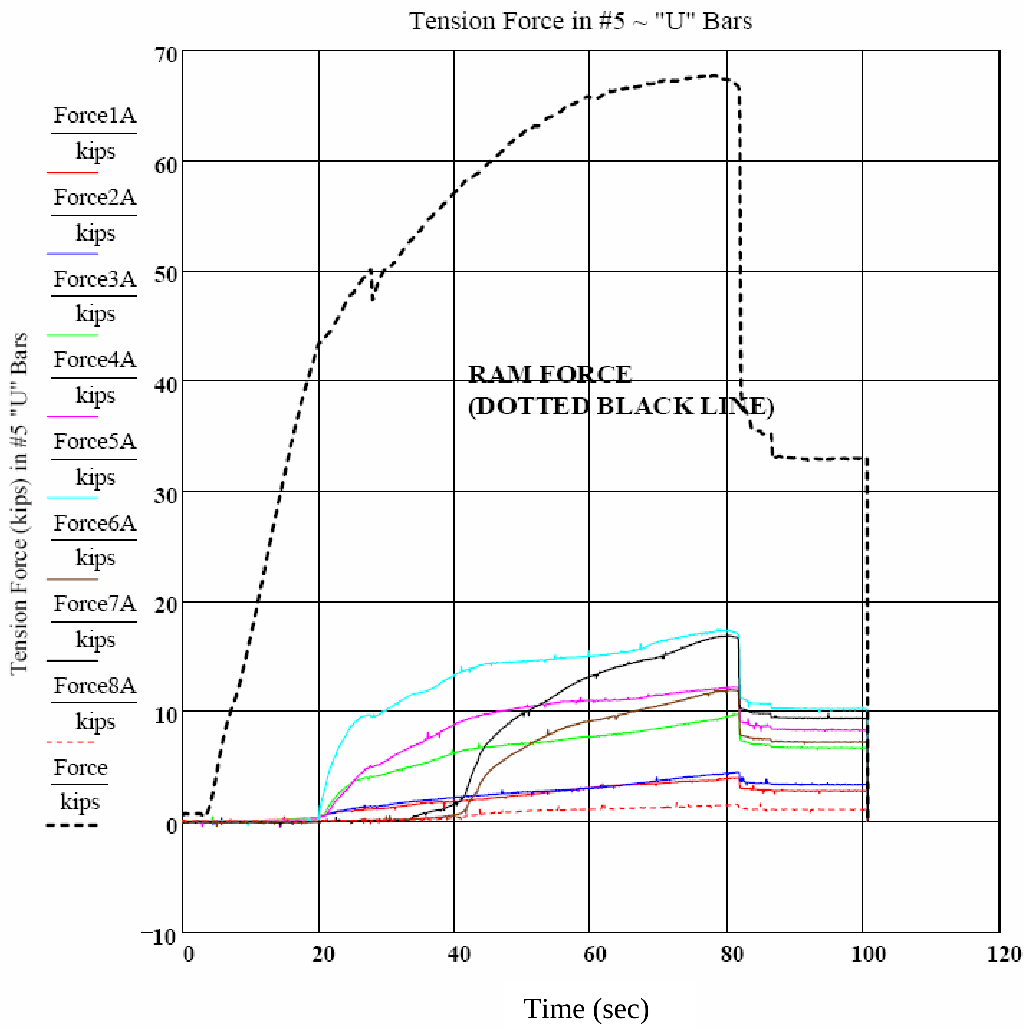
$Force4A := Strain4A \times E_s \times A_{st} \times 0.000001$

$Force5A := Strain5A \times E_s \times A_{st} \times 0.000001$

$Force6A := Strain6A \times E_s \times A_{st} \times 0.000001$

$Force7A := Strain7A \times E_s \times A_{st} \times 0.000001$

$Force8A := Strain8A \times E_s \times A_{st} \times 0.000001$



Texas Transportation Institute

Page: 4 of 4

Job #: 448234

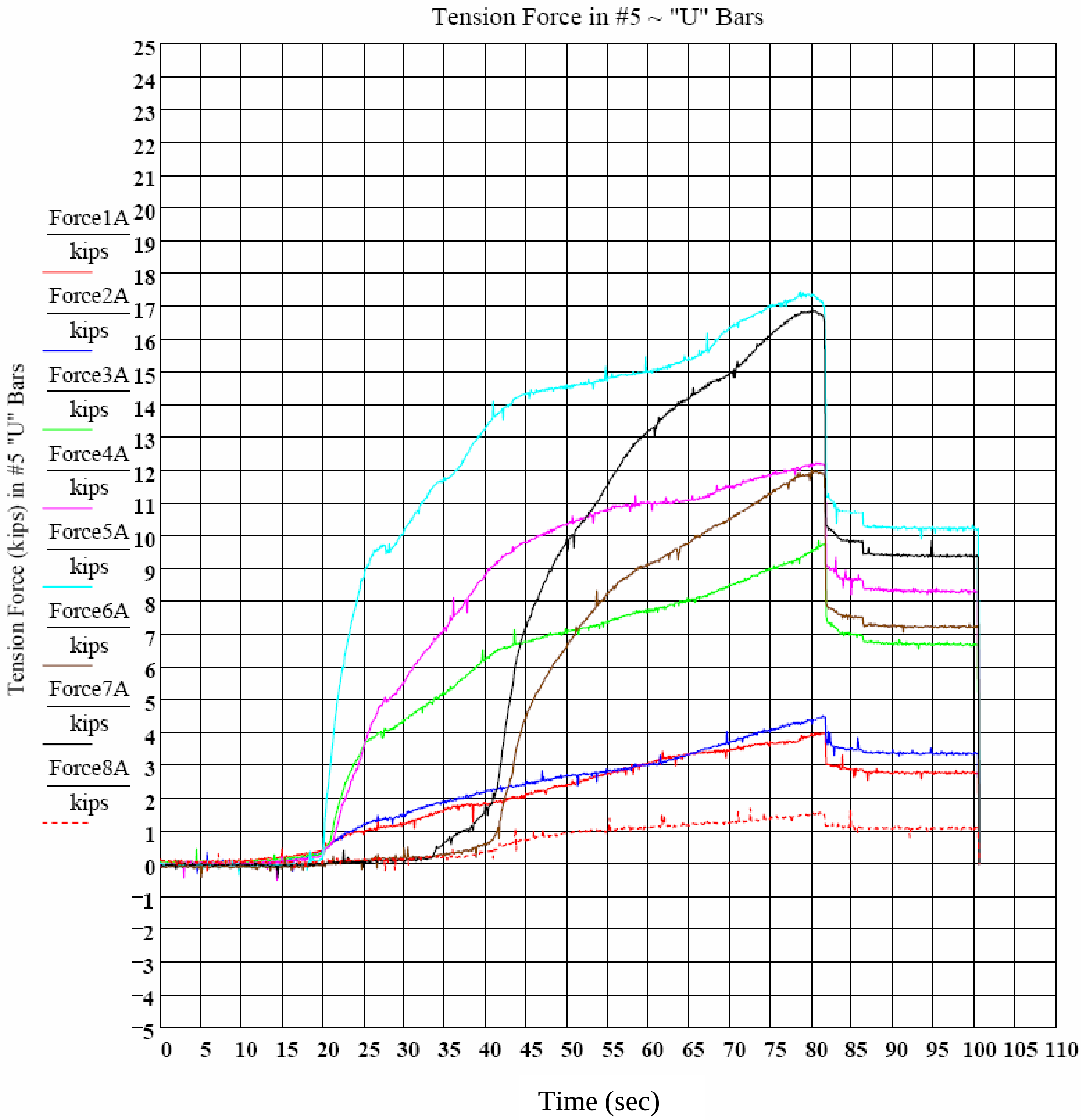
By: William Williams

Checked: ______

Subject: T501 Rail Static Load Test 4 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 4 - Location A

Sponsor: TxDOT



TEST S5 - T501 – LOCATION B

Texas Transportation Institute

Page: 1 of 4

Job #: 448234

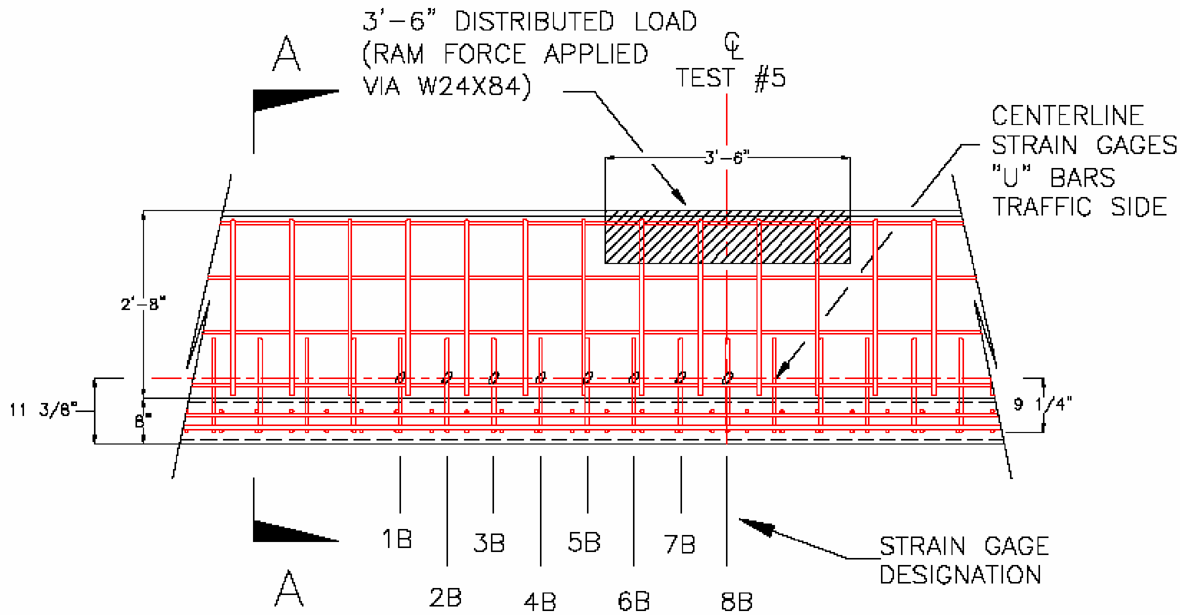
By: William Williams

Checked: ______

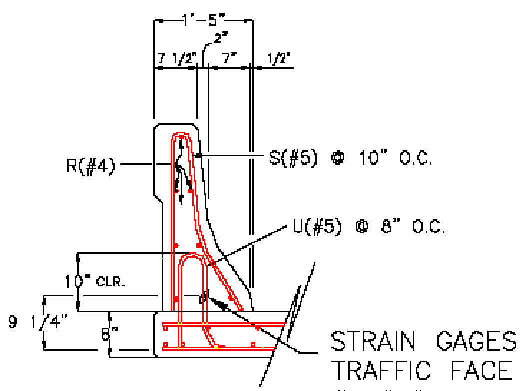
Subject: T501 Rail Static Load Test 5 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 5 - Location B

Sponsor: TxDOT



T501 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



SECTION A–A

Texas Transportation Institute

Page: 2 of 4

Job #: 448234

By: William Williams

Checked: ______

Subject: **T501 Rail Static Load Test 5 ~ Mid-Span Case**

Strain Gage Data Analysis ~ Test 5 - Location B

Sponsor: **TxDOT**

Strain Data in Excel Format from Static Testing Performed 7-16-04:

$E_s := 29000000psi$ Modulus of Steel (psi)

$A_{st} := 0.31in^2$ Area of rebar (in^2)

Bdata := T501BData(S).xls

$Time := Bdata^{\langle 1 \rangle} \times sec$

$Strain1B := Bdata^{\langle 3 \rangle}$

$Force := Bdata^{\langle 2 \rangle} \times lbf$

$Strain6B := Bdata^{\langle 8 \rangle}$

$Strain2B := Bdata^{\langle 4 \rangle}$

$Strain4B := Bdata^{\langle 6 \rangle}$

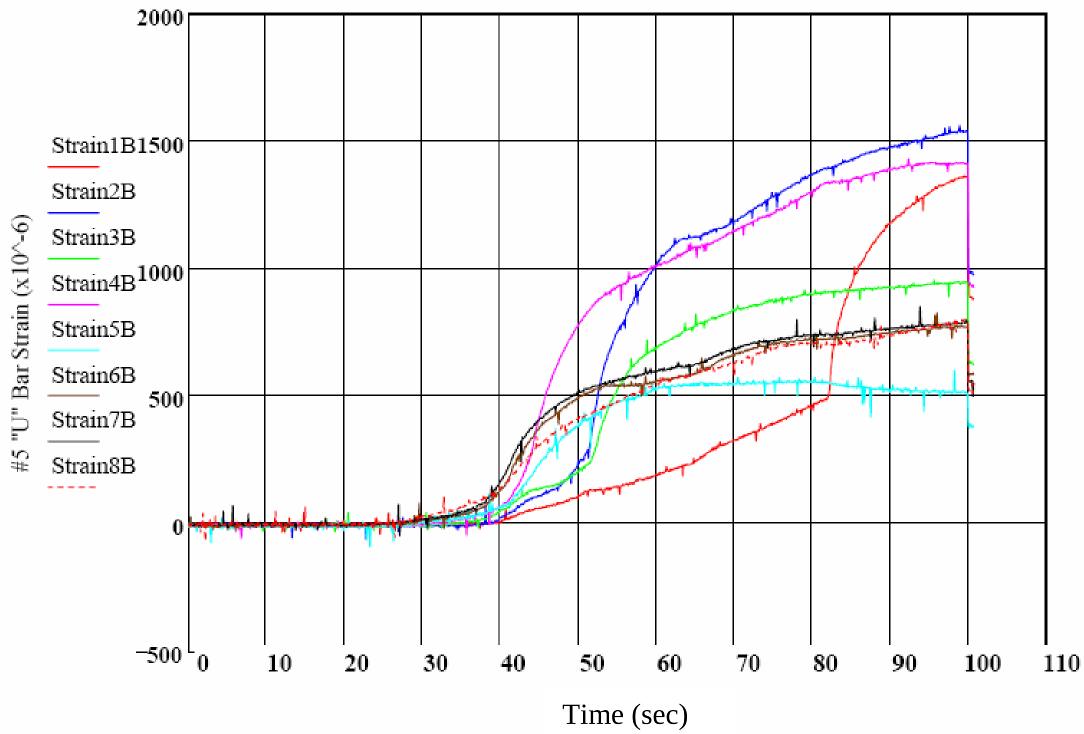
$Strain7B := Bdata^{\langle 9 \rangle}$

$Strain3B := Bdata^{\langle 5 \rangle}$

$Strain5B := Bdata^{\langle 7 \rangle}$

$Strain8B := Bdata^{\langle 10 \rangle}$

#5 "U" Bar Strain vs. Time (sec.)



Subject: T501 Rail Static Load Test 5 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 5 - Location B

$\text{Force1B} := \text{Strain1B} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force2B} := \text{Strain2B} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force3B} := \text{Strain3B} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force4B} := \text{Strain4B} \times E_s \times A_{st} \times \mathbf{0.000001}$

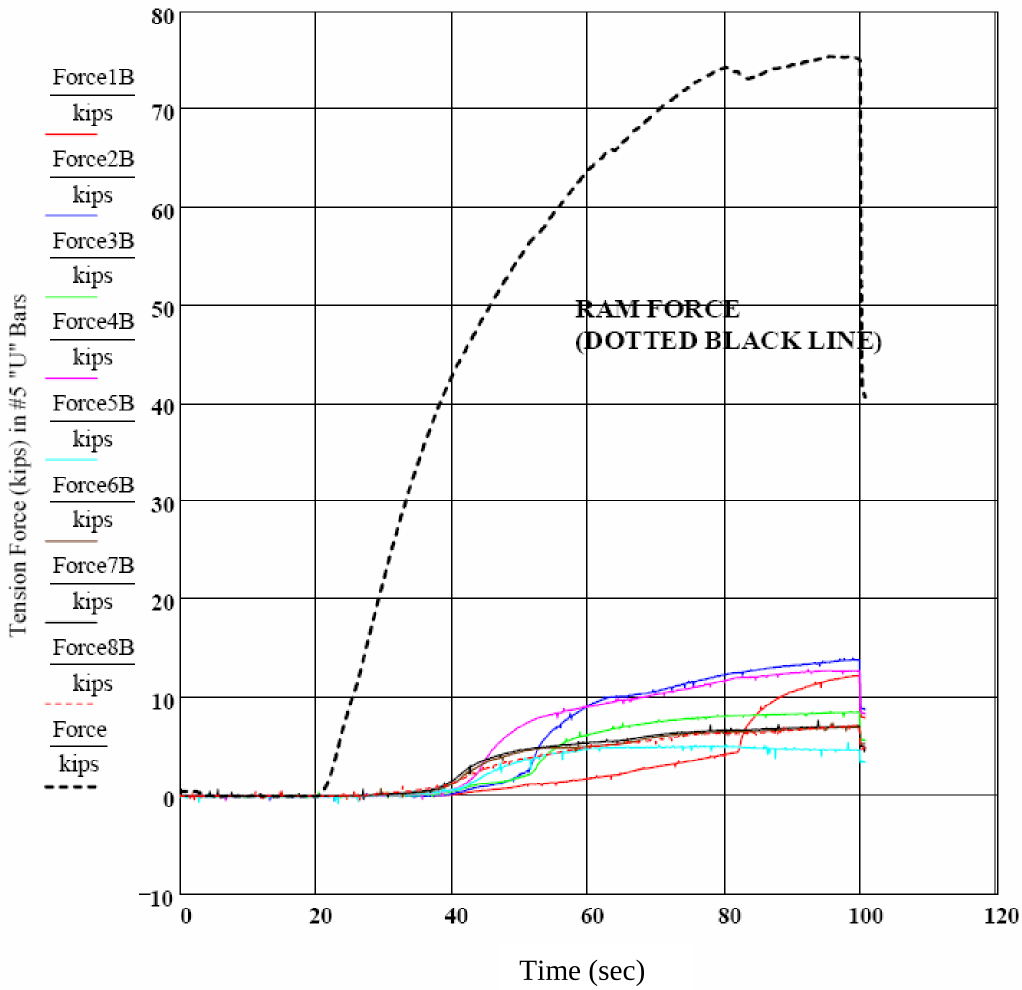
$\text{Force5B} := \text{Strain5B} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force6B} := \text{Strain6B} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force7B} := \text{Strain7B} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force8B} := \text{Strain8B} \times E_s \times A_{st} \times \mathbf{0.000001}$

Tension Force in #5 ~ "U" Bars



Texas Transportation Institute

Page: 4 of 4

Job #: 448234

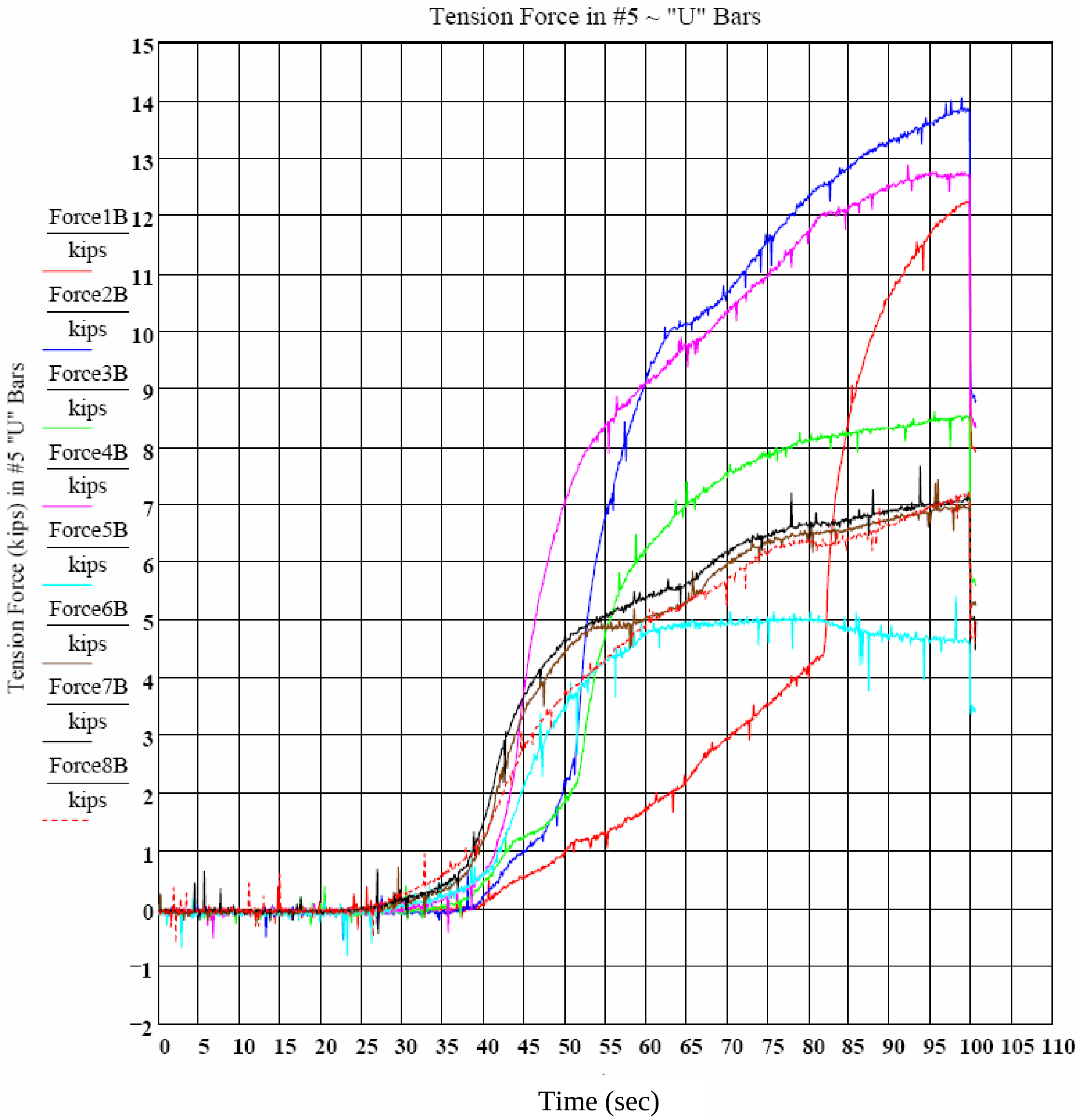
By: William Williams

Checked: ______

Subject: T501 Rail Static Load Test 5 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 5 - Location B

Sponsor: TxDOT



448234BData(S).xmcd
5/16/2006

William Williams, P.E.
Ph. # (979) 862-2297

TEST S6 - T501 – LOCATION C

Texas Transportation Institute

Subject: T501 Rail Static Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C

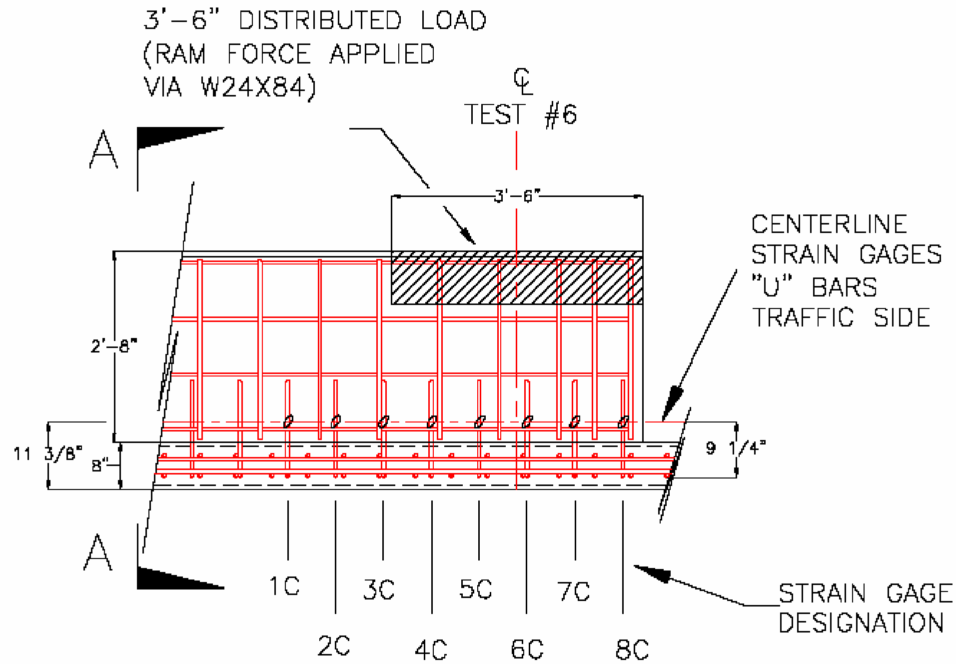
Sponsor: TxDOT

Page: 1 of 4

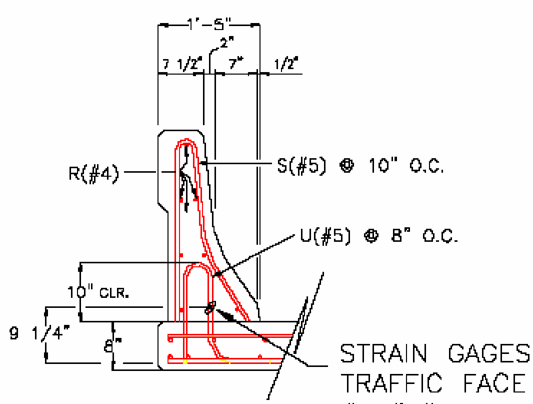
Job #: 448234

By: William Williams

Checked: ______



T501 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



SECTION A–A

448234CData(S).xmcd
5/16/2006

William Williams, P.E.
Ph. # (979) 862-2297

PAGE 1

Texas Transportation Institute

Job #: 448234

By: William Williams

Checked: ______

Subject: T501 Rail Static Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C

Sponsor: TxDOT

Strain Data in Excel Format from Static Testing Performed 7-16-04:

$E_s := 29000000\text{psi}$ Modulus of Steel (psi)

$A_{st} := 0.31\text{in}^2$ Area of rebar (in^2)

