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ABSTRACT

Highway bridges exposed to intentional or unintentional fire followed by combined vehicle impact and air blast are at risk of significant damage and, possibly, collapse. Limited studies examining complex effects of these extreme demands on bridge support elements and parametrizing their response and damage are found in the open literature. Research that is presented is part of an ongoing numerical investigation examining round, multi-column, reinforced concrete (RC), bridge pier behavior subject to multi-hazard scenarios involving fire, vehicle impact, and air blast. Detailed nonlinear finite element analysis models of single columns and multi-column piers supported by a pile foundation system were created using LS-DYNA. A unique multi-step modeling approach was developed to simulate their post fire vehicular impact and blast response and performance was assessed based on defined damage levels. Parametric studies were conducted to evaluate effects of various multi-hazard scenarios and on different multi-column pier configurations. The studies first examined pier behaviors under vehicle impact and blast, and then looked at the combined effects of fire followed by vehicle impact and blast on pier performance and robustness. The effectiveness with which select in-situ retrofit schemes mitigated damage were also investigated using the models by examining final failure modes. Model development steps will be summarized along with results from analyses from ongoing parametric and retrofit studies.

Keywords: Bridge, Pier, Modeling, Vehicle, Impact, Air, Blast, Fire, Retrofit, Rehabilitation, Multi-hazard

INTRODUCTION

Highway bridges can be subjected to extreme hazards independently or in combination, including earthquakes, tsunamis, and, as is the focus of the present research, vehicle collisions, air blasts, and fires. These multiple hazards have the possibility of causing significant damage and, potentially, collapse. While they are treated as rare events from a design and analysis perspective, several cases have been reported where bridge substructure units have been subjected to collisions, blasts, and fires, with some structures collapsing and others experiencing varying degrees of damage and surviving. Very few studies examining response of bridge support elements and systems to fire, impact, and air blast have been published. However, multiple experimental and numerical studies investigating behavior of bridge substructure units and bridge systems subjected to either vehicle impact or air blast are reported in the literature. Do et al. [1] investigated dynamic response of RC bridge columns under vehicle collisions using LS-DYNA. Heng et al. [2] parametrically evaluated RC bridge performance under heavy truck collisions using LS-DYNA. Air blast studies included experimental and finite element analyses of RC bridge columns by Williamson et al. [3] that identified damage mechanisms and failure modes and proposed a simplified method to predict blast effects on isolated columns. Yi et al. [4] used LS-DYNA to investigate performance of a three-span, RC highway bridge subjected to air blast. In addition, several research studies have examined the effect of fire on bridge response, with some focusing on fire independent of vehicle collisions [5, 6]. Studies have shown that elevated temperatures from fire mitigate dynamic increases in concrete strength encountered under high loading rates [7]. Although few studies examined performance of bridge structural elements under impact and blast coupled with fire could be located in the literature, studies of RC elements from other structural systems indicated that combined effects from these extreme demand combinations could lead to severe damage. Zhai et al. [8] investigated post-fire blast response of RC beams experimentally and numerically. Results indicated that longer fire durations resulted in more severe crack propagation and higher mid-span deflections. Kakogiannis et al. [9] examined behavior of RC hollow core slabs subjected to a post fire air blast event. Findings showed that dynamic deflections increased dramatically when the slabs were exposed to fire prior to blast. Ožbolt et al. [10] numerically studied response of RC slabs under fire and impact. Simulation results demonstrated that dynamic resistance reduced considerably for slabs subjected to fire prior to impact. Jin et al. [11] numerically examined behavior of thermally damaged RC slabs when subjected to an impact load. Again, fire duration was shown to be an essential contributor to both permanent deformations and failure modes. A study was conducted by Choi et al. [12] to numerically investigate the response of RC and prestressed concrete (PSC) wall panels under various combinations of fire, impact, and blast. Multi-step approach was utilized to simulate the structural response of the wall panels. In this approach, LS-DYNA was used initially to assess impact and blast performance, then MIDAS was used to conduct the subsequent thermal analyses. Modeling approach was validated against test results, and study findings demonstrated that PSC panels were more vulnerable to the imposed extreme demands due to the effects of prestressing forces.

Therefore, what is summarized herein focuses on investigating performance of multi-column piers under the multiple extreme demands involving fire, vehicle impact, and air blast. More specifically, the study first examined the dynamic response of multi-column piers under combined impact-blast loading and evaluated the effectiveness of in-situ retrofits for pier performance improvement. Based on these results, the study investigated the behaviors of the multi-column piers with one of the suppoting columns exposed to fire prior to vehicle impact and air blast, along with evaluation of multi-column pier damage intensity and robustness under these multi-hazard scenarios. Damage in the bridge pier were reported and results from investigations of FRP and polyurea retrofits were summarized.

