Numerical Investigation and System-Level Resilience of Prestressed Concrete Girder Bridges in Overheight Truck Impacts

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Vehicle collisions into bridges remain a major concern for transportation infrastructure, as they often lead to costly repairs, traffic disruptions, and safety risks. The National Highway Traffic Safety Administration (NHTSA) reports that about 15,000 bridge collisions occur annually in the United States.[1,2] Overheight truck impacts on prestressed concrete girders are among the most critical of these incidents that can significantly weaken a bridge's structural integrity. Recent incidents of overheight vehicle impacts include the Lordsburg Bridge in New Mexico and the State Route 410 White River Bridge in Washington State, with both structures suffering major damage after being struck by overheight vehicles. The cost of repairing damaged structures can reach a substantial portion of the expense required for full replacement, creating a heavy financial burden for transportation agencies. With more than 600,000 bridges in the United States, developing reliable and economical methods for damage assessment and repair has become essential to maintaining a safe and resilient transportation network.

Despite advances in testing and simulation, there is no unified framework to evaluate impact-induced damage, quantify residual flexural strength, and guide repair decisions. To address that gap, investigators for the Transportation Pooled Fund TPF-5(462) study, *Assessment and Repair of Prestressed Bridge Girders Subjected to Over-Height Truck Impacts*,[3] used an integrated framework combining full-scale testing, finite element modeling, and repair evaluation to develop standardized procedures for assessing and repairing impacted girders. This article focuses on the analytical investigation of the TPF-5(462) study, whereas a future *ASPIRE*® article will present the experimental evaluation and repair of prestressed concrete girder bridges subjected to overheight truck impacts. The efforts of this study will provide a foundation for advancing concrete bridge stewardship, thereby enhancing safety and improving resilience across the nation's bridge network.

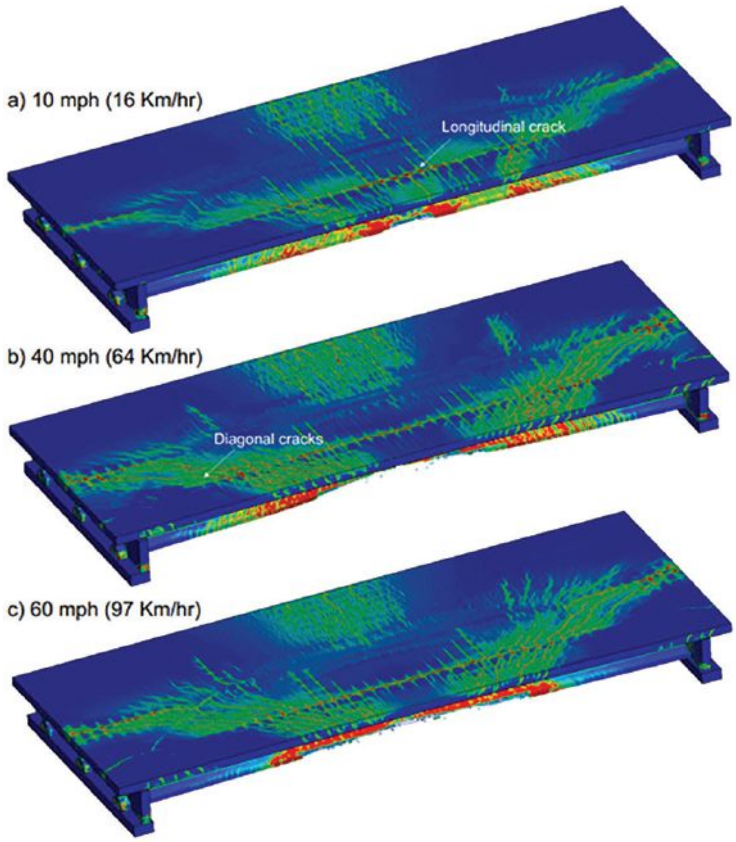
Modeling

The numerical modeling framework was developed with finite element modeling software using the nonlinear explicit analysis. Prestressed concrete girders, bridge decks, and diaphragms were modeled using a combination of solid, shell, and beam elements, whereas vehicle impacts were represented through moving rigid and deformable bodies, with impact-force transfer, through contact algorithms.