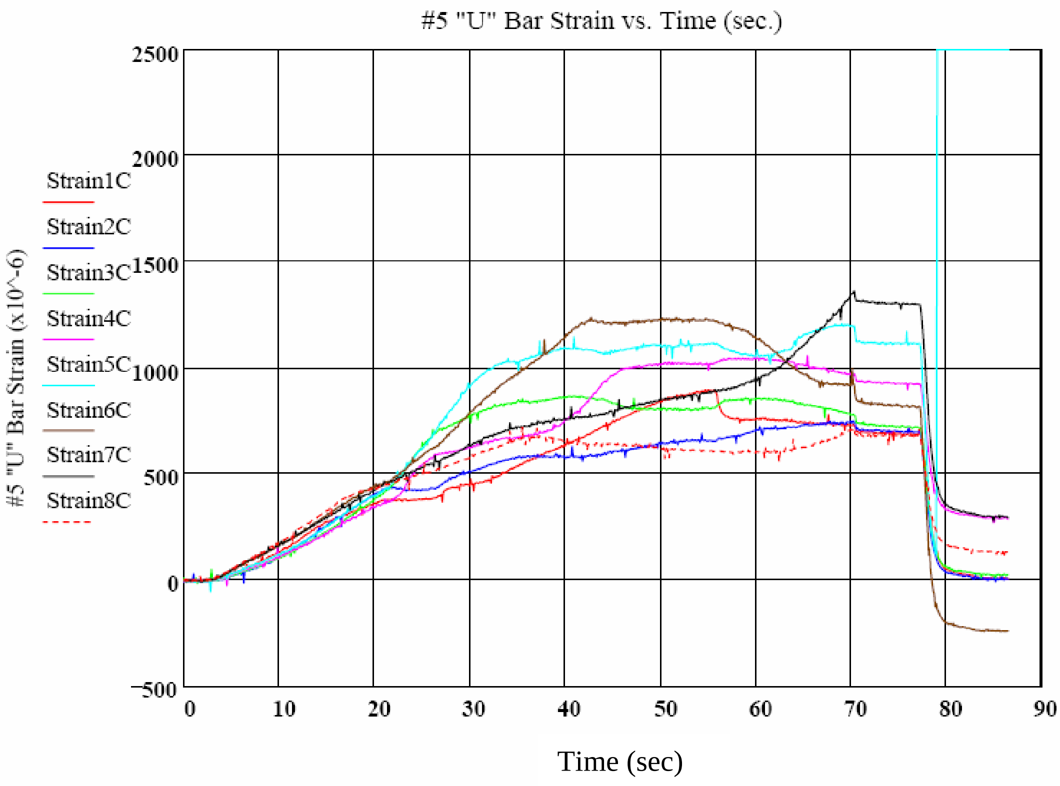
Cdata := T501CData(S).xls

$\text{Time} := \text{Cdata}^{\langle 1\rangle} \times \text{sec}$

$\text{Strain1C} := \text{Cdata}^{\langle 3\rangle}$ $\text{Force} := \text{Cdata}^{\langle 2\rangle} \times \text{lbf}$ $\text{Strain6C} := \text{Cdata}^{\langle 8\rangle}$

$\text{Strain2C} := \text{Cdata}^{\langle 4\rangle}$ $\text{Strain4C} := \text{Cdata}^{\langle 6\rangle}$ $\text{Strain7C} := \text{Cdata}^{\langle 9\rangle}$

$\text{Strain3C} := \text{Cdata}^{\langle 5\rangle}$ $\text{Strain5C} := \text{Cdata}^{\langle 7\rangle}$ $\text{Strain8C} := \text{Cdata}^{\langle 10\rangle}$



Subject: T501 Rail Static Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C

$Force1C := Strain1C \times E_s \times A_{st} \times 0.000001$

$Force2C := Strain2C \times E_s \times A_{st} \times 0.000001$

$Force3C := Strain3C \times E_s \times A_{st} \times 0.000001$

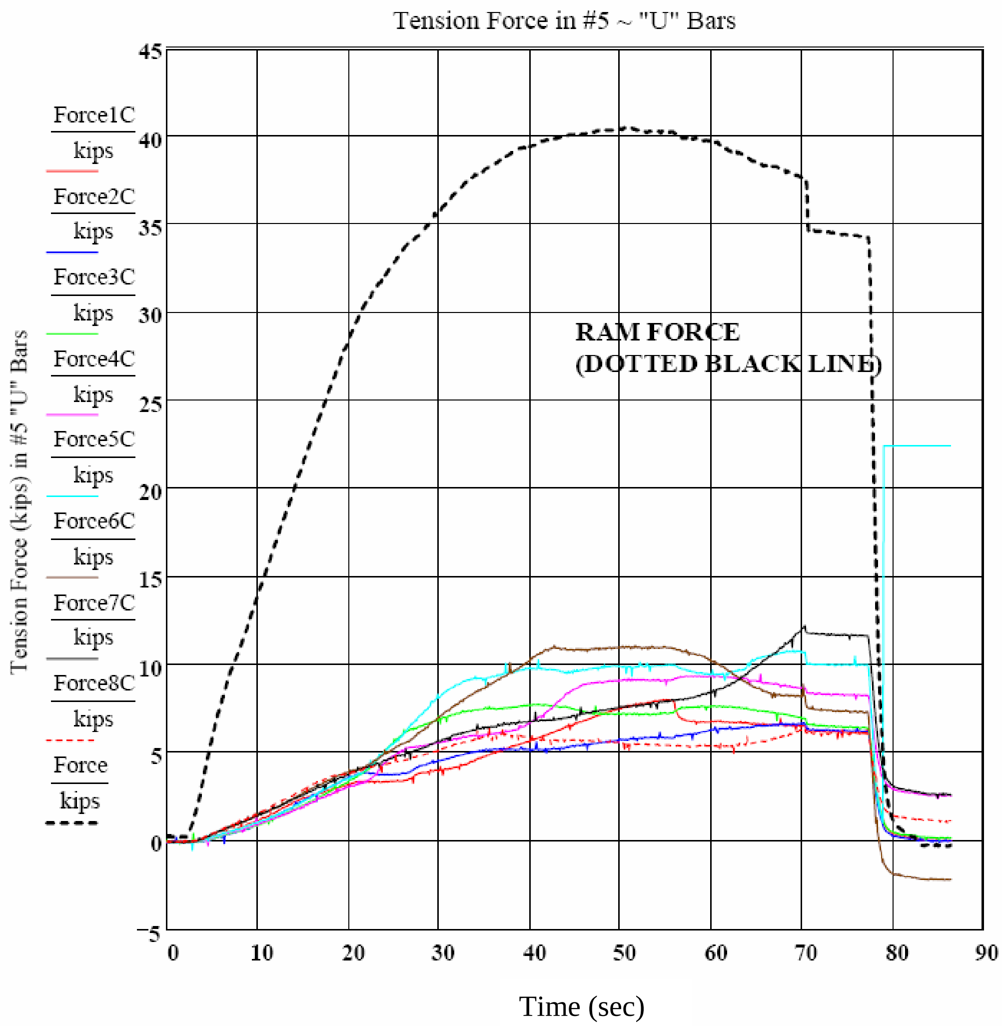
$Force4C := Strain4C \times E_s \times A_{st} \times 0.000001$

$Force5C := Strain5C \times E_s \times A_{st} \times 0.000001$

$Force6C := Strain6C \times E_s \times A_{st} \times 0.000001$

$Force7C := Strain7C \times E_s \times A_{st} \times 0.000001$

$Force8C := Strain8C \times E_s \times A_{st} \times 0.000001$



Texas Transportation Institute

Page: 4 of 4

Job #: 448234

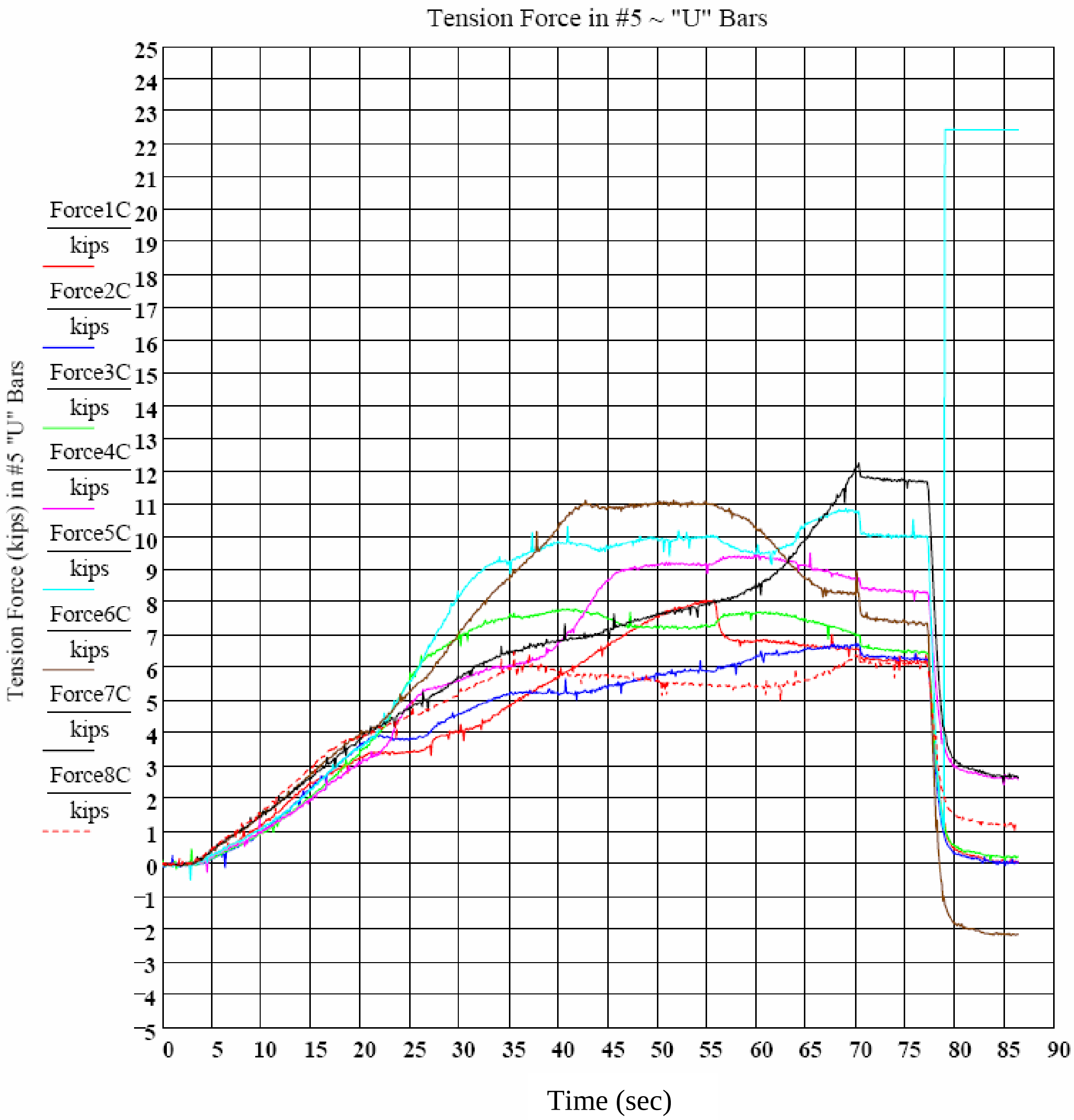
By: William Williams

Checked: ______

Subject: T501 Rail Static Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C

Sponsor: TxDOT



APPENDIX C. DATA FROM DYNAMIC TESTING

TEST B1 - T203 – LOCATION F

Texas Transportation Institute

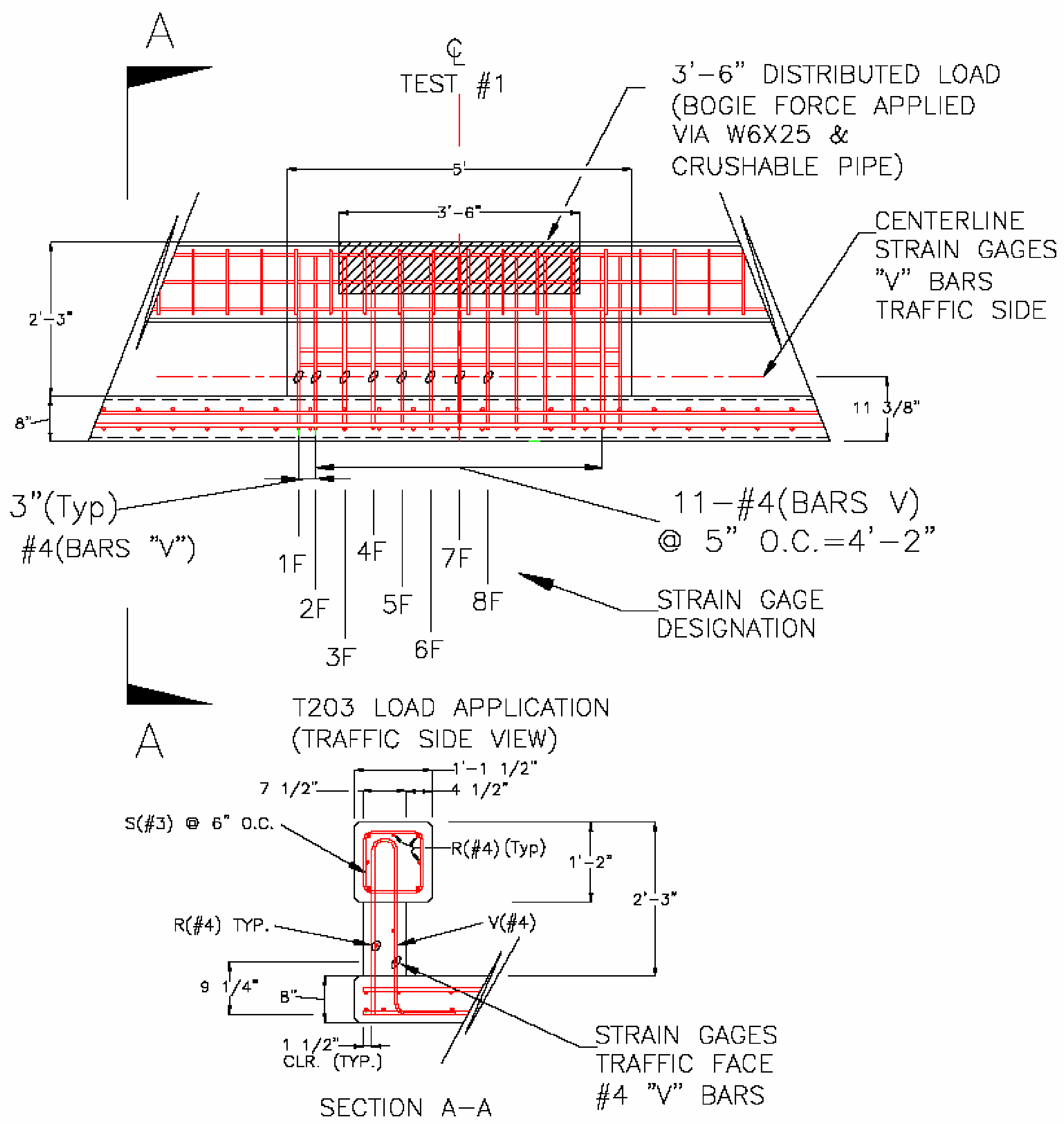
Page: **1 of 5**

Job #: **448235**

By: **William Williams**

Subject: **T203 Rail Dynamic Load Test 1 ~ Mid-Span Case**

Strain Gage Data Analysis ~ Test 1 - Location F



448235FData(Drev1).xmcd
4/4/2006

William Williams, P.E.
Ph. # (979) 862-2297

PAGE 1

Texas Transportation Institute

Page: 2 of 5

Job #: 448235

By: William Williams

Subject: T203 Rail Dynamic Load Test 1 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 1 - Location F

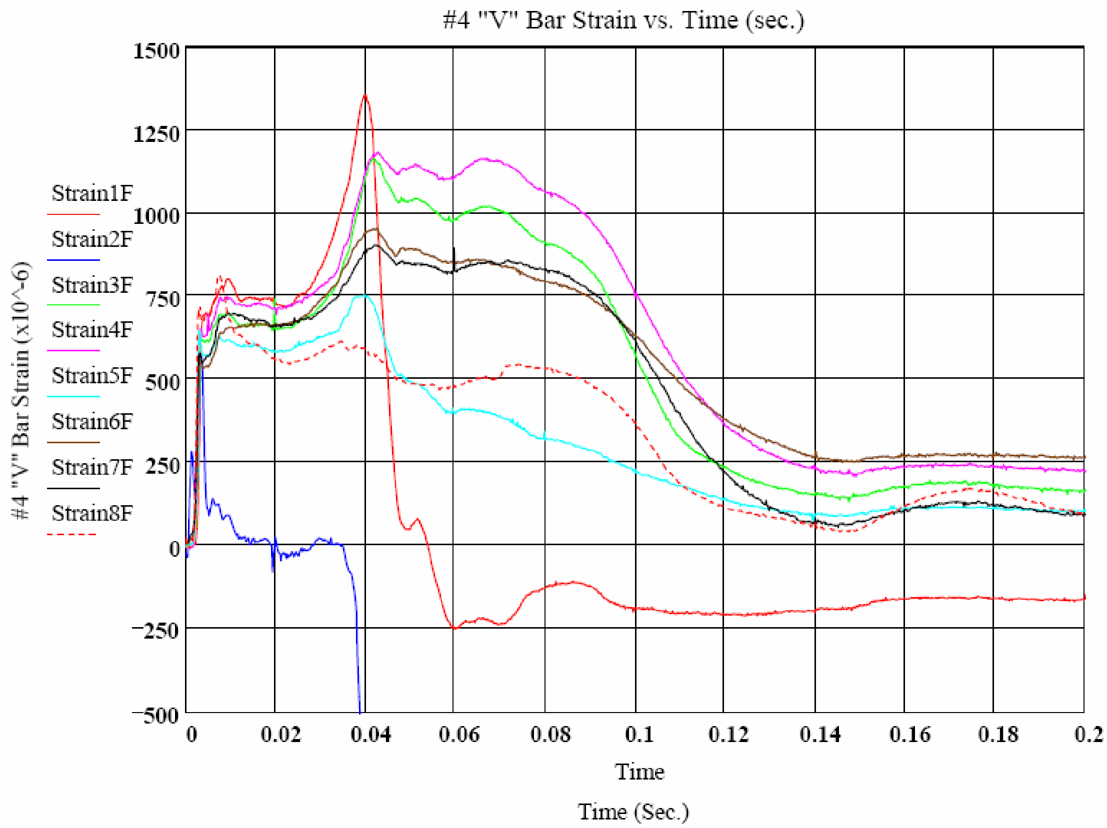
$E_s := 29000000psi$ Modulus of Steel (psi)

$A_{st} := 0.20in^2$ Area of rebar (in^2)

Data in Excel Format from Dynamic Testing Performed 2-25-05:

Dynamic Strain Gage Data from "V" Bars Here in Collapsed Region:

Dynamic Strain Gage Data



Job #: 448235

Subject: T203 Rail Dynamic Load Test 1 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 1 - Location F

$Force1F := Strain1F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force2F := Strain2F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force3F := Strain3F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force4F := Strain4F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force5F := Strain5F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force6F := Strain6F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force7F := Strain7F \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force8F := Strain8F \times E_s \times A_{st} \times \mathbf{0.000001}$

Texas Transportation Institute

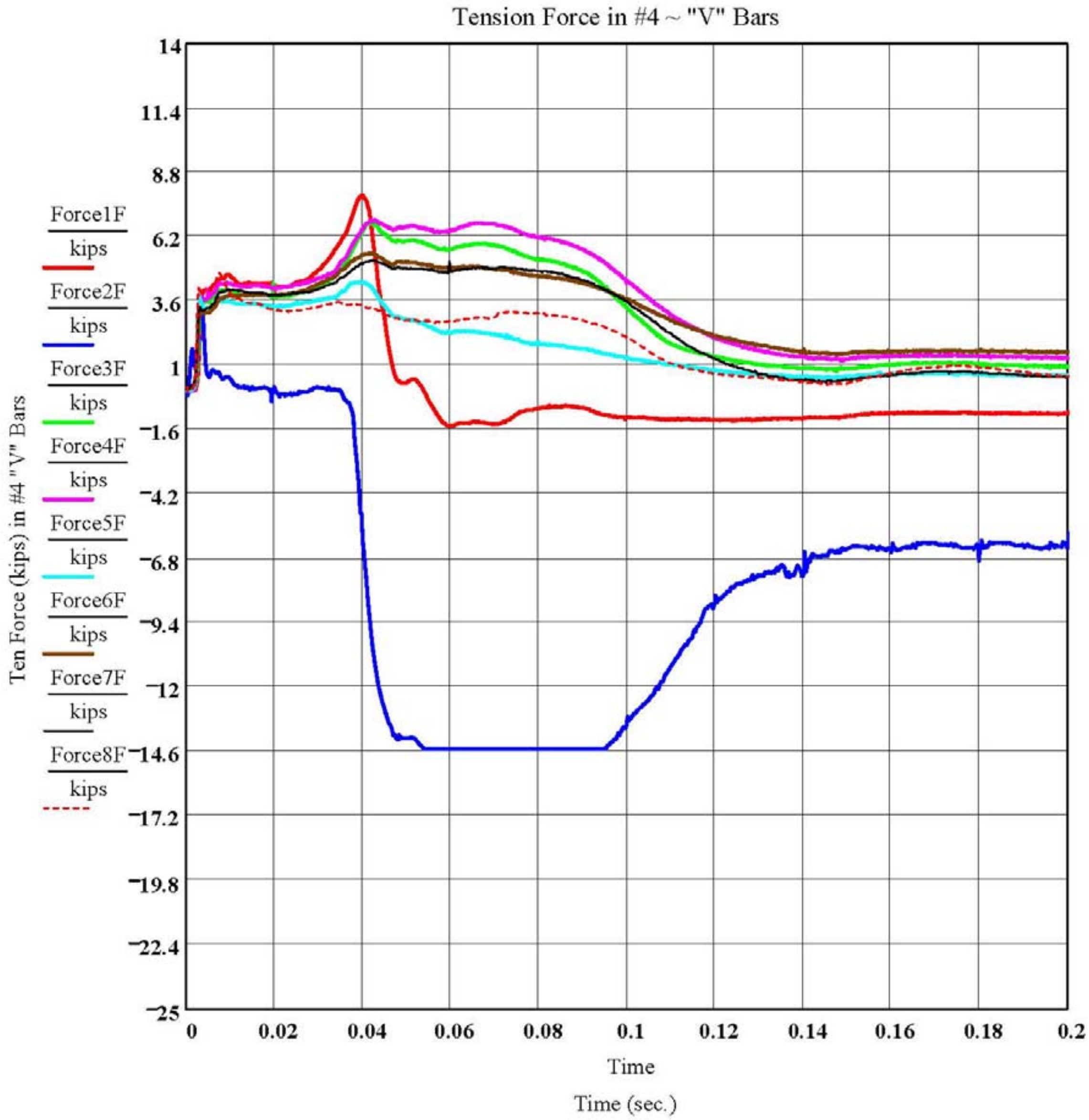
Page: 4 of 5

Job #: 448235

By: William Williams

Subject: T203 Rail Dynamic Load Test 1 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 1 - Location "F"



448235FData(Drev1).xmcd
12/13/2006

William Williams, P.E.
Ph. # (979) 862-2297

Texas Transportation Institute

Page: 5 of 5

Job #: 448235

By: William Williams

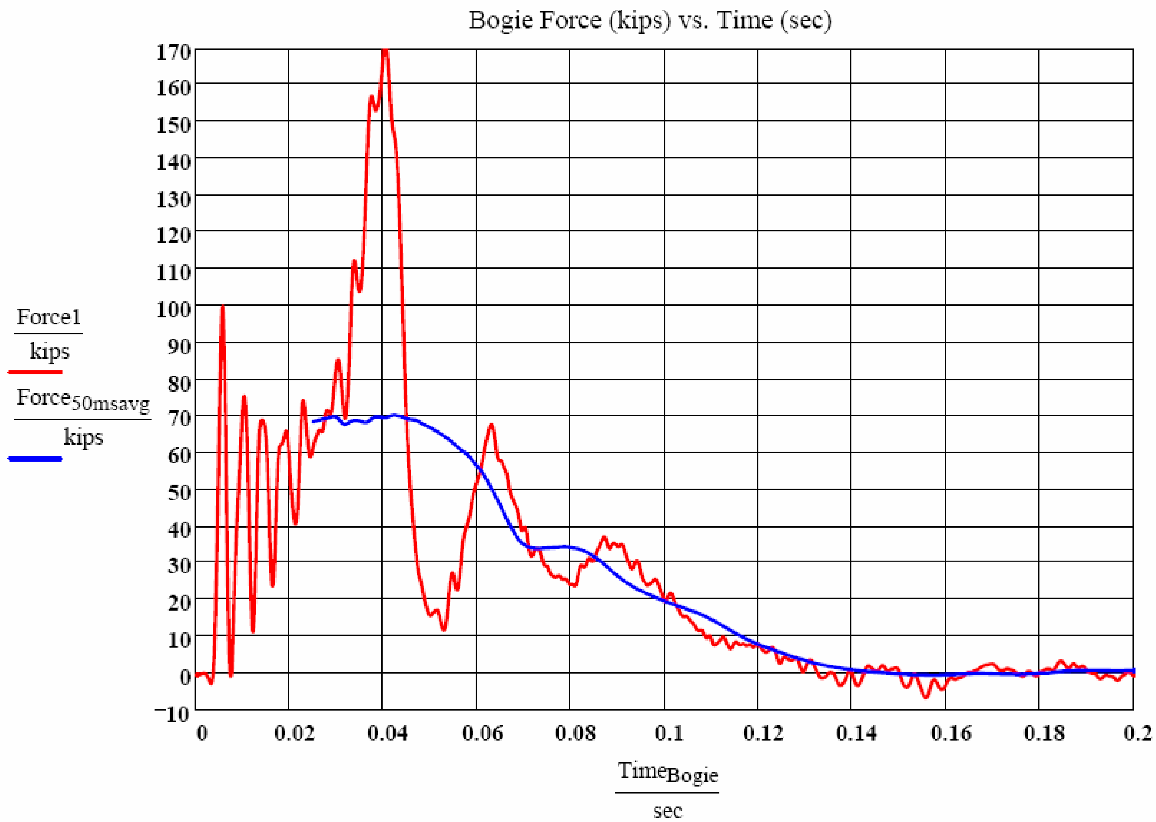
Subject: T203 Rail Dynamic Load Test 1 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 1 - Location F

Dynamic Bogie Data Here in Collapsed Region:

Dynamic Bogie Data

$Time_{Bogie} := Fbogie^{\langle 1 \rangle} \times sec$ $\quad Force1 := Fbogie^{\langle 2 \rangle} \times -5kips$ $\quad Force_{50msavg} := Fbogie^{\langle 3 \rangle} \times -5kips$



TEST B2 - T203 – LOCATION D

Texas Transportation Institute

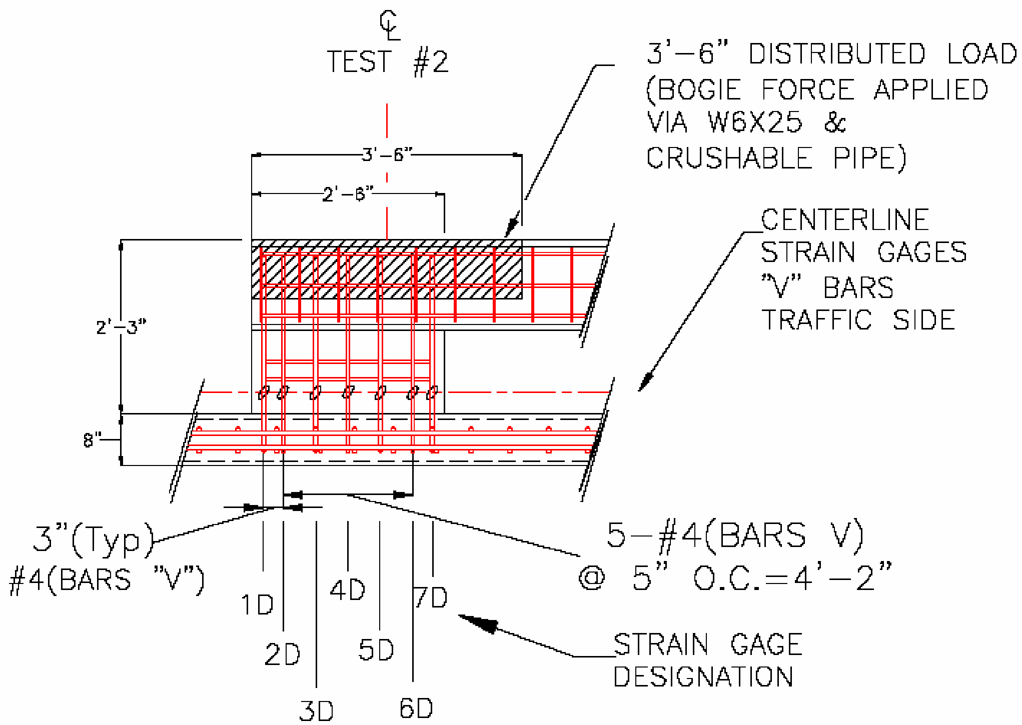
Page: 1 of 5

Job #: 448235

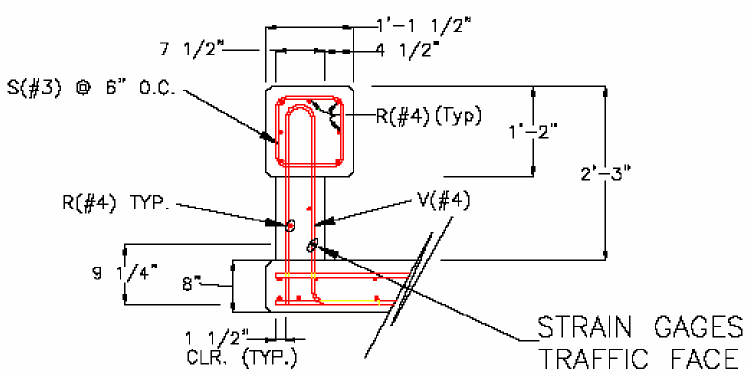
By: William Williams

Subject: T203 Rail Dynamic Load Test 2 ~ End Case

Strain Gage Data Analysis ~ Test 2 - Location D



T203 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



END VIEW

Texas Transportation Institute

Job #: 448235

By: William Williams

Subject: T203 Rail Dynamic Load Test 2 ~ End Case

Strain Gage Data Analysis ~ Test 2 - Location "D"

