Guidelines for Adjacent Precast Concrete Box-Beam Bridge Systems: Addressing Performance of Shear Keys

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Adjacent precast concrete box-beam bridge systems offer an efficient solution for short-span bridges, particularly in cases where vertical clearance is a concern. These systems rely on load transfer between adjacent beams through grouted shear keys. However, a persistent challenge has been the cracking and subsequent leakage of these shear keys, which can lead to the corrosion of prestressing strands and reinforcing steel, ultimately compromising the bridge's structural integrity and service life. The National Cooperative Highway Research Program (NCHRP) Research Report 1026, *Guidelines for Adjacent Precast Concrete Box Beam Bridge Systems*,[1] provides a comprehensive investigation into this problem and proposes revised design and construction guidelines to enhance the performance of connections and extend bridge service lives. This article summarizes the key findings and recommendations of NCHRP Research Report 1026, offering valuable insights for structural engineers and transportation agencies.

Understanding Shear-Key Cracking

Previous research, summarized in the NCHRP Report, has shown that thermal movements are the primary cause of the cracking in shear-key joints. Live loads do not typically initiate cracks in intact shear keys, but they can cause existing temperature-induced cracks to propagate. The thermal gradient within the concrete beams, which is particularly pronounced over the top 4 in. due to solar heating, induces expansion-and-contraction cycles. Shear keys are often placed during the day when the beams are in an expanded state. After placement, as the temperature drops at night, the beams contract and tensile stresses develop within the shear-key material and at the interface with the beams. The literature review in the NCHRP report also indicates that cracking often occurs within the first few weeks after placing grout in the shear keys. The cracks initiate near the ends of the beams, possibly due to the restraint in the transverse direction offered by bearing pads.

The Research Approach

To investigate complexities of shear-key performance, the research team employed a twofold approach: detailed analytical modeling using finite element analysis (FEA), followed by full-scale testing.

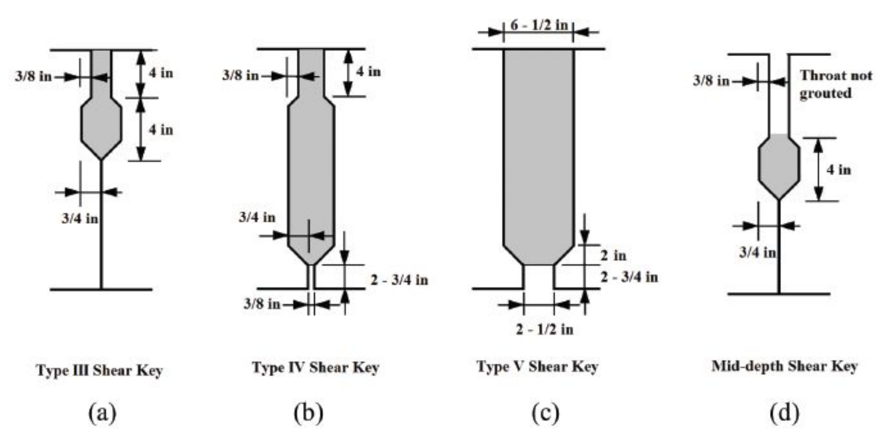
Analytical Modeling

The researchers developed three-dimensional FEA models to simulate the behavior of adjacent box-beam bridges under various loading and environmental conditions. These models incorporated various shear-key configurations, including the commonly used partial-depth Type III, the proposed full-depth Types IV and V, and a mid-depth key (**Fig. 1** and **2**). Other variables considered were span lengths, beam depths, skew angles, and deck types. The analysis assessed the stresses within the shear keys due to temperature changes, live loads (HL-93 truck loading), and lateral post-tensioning forces (varying from 93 to 106 ksi). The effect of reinforcement in shear keys was also investigated. Neither post-tensioning nor reinforcement in the shear keys contributed significantly to crack mitigation; therefore, these aspects of the study are not discussed in detail in this article. Detailed findings of the analytical investigation can be found in the full NCHRP research report.