FINITE ELEMENT MODEL

Pier geometry and design details

A four-column bridge pier obtained from a FHWA design example was used as the prototype unit for this portion of the study [13]. The pier was 6600 mm in height and 16500 mm wide. Four 1050-mm diameter circular columns with a height of 5400 mm spaced 4300 mm center-to-center supported the cap. The columns were reinforced using 18 No. 25 longitudinal bars (i.e., a 1% longitudinal reinforcement ratio) with transverse No. 10 bars spaced at 300 mm along the length of the pier cap. A foundation consisting of a 3600 mm wide, 3600 mm long, and 900 mm thick pile cap and eight piles supported the pier. The pile cap was reinforced using No. 10 bars spaced at 300 mm in each direction. The square supporting piles were 450 mm by 450 mm and 6000 mm long. The pier cap had a square cross section that was 1200 mm wide, 1200 mm deep, and 16500 mm long. Figure 1 depicts the pier LS-DYNA finite element model.

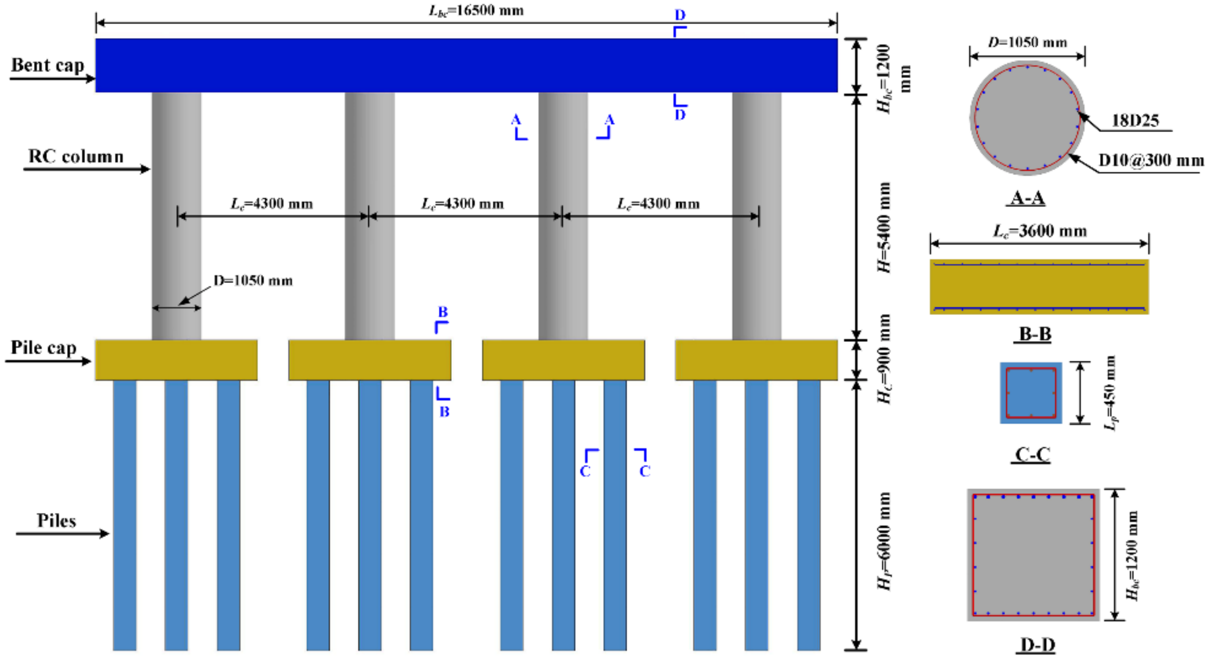


Figure 1. Geometry, LS-DYNA model, prototype four-column pier [13]

Model development

All concrete was modeled using Lagrangian meshes and eight-node, solid elements. LS-DYNA's *Mat CSCM Concrete* (Mat_159) constitutive model was used to represent response to vehicle impact and air blast. The compressive strength was set to 28 MPa, and the maximum aggregate size to 19 mm. Reinforcement was modeled using Lagrangian meshes using a Hughes-Liu beam element, with material response simulated using LS-DYNA's *Mat Piecewise Linear Plasticity* model (Mat_24). The yield strength was set to 475 MPa and Poisson's ratio to 0.3. Interaction between concrete and reinforcement was simulated using LS-DYNA's *Constrained Lagrange In Solid* algorithm.

The pier was subjected to simulated impacts from a single-unit truck (SUT) at assigned velocities, with the truck oriented as depicted in Figure 2. LS-DYNA's *Contact Automatic Surface to Surface* algorithm with a penalty-based formulation was used to simulate contact between the pier and SUT. LS-DYNA's *Multi-Material Arbitrary Lagrangian Eulerian* (MM-ALE) formulation was employed to simulate an air blast adjacent to the column in association with the impact. The blast, air, and soil were represented with ALE meshes using an eight-node solid element and a multi-material ALE formulation. The blast was modeled using LS-DYNA's *Mat High Explosive Burn* and the *JWL EOS* equation of state, and the air was represented as an ideal gas using LS-DYNA's null material model (*MAT_NULL*) and a linear EOS. Soil properties were simulated using LS-DYNA's *Mat FHWA Soil* model (*Mat_147*). More information on air and soil properties is provided elsewhere [14]. LS-DYNA's *Constrained Lagrange In Solid* algorithm with a penalty-based formulation was again utilized to simulate contact between the pier and air and between the foundation and soil.