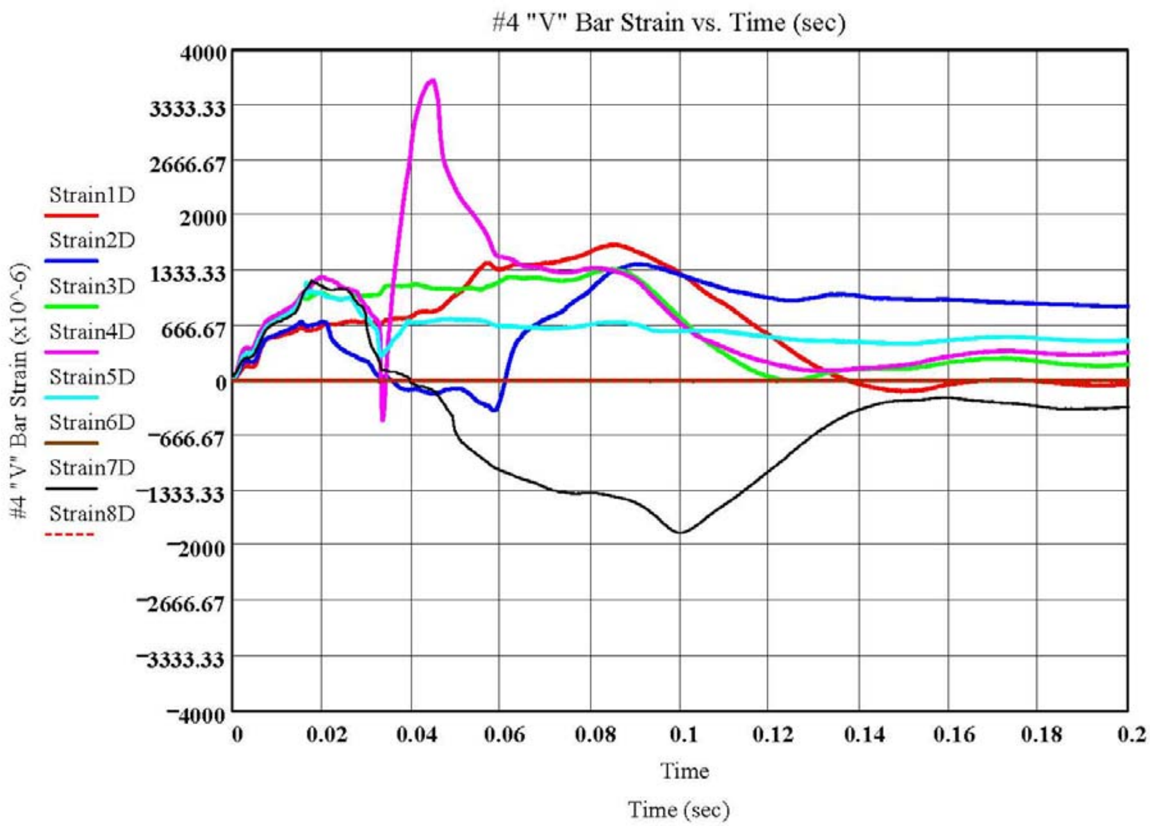
$E_s := 29000000 psi$ Modulus of Steel (psi)

$A_{st} := 0.20 in^2$ Area of rebar (in^2)

Data in Excel Format from Dynamic Testing Performed 2-25-05:

Dynamic Strain Gage Data from "V" Bars Here in Collapsed Region:

Dynamic Strain Gage Data



Subject: T203 Rail Dynamic Load Test 2 ~ End Case

By: William Williams

Strain Gage Data Analysis ~ Test 2 - Location D

$\text{Force1D} := \text{Strain1D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force2D} := \text{Strain2D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force3D} := \text{Strain3D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force4D} := \text{Strain4D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force5D} := \text{Strain5D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force6D} := \text{Strain6D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force7D} := \text{Strain7D} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force8D} := \text{Strain8D} \times E_s \times A_{st} \times \mathbf{0.000001}$

Texas Transportation Institute

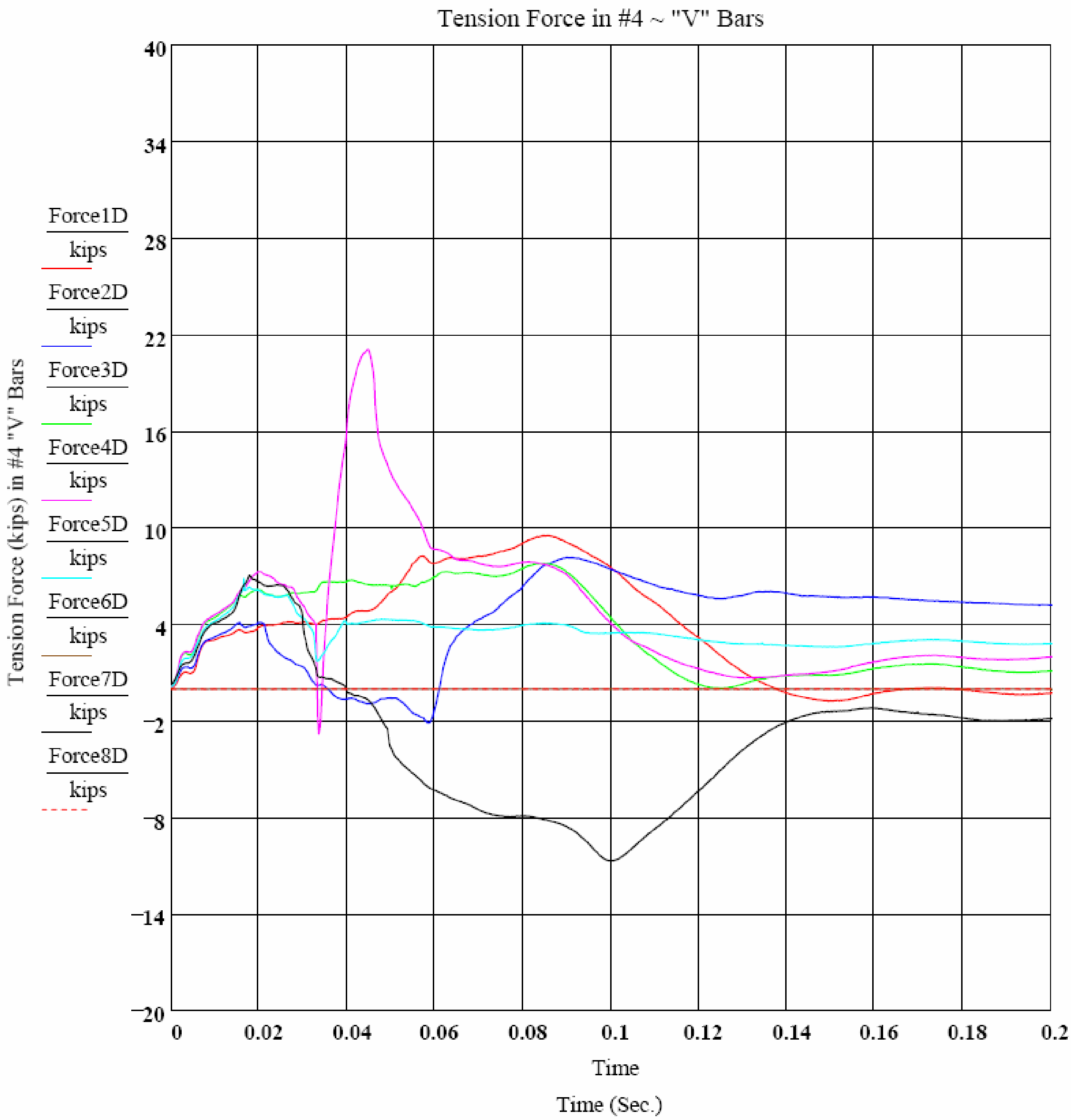
Page: 4 of 5

Job #: 448235

Subject: T203 Rail Dynamic Load Test 2 ~ End Case

By: William Williams

Strain Gage Data Analysis ~ Test 2 - Location D



448235DData(Drev1).xmcd
4/4/2006

William Williams, P.E.
Ph. # (979) 862-2297

Texas Transportation Institute

Page: 5 of 5

Job #: 448235

By: William Williams

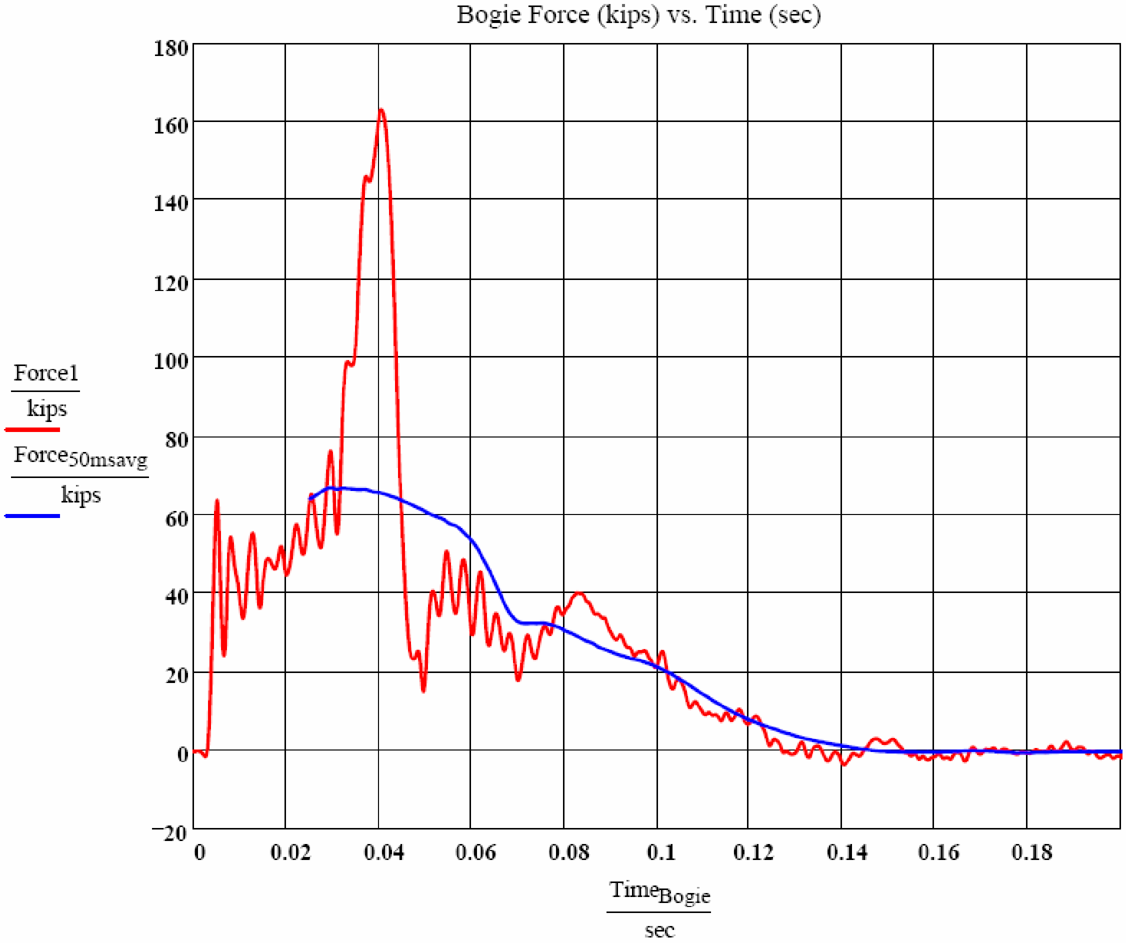
Subject: T203 Rail Dynamic Load Test 2 ~ End Case

Strain Gage Data Analysis ~ Test 2 - Location D

Dynamic Bogie Data Here in Collapsed Region:

Dynamic Bogie Data

$Time_{Bogie} := Dbogie^{\langle 1 \rangle} \times sec \qquad Force1 := Dbogie^{\langle 2 \rangle} \times -5kips \qquad Force_{50msavg} := Dbogie^{\langle 3 \rangle} \times -5kips$



TEST B3 - T203 – LOCATION E

Texas Transportation Institute

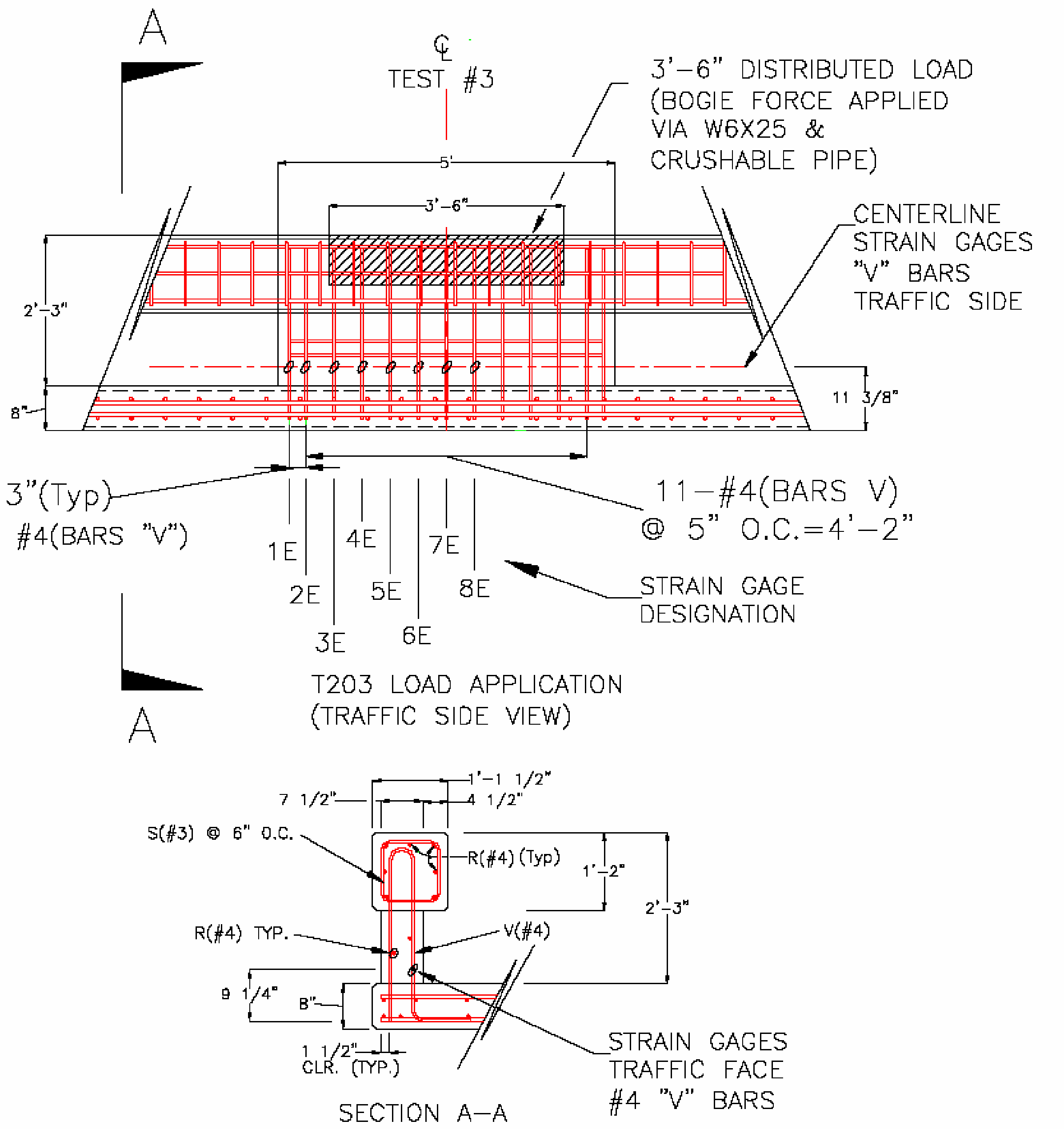
Page: 1 of 5

Job #: 448235

Subject: T203 Rail Dynamic Load Test 3 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 3 - Location E

By: William Williams



Texas Transportation Institute

Job #: 448235

Subject: T203 Rail Dynamic Load Test 3 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 3 - Location "E"

By: William Williams

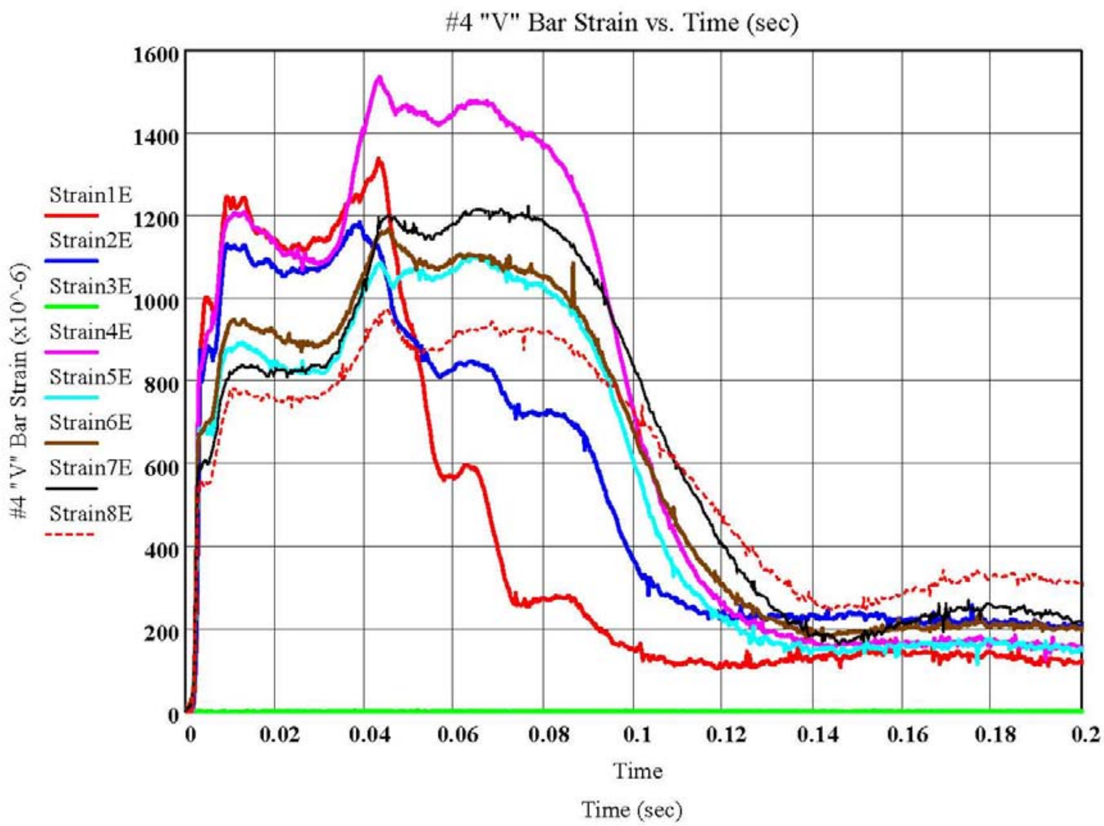
$E_s := 29000000psi$ Modulus of Steel (psi)

$A_{st} := 0.20in^2$ Area of rebar (in^2)

Data in Excel Format from Dynamic Testing Performed 2-28-05:

Dynamic Strain Gage Data from "V" Bars Here in Collapsed Region:

Dynamic Strain Gage Data



Texas Transportation Institute

Page: 3 of 5

Job #: 448235

By: **William Williams**

Subject: **T203 Rail Dynamic Load Test 3 ~ Mid-Span Case**

Strain Gage Data Analysis ~ Test 3 - Location E

$Force1E := Strain1E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force2E := Strain2E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force3E := Strain3E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force4E := Strain4E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force5E := Strain5E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force6E := Strain6E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force7E := Strain7E \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force8E := Strain8E \times E_s \times A_{st} \times \mathbf{0.000001}$

Texas Transportation Institute

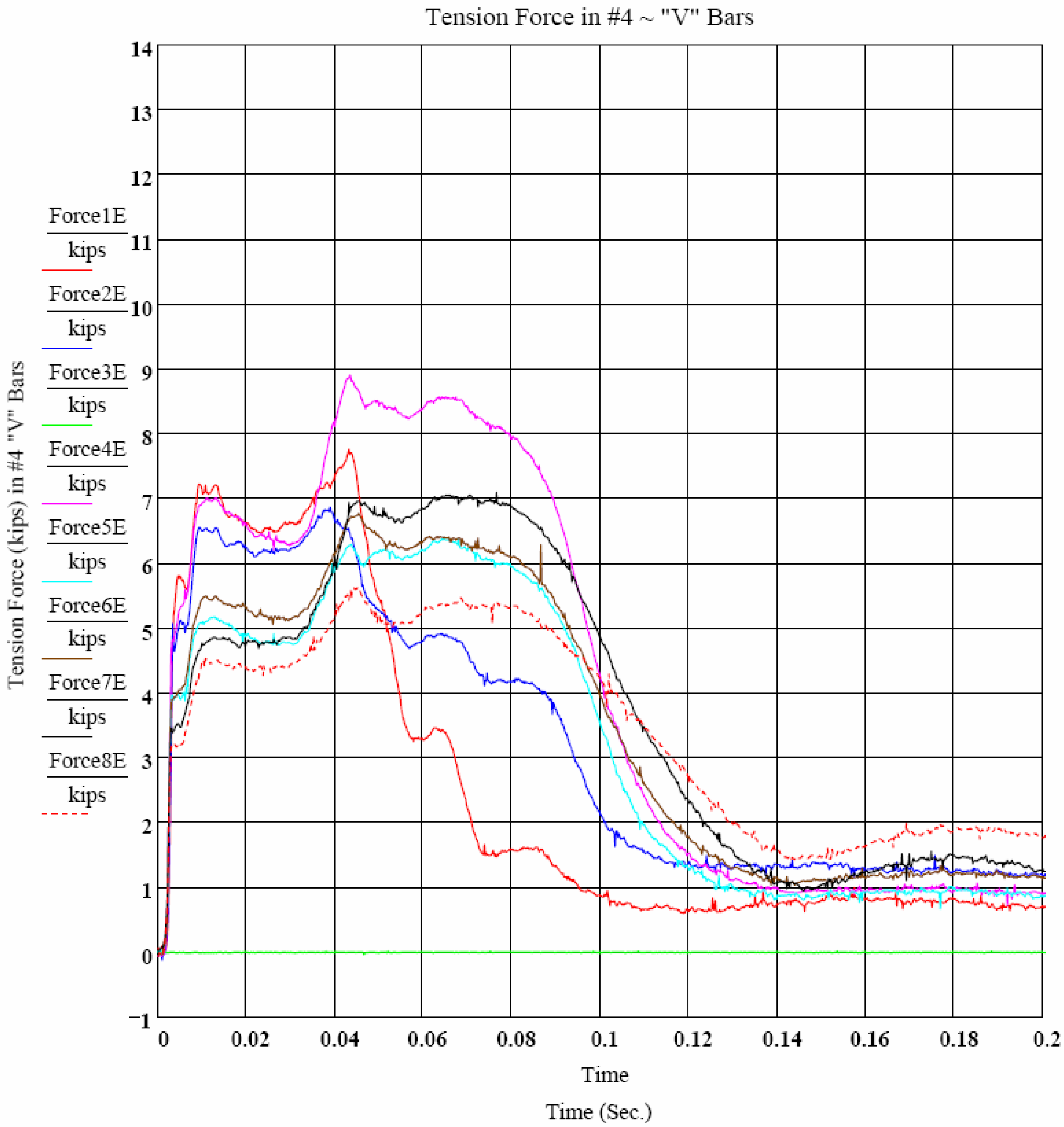
Page: 4 of 5

Job #: 448235

By: William Williams

Subject: T203 Rail Dynamic Load Test 3 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 3 - Location E



Texas Transportation Institute

Page: 5 of 5

Job #: 448235

Subject: T203 Rail Dynamic Load Test 3 ~ Mid-Span Case

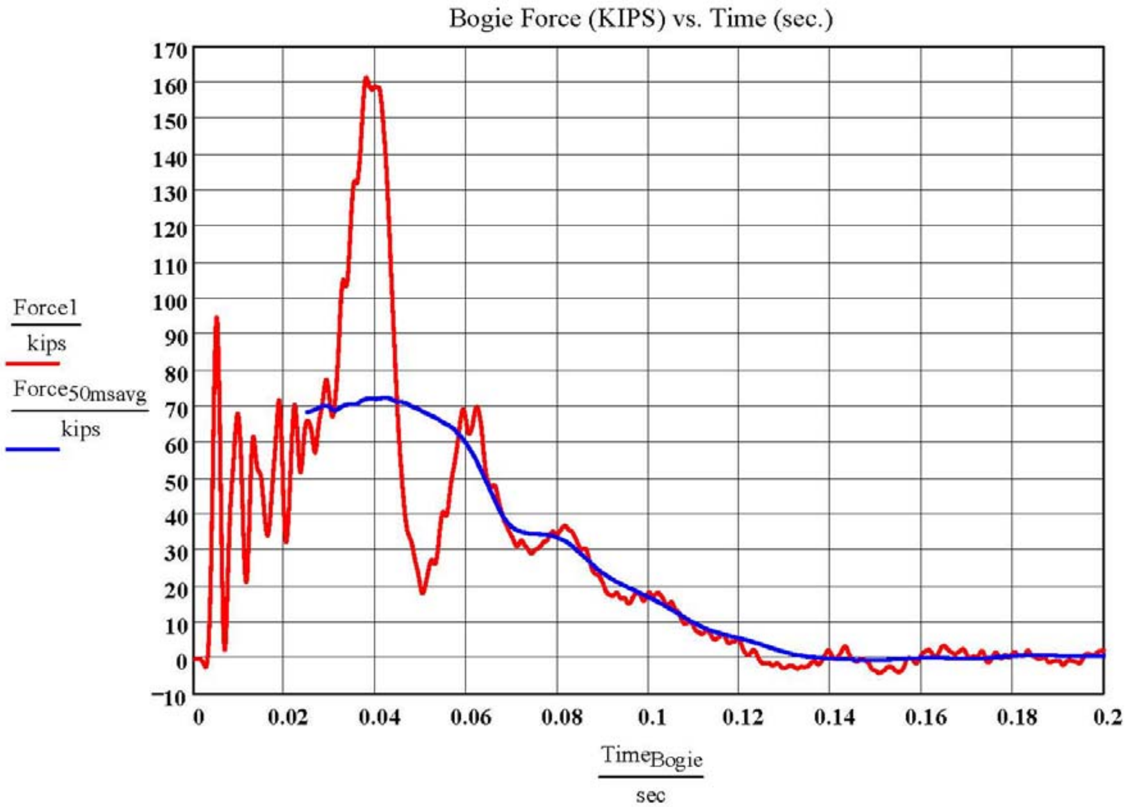
Strain Gage Data Analysis ~ Test 3 - Location "E"