Full-Scale Testing

Two full-scale bridge sections, each consisting of three beams and two shear-key joints, were constructed and tested in the laboratory (**Fig. 3**). These tests evaluated the performance of a narrow, full-depth (Type IV) shear key filled with either a standard nonshrink grout or a high-bond grout, and a wide, full-depth (Type V) shear key filled with small-aggregate concrete. The beams were preheated to simulate field temperature gradients before the shear keys were cast. The specimens were then subjected to 30 cycles of temperature

Figure 1. Shear-key configurations: typical shear key (a), and proposed shear-key configurations (b–d). All Photos and Figures from Miller et al.[1]



variation and 100,000 cycles of live-load application. Dye-penetration tests were conducted to assess leakage at various stages. Additionally, ASTM C1583[2] pull-off tests were performed to evaluate the bond strength between various shear-key materials and different beam surface preparations (smooth, exposed aggregate, sandblasted) under both dry and prewetted conditions.

Key Findings and Their Implications

The research yielded several significant findings that have direct implications for the design and construction of adjacent precast concrete box-beam bridge systems:

- **Temperature stresses dominate.** The FEA results demonstrated that temperature-induced stresses are significantly larger than those caused by live loads, confirming that temperature fluctuations are the primary driver of shear-key cracking.
- **Deeper shear keys perform better.** In both the analytical modeling and the full-scale testing, deeper shear keys—especially those that were full depth—performed better than traditional partial-depth shear keys. Full-depth shear keys provide a larger bonded area between the shear key material and the beam, and the FEA suggests that compressive stresses can develop at the bottom of these keys, potentially preventing full-depth crack propagation and leakage.
- **An "ungrouted top" helps prevent leakage.** Measurements of the thermal gradients in the beams, taken while the beams were stored in the fabricator's yard, confirmed that the thermal gradient shown in Article 3.12.3 of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[3] is reasonably accurate for box beams. There is a considerable temperature gradient over the top 4 in. of the beam when the top surface is heated by the sun but the face is shaded. A crucial finding was that stress in the area most susceptible to thermal gradients was significantly reduced when the top 4 in. of the shear key was not filled with grout. This approach, combined with a deeper shear key, moves the grouted area away from the region of highest thermal stress, and that reduces the overall tensile stress in the key and mitigates cracking. Full-scale tests confirmed the effectiveness of this detail in preventing leakage.
- **Bond plays a critical role.** The research demonstrated the importance of achieving a strong bond between the shear-key material and the beam

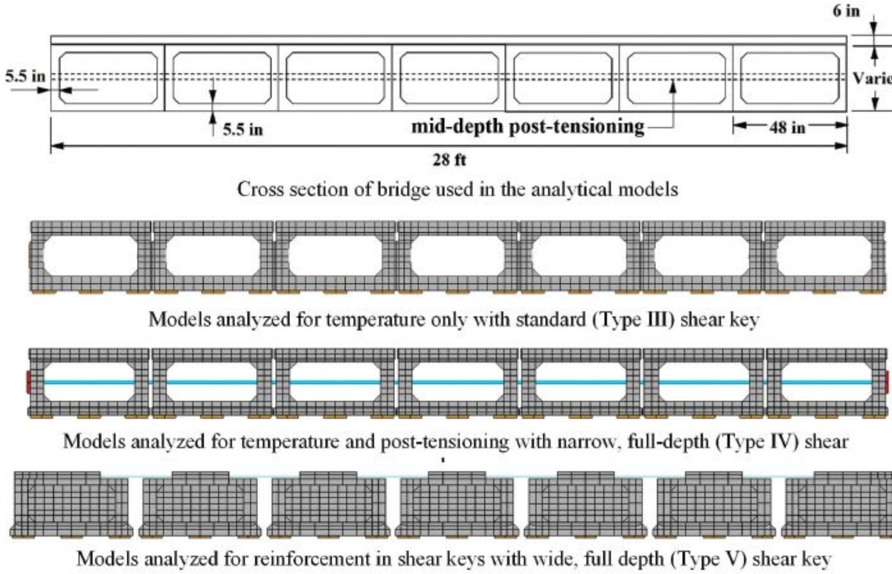


Figure 2. Cross sections of the adjacent precast concrete box-beam bridge models subjected to analytical testing.

