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**Progress Report – July 1 – September 30, 2024**

**Title:** Assessment and Repair of Prestressed Bridge Girders Subjected to Over-height Truck Impacts Pooled Fund Project

**Project Number:** TR202011

**Principal Investigator (PI):** Mohamed ElGawady PhD (PI)

**Co-PI(s):** William Schonberg PhD, PE (Co-PI)

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| **Award date:** | **1/1/2021** | | |
| **Scheduled completion date:** | **12/31/2023** | **% of project completed to date:** | **94%** |
| **Total budget:** | **$**805,000 | **% of budget expended to date:** | **95%** |
| **Draft report due:** | **9/30/2023** | **Final report due:** | **12/1/2023** | |

Provide a short description of the **work currently underway**.

*Use* [*additional notes section*](#bookmark=id.1t3h5sf) *if you need to provide more information.*

***Task 2. Experimental testing of bridge girders subjected to lateral impacts:***

This task was concluded

***Task 3. Determine the residual flexural and shear strengths of the damaged bridge girders***

This task has been concluded. See example of the new results obtained during this period in the next section.

***Task 5: Repair Evaluation***

Four different girders were repaired using strand splice. One girder was repaired using CFRP. There remain two girders to be repaired using CFRP. The results of the repair is shown in the next section.

Identify any circumstances or **issues that may need to be addressed**.*Provide a summary of issues that are important for the TAC to know. For example, staffing difficulties or supply chain delays.*

The project is currently experiencing a four-month delay, and we recognize the importance of addressing this impact. Our team remains fully committed to the project goals and has worked diligently to overcome significant challenges while maintaining technical quality.

The primary cause of the delay has been a gap in technical support due to the resignation of two departmental technicians, which left the team without essential resources for the past year. To mitigate this, team members and students took on additional responsibilities, and we engaged local shops for specific tasks such as drilling and welding, helping to alleviate the impact of these staffing changes.

Additionally, sourcing a critical component for strand tensioning proved more challenging than anticipated. Despite advanced planning, the required part became difficult to obtain, leading us to develop a custom solution that is now in place and has allowed us to tension three different girders.

Despite these setbacks, the team has maintained quality standards and remains confident in the project’s technical success. We appreciate your continued support and understanding as we complete the remaining work.

Provide a short description of the **noteworthy activities/accomplishments** during this reporting period.

*Use* [*additional notes section*](#bookmark=id.1t3h5sf) *if you need to provide more information.*

***Task 3. Determine the residual flexural and shear strengths of the damaged bridge girders*** As a new addition to this task, the validated FE models were used to create fifteen FE models to assess the flexural resistance of an AASHTO Bulb-Tee 72 prestressed concrete girder. Force-deflection relationships were established, and FE model results were compared to AASHTO LRFD outcomes. The study concluded that the lateral bending moment due to asymmetric loss of prestressing strands up to 50% reduced the flexural resistance by 13% compared to beams having symmetric loss of the strands. Therefore, the asymmetric loss of the presstressing was not significantly affected the strength of girders. Table 1 and Figures 1 through 4 show a summary of the investigated cases. Figure 5 shows the reduction in the ultimate flexural strength.

**TABLE 1 Summary of the FE models**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Case | % of strands loss | Symmetry condition | Damage Severity | Number of removed strands | The remaining strands | % Concrete section loss |
| Control | 0 | Symmetric | No damage | 0 | 48 | 0.0 |
| Symm-S12.5%-C0% | 12.5 | Symmetric | II | 6 | 42 | 0.0 |
| Symm-S20.8%-C0% | 20.8 | III | 10 | 38 | 0.0 |
| Symm-S33%-C0% | 33.0 | III | 16 | 32 | 0.0 |
| Symm-S50%-C0% | 50.0 | IV | 24 | 24 | 0.0 |
| Asymm-S12.5%-C0% | 12.5 | Asymmetric | II | 6 | 42 | 0.0 |
| Asymm-S20.8%-C0% | 20.8 | III | 10 | 38 | 0.0 |
| Asymm-S33%-C0% | 33.0 | III | 16 | 32 | 0.0 |
| Asymm-S50%-C0% | 50.0 | IV | 24 | 24 | 0.0 |
| Asymm-S12.5%-C12.5% | 12.5 | Symmetric | II | 6 | 42 | 12.5 |
| Asymm -S33%-C28% | 33.0 | IV | 16 | 32 | 28.0 |
| Asymm -S50%-C56% | 50.0 | IV | 24 | 24 | 56.0 |
| Asymm -S12.5%-C12.5% | 12.5 | Asymmetric | II | 6 | 42 | 12.5 |
| Asymm -S33%-C28% | 33.0 | IV | 16 | 32 | 28.0 |
| Asymm -S50%-C56% | 50.0 | IV | 24 | 24 | 56.0 |