By: William Williams

Dynamic Bogie Data Here in Collapsed Region:

▶ Dynamic Bogie Data

$\mathrm{Time}_{\mathrm{Bogie}} := \mathrm{Ebogie}^{\langle 1 \rangle} \times \mathrm{sec}$ $\mathrm{Force1} := \mathrm{Ebogie}^{\langle 2 \rangle} \times -5\mathrm{kips}$ $\mathrm{Force}_{\mathrm{50msavg}} := \mathrm{Ebogie}^{\langle 3 \rangle} \times -5\mathrm{kips}$



448235EData(Drev1).xmcd
12/13/2006

William Williams, P.E.
Ph. # (979) 862-2297

TEST B4 - T501 – LOCATION A

Texas Transportation Institute

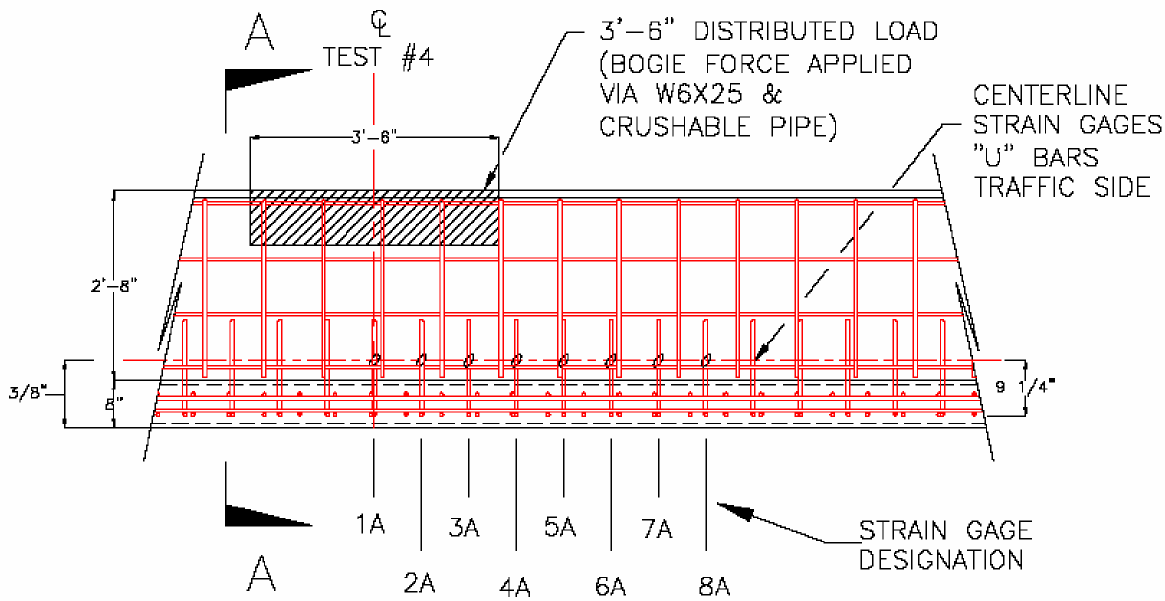
Page: 1 of 5

Job #: 448235

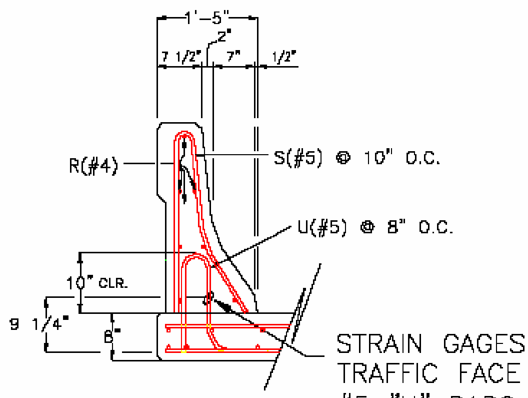
Subject: T501 Rail Dynamic Load Test 4 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 4 - Location A

By: William Williams



T501 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



SECTION A–A

Subject: T501 Rail Dynamic Load Test 4 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 4 - Location "A"

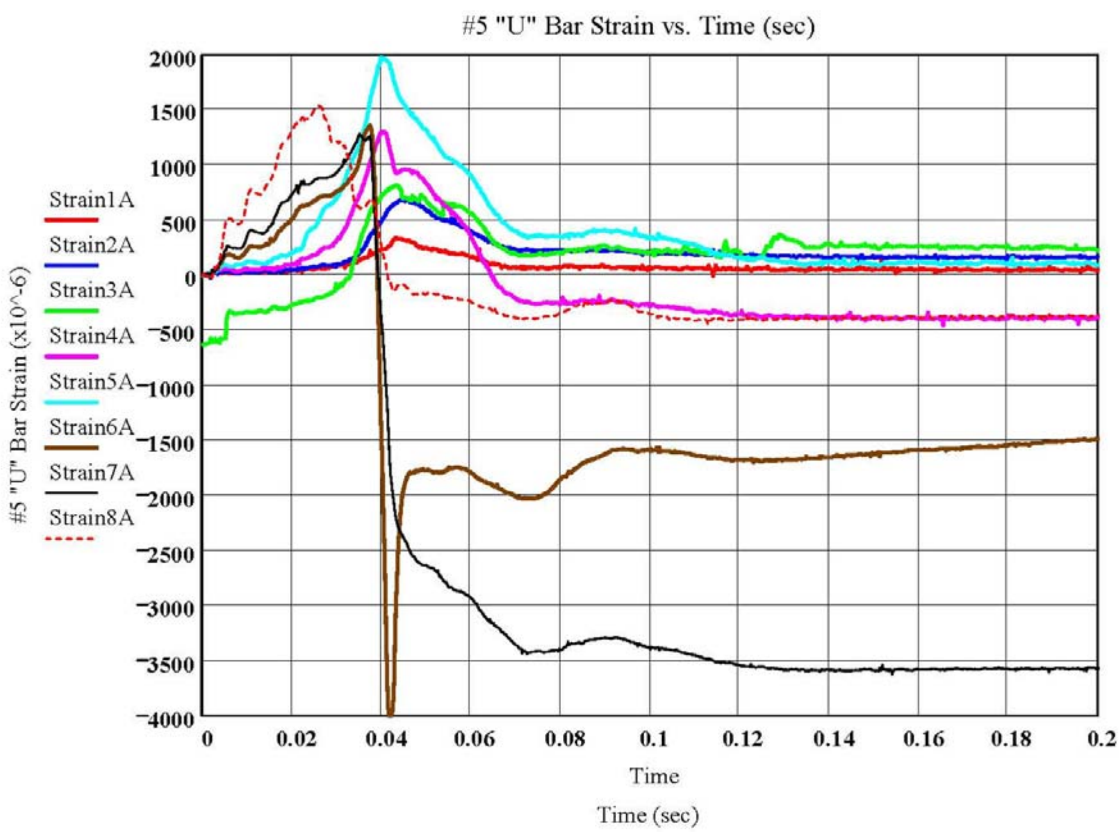
$E_s := 29000000psi$ Modulus of Steel (psi)

$A_{st} := 0.31in^2$ Area of rebar (in^2)

Data in Excel Format from Dynamic Testing Performed 2-28-05:

Dynamic Strain Gage Data from "U" Bars Here in Collapsed Region:

▶ Dynamic Strain Gage Data



Subject: T501 Rail Dynamic Load Test 4 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 4 - Location A

$\text{Force1A} := \text{Strain1A} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force2A} := \text{Strain2A} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force3A} := \text{Strain3A} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force4A} := \text{Strain4A} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force5A} := \text{Strain5A} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force6A} := \text{Strain6A} \times E_s \times A_{st} \times \mathbf{0.000001}$

$\text{Force7A} := \text{Strain7A} \times E_s \times A_{st} \times \mathbf{0.000001}$

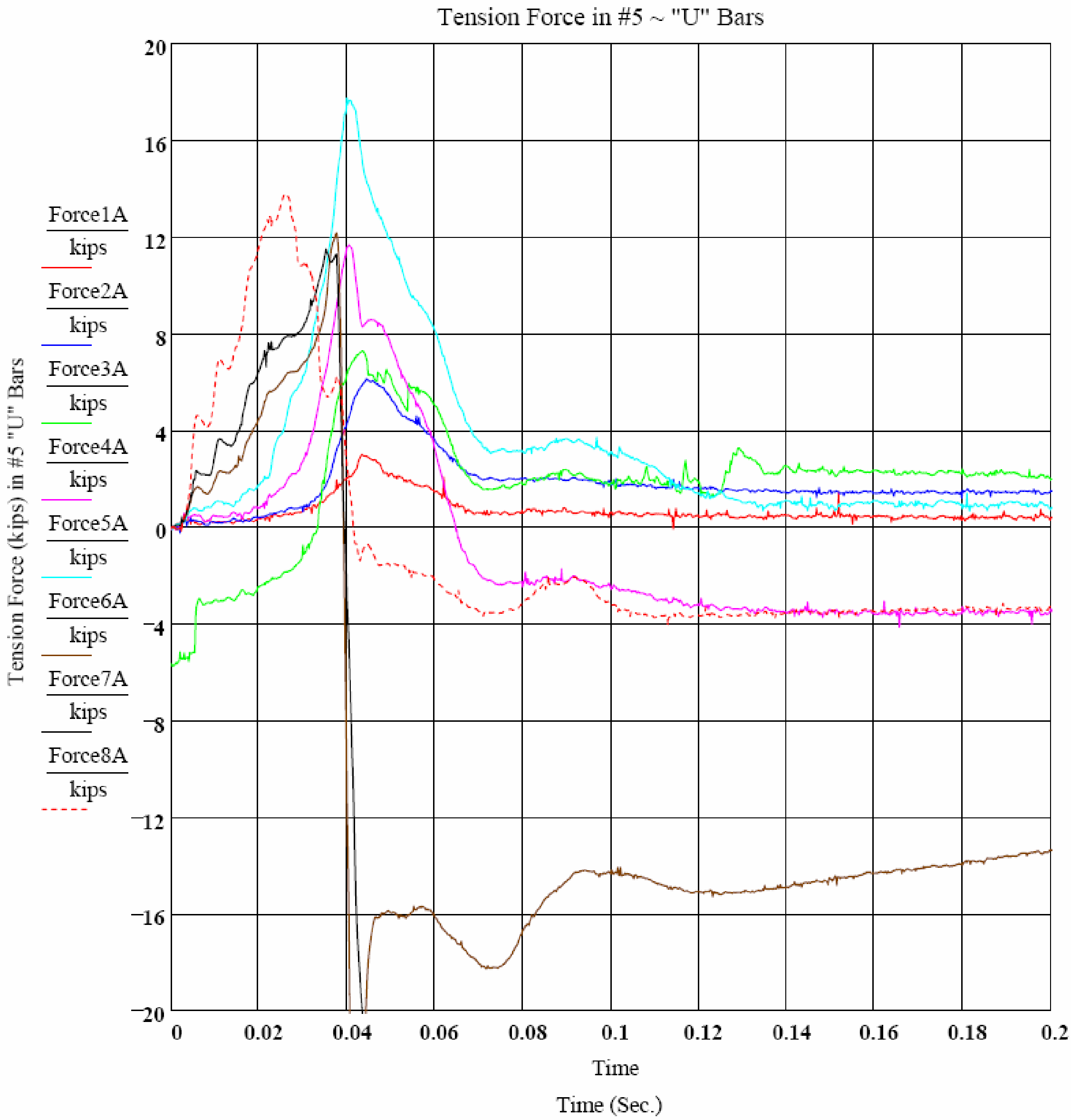
$\text{Force8A} := \text{Strain8A} \times E_s \times A_{st} \times \mathbf{0.000001}$

Job #: 448235

Subject: T501 Rail Dynamic Load Test 4 ~ Mid-Span Case

By: William Williams

Strain Gage Data Analysis ~ Test 4 - Location A



Texas Transportation Institute

Job #: 448235

Subject: T501 Rail Dynamic Load Test 4 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 4 - Location "A"

By: William Williams

Client: TxDOT

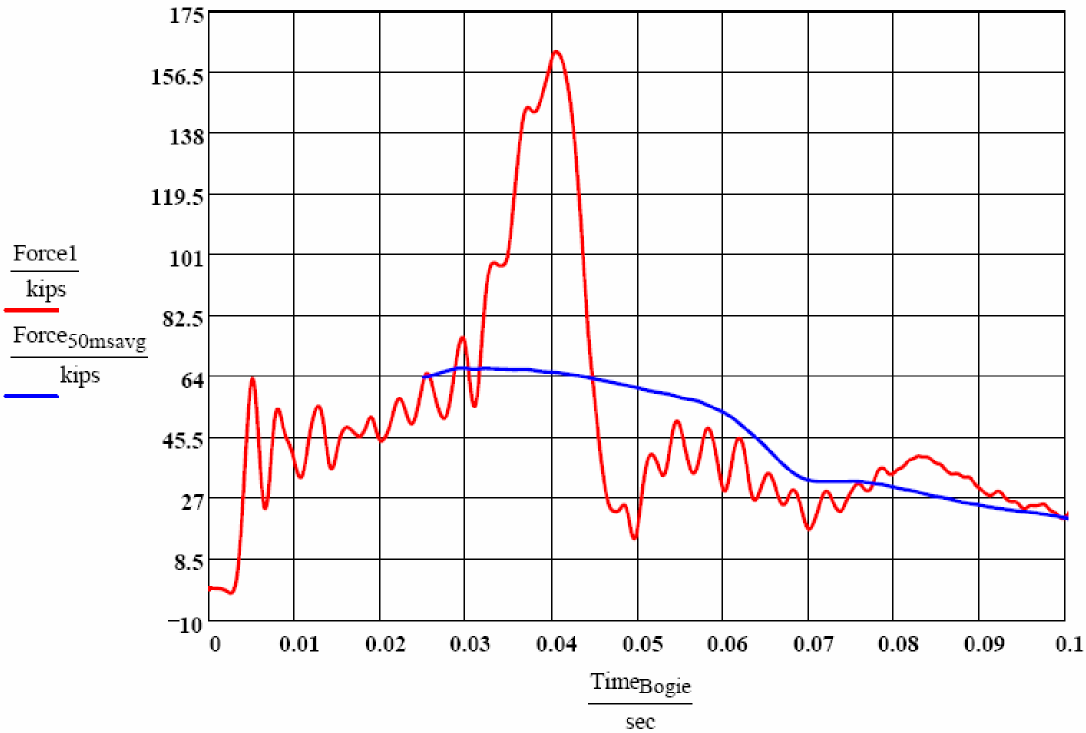
ORIGIN := 1

Dynamic Bogie Data Here in Collapsed Region:

Dynamic Bogie Data

$Time_{Bogie} := Abogie^{\langle 1 \rangle} \times sec$ $Force1 := Abogie^{\langle 2 \rangle} \times -5kips$ $Force_{50msavg} := Abogie^{\langle 3 \rangle} \times -5kips$

Bogie Force (kips) vs. Time (sec)



TEST B5 - T501 – LOCATION B

Texas Transportation Institute

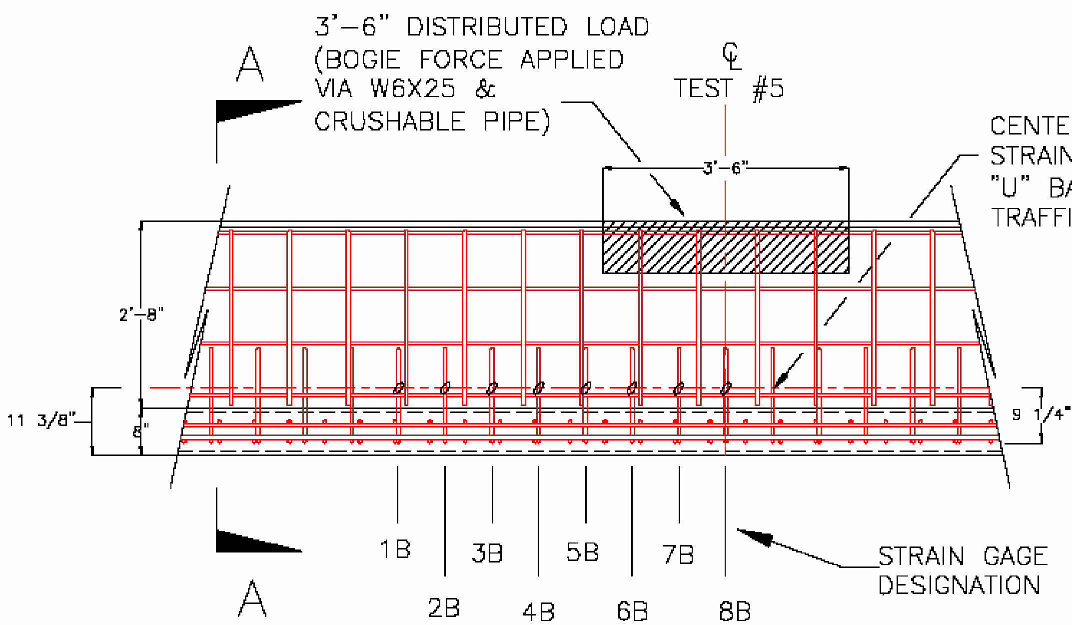
Page: **1 of 5**

Job #: **448235**

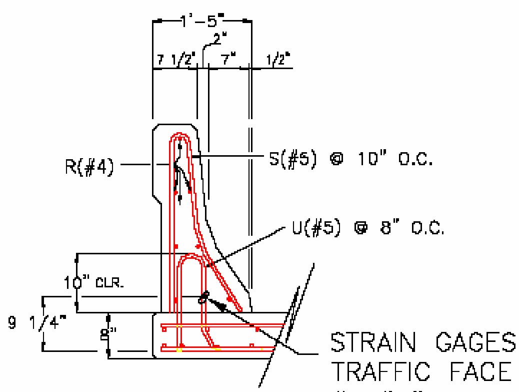
By: **William Williams**

Subject: **T501 Rail Dynamic Load Test 5 ~ Mid-Span Case**

Strain Gage Data Analysis ~ Test 5 - Location B



T501 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



SECTION A–A

Texas Transportation Institute

Page: 2 of 5

Job #: 448235

Subject: **T501 Rail Dynamic Load Test 5 ~ Mid-Span Case**

Strain Gage Data Analysis ~ Test 5 - Location "B"

By: **William Williams**

$E_s := \mathbf{29000000}\text{psi}$ Modulus of Steel (psi)

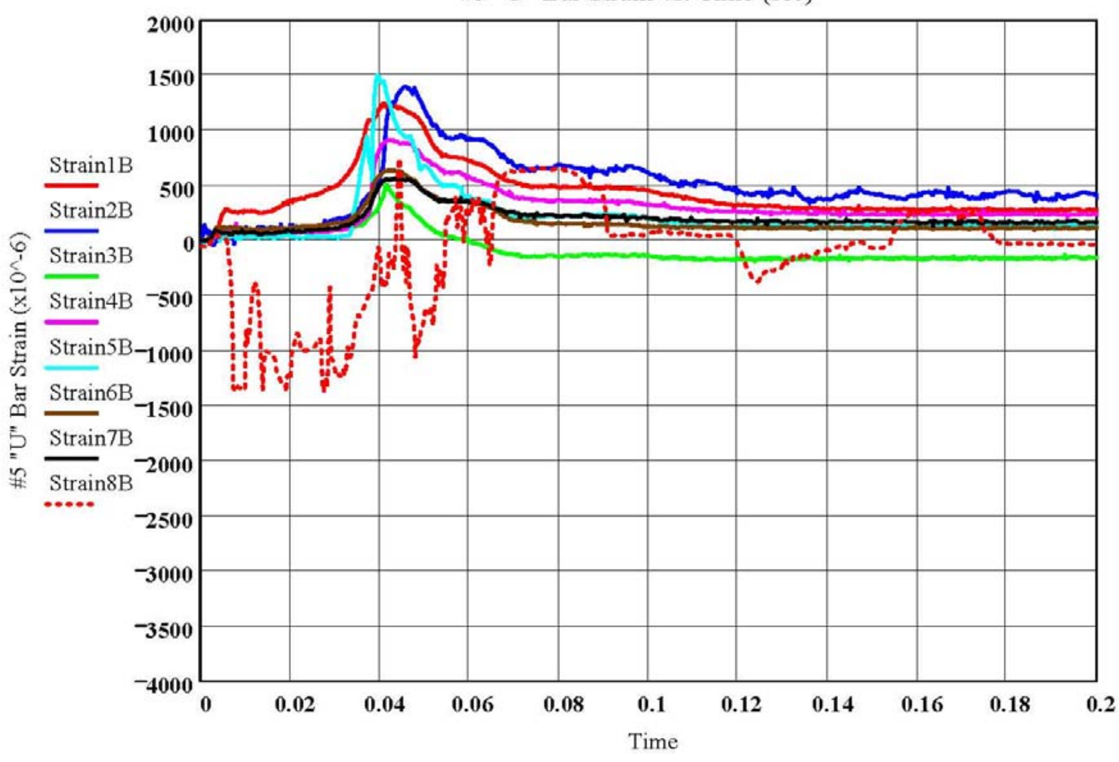
$A_{st} := \mathbf{0.31}\text{in}^2$ Area of rebar (in^2)

Dynamic Data in Excel Format from Dynamic Testing Performed 2-25-05:

Dynamic Strain Gage Data from "U" Bars Here in Collapsed Region:

▶ Dynamic Strain Gage Data

#5 "U" Bar Strain vs. Time (sec)



Time (sec)

Subject: T501 Rail Dynamic Load Test 5 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 5 - Location B

$Force1B := Strain1B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force2B := Strain2B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force3B := Strain3B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force4B := Strain4B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force5B := Strain5B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force6B := Strain6B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force7B := Strain7B \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force8B := Strain8B \times E_s \times A_{st} \times \mathbf{0.000001}$

Texas Transportation Institute

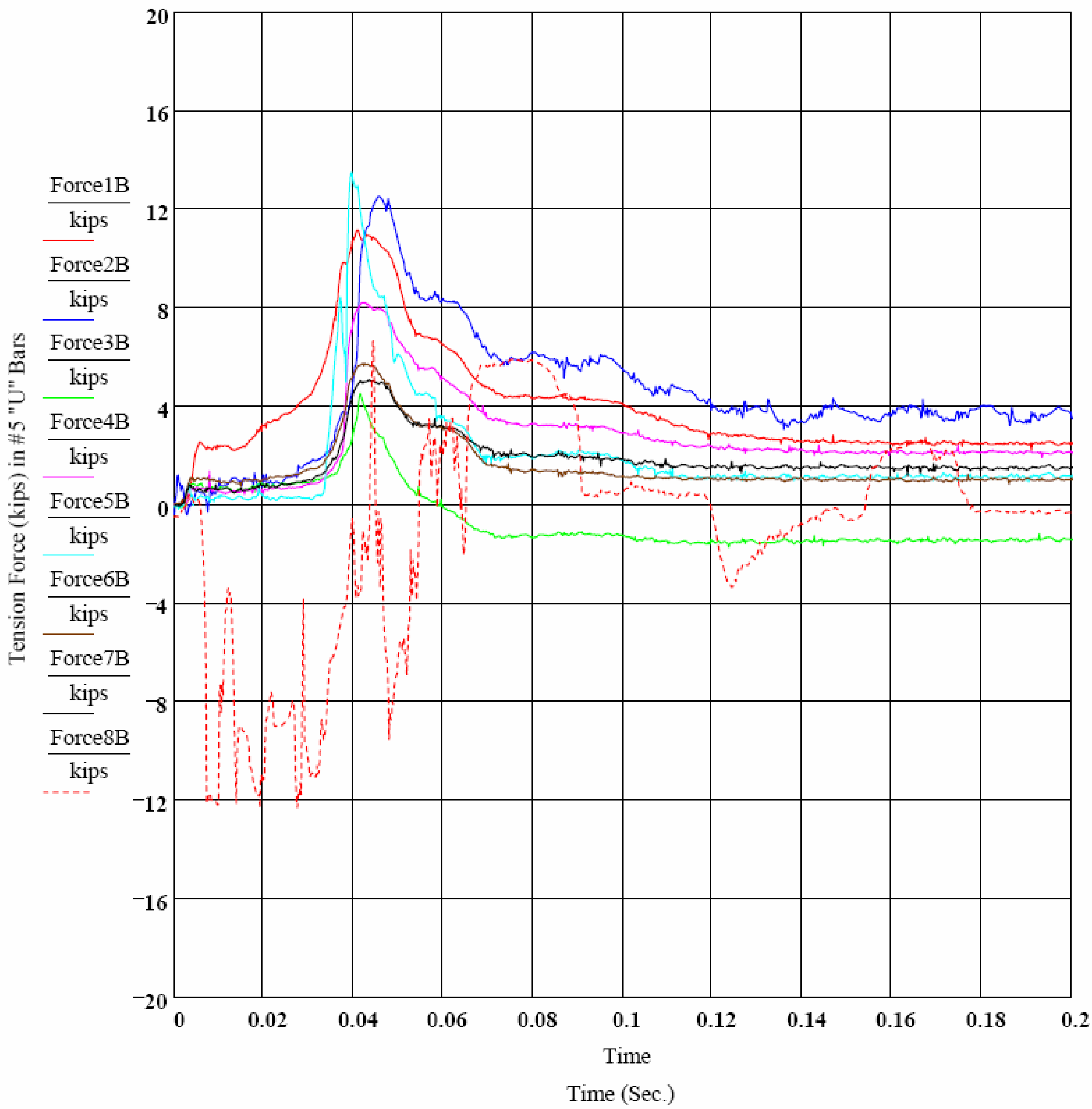
Job #: 448235

By: William Williams

Subject: T501 Rail Dynamic Load Test 5 ~ Mid-Span Case

Strain Gage Data Analysis ~ Test 5 - Location B

Tension Force in #5 ~ "U" Bars



Subject: T501 Rail Dynamic Load Test 5 ~ Mid-Span Case

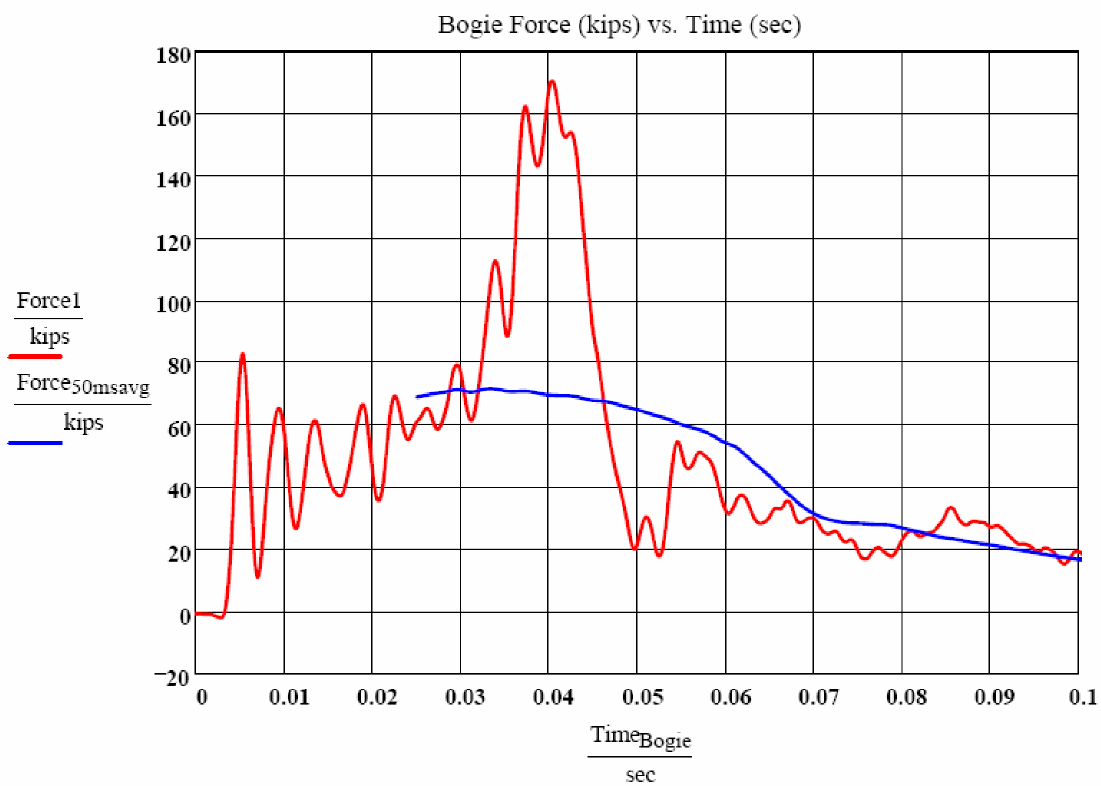
Strain Gage Data Analysis ~ Test 5 - Location B