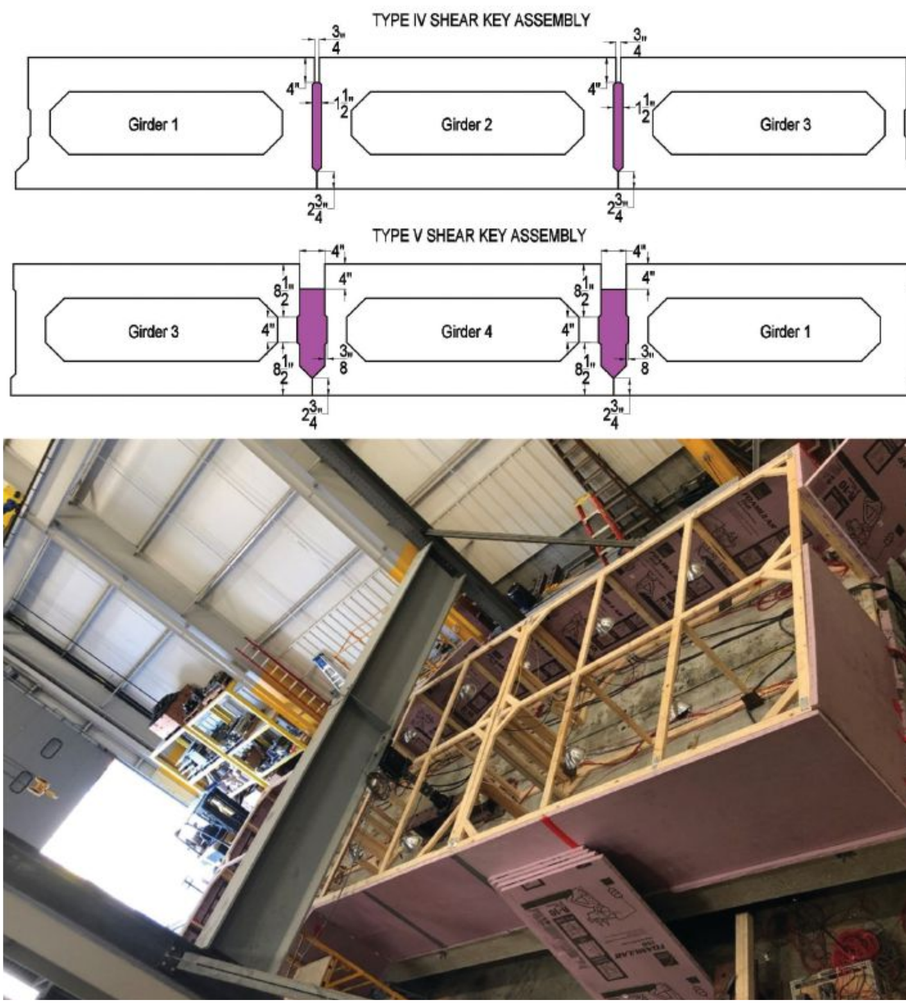


Figure 3. Test cross sections (top), and testing setup showing details of thermal loading (bottom). An insulated box with high-intensity heaters and heat lamps generated heat over a three-girder assembly. Thermocouples and vibrating wire strain gages were used to monitor thermal gradient and strain across shear keys.