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| (a) | (b) | (c) | (d) |

**Figure 1 Symmetric loss of strands configuration (a) S12.5%-C0%, (b) S20.80%-C0%, (c) S33% -C0%, and (d) S50%-C0%**

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| (a) | (b) | (c) | (d) |

**Figure 2 Asymmetric loss of strands configuration (a) S12.5%-C0%, (b) S20.80%-C 0%, (c) S33%-C0%, and (d) S50%-C0%**

*Note “S” stands for prestressing stand loss, “C” stands for concrete section loss.*

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| (a) | (b) | (c) |

**Figure 3 Symmetric loss of strands with concrete loss configurations (a) S12.5%-C12.5%, (b) S33%-C28% (c) S50%-C56%**

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| (a) | (b) | (c) |

**Figure 4 Asymmetric loss of strands configuration (a) S12.5%-C12.5%, (b) S33%-C28% (c) S50%-C56%**

*Note “S” stands for prestressing stand loss, “C” stands for concrete section loss.*

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| (a) | **(b)** |

**Figure 5 Reduction in ultimate flexural strength due to: (a) Loss of strands, and (b) Loss of strands and concrete section**

***Task 5: Repair Evaluation***

Method 1: Mechanical splicing

**Experimental Work**

To evaluate the effectiveness of the Grabb-It strand splicing repair technique, a comprehensive experimental program was conducted. The repaired girders were subjected to rigorous structural assessment through four-point bending tests under simply supported conditions. This testing configuration was chosen to simulate real-world loading scenarios and to assess the girders' performance under flexural stress.

*Assessment of Damage Extent*

The first crucial step involved a thorough evaluation of the damage to the prestressing strands. This assessment likely included visual inspection, strain gage data, and potentially destructive testing – G2, G3, and G4 – to accurately determine the extent of damage to the prestressing strands.

*Preparation of Damaged Area*

The preparation of the damaged area was carried out as follows:

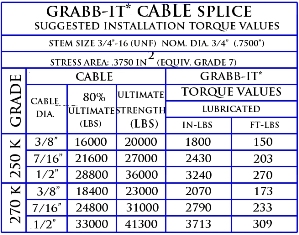
* Loose concrete was removed using a jackhammer to expose the damaged strands and surrounding area.
* The exposed area ranged from a minimum length of 4 feet to a maximum of 7 feet, depending on the severity of the damage and the extent of the repair to be done.
* This step was crucial to ensure a clean, sound surface for the repair and to fully expose the damaged strands for splicing.

*Application of Grabb-It Strand Splicing Technique*

The Grabb-It strand splicing technique was applied with the following considerations:

* Strand splices were staggered as recommended by earlier researchers (Zobel et al., 1998;Olsen et al., 1992). This staggering helps to distribute stresses more evenly and reduce stress concentrations.
* The strands were stressed up to 80% of the ultimate tensile strength (fpu) using the manufacturer's recommended prestressing chart in Table 1. This level of prestressing is typical for pretensioned concrete members and helps to ensure the repaired section behaves similarly to the original undamaged section.

Table 1- Torque Wrench Method Conversion to Prestress Force. Prestress Supply Incorporated. (2010). Grabb-It Cable Splice.



*Restoration of Concrete Cover*

The final step in the repair process involved restoring the concrete cover:

* High-strength grout was used to patch the repair area.
* Importantly, this patching was done after the girder was preloaded. This preloading step is crucial as it helps to prevent concrete pop-out failure during subsequent testing of the girder.
* The use of high-strength grout ensures that the repaired section has adequate strength and durability to match or exceed that of the original concrete.

These detailed repair steps were crucial in ensuring the effectiveness of the Grabb-It strand splicing technique and the overall success of the girder repair. The careful execution of each step contributes to the restored structural integrity and load-bearing capacity of the repaired girders.