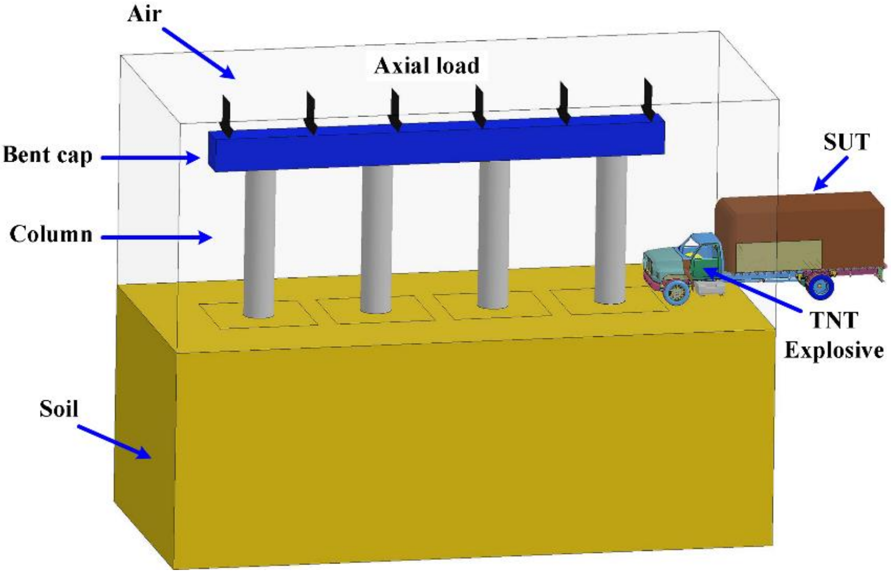


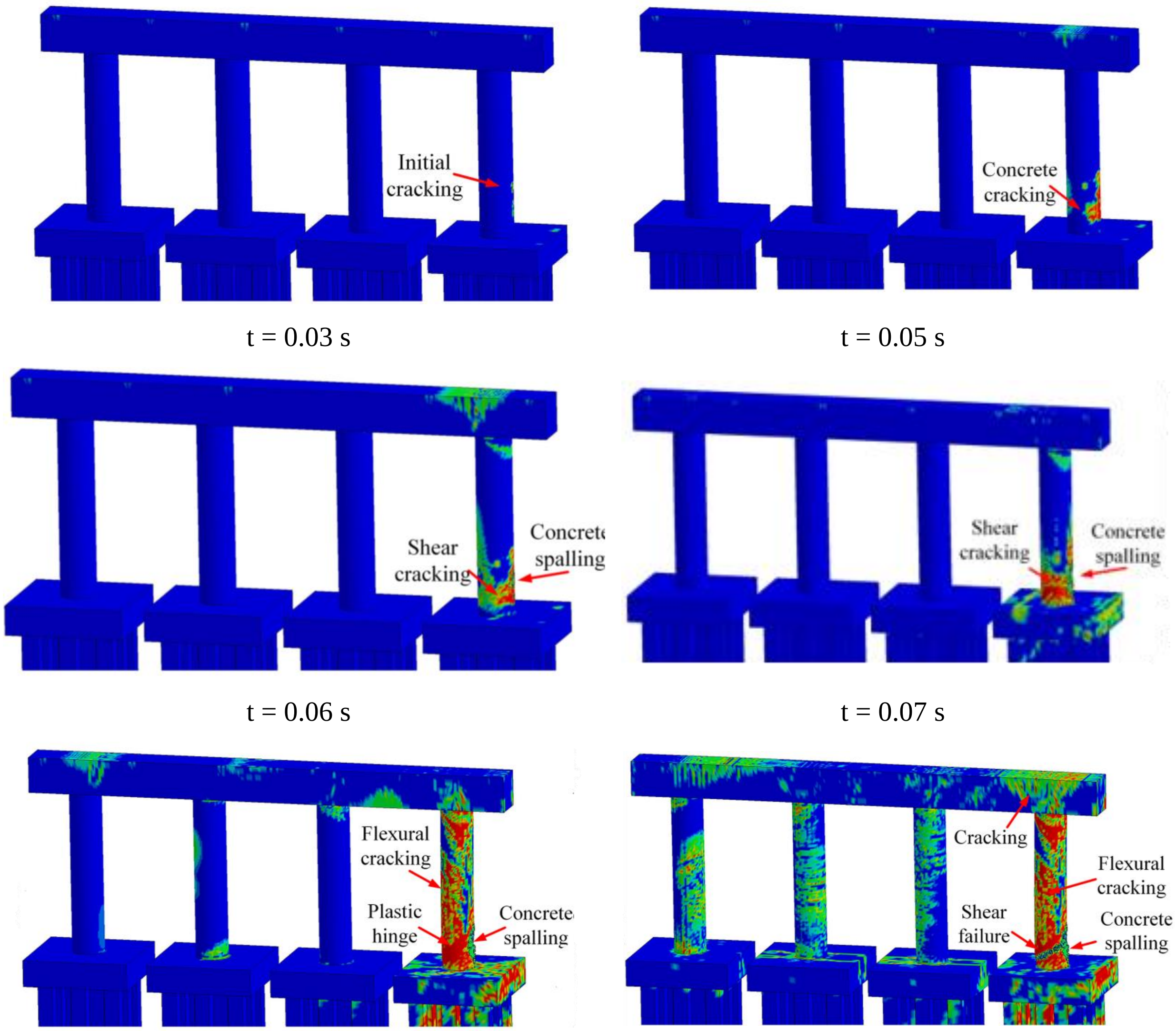
Figure 2. Model multi-hazard scenarios

Non-reflecting boundary conditions were defined along all sides using LS-DYNA's *Boundary Non_Reflecting* command to simulate infinite air and soil domains around the pier. Superstructure dead load was represented by an axial load at top of the pier whose magnitude equaled a total of 6% of nominal axial capacity for the columns. Simulation of the combined vehicle impact and air blast was conducted by: (1) applying an increasing axial load at the top of the bent cap to simulate the design dead load, (2) having the SUT impact the four-column pier as shown in Figure 2 at a specified speed, and (3) inducing air blast at a specified scaled distance.

BEHAVIOR OF BRIDGE PIERS UNDER COMBINED VEHICLE IMPACT AND BLAST

Impact and blast loading, pier response

Figure 3 depicts pier response at an impact speed of 95 km/h for a scaled distance of 0.25 $m/kg^{1/3}$. The pier was impacted by the SUT at t = 0.03 s, with initial cracking generated on the front (i.e., impact) face of the column. As the impact load increased, cracking propagated from the impact