Client: TxDOT

Dynamic Bogie Data Here in Collapsed Region:

Dynamic Bogie Data

$\mathrm{Time}_{Bogie} := \mathrm{Bbogie}^{\langle 1 \rangle} \times \mathrm{sec}$ $\quad$ $\mathrm{Force1} := \mathrm{Bbogie}^{\langle 2 \rangle} \times -5\mathrm{kips}$ $\quad$ $\mathrm{Force}_{50msavg} := \mathrm{Bbogie}^{\langle 3 \rangle} \times -5\mathrm{kips}$



TEST B6 - T501 – LOCATION C

Texas Transportation Institute

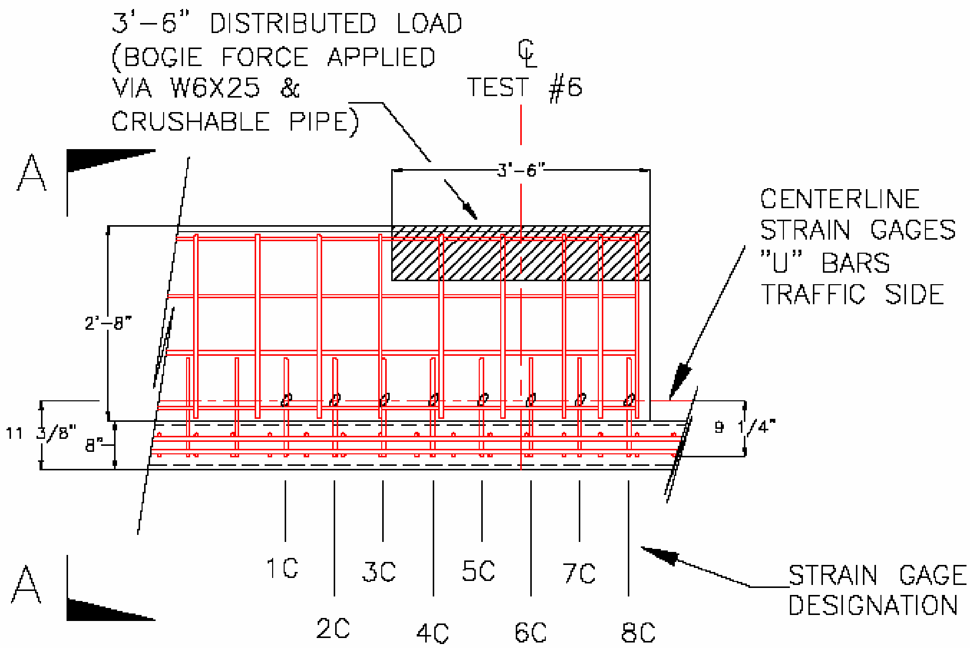
Page: 1 of 5

Job #: 448235

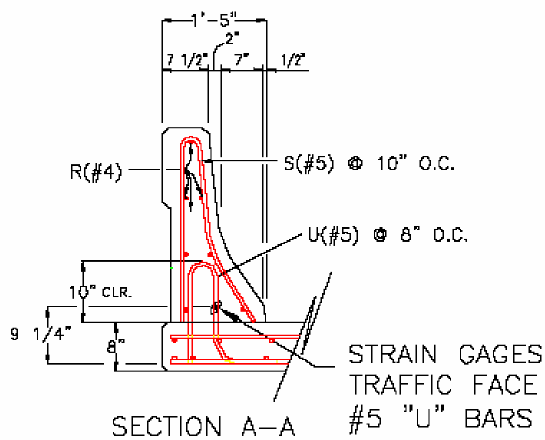
By: William Williams

Subject: T501 Rail Dynamic Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C



T501 LOAD APPLICATION
(TRAFFIC SIDE VIEW)



SECTION A–A

Page: 2 of 5

Job #: 448235

By: William Williams

Subject: T501 Rail Dynamic Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location "C"

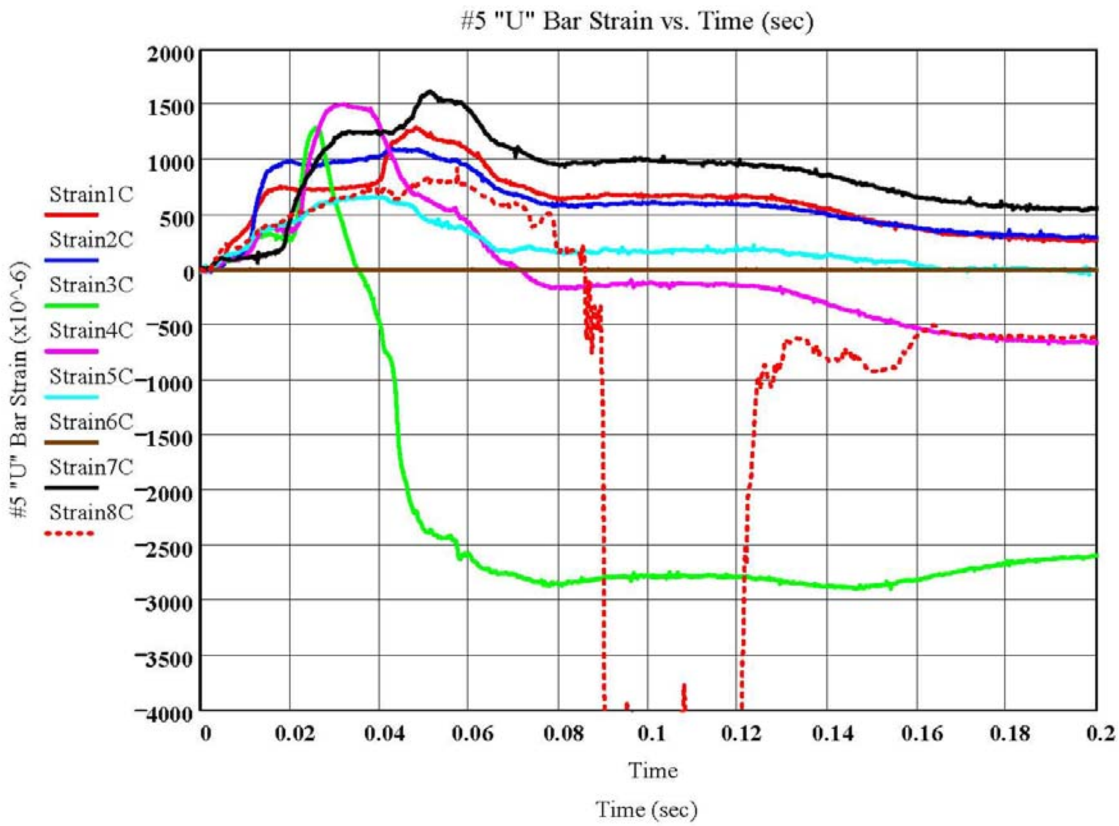
$E_s := 29000000\text{psi}$ Modulus of Steel (psi)

$A_{st} := 0.31\text{in}^2$ Area of rebar (in^2)

Data in Excel Format from Dynamic Testing Performed 3-01-05:

Dynamic Strain Gage Data from "U" Bars Here in Collapsed Region:

▶ Dynamic Strain Gage Data



Subject: T501 Rail Dynamic Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C

$Force1C := Strain1C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force2C := Strain2C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force3C := Strain3C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force4C := Strain4C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force5C := Strain5C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force6C := Strain6C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force7C := Strain7C \times E_s \times A_{st} \times \mathbf{0.000001}$

$Force8C := Strain8C \times E_s \times A_{st} \times \mathbf{0.000001}$

Texas Transportation Institute

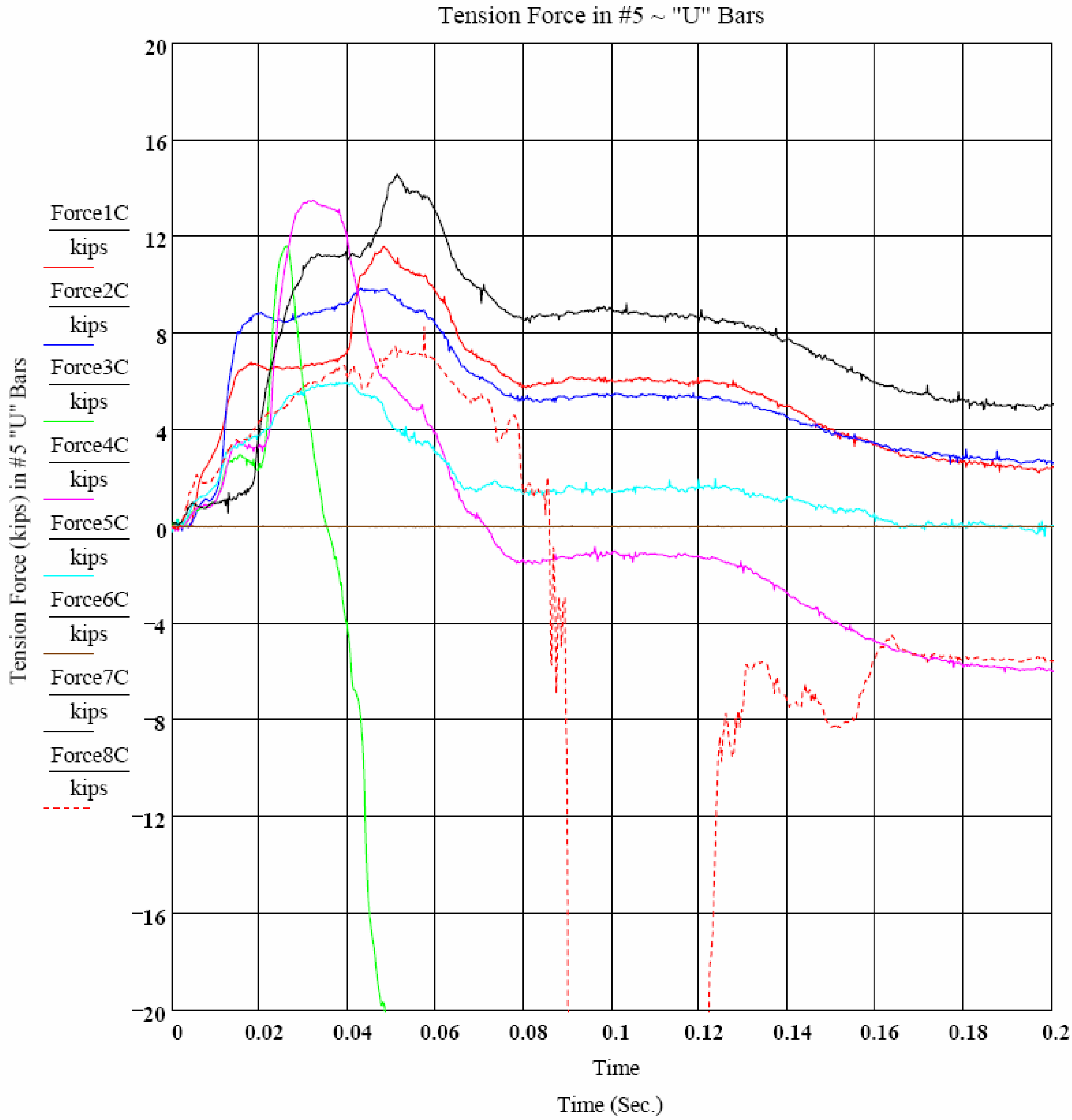
Page: 4 of 5

Job #: 448235

By: William Williams

Subject: T501 Rail Dynamic Load Test 6 ~ End Case

Strain Gage Data Analysis ~ Test 6 - Location C



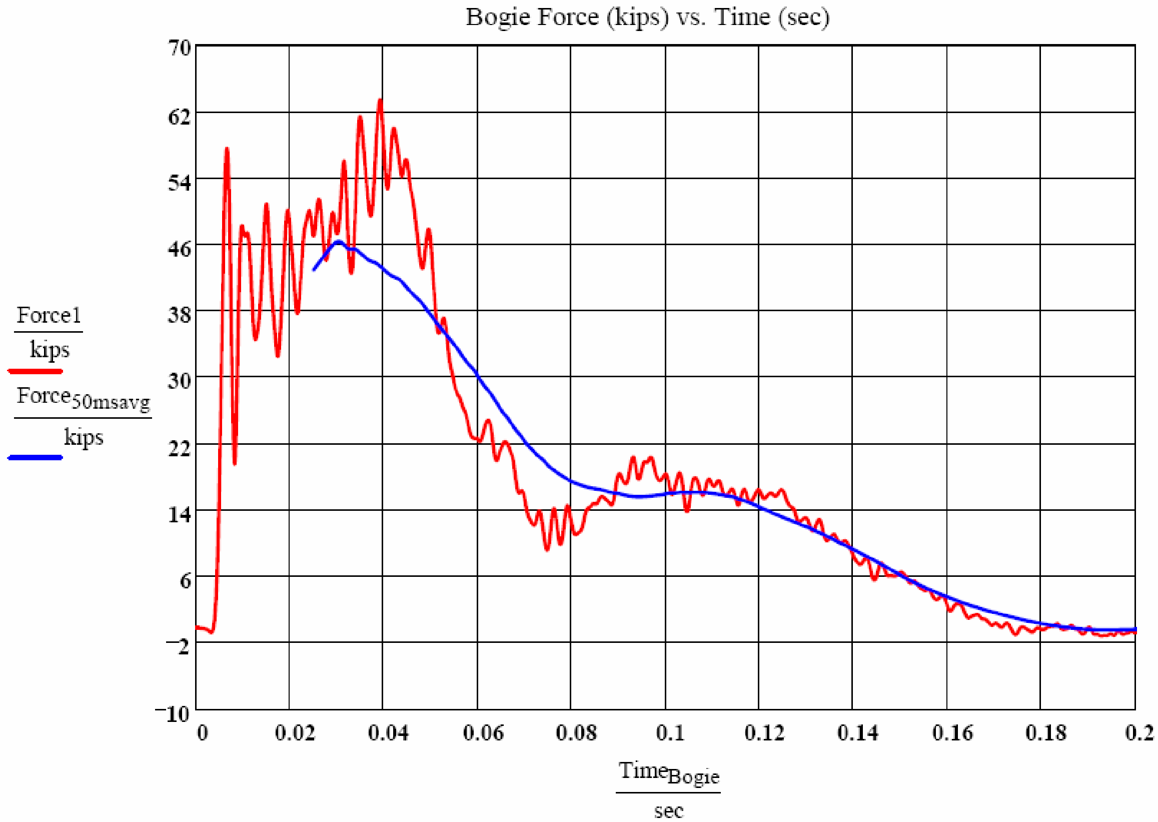
Subject: **T501 Rail Dynamic Load Test 6 ~ End Case**

Strain Gage Data Analysis ~ Test 6 - Location C

Dynamic Bogie Data Here in Collapsed Region:

Dynamic Bogie Data

$Time_{Bogie} := Cbogie^{\langle 1 \rangle} \times sec$ $\quad$ $Force1 := Cbogie^{\langle 2 \rangle} \times -5kips$ $\quad$ $Force_{50msavg} := Cbogie^{\langle 3 \rangle} \times -5kips$



APPENDIX D. ANALYTICAL CALCULATIONS FOR RETROFIT/REPAIR OF THE T501 BRIDGE RAILING

Texas Transportation Institute

Page: 1 of 6

Job #: 448235

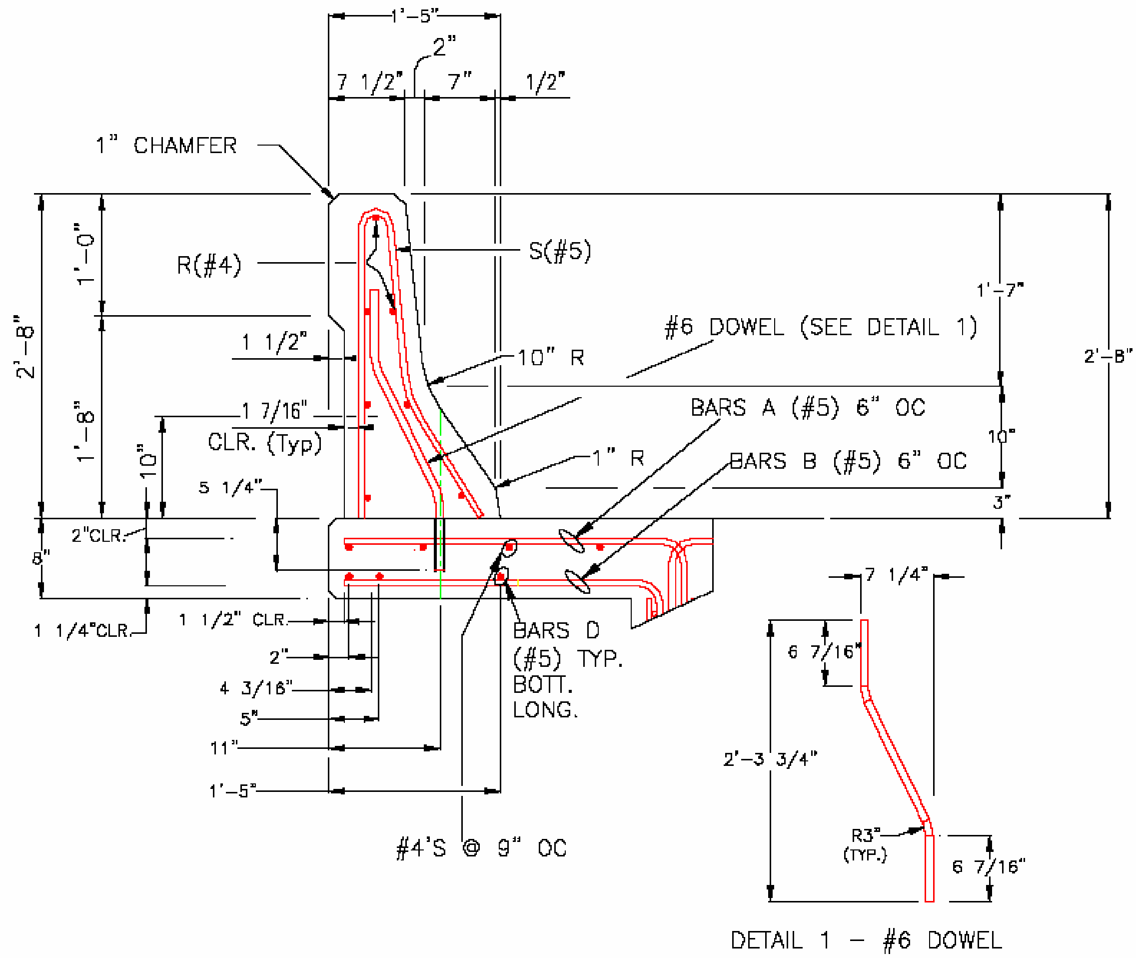
Subject: Adhesive Anchors Retrofit/Repair Design

By: William Williams

Hilti RE 500 Anchoring System for T501

11" Offset Distance for #6 Dowel Bars

1.) Given Design Information & Details, Determine Equivalent #6 Dowel Spacing Requirements :



Texas Transportation Institute

Job #: 448235

Subject: **Adhesive Anchors Retrofit/Repair Design**

Hilti RE 500 Anchoring System for T501

By: **William Williams**

Design Information:

$f'_c := \mathbf{4000}psi$ Concrete Strength, f'c (psi)

$S := \mathbf{12}in$ Minimum Anchor Spacing (@ end) (in)

$C := \mathbf{11.0}in$ New Edge Distance for anchor (in.)

$d := C - \mathbf{1.5}in$ Distance from Barrier Edge to CL of Tension Steel (in.) $d = \mathbf{9.5}\,in$

$h_{ef} := \mathbf{5.25}in$ Actual Embedment (in.)

$S_{min} := \mathbf{0.5} \cdot h_{ef}$ Minimum Anchor Spacing (in.) for Hilti Anchor $S_{min} = \mathbf{2.63}\,in$

$S_{cr} := \mathbf{1.5} \cdot h_{ef}$ Preferred Min. Spacing (in.) for Hilti Anchor $S_{cr} = \mathbf{7.88}\,in$

$N_{mid} := \mathbf{10}kips$ $N_{end} := \mathbf{12}kips$ Actual Rebar Tension (kips) from Dynamic & Static Testing

$S_{actual} := \mathbf{8}in$ $d_{actual} := \mathbf{7.25}in$ AS-IS Transverse & Longitudinal "U" Bar Locations

From Hilti 2002 Design Guide, pg. 115

$Ultimate_{Bond5} := \mathbf{27.8}kips$ $Ultimate_{Yield5} := \mathbf{18.6}kips$ ... #5 Anchor Information

$Ultimate_{Bond6} := \mathbf{32.1}kip$ $Ultimate_{Yield6} := \mathbf{26.4}kips$ .... #6 Anchor Information

$kips \equiv \mathbf{1000}lbf$

2.) Calculate the Actual Resistance of the #5 "U" Bars considering the forces in the bars observed from the static & dynamic testing, actual "U" Bar "d" Spacing (7 1/4") (.... or 8 3/4" from Deck Edge) and the Longitudinal Spacing "S_{actual}":

$\phi_t := 0.75$ Reduction factor for bar strength $\phi_{temp} := 0.90$ Strength Reduction for 135 deg. temp.

$d_{actual} = 7.25\,in$ As-Is (Current) transverse distance from barrier field side edge to Centerline of Tension "U" Bar (inches)

$S_{actual} = 8\,in$ As-Is (Current) Spacing of Tension "U" Bars (inches)

$N_{mid} = 10\,kips$ Actual "As-Is" Tension (kips)

$$R_{actualmid} := \frac{N_{mid} \cdot d_{actual}}{S_{actual}} \qquad R_{actualmid} = 9.06\,\frac{kip \cdot ft}{ft} \qquad R_{actualmid} = 6.04\,\frac{kip \cdot ft}{8in}$$

$$R_{actualend} := \frac{N_{end} \cdot d_{actual}}{S_{actual}} \qquad R_{actualend} = 10.87\,\frac{kip \cdot ft}{ft} \qquad R_{actualend} = 7.25\,\frac{kip \cdot ft}{8in}$$

Target "U" Bar Strength Values from Testing

Select a New Longitudinal Spacing "S_{newmid} & S_{newend}" .... $S_{newmid} := 16in$ $S_{newend} := 16in$

Select a New Transverse "d" Spacing "d_{new}": $d_{new} := 11in$

3.) Calculate the Usable Resistance ϕR_{mid} & ϕR_{end} for new #6 Anchor Spacing & "d" Distance

Calculate/Check Reduction Factors for Spacing (Tension & Shear), "f_A"

Spacing (inches) Edge Dist. (inches)

$S = 12\,in$ $C = 11\,in$

$$f_A := \left| \begin{array}{l} f_A \leftarrow 0.3 \cdot \left(\frac{S}{h_{ef}}\right) + 0.55 \text{ if } S_{cr} \ge S \ge S_{min} \\ f_A \leftarrow 1.0 \text{ if } S \ge S_{cr} \\ f_A \leftarrow 0 \text{ if } S < S_{min} \end{array} \right.$$

$f_A = 1$

Subject: **Adhesive Anchors Retrofit/Repair Design**

By: **William Williams**

Hilti RE 500 Anchoring System for T501

Calculate Reduction Factors for Edge Distance Tension, "f_{RN}"

$C_{min} := 0.5 \cdot h_{ef}$ Minimum Edge Distance (in.) $C_{cr} := 1.5 \cdot h_{ef}$ Preferred Clearance (in.)

$C_{min} = 2.63\,in$ $C_{cr} = 7.88\,in$

$$f_{RN} := \left| \begin{array}{l} f_{RN} \leftarrow 0.3 \cdot \left(\dfrac{C}{h_{ef}}\right) + 0.55 \ \text{ if } C_{cr} \ge C \ge C_{min} \\ f_{RN} \leftarrow 1.0 \ \text{ if } C \ge C_{cr} \\ f_{RN} \leftarrow 0 \ \text{ if } C < C_{min} \end{array} \right.$$

$f_{RN} = 1$

Calculate total combined Reduction Factors for tension:

$f_A = 1$ $f_{RN} = 1$ $\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN})}$ $\phi_{tension} = 1$

Calculate the allowable Tension Strength of #6 Anchor considering Spacing & Edge Distance:

$F_{tension6} := \phi_{tension} \cdot Ultimate_{Bond6}$

$F_{tension6} = 32.1\,kip$ .... o.k. fractured bond strength still greater than yield strength ..... use yield strength!!

for:

$Ultimate_{Yield6} = 26.4\,kips$ Limiting strength of #6 Bar

$d_{new} = 11\,in$ New "d" Spacing (in.)

$S_{newmid} = 16\,in$ New Longitudinal Anchor Spacing (in.)