*Restoration of Concrete Cover and Crack Treatment*

The final steps in the repair process involved restoring the concrete cover and addressing any resulting cracks:

* High-strength grout was used to patch the repair area.
* Importantly, this patching was done after the girder was preloaded. This preloading step is crucial as it helps to prevent concrete pop-out failure during subsequent testing of the girder.
* The use of high-strength grout ensures that the repaired section has adequate strength and durability to match or exceed that of the original concrete.
* After the concrete casting and initial curing, a thorough inspection was conducted to identify any cracks that were formed from the impact test due to stress redistribution.

Once identified, the cracks were first opened up and chased. This process involves:

* Carefully widening the surface of the crack using appropriate tools (e.g., a crack chaser), following the crack's path to ensure its full extent is exposed and accessible.
* Cleaning out any debris or loose material from within the crack.
* These were then treated using epoxy injection. This process involves injecting a low-viscosity epoxy resin into the cracks under pressure, effectively sealing them and restoring the continuity of the concrete.
* The epoxy injection serves multiple purposes:
  1. It prevents water and other potentially corrosive substances from penetrating the concrete and reaching the reinforcement or prestressing strands.
  2. It helps restore the structural integrity of the repaired section by bonding the cracked surfaces together.
  3. It enhances the durability of the repair, potentially extending the service life of the girder.

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| A group of men in hard hats working on a construction site  Description automatically generated | A construction site with a few metal rods  Description automatically generated with medium confidence |
| Strand splicing operation | Prepared formwork for concrete patching |
| A concrete slab with metal rods  Description automatically generated with medium confidence | A concrete beam with a chain  Description automatically generated |
| Patched area with high strength grout | Crack injection with epoxy |

Figure 6 Repair steps using strand splice

*Test setup and instrumentation*

The experimental setup was meticulously designed to provide accurate and detailed data on the performance of the repaired girders. The test utilized a 44-foot simply supported span, within which there was a 14.5-foot distance between the supports and a 15-foot constant moment zone in the center as shown in Figure 7. This configuration allowed for a realistic simulation of the load distribution typically experienced by bridge girders in service. To apply the load, two 500-kip hydraulic cylinders were employed. Each cylinder was equipped with a load cell to precisely measure the applied force, ensuring accurate load data throughout the testing process. The use of two cylinders allowed for even distribution of the load across the girder, mimicking the effect of distributed loads on a bridge structure. Crucial to the success of the experiment was the implementation of an electronic data acquisition system. This system captured real-time measurements throughout the duration of the test, ensuring continuous monitoring of the girder's response to the applied loads. The real-time data collection allowed researchers to observe and analyze the girder's behavior as it occurred, providing invaluable insights into the performance of the repaired structure. To gain a comprehensive understanding of the girder's behavior under load, a variety of measurement instruments were strategically placed. Linear Variable Differential Transformers (LVDTs) were positioned at the girder ends and gravity supports to detect any horizontal movement. This data was crucial in understanding the overall stability of the girder and identifying any unexpected lateral displacements that could indicate structural issues.

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| Figure 7 Test setup |

Complementing the LVDTs, string potentiometers were attached to the girder at three critical locations: beneath each load point and at the midspan. These devices provided accurate measurements of vertical deflection, allowing researchers to map the deformation profile of the girder under various load conditions. The midspan measurement was particularly important as it typically represents the point of maximum deflection in a simply supported beam. Prior to the casting of concrete, strain gauges were installed on the prestressing strands of each girder. These gauges were then connected to the data acquisition system, allowing for continuous monitoring of strain levels during the testing process. This detailed strain data provided crucial information about the stress distribution within the girder, particularly in the repaired areas, and helped in assessing the effectiveness of the Grabb-It strand splicing technique in restoring the girder's structural integrity. This comprehensive instrumentation setup enabled to collect a wealth of detailed data on load-deflection behavior, strain distribution, and potential horizontal movement of the girders throughout the testing process.

The data collected from this rigorous testing program formed the basis for the analysis and conclusions presented in the subsequent sections of this report, providing a solid foundation for evaluating the effectiveness of the Grabb-It strand splicing technique in repairing prestressed bridge girders damaged by over-height vehicle collisions.