Four concrete constitutive models were evaluated: the continuous surface cap model (CSCM), Karagozian & Case concrete (KCC) model, Winfrith concrete model, and concrete damage plasticity model. Among these, the KCC and CSCM models were selected for most analyses because of their superior predictive accuracy and robust handling of strain-rate effects and element erosion. Both models captured triaxial concrete confinement, strain-rate sensitivity, and post-peak softening—features essential for simulating high-energy impacts. Material parameters were calibrated through laboratory compression and tension tests and benchmarked against established data in the literature.[4,5]

Both mild steel reinforcement and prestressing strands were modeled using plastic-kinematic formulations incorporating strain rate–dependent hardening. For the 270-ksi low-relaxation strands, stress-strain behavior was experimentally characterized through Split-Hopkinson tensile bar tests, which indicated a 5% to 15% increase in ultimate strength under impact strain rates. These findings

The experimental testing setup at Missouri University of Science and Technology. All Photos and Figures: Missouri University of Science and Technology.



Results of the finite element analyses illustrate the overall damage patterns of the prestressed concrete girder bridges when impacted at different speeds.

provide direct experimental validation for incorporating dynamic increase factors in both design assessment and numerical simulation.

Prestressing was introduced into the models using a thermal stress-relaxation procedure that accurately reproduced the initial pretensioning stresses and subsequent stress redistribution following impact. Bond-slip behavior was neglected in the localized region of impact, where damage and material degradation dominated the overall response.

Validation

Investigators conducted a comprehensive, multiscale validation program using laboratory and field data at the materials, component, and system levels.[3] At the materials level, the CSCM was validated against compression and impact tests on concrete cubes. The simulations reproduced the measured stress-strain response and strain-rate enhancement with close agreement, confirming the model's reliability for representing concrete behavior under dynamic loading.

Because full-scale dynamic impact tests of prestressed concrete girders are limited, component-level experimental validation used static four-point bending of prestressed concrete girders and drop-weight impact testing on reinforced concrete beams. Both the KCC and CSCM models accurately captured load-deflection behavior, crack development, and localized damage mechanisms, with peak responses deviating from experimental measurements by less than 10% to 12%.

At the system level, comparisons with full-scale bridge impact experiments conducted by the Iowa Department of Transportation[6] verified the accuracy of global load-sharing behavior, diaphragm action, and deck-girder interaction under impact loading. Furthermore, mesh-sensitivity analyses confirmed numerical convergence for 1- to 2-in. element sizes in critical regions while maintaining hourglass energy within acceptable limits. This comprehensive validation established a robust foundation for the parametric and analytical investigations.

Bridge Prototype Modeling and Scenarios

A comprehensive set of impact scenarios was analyzed using more than 100 models, covering vehicle speeds from 10 to 90 mph and impact weights between 4 and 80 kips. The study included three girder types—Missouri Department of Transportation (MoDOT) Type II, MoDOT Type VI, and Nebraska University (NU) 35—to capture the range of geometries commonly used in regional highway bridges.

The baseline bridge model consisted of a 45-ft-long, 54-in.-deep MoDOT Type II girder with a system-level configuration that included three girders spaced at 6 ft, an 8-in.-thick reinforced concrete composite deck, and reinforced concrete diaphragms and supporting elements to simulate realistic load-sharing and boundary conditions.

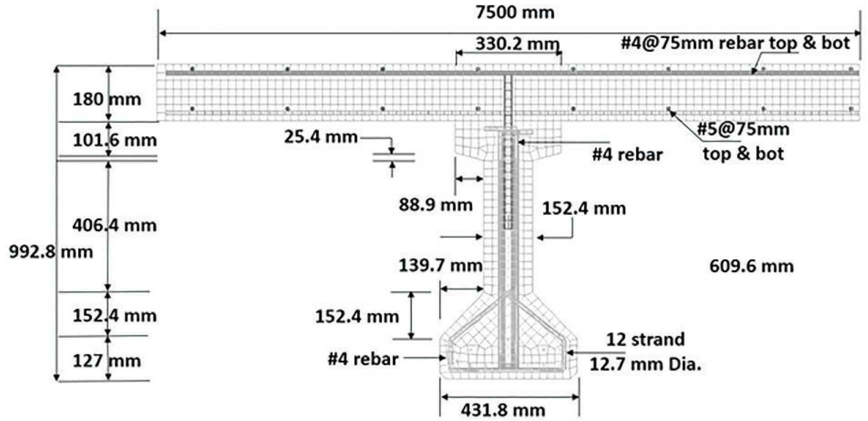
A standard tractor-trailer, with a gross vehicle weight ranging from 55 to 80 kips, was used to simulate impact events at various speeds and heights. To expand the parametric database, a simplified rigid-cylinder impactor was also used to isolate the influences of vehicle speed, mass, impact location, and diaphragm configuration.