location along the impacted column height. At t = 0.06 s, the SUT engine hit the column and created maximum impact load, with a shear crack and spalling occurring at the impact location. As the air blast impinged upon the pier at t = 0.07 s, a shear crack was observed on the non-impact face of that column at its base, with additional concrete spalling at the impact location. At t = 0.08 s, the combined impact and blast energy produced severe concrete spalling and reinforcement buckling on the impacted face of the lead column with a plastic hinge forming at its base. Resulting column deformation produced cracking in the pier cap. At t = 0.095 s and as the blast wave engulfed the pier, the impacted column could not resist additional load and a shear crack developed in the pier cap above the column. The other columns remained largely intact throughout the rest of the event, which demonstrated the importance of the cap with respect to pier resiliency against collapse.



t = 0.03 s

t = 0.05 s

t = 0.06 s

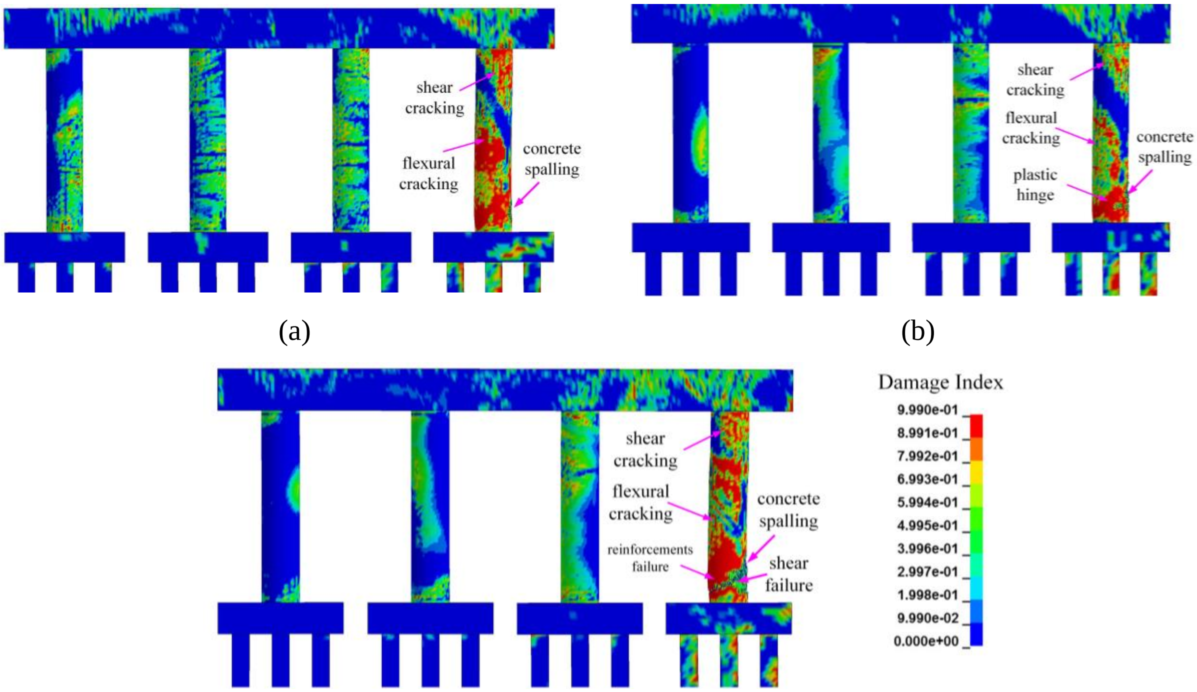
t = 0.07 s

t = 0.08 s

t = 0.10 s

Figure 3. Pier damage states under impact and blast load, v_0 – 95 km/h, Z – 0.25 kg/m$^{1/3}$