**Discussion of Results**

*Girder 5 – 33% damage repaired*

Analysis of the internal strain gauge data from G5 revealed the severity of the collision's impact. Four of the prestressing cables either reached their yield strength or experienced a substantial loss of their initial tension, resulting in a target damage level of 33%. This level of damage significantly compromised the girder's structural integrity, presenting a challenging test case for the Grabb-It repair technique since more than 15% of strands damage are not considered to be repaired using strand splicing (Zobel et al., 1998). Following the impact test and subsequent strand severance, the girder exhibited a 1.375-inch camber with a lateral displacement of 0.3125 inches. Interestingly, after the application of prestressing, the camber increased to 1.625 inches, indicating recovery of the girder's pre-tensioned state. This change in camber suggests that the Grabb-It splicing technique was successful in reintroducing some level of prestress into the damaged strands.

The flexural assessment of the repaired girder yielded noteworthy observations. Initial crack formation became visible at a 61-kip load, originating in the constant moment region and extending beyond the existing impact-induced fractures. As loading continued, additional bending-related cracks appeared, primarily concentrating within the constant moment zone. The experiment proceeded until the beam reached a deflection of 2.31 inches, at which point the load application plateaued while combined flexural-shear cracks expanded beyond 0.1 inches in width.

Interestingly, the specimen demonstrated increased ductility in its failure mode, and subsequently a concrete compression failure. The girder ultimately failing at one of the loading points, was attributed to the location of the harped strands at the loading point, which experienced 2% higher stresses than the straight strands. The girder reached its structural limit at 94.96 kips, corresponding to a maximum moment capacity of 688.46 ft-kips.

Despite these encouraging signs of partial recovery and ductile behavior, the repair did not fully achieve the targeted strength for the 33% damaged girder. This limitation can be attributed to two primary factors. First, the Grabb-It splice connectors may have a maximum load capacity that is lower than the ultimate capacity of the prestressing force in the strands. When a significant portion of the strands (33% in this case) is repaired using these splices, the cumulative effect of this limitation becomes more pronounced, reducing the overall strength of the repaired section.

Secondly, the high stiffness of the mechanical splice may result in stress concentrations at the ends of the strand splice chuck area. These localized stress concentrations can affect the overall performance of the girder, potentially leading to premature failure or reduced load-bearing capacity.

It is important to note, however, that despite not reaching the targeted strength, the repair still provided a significant improvement over the damaged state. This enhancement potentially extends the service life of the girder, allowing time for more comprehensive repair or replacement strategies to be implemented. The partial recovery of strength and the ductile failure mode observed suggest that the Grabb-It strand splicing technique can be a valuable tool for emergency repairs or as an interim solution for severely damaged prestressed bridge girders.

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| (a) | (b) |
| A close-up of a hole in a concrete wall  Description automatically generated | A broken concrete wall with wires  Description automatically generated |
| (c) | (d) |
| Figure 8 Failure of girder having 33% repaired strands | |

These findings underscore the complexity of repairing heavily damaged prestressed concrete girders and highlight the need for careful consideration of repair techniques based on the extent of damage. While the Grabb-It strand splicing technique showed promise in restoring some structural capacity, further research and development may be necessary to address its limitations in cases of severe damage.

*16% damage repaired*

In contrast to the challenges faced with the 33% damaged girder, the results for Girder 9, which represented a 16% damage scenario, were significantly more promising. This virgin girder was intentionally damaged, repaired, and tested to provide a comprehensive understanding of the Grabb-It prestress strand splice behavior under more moderate damage conditions.

Following concrete removal and strand severance to simulate a 16% damage level, Girder 9 exhibited a 1.812-inch camber with a slight lateral displacement of 0.125 inches. Interestingly, after the application of prestressing through the Grabb-It technique, the camber increased to 1.995 inches. This increase in camber suggests a successful reintroduction of prestress into the damaged strands, indicating the repair's effectiveness in restoring some of the girder's original structural properties. The flexural assessment of Girder 9 revealed impressive performance characteristics. Initial crack formation was observed at a substantial load of 91 kips, originating in the constant moment region. As loading continued, additional bending-related cracks appeared, primarily concentrating within the constant moment zone. The girder demonstrated remarkable resilience, with these cracks progressing to the beam's upper flange only at 132 kips, signaling the approach of the ultimate load capacity.

At 138 kips, diagonal cracks indicative of shear stress began to manifest beyond the constant moment area, highlighting the complex stress distribution within the repaired girder. The experiment continued until the beam reached a significant deflection of 6.06 inches, demonstrating considerable ductility. At this point, the load application plateaued while combined flexural-shear cracks expanded beyond 0.1 inches in width.