$\phi_t = 0.75$ Strength Reduction Factor Used for This Analysis

Therefore: $\phi_{temp} = 0.9$ Strength Reduction Factor for 135-degree temperature

$$\phi R_{mid} := \frac{Ultimate_{Yield6} \cdot d_{new}}{S_{newmid}} \cdot \phi_t \cdot \phi_{temp}$$

$\phi R_{mid} = 12.25 \dfrac{kip \cdot ft}{ft}$ o.k.... greater than or near equal to $R_{actualmid}$

$$\phi R_{end} := \frac{Ultimate_{Yield6} \cdot d_{new}}{S_{newend}} \cdot \phi_t \cdot \phi_{temp}$$

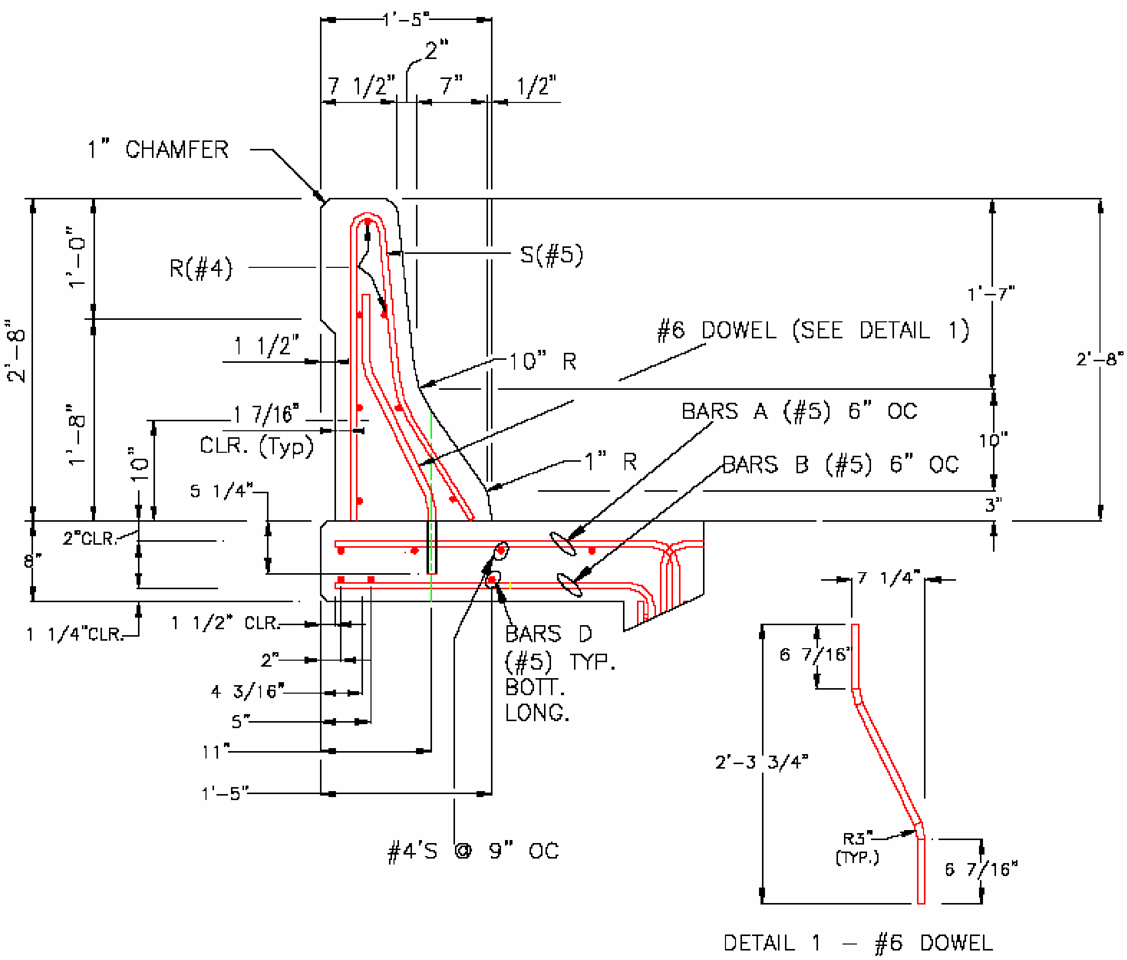
$\phi R_{end} = 12.25 \dfrac{kip \cdot ft}{ft}$ o.k.... greater than or near equal to $R_{actualend}$

Subject: Adhesive Anchors Retrofit/Repair Design

Hilti RE 500 Anchoring System for T501

By: William Williams

4.) Retrofit/Repair Option using Hilti RE 500 Anchoring Sysytem & 11" Offset Distance for #6 Dowel Bars:



FINAL DESIGN DETAILS: #6 DOWEL BARS IN MID-SPAN SPACED @ 16" O.C.

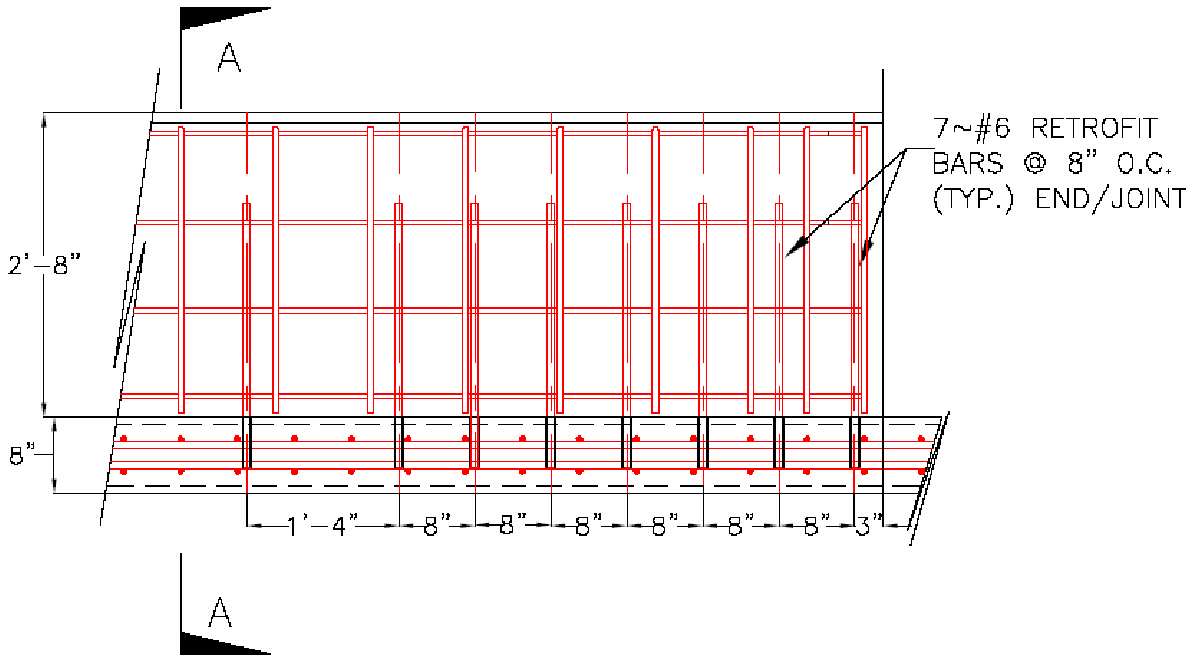
Page: 6 of 6

Job #: 448235

Subject: Adhesive Anchors Retrofit/Repair Design

Hilti RE 500 Anchoring System for T501

By: William Williams



FINAL DESIGN DETAILS: #6 DOWEL BARS @ 8" O.C. END/JOINT

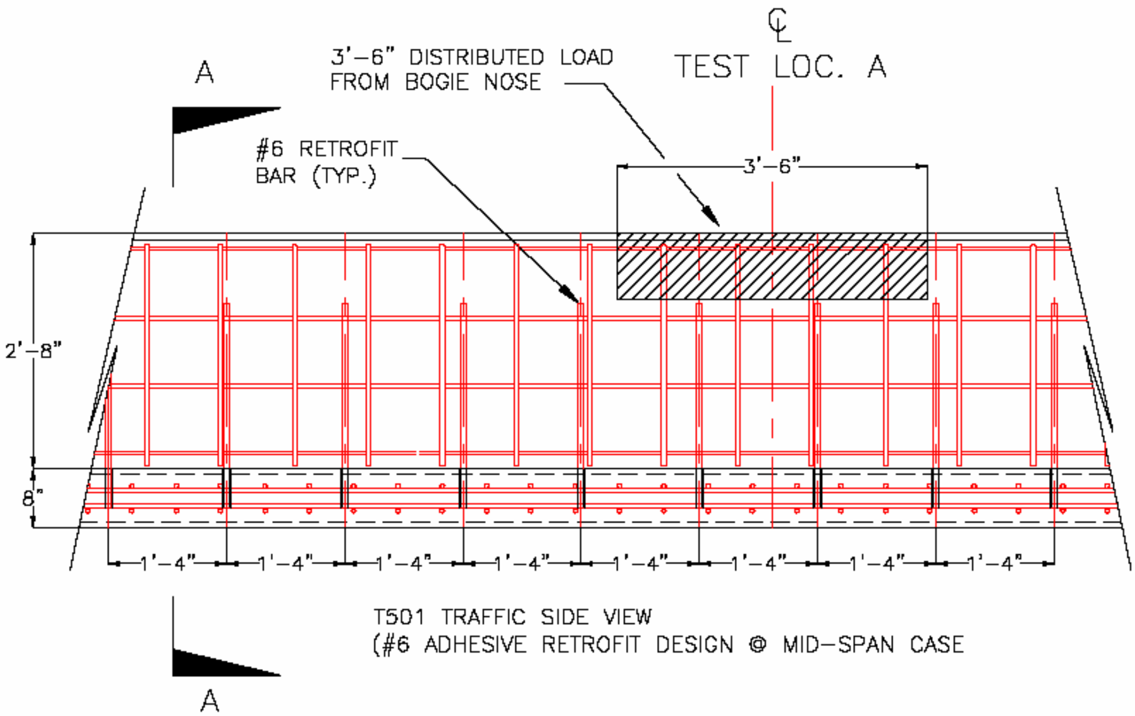
APPENDIX E. DATA FROM DYNAMIC TESTING OF REPAIR/RETROFIT OF THE T501 BRIDGE RAILING

TEST B7 - T501 – LOCATION A

Texas Transportation Institute

Job #: **452106**

Subject: **T501 Rail Retrofit Location A ~ Mid-Span Case**



T501 TRAFFIC SIDE VIEW
(#6 ADHESIVE RETROFIT DESIGN @ MID–SPAN CASE

Note: Hilti HIT RE 500 Injection Adhesive Anchoring System used with Grade 60 Reinforcement

452106AData(Rrev1).xmcd
4/4/2006

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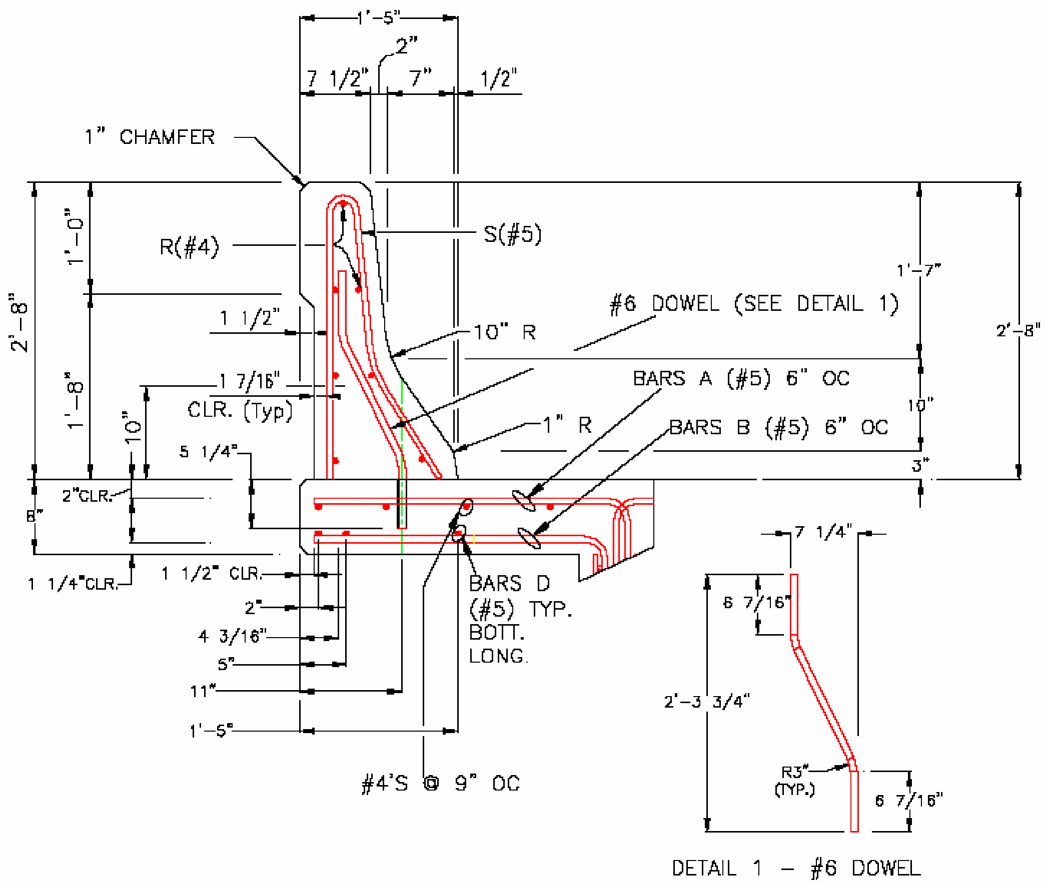
PAGE 1

Texas Transportation Institute

Job #: 452106

Subject: T501 Rail Retrofit Location A ~ Mid-Span Case Section A-A



SECTION A-A

Bogie Acceleration Data

452106AData(Rrev1).xmcd
4/4/2006

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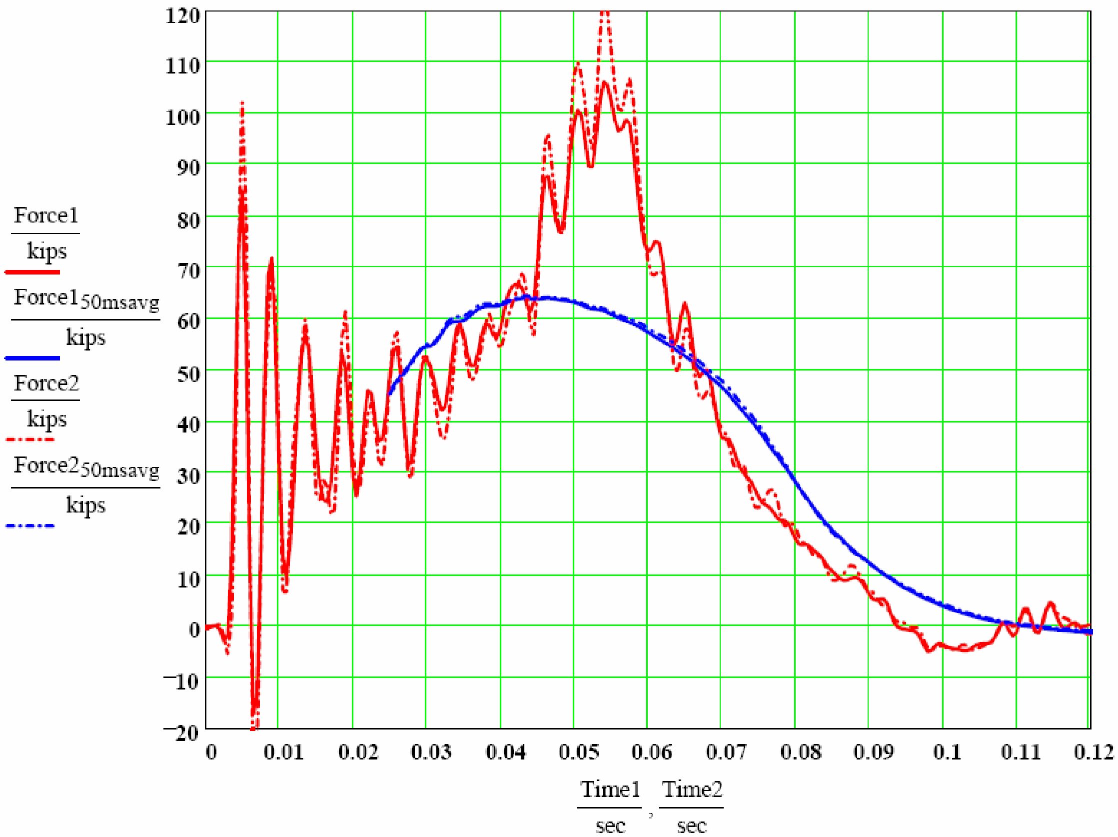
PAGE 2

Texas Transportation Institute

Job #: **452106**

Subject: **T501 Rail Retrofit Location A ~ Mid-Span Case**



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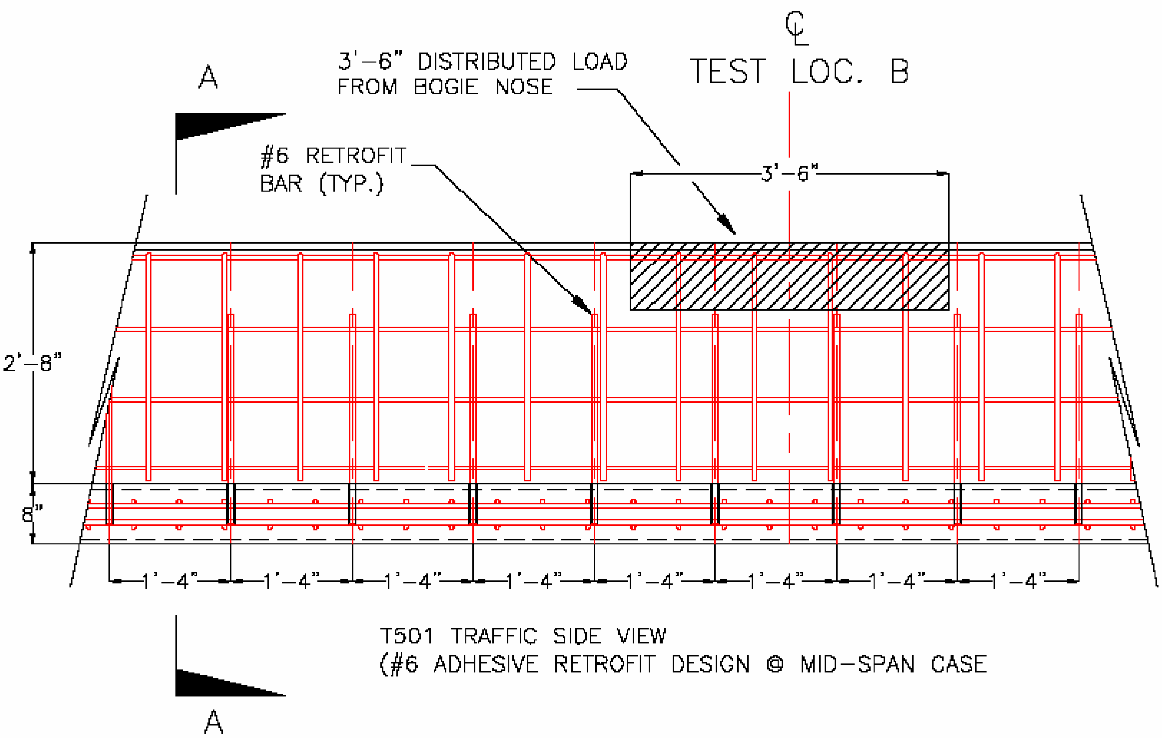
TEST B8 - T501 – LOCATION B

Texas Transportation Institute

Job #: 452106

Subject: T501 Rail Retrofit Location B ~ Mid-Span Case



T501 TRAFFIC SIDE VIEW
(#6 ADHESIVE RETROFIT DESIGN @ MID-SPAN CASE

Note: Hilti HIT RE 500 Injection Adhesive Anchoring System used with Grade 60 Reinforcement

452106BData(Rrev1).xmcd
4/4/2006

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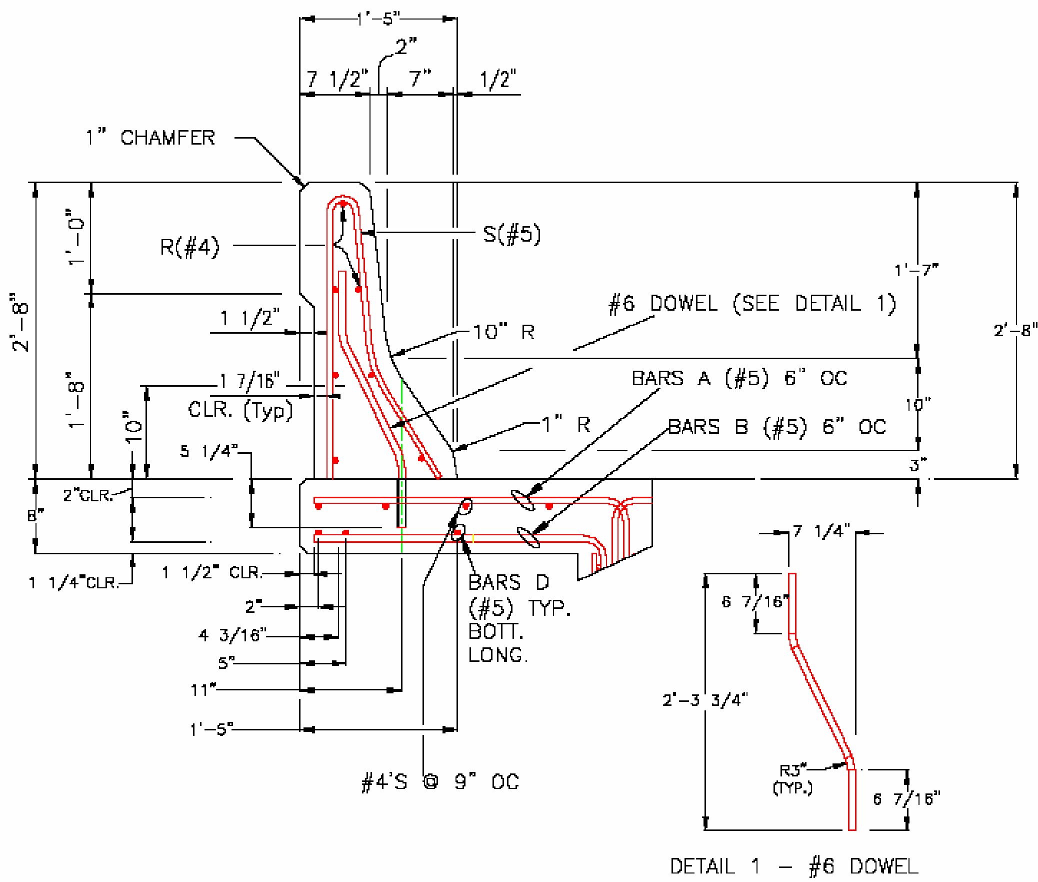
PAGE 1

Job #: 452106

Subject: **T501 Rail Retrofit Location B ~ Mid-Span Case Section A-A**



SECTION A-A

▶ Bogie Acceleration Data

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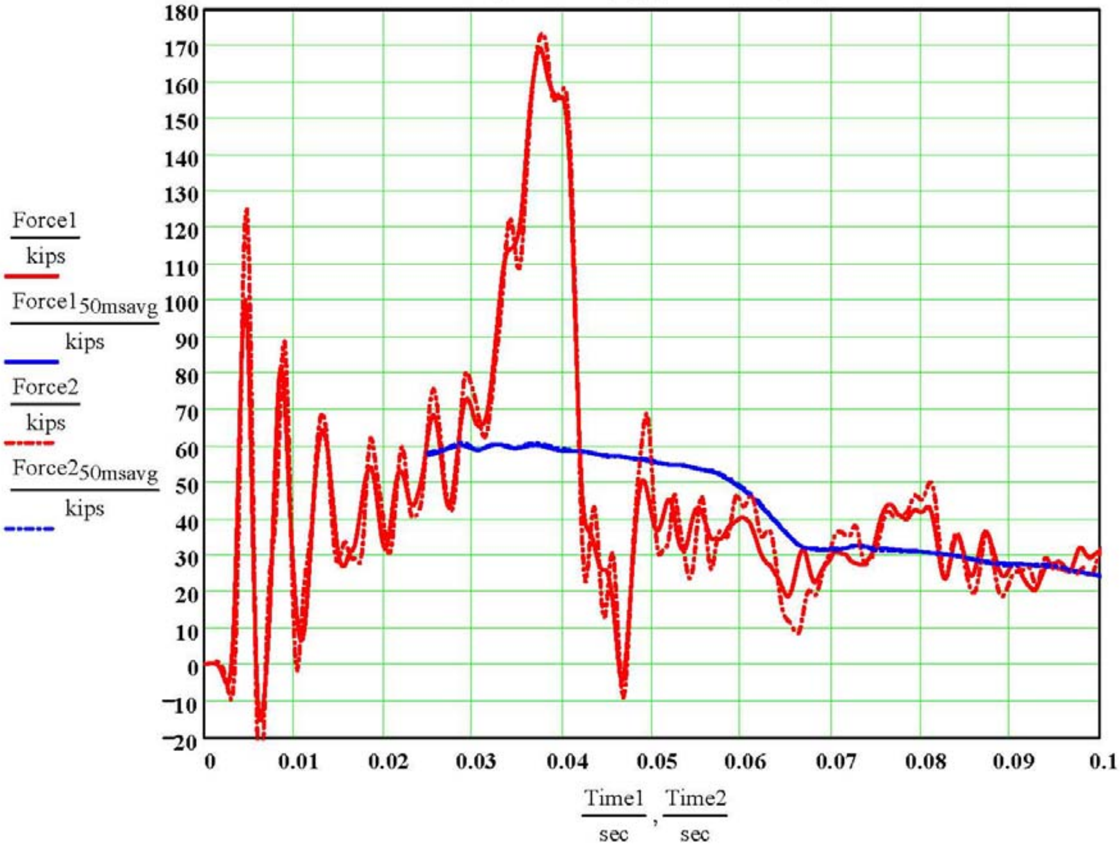
Subject: **T501 Rail Retrofit Location B ~ Mid-Span Case**

Bogie Force (kips) vs. Time (sec)



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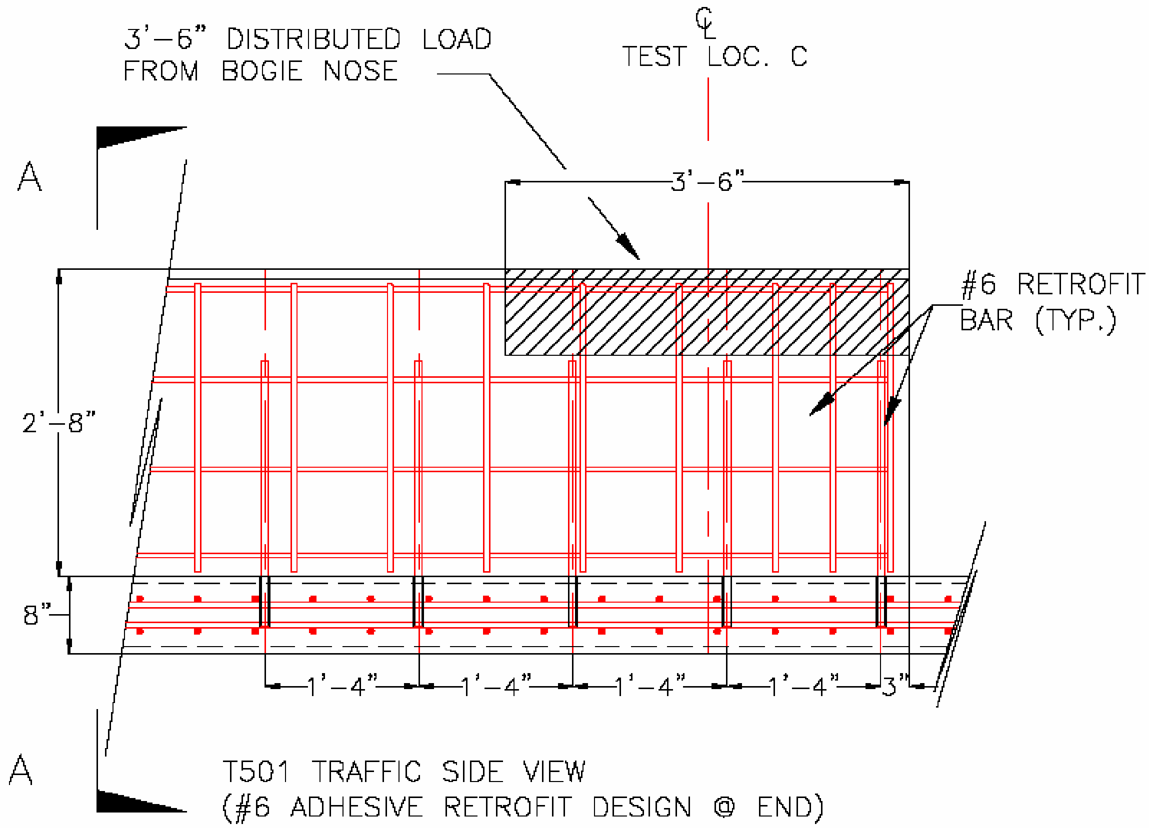
TEST B9 - T501 – LOCATION C