Figure 4 depicts final damage states to demonstrate pier performance at various multi-hazard demand levels. As demand increased, damage levels increased, as expected, to the point where the impacted column failed in shear as shown in Figure 4 (c). While damage to the pier cap and adjacent column also naturally increased, observed damage was never associated with pier collapse. While temporary measures could be taken that would allow for the pier to support some level of reduced bridge live load, in all cases extensive repair would certainly be needed to restore the pier to its original level of performance.



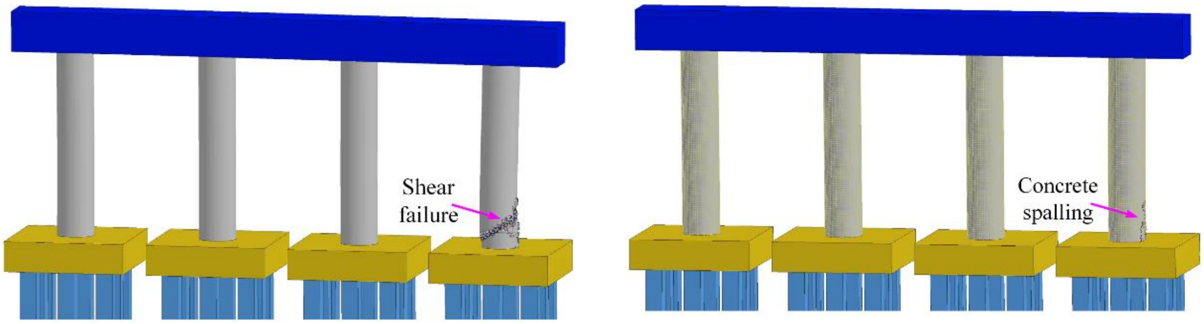
(a) (b)

(c)

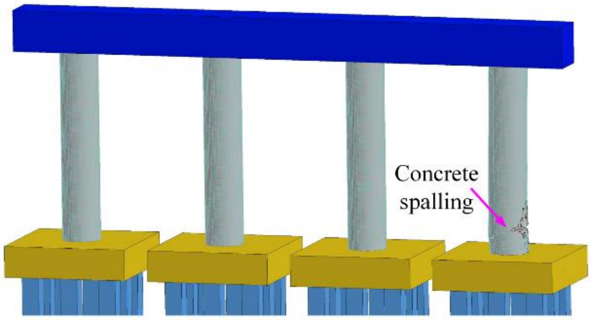
Figure 4. Pier damage: (a) v_0 – 65 km/h, Z – 0.25 kg/m$^{1/3}$; (b) v_0 – 95 km/h, Z – 0.30 kg/m$^{1/3}$; (c) v_0 – 120 km/h, Z – 0.25 kg/m$^{1/3}$

In-situ retrofits

Completed in-situ retrofit finite element studies examined use of fiber reinforced polymer (FRP) wraps and polyurea coatings on the pier columns. Both the FRP and polyurea were modeled using Belytschko-Tsay shell elements. Interaction between the coating and pier was modeled as adhesive contact using LS-DYNA's *Automatic Surface to Surface Tiebreak* command using the following failure parameters: (1) FRP, $NFLS_{FRP}$ = 32 MPa and $SFLS_{FRP}$ = 29.4 MPa; (2) polyurea, $NFLS_{POL}$ = 1.04 MPa and $SFLS_{POL}$ = 6.90 MPa [15]. Here *NFLS* and *SFLS* represent normal and shear failure limits, respectively. More information on FRP and polyurea material properties is located elsewhere [14, 16]. The current study examined FRP and polyurea applied around the periphery of all columns. Figure 5 depicts final damage states for uncoated and retrofitted piers subjected to 95 km/h SUT impact and air blast at a scaled distance of 0.25 m/kg$^{1/3}$. The modeled FRP thickness was 1 mm and the polyurea thickness 9 mm, with thicknesses selected so that column axial load capacity between the FRP wrap and polyurea coating were largely equal. Both FRP wrap and polyurea coating were observed to effectively mitigate pier damage, with the wrap providing more benefit based on the volume of spalled concrete.