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| (b) | |
| A broken wall with wires and a rope  Description automatically generated with medium confidence | A construction site with a few metal beams and a chain  Description automatically generated with medium confidence |
| (c) | (d) |
| Figure 9. Photos showing (a) Failure of 16% damage repaired girder at load point (b) close up view of girder failure (c) Prestress strand showing yielding and unbundling (harped strands), and (d) top view of girder failure | |

Girder 9 exhibited an increased ductility in its failure mode, with audible popping noises occurring at 144 kips, followed by sounds of concrete crushing at 149 kips. The presence of pronounced vertical fissures was attributed to the reduced prestress in the repaired section, which forced the concrete to bear tensile stresses without the full assistance of the prestressing strands. Despite these challenges, the girder impressively reached its structural limit at 150.69 kips, corresponding to a maximum moment capacity of 1092.36 ft-kips.

*Force-deflection curve*

During the tests, load-displacement data was collected for each girder. The maximum force sustained primarily reflects the remaining strength and overall stiffness of the girder after impact. The analysis showed that G9 outperformed G5. Comparing the test results to the AASHTO breaking force, G5 experienced a 35.3% reduction in strength following repair and retesting, whereas G9 exhibited a 3.2% improvement in the flexural capacity of the repaired girder.

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Figure 10. Force deflection plots for control girder, G5, and G9

Figure 11 illustrates the correlation between the proportion of spliced strands and the remaining flexural strength in prestressed concrete girder structures. It presents a comparison of data from repaired specimens using strand splicing, unrepaired samples, and a theoretical flexural strength line. The plot incorporates findings from various researchers, providing a comprehensive view of the Grabb-It strand splice's capabilities and limitations. Data points from different studies are included to offer a broader perspective. A clear pattern emerges from the graph: as the percentage of spliced strands grows, there's a corresponding decline in residual flexural strength. This relationship is crucial for understanding the structural implications of strand splicing in repair scenarios.

The analysis of this data is intended to contribute to the development of an analytical model. Such a model would aim to provide accurate estimates of a repaired girder's capacity when strand splicing is employed, taking into account the extent of the initial damage. This research has significant implications for assessing and predicting the effectiveness of strand splicing as a repair technique in prestressed concrete structures.



Figure 11. Relationship between spliced strand percentage and residual flexural strength in prestressed concrete girders, comparing repaired, non-repaired, and hypothetical scenarios across multiple studies.

**Method 2: Externally Bonded CFRP**

Two prestressed concrete (PC) girders are scheduled to undergo retrofitting using externally bonded carbon fiber reinforced polymer (CFRP) wraps. These girders were subjected to lateral impact loads in varying configurations to induce different levels of damage. However, in some of the configurations, the intensity of the impact was insufficient to cause significant damage across all girders. To ensure a consistent evaluation of the retrofitting process, the prestressing strands in the girders were deliberately exposed and cut to achieve specific levels of prestressing strand loss. This approach allowed for a more controlled assessment of the effects of the CFRP repair.

Three distinct levels of prestressing strand loss were targeted—16.7%, 25%, and 33%. The 33% strand loss was applied to two girders to test two different methods of anchoring the CFRP U-wraps. One girder utilized steel channels as part of the anchorage system, while the other did not, providing an opportunity to compare the effectiveness of mechanical anchorage in delaying the debonding of the longitudinal CFRP. This comparison will also help assess the impact of the anchorage method on the flexural strength of the repaired girders, offering valuable insights into the performance of CFRP retrofitting under varying conditions.

**Lateral Static Failure Load of Prestressed Girders**

To compare the performance of the prestressed girders under static and dynamic loads, one girder was subjected to static lateral load. The girder ultimately failed at a peak lateral load of 22.1 kips, slightly above the calculated value of 21 kips. During the test, four prestressing strands yielded, and a plastic hinge formed at the mid-span loading point. Significant concrete loss occurred in both the top and bottom flanges, with up to 60% of the cross-sectional area compromised, particularly in the middle of the girder. The corresponding prestress loss was measured at 33%, further highlighting the severity of the damage.

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| A person standing next to a wall  Description automatically generated | A white rectangular object with wires and wires  Description automatically generated |

Figure 12. damage to girder subjected to static load

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Figure 13 Lateral static loading

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Figure 14. Concrete patching formwork of the laterally damaged girder