Texas Transportation Institute

Job #: 452106

Subject: T501 Rail Retrofit Location C ~ End Case



T501 TRAFFIC SIDE VIEW
(#6 ADHESIVE RETROFIT DESIGN @ END)

Note: Hilti HIT RE 500 Injection Adhesive Anchoring System used with Grade 60 Reinforcement

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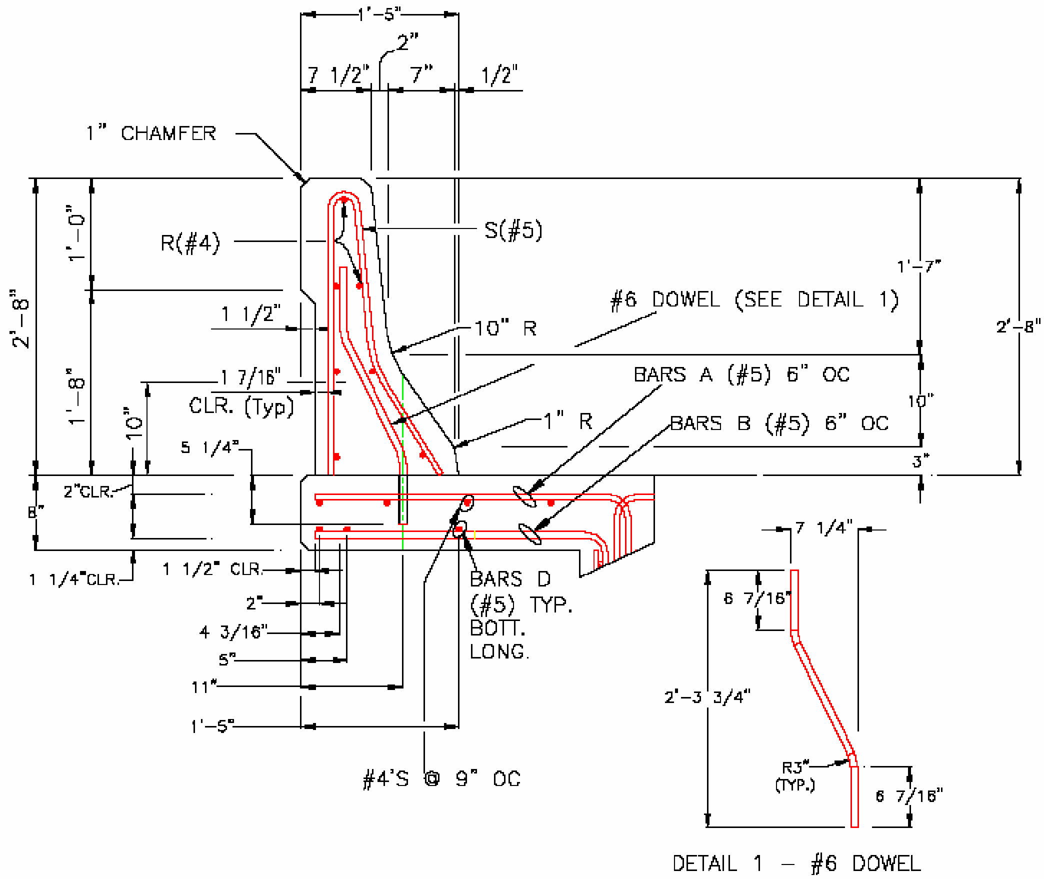
Texas Transportation Institute

Job #: 452106

Subject: T501 Rail Retrofit Location C ~ End Case Section A-A



SECTION A-A

Bogie Acceleration Data

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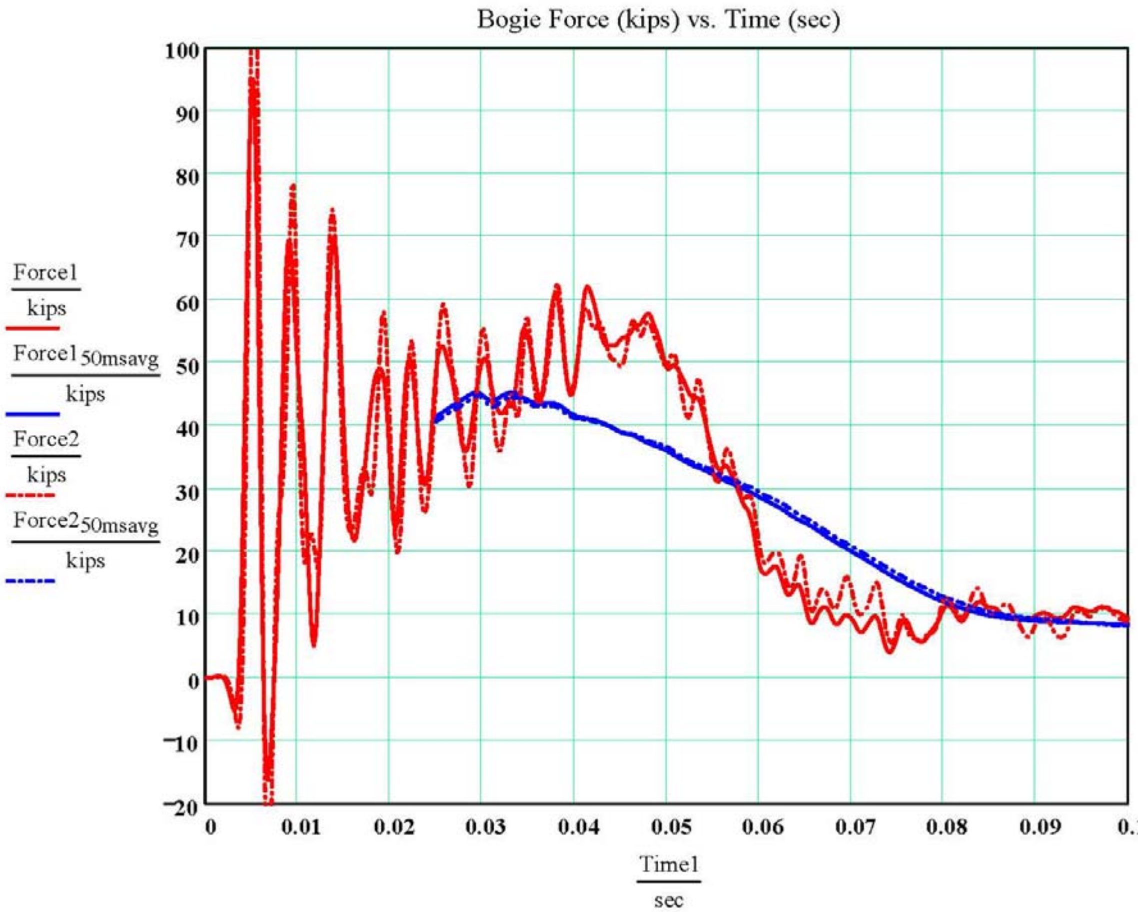
Texas Transportation Institute

Job #: **452106**

Subject: **T501 Rail Retrofit Location C ~ End Case**



APPENDIX F. ANALYTICAL CALCULATIONS FOR RETROFIT/REPAIR OF THE T203 BRIDGE RAILING

Texas Transportation Institute

Page: 1 of 6

Job #: 448235

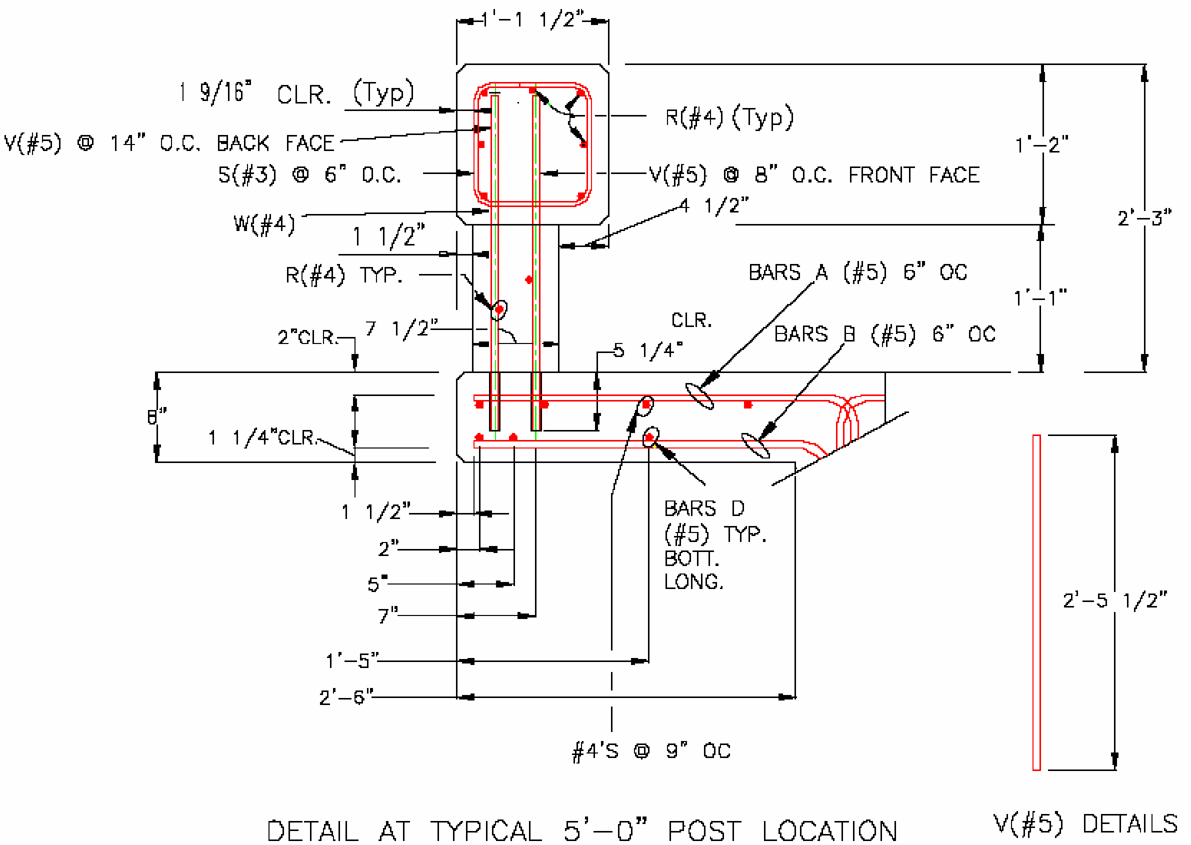
Subject: Adhesive Anchors Retrofit/Repair Design

By: William Williams

Hilti RE 500 Anchoring System for T203

7" Offset Distance for #5 Dowel Bars

1.) Given Design Information & Details, Determine Equivalent #5 Dowel Spacing Requirements :



DETAIL AT TYPICAL 5'-0" POST LOCATION

V(#5) DETAILS

William Williams, P.E.
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Subject: **Adhesive Anchors Retrofit/Repair Design**

Hilti RE 500 Anchoring System for T203

By: **William Williams**

Design Information:

$f'_c := 4000psi$ Concrete Strength, f'c (psi)

$S := 6.5in$ Minimum Anchor Spacing (@ end) (in)

$C := 7.0in$ New Edge Distance for anchor (in.)

$d := C - 1.5in$ Distance from Barrier Edge to CL of Tension Steel (in.) $d = 5.5\,in$

$h_{ef} := 5.25in$ Actual Embedment (in.)

$S_{min} := 0.5 \cdot h_{ef}$ Minimum Anchor Spacing (in.) for Hilti Anchor $S_{min} = 2.63\,in$

$S_{cr} := 1.5 \cdot h_{ef}$ Preferred Min. Spacing (in.) for Hilti Anchor $S_{cr} = 7.88\,in$

$N_{mid} := 8kips$ $N_{end} := 10kips$ Actual Rebar Tension (kips) from Dynamic & Static Testing

$S_{actual} := 5in$ $d_{actual} := 5.75in$ AS-IS Transverse & Longitudinal "V" Bar Locations

From Hilti 2002 Design Guide, pg. 115

$Ultimate_{Bond5} := 27.8kips$ $Ultimate_{Yield5} := 18.6kips$ ... #5 Anchor Information

$Ultimate_{Bond4} := 18.54kip$ $Ultimate_{Yield4} := 12.0kips$ .... #4 Anchor Information

$kips \equiv 1000lbf$

William Williams, P.E.
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Subject: **Adhesive Anchors Retrofit/Repair Design**

By: **William Williams**

Hilti RE 500 Anchoring System for T203

2.) Calculate the Actual Resistance of the #4 "V" Bars considering the forces in the bars observed from the static & dynamic testing, actual "V" Bar "d" Spacing (5 1/4") (.... or 7 1/4" from Deck Edge) and the Longitudinal Spacing "S_{actual}":

$\phi_t := \mathbf{0.85}$ Reduction factor for bar strength $\phi_{temp} := \mathbf{0.90}$ Strength Reduction for 135 deg. temp.

$d_{actual} = \mathbf{5.75}\,in$ As-Is (Current) transverse distance from barrier field side edge to Centerline of Tension "U" (inches)

$S_{actual} = \mathbf{5}\,in$ As-Is (Current) Spacing of Tension "V" Bars (inches)

$$R_{actualmid} := \frac{N_{mid} \cdot d_{actual} \cdot \mathbf{13}}{\mathbf{5}ft} \qquad R_{actualmid} = \mathbf{9.97}\frac{kip \cdot ft}{ft} \qquad R_{actualmid} = \mathbf{4.15}\frac{kip \cdot ft}{\mathbf{5}in}$$

$$R_{actualend} := \frac{N_{end} \cdot d_{actual} \cdot 7}{\mathbf{2.5}ft} \qquad R_{actualend} = \mathbf{13.42}\frac{kip \cdot ft}{ft} \qquad R_{actualend} = \mathbf{5.59}\frac{kip \cdot ft}{\mathbf{5}in}$$

Target "V" Bar Strength Values from Testing

Select a New Longitudinal Spacing "S_{newmid} & S_{newend}" .... $S_{newmid} := \mathbf{8}in$ $S_{newend} := \mathbf{6.5}in$

Select a New Transverse "d" Spacing "d_{new}": $d_{new} := \mathbf{5.5}in$

3.) Calculate the Usable Resistance ϕR_{mid} & ϕR_{end} for new #6 Anchor Spacing & "d" Distance

for:

$Ultimate_{Yield5} = \mathbf{18.6}\,kips$ Limiting strength of #5 Bar

$d_{new} = \mathbf{5.5}\,in$ New "d" Spacing (inches)

$S_{newmid} = \mathbf{8}\,in$ New Longitudinal Anchor Spacing (inches)

$\phi_t = \mathbf{0.85}$ Strength Reduction Factor Used for This Analysis

Therefore: $\phi_{temp} = \mathbf{0.9}$ Strength Reduction Factor for 135-degree temperature

Calculate Reduction Factor for Spacing (Tension & Shear), "f_A"

$$f_A := \left| \begin{array}{l} f_A \leftarrow \mathbf{0.3} \cdot \left(\frac{S}{h_{ef}}\right) + \mathbf{0.55} \ \text{ if } S_{cr} \ge S \ge S_{min} \\ f_A \leftarrow \mathbf{1.0} \ \text{ if } S \ge S_{cr} \\ f_A \leftarrow \mathbf{0} \ \text{ if } S < S_{min} \end{array} \right.$$

Spacing (in.)	Edge Dist. (in.)
$S = \mathbf{6.5}\,in$	$C = \mathbf{7}\,in$

$f_A = \mathbf{0.92}$

By: William Williams

Subject: **Adhesive Anchors Retrofit/Repair Design**

Hilti RE 500 Anchoring System for T203

Calculate Reduction Factor for Edge Distance Tension, "f_{RN}"

$C_{min} := 0.5 \cdot h_{ef}$ Minimum Edge Distance (in.) $C_{cr} := 1.5 \cdot h_{ef}$ Preferred Clearance (in.)

$C_{min} = 2.63\,in$ $C_{cr} = 7.88\,in$

$$f_{RN} := \begin{cases} f_{RN} \leftarrow 0.3 \cdot \left(\dfrac{C}{h_{ef}}\right) + 0.55 & \text{if } C_{cr} \ge C \ge C_{min} \\ f_{RN} \leftarrow 1.0 & \text{if } C \ge C_{cr} \\ f_{RN} \leftarrow 0 & \text{if } C < C_{min} \end{cases}$$

$f_{RN} = 0.95$

Calculate total combined Reduction Factors for tension:

$f_A = 0.92$ $f_{RN} = 0.95$

$$\phi_{tension} := \overrightarrow{\left(f_A \cdot f_{RN}\right)}$$

$\phi_{tension} = 0.88$

Calculate the allowable Tension Strength of #5 Anchor considering Spacing & Edge Distance:

$F_{tension5} := \phi_{tension} \cdot Ultimate_{Bond5}$ $d_{new} = 5.5\,in$

$F_{tension5} = 24.33\,kip$ .... o.k. fractured bond strength still greater than yield strength ..... use yield strength $S_{newmid} = 8\,in$

$Ultimate_{Yield5} = 18.6\,kips$

$$\phi R_{mid} := \frac{Ultimate_{Yield5} \cdot d_{new} \cdot 8}{5ft} \cdot \phi_t \cdot \phi_{temp}$$ $\phi R_{mid} = 10.43\,\dfrac{kip \cdot ft}{ft}$ o.k.... greater than or near equal to $R_{actualmid}$

$$\phi R_{end} := \frac{Ultimate_{Yield5} \cdot d_{new} \cdot 5}{2.5ft} \cdot \phi_t \cdot \phi_{temp}$$ $\phi R_{end} = 13.04\,\dfrac{kip \cdot ft}{ft}$ o.k.... greater than or near equal to $R_{actualend}$

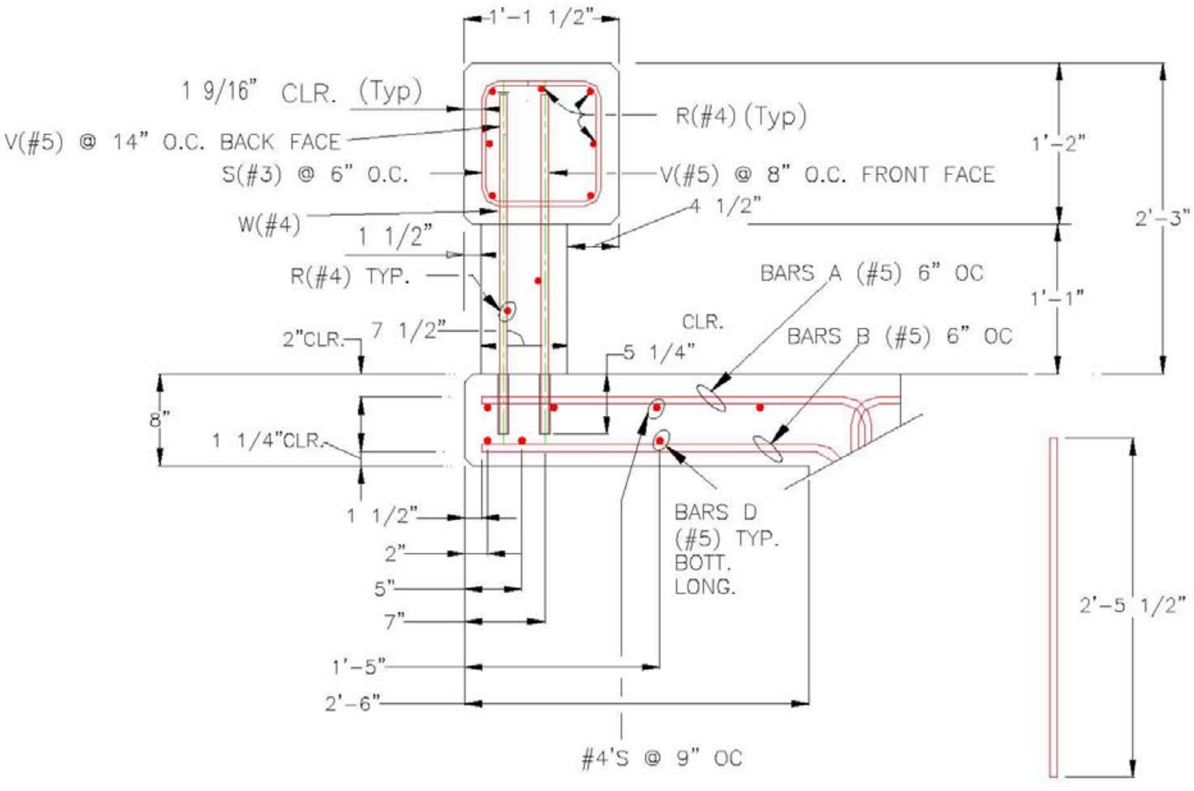
$d_{actual} = 5.75\,in$

Subject: Adhesive Anchors Retrofit/Repair Design

Hilti RE 500 Anchoring System for T203

By: William Williams

4.) Retrofit/Repair Option using Hilti RE 500 Anchoring System & 7" Offset Distance for #5 Dowel Bars:



DETAIL AT TYPICAL 5'-0" POST LOCATION

V(#5) DETAILS

Recommended Retrofit Design (5'-0" Post in Mid-Section):

#5 "V" Dowel Bars @ 8 Inches O.C. in Mid-Section Post (8 Bars) FRONT FACE

#5 "V" Dowel Bars @ 14 Inches O.C. in Mid-Section Post (5 Bars) BACK FACE

Recommended Retrofit Design (2'-6" End Post):

#5 "V" Dowel Bars @ 6.5 Inches O.C. in 2'-6" End Post FRONT FACE

#5 "V" Dowel Bars @ 13 Inches O.C. in 2'-6" End Post (3 Bars) BACK FACE

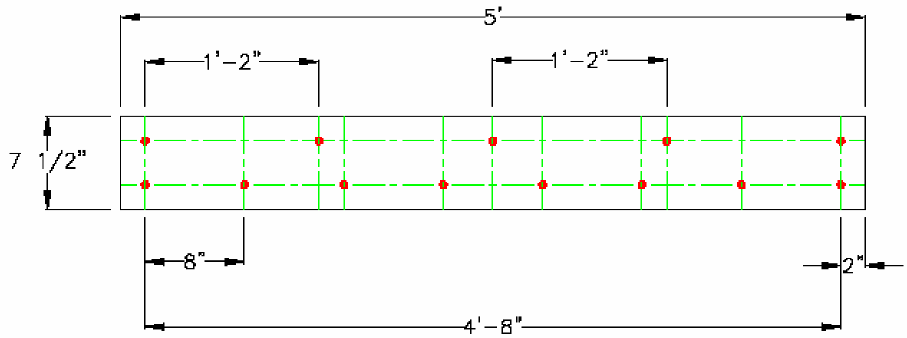
Texas Transportation Institute

Job #: 448235

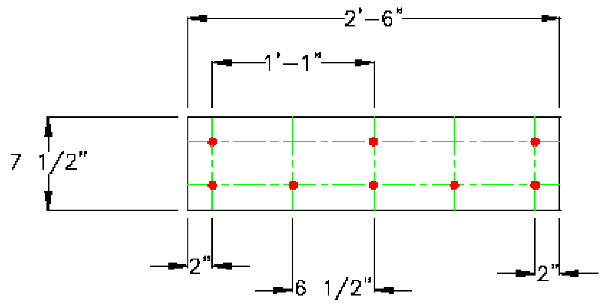
Subject: **Adhesive Anchors Retrofit/Repair Design**

By: **William Williams**

Hilti RE 500 Anchoring System for T203



PLAN VIEW 5-FT POST



PLAN VIEW 2'-6" END POST

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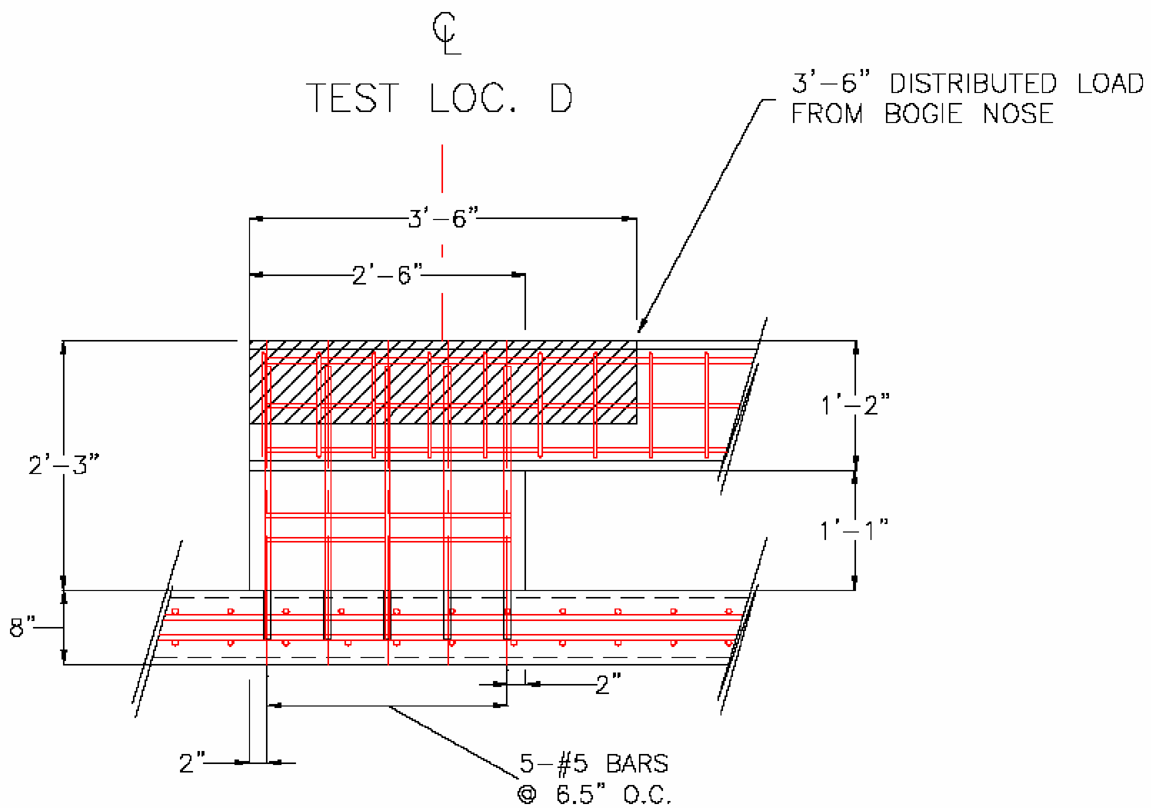
APPENDIX G. DATA FROM DYNAMIC TESTING OF REPAIR/RETROFIT OF THE T203 BRIDGE RAILING