(a) Bare pier (b) FRP wrapped pier



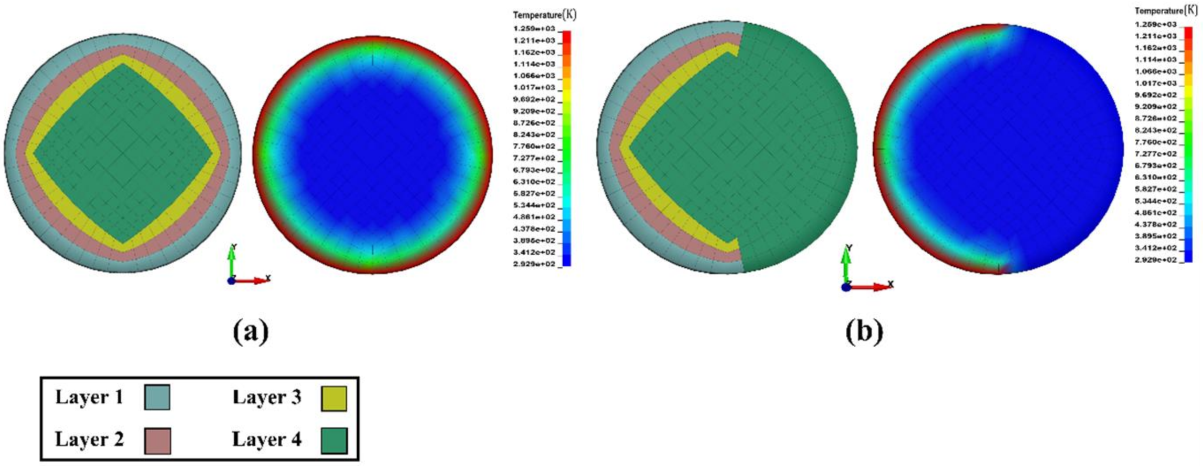
(c) Polyurea coated pier

Figure 5. Damage comparison, bare, wrapped, coated pier, v_0 – 95 km/h, Z – 0.25 kg/m$^{1/3}$

COMBINED EFFECTS OF FIRE, IMPACT, AND AIR BLAST

Modeling approach

To examine the combined effects of elevated temperatures from fire and high strain rates on pier column performance, a pier column was exposed to simulated fire prior to imposing vehicle impact and blast. A multi-step FE modeling approach is commonly used when examining response of structural elements under a combination of dynamic and static or quasi-static loads having different time scales [17]. To effectively address these three hazards, a unique two-step modeling approach that involved uncoupled implicit thermal analyses and explicit structural analyses was developed in LS-DYNA. First, three-dimensional heat transfer analyses of the four-column pier with one of the columns exposed to fire were completed. In this analysis stage, the impacted pier column was first subjected to various fire exposure conditions and durations, with variation of temperature over time being defined using ISO-834 standard fire curves [18]. Resulting temperature profiles through the cross section were employed to divide the column into layers, with each layer having reduced strength based on element maximum temperatures and corresponding unconfined compressive strength (f_c') reduction factors from Eurocode 2, *Design of Concrete Structures, Part 1-2 General Rules, Structural Fire Design* [19]. Representative temperature profiles and corresponding layers of the column are illustrated in Figure 6. LS-DYNA's *Interface Springback* [20] keyword was then employed so that resulting thermal stresses and strains and any element erosion, nodal constraints, and geometric imperfections caused by column fire exposure would be initial conditions for subsequent impact and blast explicit analyses. In the second stage, response of the pier with the fire damaged column was investigated under prescribed SUT impact speeds and blast scaled distances. Additional details on the proposed modeling technique, validation studies, and fire exposure scenarios can be found elsewhere [21].



(a)

(b)

Figure 6. Temperature profiles and corresponding column layers: (a) full surface area, 90-minute fire exposure; (b) half surface area, 90-minute fire exposure

Post-fire impact and blast performance

A representative thermal stress distribution resulting from a 90-minute fire exposure of the entire periphery of a single 1050 mm diameter column is depicted in Figure 7. This figure indicates that the fire damaged column experienced flexural-shear cracks along its height. Concrete surface cracks also initiated at the interface between pier columns and bent cap.