Dynamic Response: Global versus Local Behavior

The finite element simulations revealed two distinct behavioral regimens:

- Low-velocity impacts (30 mph or lower): Global flexural and torsional

Structural damage induced on a model of a prestressed concrete bridge with a 2-in.-thick concrete deck by the impact of a tractor-trailer truck traveling at 80 mph (for illustration).



A comprehensive set of impact scenarios was analyzed using more than 100 models, covering various vehicle speeds, impact weights, girder types, and system configurations. This figure shows a Missouri Department of Transportation Type II girder used in the analysis models.

deformation dominated the response, with minimal concrete spalling or localized damage.

- High-velocity impacts (greater than 30 mph): Localized shear-plug formation, web crushing, and concrete fragmentation developed at the impact zone, leading to pronounced material degradation.

Peak simulated impact forces ranged from 170 to 341 kips, with up to 93% of the total kinetic energy dissipated within the impacted girder. This concentration of energy confirmed that localized repair strategies can be both effective and economical. Full-bridge models produced slightly higher peak forces than isolated girders—227 versus 201 kips—due to increased lateral stiffness and composite deck restraint. The collision duration in the full-bridge model was approximately four times longer, as impact energy propagated through diaphragms and adjacent girders.

At an impact velocity of 70 mph, damage maps indicated web shear fractures, bottom-flange spalling, and rupture of up to 20% of the prestressing strands. Erosion visualization closely matched the damage patterns documented in post-impact field inspections, validating the predictive capability of the numerical model.

Diaphragms and System Resilience

Based on the finite element analyses, intermediate diaphragms proved to be among the most effective design features for mitigating impact-induced damage.

- Reinforced concrete diaphragms reduced impact-induced lateral midspan deflection and cracking by approximately 25%.
- Steel-channel diaphragms provided comparable performance but exhibited localized yielding under severe impacts.
- Dual-diaphragm configurations positioned at one-third span locations offered an optimal balance of stiffness and energy dissipation for the 45-ft-long girder that was investigated.

Diaphragms also played a crucial role in redistributing impact energy across adjacent girders, reducing stress concentrations by nearly half and preserving partial load-carrying capacity even after localized damage. These results emphasize the importance of diaphragm installation, maintenance, and retrofit—particularly in regions where bridge strikes are frequent—to enhance overall system resilience and post-impact performance.

Equivalent Static Force: Simplifying Impact Loads

While detailed dynamic analyses are invaluable for research, bridge owners and transportation agencies often require simplified tools for rapid assessment of post-impact residual flexural strength. To address this need, the investigators developed an equivalent static force (ESF) method—a practical approach for representing transient impact loads with static forces that generate comparable structural effects.

A 25-millisecond moving-average filter was applied to the dynamic force–time histories to obtain ESF values. Across all nine scenarios, the mean ESF was approximately 128 kips (with a standard deviation of 25 kips), which is about 14% higher than the 112 kips specified in Table 4.2 of Eurocode EN-1991-1-7(2006)[7] for bridge impacts. This finding suggests that U.S. bridges, which are subjected to heavier truck loads and distinct clearance geometries, may require regionally calibrated ESF values to achieve accurate post-impact assessments.