TEST B10 - T203 – LOCATION D

Texas Transportation Institute

Job #: 452106

Subject: T203 Rail Retrofit Location D ~ End Case



T203 TRAFFIC SIDE VIEW
(#5 ADHESIVE RETROFIT DESIGN @ END)

Note: Hilti HIT RE 500 Injection Adhesive Anchoring System used with Grade 60 Reinforcement

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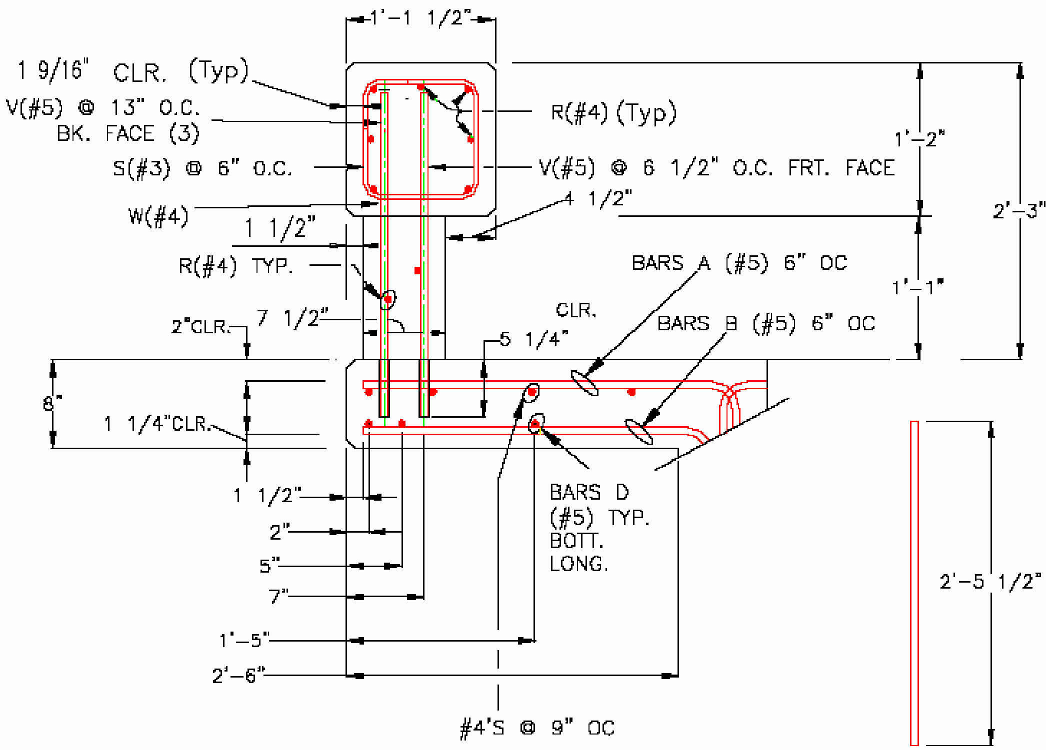
Texas Transportation Institute

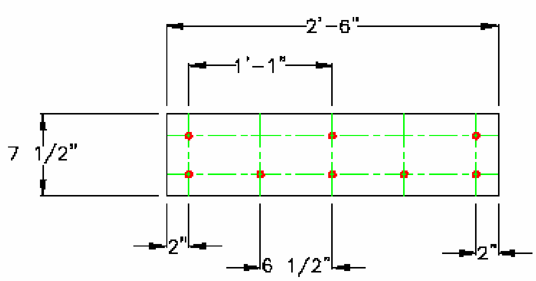
Job #: 452106

Subject: **T203 Rail Retrofit Location D ~ End Case**



SECTION AT TYPICAL 2'-6" END POST

V(#5) DETAILS



PLAN VIEW 2'-6" END POST

Bogie Acceleration Data

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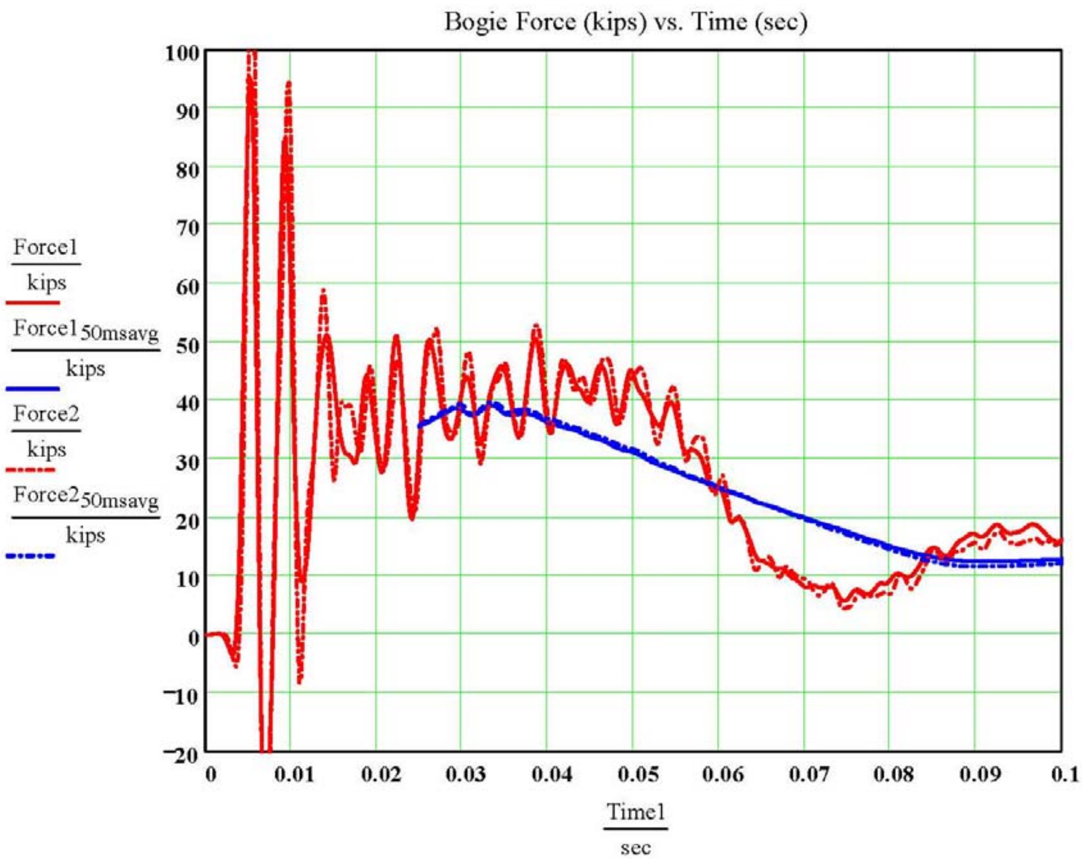
Texas Transportation Institute

Job #: **452106**

Subject: **T203 Rail Retrofit Location D ~ End Case**

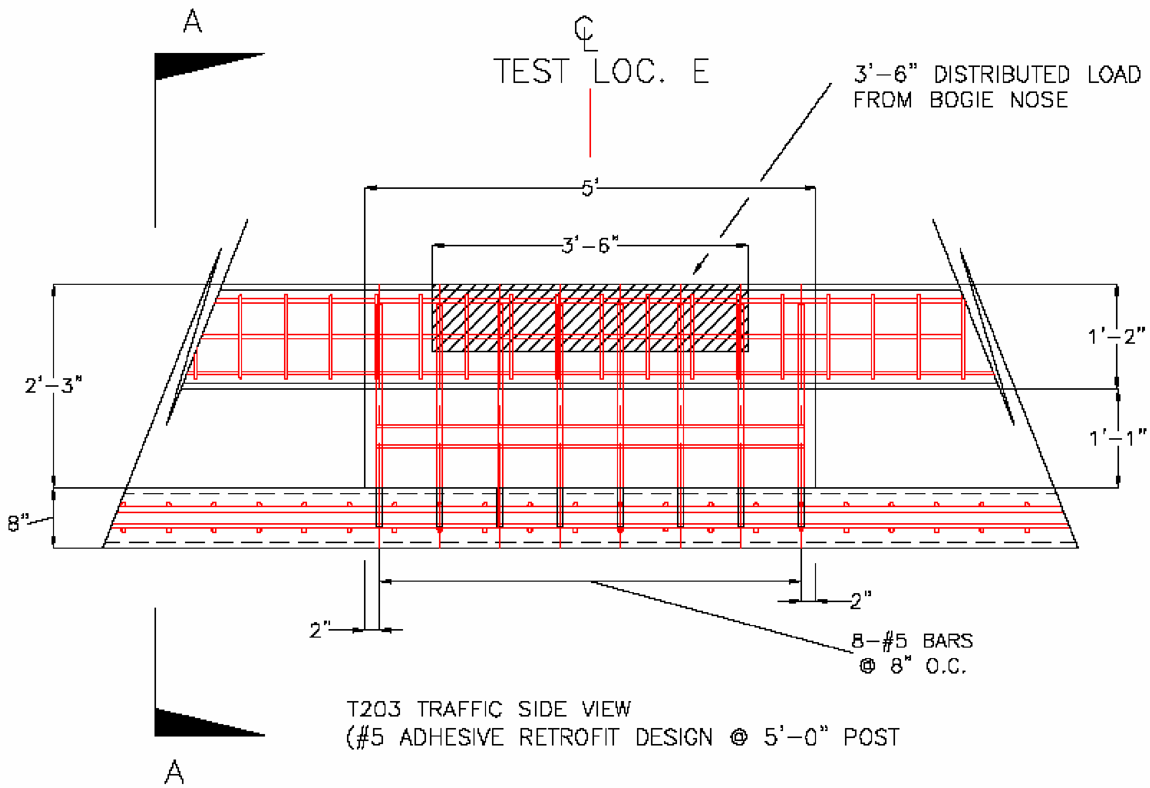


TEST B11 - T203 – LOCATION E

Texas Transportation Institute

Job #: **452106**

Subject: **T203 Rail Retrofit Location E ~ Mid-Span Case**



T203 TRAFFIC SIDE VIEW
(#5 ADHESIVE RETROFIT DESIGN @ 5'–0" POST

Note: Hilti HIT RE 500 Injection Adhesive Anchoring System used with Grade 60 Reinforcement

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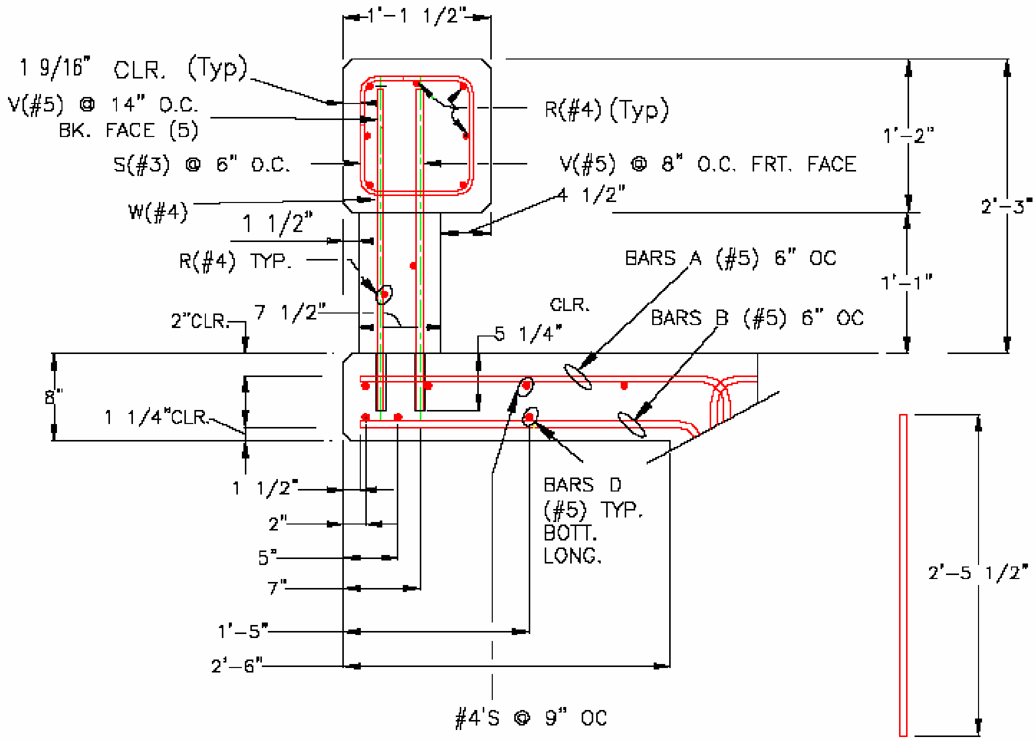
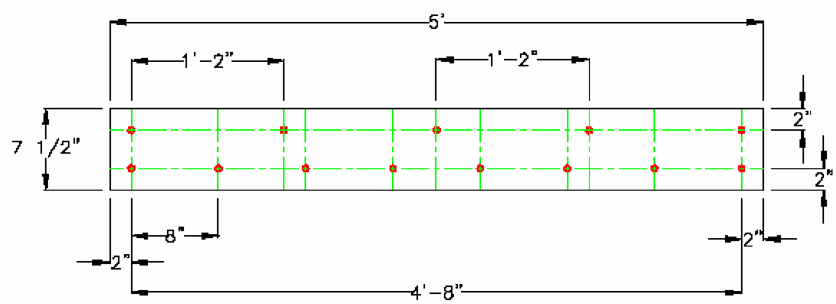
SECTION A-A



DETAIL AT TYPICAL 5'-0" POST

V(#5) DETAILS



PLAN VIEW 5-FT POST

Bogie Acceleration Data

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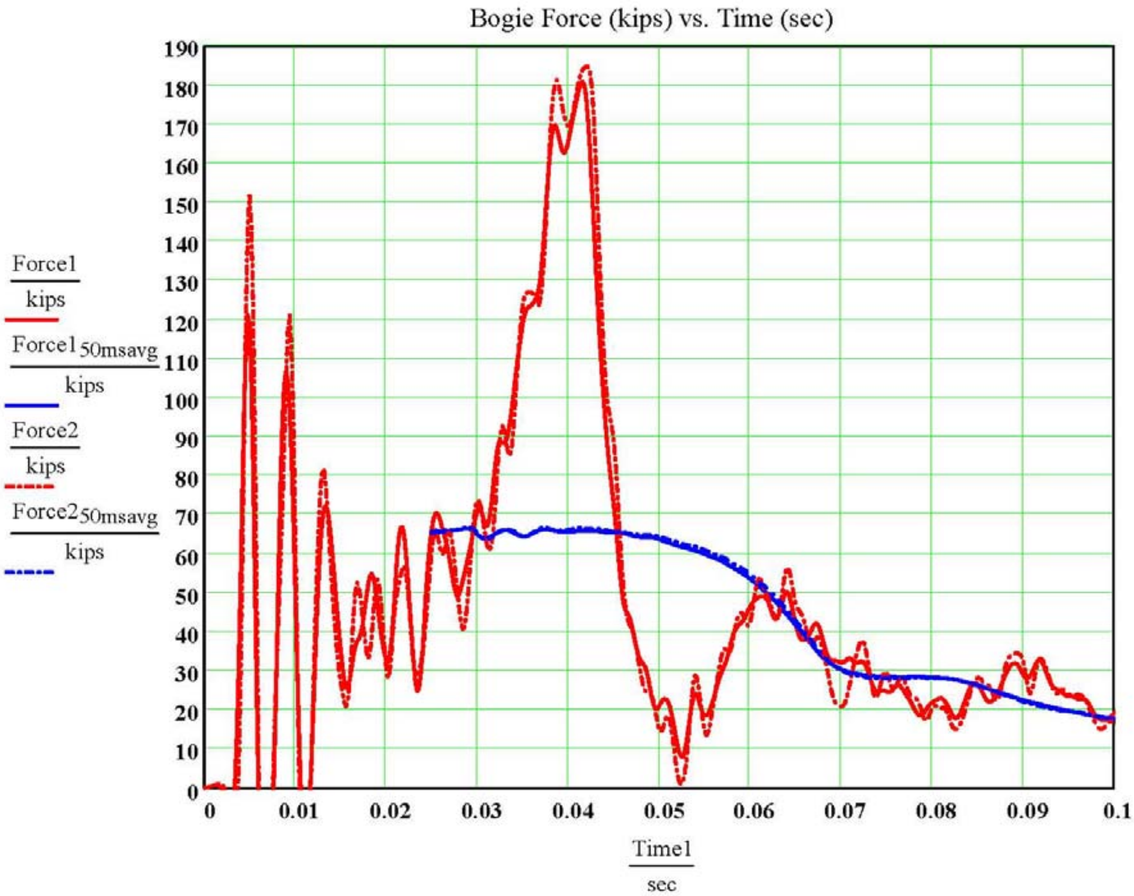
Subject: **T203 Rail Retrofit Location E ~ Mid-Span Case**



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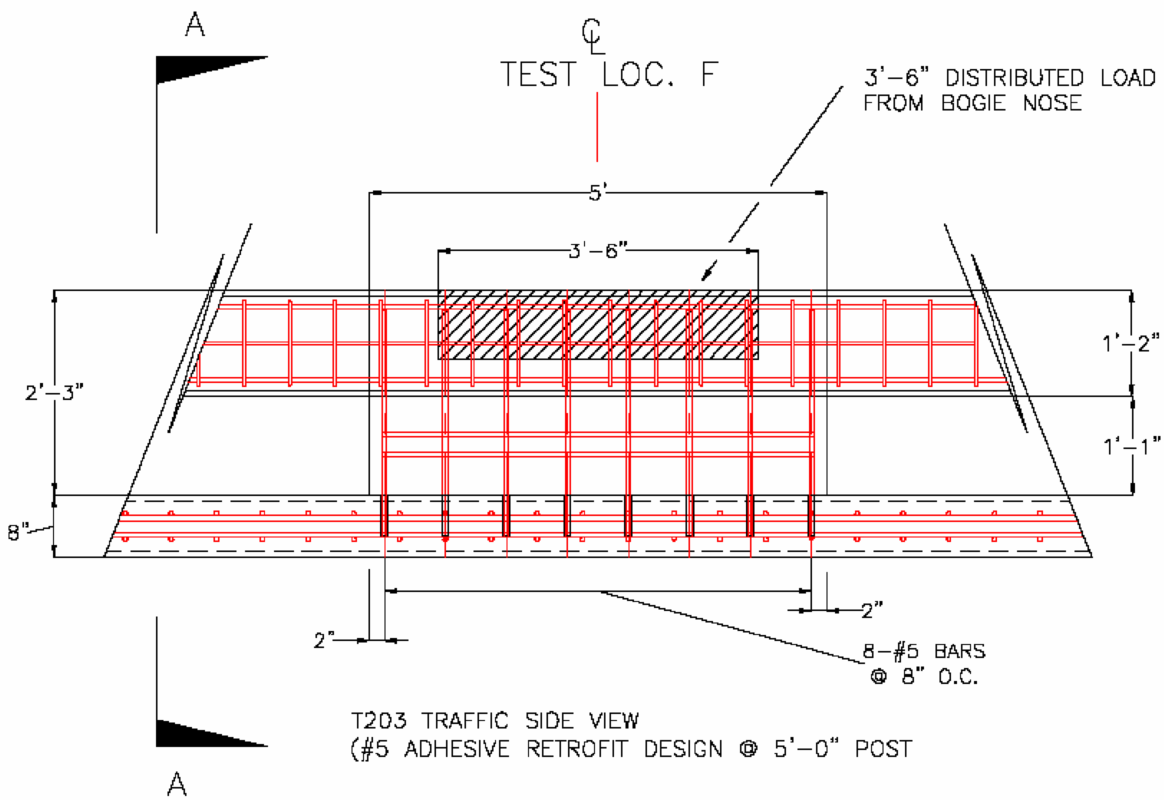
TEST B12 - T203 – LOCATION F

Texas Transportation Institute

Job #: 452106

Subject: T203 Rail Retrofit Location F ~ Mid-Span Case



T203 TRAFFIC SIDE VIEW
(#5 ADHESIVE RETROFIT DESIGN @ 5'–0" POST

Note: Hilti HIT RE 500 Injection Adhesive Anchoring System used with Grade 60 Reinforcement

452106FData(Rrev1).xmcd
4/4/2006

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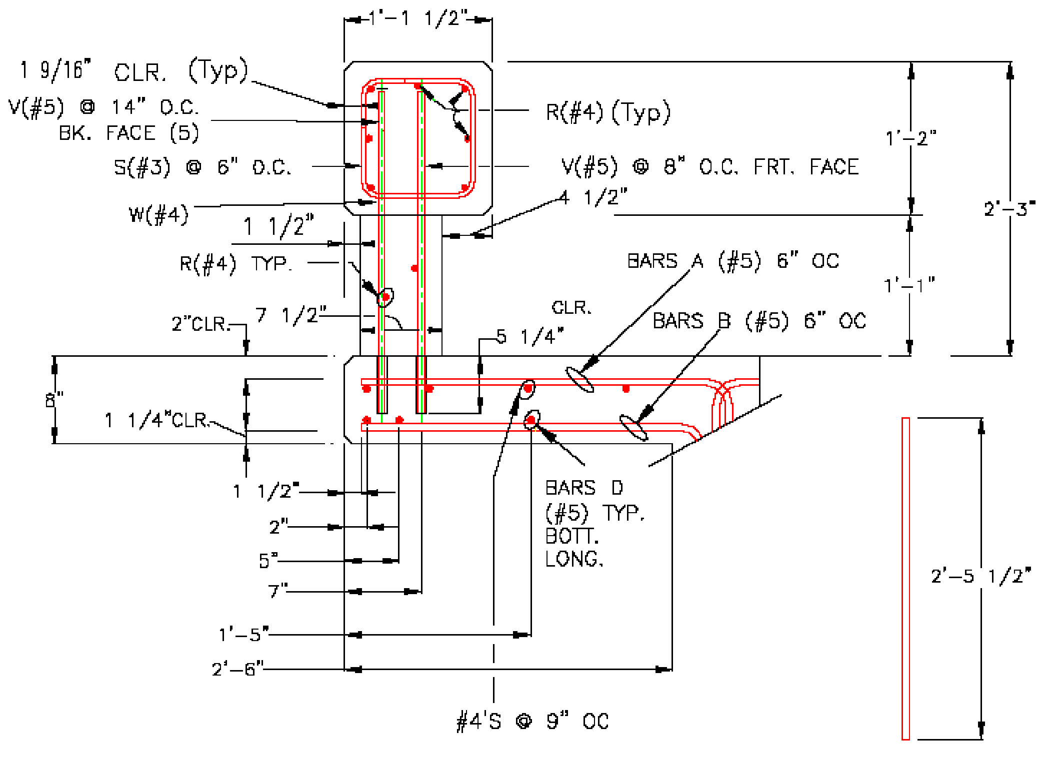
Job #: 452106

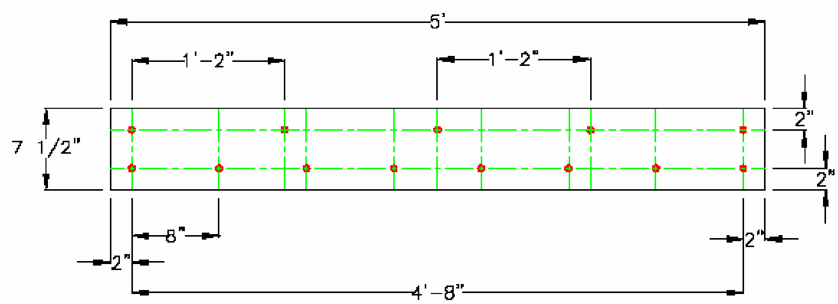
Subject: T203 Rail Retrofit Location F ~ Mid-Span Case

SECTION A-A



DETAIL AT TYPICAL 5'-0" POST

V(#5) DETAILS



PLAN VIEW 5-FT POST

Bogie Acceleration Data

452106FData(Rrev1).xmcd
4/4/2006

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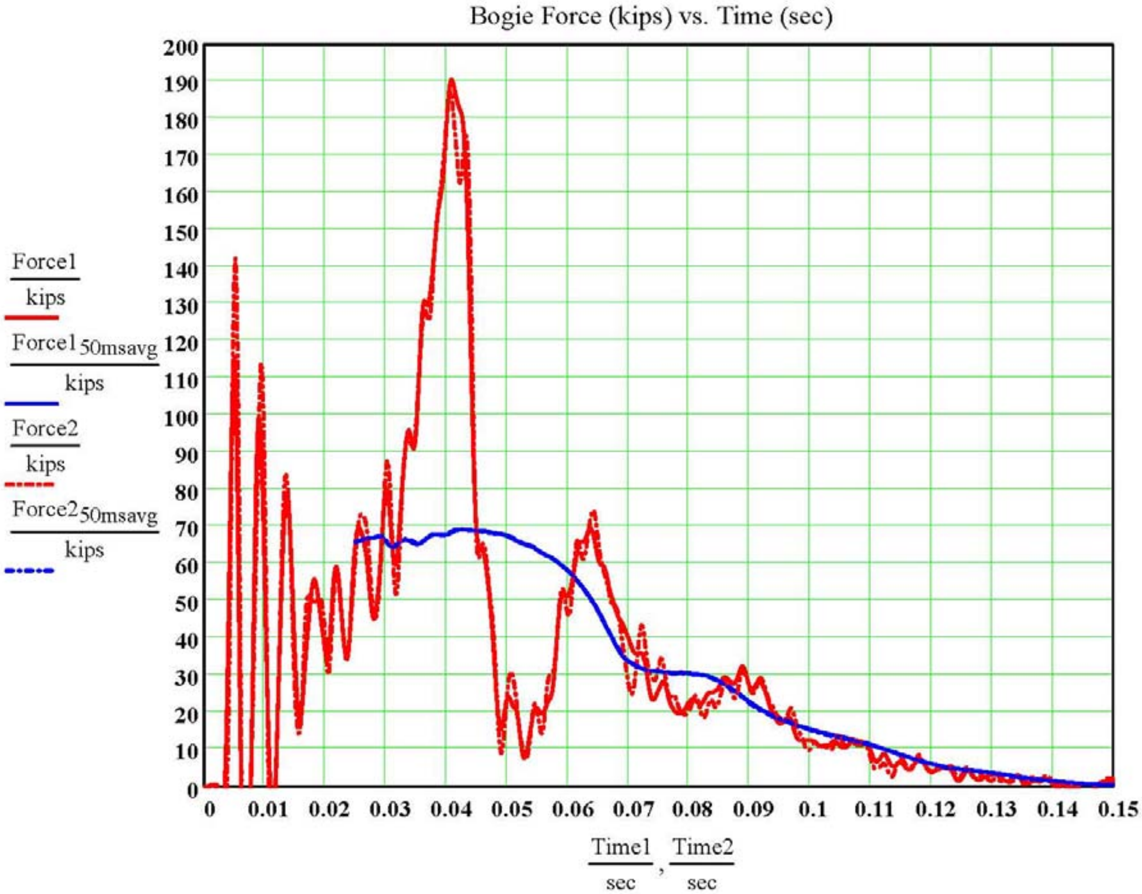
Job #: **452106**

Subject: **T203 Rail Retrofit Location F ~ Mid-Span Case**



452106FData(Rrev1).xmcd
12/13/2006

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