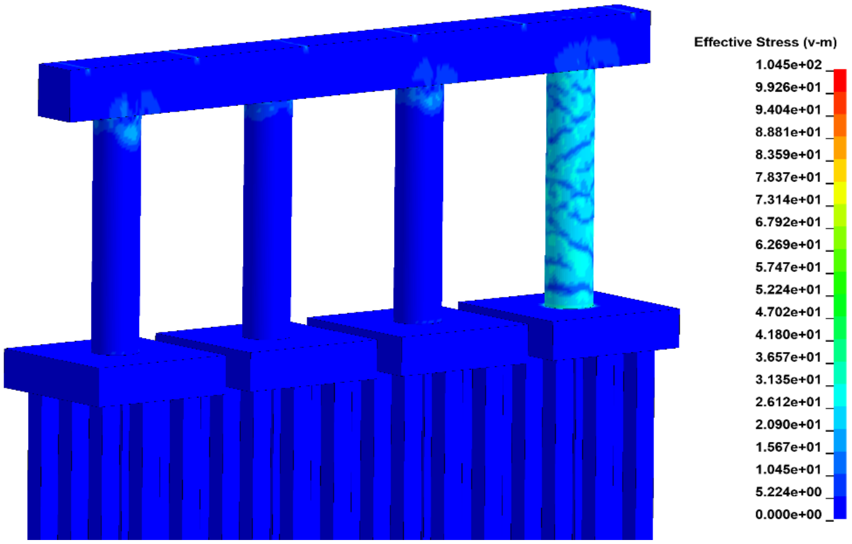
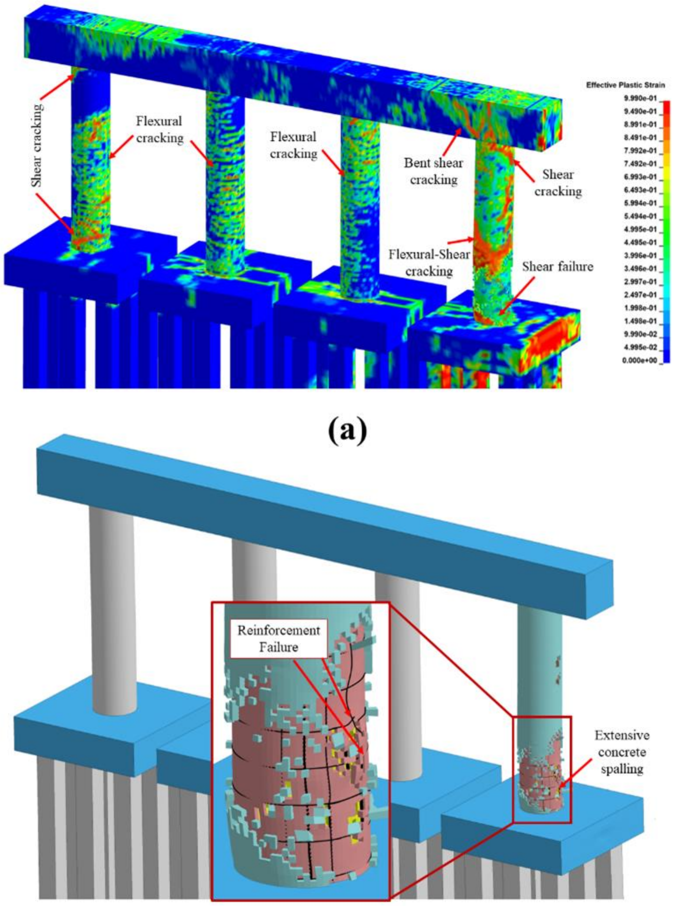


Figure 7. Effective thermal stress distribution, fire damaged column, 90-minute exposure, entire periphery

Figure 8 illustrates pier response and final damage state when the fire damaged column was then subjected to an SUT impact speed of 120 km/h and a blast scaled distance of 0.25 m/kg$^{1/3}$. The multi-hazard event produced extensive concrete cracking in all pier columns, with more critical cracking observed in the fire damaged column. Shear failure at the impacted column base was clear as two reinforcing bars fractured, significant flexural and shear cracks formed on the non-collision side, and concrete core breaching initiated. Additionally, extensive cracks occurred in the pile cap and piles below and pier cap above the impacted column. However, the other pier columns maintained sufficient integrity so that collapse was not expected.

The pier could potentially be repaired rather than replaced but more extensive studies are required to verify this conclusion. These studies are part of ongoing research. Compared to the case that involved solely impact and blast (Figure 4c), exposing the impacted column to fire prior to impact and blast resulted in more severe spalling more comprehensive flexural and shear cracking propagated along the height of the three non-impacted columns.



(a)

(b)

Figure 8. Pier damage: (a) Crack propagation; (b) Final damage state

CONCLUSIONS

The ongoing study summarized herein is computationally investigating round, multi-column, RC, bridge pier behavior under multi-hazard scenarios involving fire, vehicle impact, and air blast. Three-dimensional finite element models of a prototype four-column pier, including the foundation system and surrounding soil and air volumes, were developed in LS-DYNA. Pier performance and robustness was examined under multi-hazard scenarios, with vehicle impact and air blast being studied first followed by fire before impact and blast. Due to different time scales needed to effectively estimate fire effects verses blast and impact effects, multi-step, uncoupled heat transfer analyses were performed followed by explicit impact and blast analyses. LS-DYNA's *Interface Springback* keyword was employed so that thermal stresses, strains, and geometric imperfections from thermal analyses would be used as initial conditions for subsequent impact and blast analyses. To address concrete strength degradation caused by fire, resulting temperature profiles were utilized to divide the column into layers containing elements of similar temperature that were assigned a unique reduced strength.

The study found that:

1. (1) Damage to the impacted column increased with higher velocity and blast loads, as expected, but prototype pier collapse appeared unlikely for studied impact velocities and scaled distances.
2. (2) Pier resiliency to SUT impact and air blast appeared to improve with placement of FRP wrap or polyurea coating on all columns.
3. (3) The developed two-step modeling technique used to simulate could predict key thermal and structural response parameters.
4. (4) A bridge column previously exposed to fire and subsequently subjected to SUT impact and air blast suffered more extensive damage but did not appear to collapse.