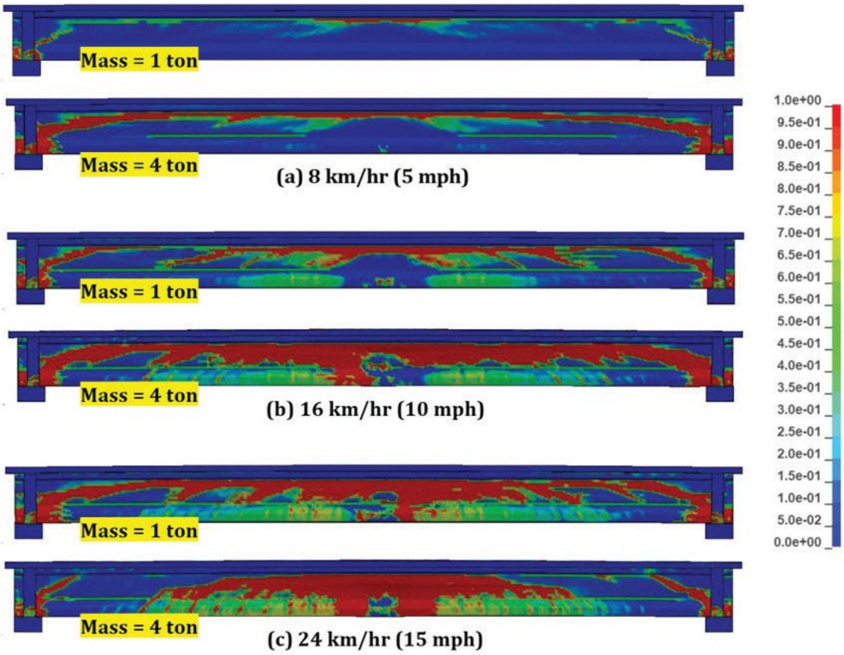
Residual Flexural Strength and Post-Impact Assessment

Beyond the immediate damage phase, the residual flexural strength of impacted girders is an essential consideration when determining whether a bridge can remain open to traffic. Analytical studies of a 120-ft-long AASHTO BT-72 girder with 48 prestressing strands quantified the effects of asymmetric strand rupture—a realistic condition when impacts sever strands on one side of the section.[3] The analyses considered various combinations of damage scenarios, including the loss of 12.5% to 50% of the number of prestressing strands and concrete section reductions up to 56%.

The results from the analysis of the BT-72 girder indicated the following:

- Flexural strength was reduced up to 60% for combined strand and concrete damage.
- Stiffness was reduced between 10% and 40%, and the ductility loss was between 20% and 45%.
- The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[8] overestimated residual flexural strength by 11% to 18% under asymmetric conditions.
- Biaxial effects caused by accidental lateral eccentricity reduced flexural capacity by approximately 15%.
- The live-load distribution factor of the interior girder increased by up to 27% under a 50% stiffness reduction in the exterior girder caused by strand loss and its asymmetric pattern.

Based on these findings, the following method is recommended to evaluate the residual flexural strength of impact-damaged girders. Design engineers should first calculate the flexural strength of the damaged girder using only the remaining undamaged prestressing strands. To account for the effects of asymmetry, biaxial bending, and residual stress redistribution resulting from strand loss, a residual-strength factor Ψ_{IM} of 0.85 should then be applied to this calculated strength.



Effective plastic damage patterns of the prestressed concrete girder bridges at different impact weights and speeds. Effective plastic strain values quantify the amount of plastic deformation that a material undergoes beyond its elastic limit under loading conditions.

Practical Implications and Concluding Remarks

The validated finite element analysis framework provides a design-ready basis for assessing and mitigating bridge impacts with engineering accuracy. Based on the results of this study, investigators recommend the following guidance for bridge engineers, owners, and asset managers:

- Assessment: Use a lateral ESF of approximately 128 kips to represent the static effect of the impact when evaluating prestressed concrete girders for rapid load posting and preliminary safety evaluations.
- Design: Beyond the factors prescribed in the AASHTO LRFD specifications, apply a residual-strength factor Ψ_{IM} = 0.85 to account for asymmetric strand rupture and biaxial interaction effects observed under impact conditions.
- Mitigation: Install or retrofit diaphragms to reduce lateral displacements by 10% to 70% and improve load redistribution.
- Inspection and policy: Incorporate nondestructive testing (for example, radar or ultrasonic methods) calibrated to numerical damage maps within risk-based inspection programs.
- Asset management: Because more than 90% of the impact energy is confined to the struck girder, targeted repair is typically more economical than full superstructure replacement.

Collectively, these findings advance concrete bridge stewardship by providing simplified yet robust tools for impact evaluation and post-event decision-making. The integration of ESF loading, Ψ_{IM} factor, and dynamic increase factors bridges the gap between high-fidelity modeling and practical field application.

A subsequent article in *ASPIRE* will present the experimental findings, including full-scale impact tests, post-repair performance, and the effectiveness of strengthening methods that use carbon-fiber-reinforced polymers.

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