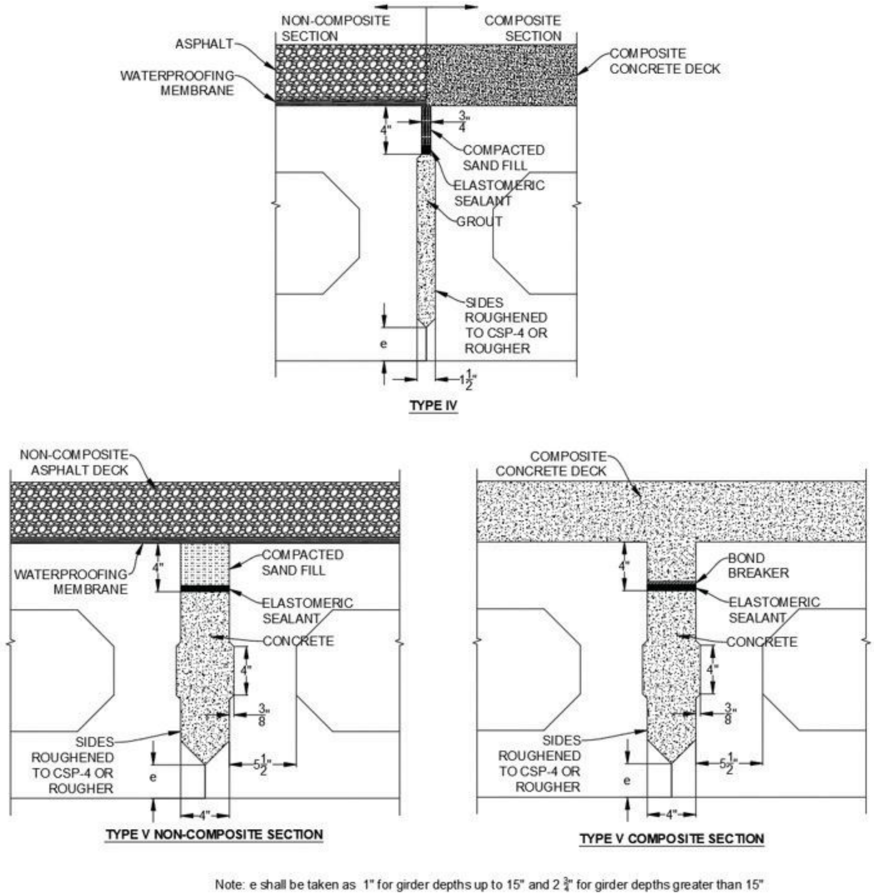


Figure 4. Shear-key configurations proposed as a result of analytical and experimental testing.

surface. Pull-off testing revealed that roughening the beam surface through sandblasting to a concrete surface profile (CSP) of at least 4 (as defined by the International Concrete Repair Institute[4]) or using an exposed-aggregate surface significantly enhances bond strength. Prewetting the beam surfaces before the shear-key material is placed also demonstrably improves bond. A minimum bond strength of 200 psi is recommended.

- **Material selection is key.** The full-scale tests highlighted the superior performance of a high-bond-strength, nonshrink grout in preventing leakage and achieving excellent bond. While a standard nonshrink grout and small-aggregate concrete also performed acceptably, the importance of using materials with high-bond properties and nonshrink characteristics is evident.

Recommendations for Implementation

Based on the comprehensive research findings, NCHRP Report 1026 proposes several key recommendations for the design and construction of adjacent precast concrete box-beam bridge systems:

- Adopt the deepest possible shear key and intentionally leave the top 4 in. ungrouted. This strategy maximizes the bonded area and minimizes stress concentrations in the critical thermal gradient zone. **Figure 4** presents proposed details for Type IV and Type V shear keys that incorporate this feature.
- Ensure that the beam surfaces that interface with the shear-key material are roughened to achieve a moderately roughened surface greater than or equal to CSP-4. Exposed-aggregate surfaces are also highly recommended, especially when the fill material is concrete. Prewetting the beam surface before the shear key material is placed also improves bond.
- Prioritize the use of high-bond-strength, nonshrink grout for filling shear keys. If concrete is used, incorporating a nonshrink additive is strongly advised. A minimum average bond strength of 200 psi—as demonstrated by ASTM C1583 pull-off testing—is suggested as a benchmark for acceptable performance.

Conclusion

NCHRP Research Report 1026 is a valuable contribution to the body of knowledge on adjacent precast concrete box-beam bridge systems. By investigating the causes of shear-key cracking and leakage through a combination of analytical modeling and full-scale testing, the research team developed evidence-based guidelines for improved design and construction practices. With an emphasis on deeper shear keys with ungrouted top regions, proper surface preparation, high-quality bonding materials, and the rational assessment of bond strength, the guidelines provide a clear path toward enhancing the durability and service life of these bridge systems. The findings strongly suggest that implementing these recommendations will substantially reduce shear-key cracking and leakage, ultimately contributing to a more durable bridge infrastructure.

References

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