Ongoing studies are being completed to:

1. (1) Investigate the feasibility of repairing fire damage columns to improve impact and blast performance.
2. (2) Evaluate the performance of bridge system under post and pre-fire impact and blast.
3. (3) Assess feasibility of the equivalent static force (ESF) analysis method recommended by the AASHTO-LRFD bridge design specifications.
4. (4) Recommend potential modifications to bridge design and analysis tools and criteria to incorporate effects of fire.

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REFERENCES

1. Do, T. V., Pham, T. M., and Hao, H. (2018) Dynamic responses and failure modes of bridge columns under vehicle collision. *Engineering Structures*, 156, 243-259.
2. Heng, K., Li, R., Li, Z., and Wu, H. (2021) Dynamic responses of highway bridge subjected to heavy truck impact. *Engineering structures*, 232, 111828.
3. Williamson, E. B., Bayrak, O., Davis, C., and Williams, G. D. (2011) Performance of bridge columns subjected to blast loads. I: Experimental program. *Journal of Bridge Engineering*, 16(6), 693-702.
4. Yi Z., Agrawal A., Ettouney, M., and Alampalli, S. (2013) Blast load effects on highway bridges. I: Modeling and blast load effects. *Journal of Bridge Engineering* 19: 04013023.
5. Kodur, V., Gu, L., Garlock, M.E.M. (2010) Review and assessment of fire hazard in bridges, Transp. Res. Rec. 2172: 23–29.
6. Wright, W., Lattimer, B., Woodworth, M., Nahid, M., and Sotelino, E. (2013). Highway bridge fire hazard assessment draft final report. Virginia Polytechnic Institute and State University, Blacksburg, VA.
7. Ruta, D. (2018) Numerical and experimental study of concrete structures exposed to impact and fire, Doctoral dissertation. University of Stuttgart, Stuttgart, Germany.

8. Zhai, C., Chen, L., Xiang, H., and Fang, Q. (2016). Experimental and numerical investigation into RC beams subjected to blast after exposure to fire. *International Journal of Impact Engineering*, 97, 29–45.
9. Kakogiannis, D., Pascualena, F., Reymen, B., Pyl, L., Ndambi, J. M., Segers, E., Lecompte, D., Vantomme, J., and Krauthammer, T. (2013). Blast performance of reinforced concrete hollow core slabs in combination with fire: Numerical and experimental assessment. *Fire Safety Journal*, 57, 69–82.
10. Ožbolt, J., Ruta, D., and Irhan, B. (2019). Numerical study of reinforced concrete slabs under extreme loading conditions: Impact and fire. *IOP Conference Series: Materials Science and Engineering*, 615, 012012.
11. Jin, L., Bai, J., Zhang, R., Li, L., and Du, X. (2021). Effect of elevated temperature on the low-velocity impact performances of reinforced concrete slabs. *International Journal of Impact Engineering*, 149, 103797.
12. Choi, S.J., Lee, S.W., and Kim, J.H.J. (2017). Impact or blast induced fire simulation of bi-directional PSC panel considering concrete confinement and spalling effect. *Engineering Structures*, *149*, 113–130.
13. Wassef W., Smith C., and Clancy C. (2003) Comprehensive design example for prestressed concrete (PSC) girder superstructure bridge with commentary. Washington, DC: US Government Printing Office: Federal Highway Administration.
14. Fang, C., Yosef, T.Y., Linzell, D.G., and Rasmussen, J.D. (2021). Computational modeling and dynamic response of highway bridge columns subjected to combined vehicle collision and air blast. *Engineering Failure Analysis*, 125, 105389.
15. Dinan R., Fisher J., and Hammons M.I. (2003) Failure mechanisms in unreinforced concrete masonry walls retrofitted with polymer coatings. Air Force Research Lab.
16. Fang, C., Linzell, D.G., Yosef, T.Y., and Rasmussen, J.D. (2022). Numerical Modeling and Performance Assessment of Bridge Column Strengthened by FRP and Polyurea under Combined Collision and Blast Loading. *Journal of Composites for Construction*, 26(2), 04022002.
17. Garlock, M., Paya-Zaforteza, I., Kodur, V., and Gu, L. (2012). Fire hazard in bridges: Review, assessment, and repair strategies. *Engineering structures*, 35, 89-98.
18. ISO 834 (1999). Fire resistance tests − elements of building construction, International Standard.
19. Eurocode 2, (2004). Eurocode 2: Design of concrete structures − Part 1-2: General rules − Structural fire design.
20. Hallquist, J.O. (2014). LS-DYNA® keyword user’s manual, LS-DYNA 10.1, Livermore Software Technology Corporation.
21. Alomari, Q. A., and Linzell, D. G. (2022). Bridge pier column multi-hazard response – fire, impact, and blast. *Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability*: pp. 2276–2284.