International Journal of Railway Research, Vol. 12, No. 1, (2025), 34-39

Iran University of Science and Technology

International Journal of

Railway Research

ISSN: 2423-3838

Dynamic Behavior Assessment of a Railway Bridge in Isfahan under Over-Height Vehicle Collision Loads and Proposing Maintenance Strategies to Enhance Its Performance

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ARTICLE INFO

Article history:

Received: 20.04.2025

Accepted: 20.05.2025

Published: 29.06.2025

Keywords:

Over-height vehicle collision

Bridge retrofitting and repair methods

Finite element method

Aluminum sheets

Vibration-absorbing materials

ABSTRACT

In recent years, collisions between over-height road vehicles and railway bridge superstructures have become increasingly common, especially in urban areas, compromising structural safety and traffic flow. For instance, in Beijing, approximately 50% of bridges are exposed to impact loads, with around 20% of these impacts resulting from truck tops striking bridge superstructures, leading to damage to girders and concrete decks. In Iran, similar incidents have caused severe structural damage to railway bridges, creating uncertainties in bridge serviceability, operational safety, and in some cases, line closures. This study investigates the dynamic behavior of a railway bridge located in the Badrud–Spidan region of Isfahan under the impact of a truck top colliding with its superstructure. A three-dimensional finite element model of the bridge and the impact load was developed using ABAQUS software. The collision force was simulated as a time-dependent impulsive load applied at mid-span. The dynamic responses analyzed include displacement and acceleration time-history diagrams of the main structural elements such as girders and flat concrete slabs. The results indicate that applying honeycomb-structured aluminum sheets along the impact zone on the concrete girders significantly mitigates impact severity. Moreover, using vibration-absorbing materials to dampen responses and reduce damage to the structural components is shown to be highly effective.

1. Introduction

Frequent collisions between over-height heavy vehicles and railway bridges in Iran have led to severe structural damage and operational uncertainties, including limited usability, increased need for rehabilitation, and potential service disruption. As of 2022, over 1,140 railway bridges intersect with roadways in various regions of Iran, with a significant proportion of them (more than 89%) being concrete structures. Failure in even a small segment of a bridge often results in complete shutdown of the rail line. This paper focuses on a case study involving a railway bridge located in the Badrud–Spidan region of Isfahan that suffered major damage due to such an impact. The study aims to model and analyze the dynamic response of the bridge and to propose effective maintenance and repair strategies.

2. Approach

A three-dimensional finite element model of the railway bridge at kilometer marker 376+586 on the Badrud–Spidan line was developed using

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ABAQUS software. Figure 1 illustrates the damaged bridge caused by vehicle collision. Table 1 provides the geometric details of the bridge.

Figure 1. Railway bridge at kilometer 376+586 m subjected to over-height vehicle collision

Table 1. Geometric Specifications of the railway bridge located in the Badrud–Spidan region of Isfahan

Parameter	Value
Number of spans	1
Span length	10 m
Bridge width	4.6 m
Material type	Concrete

The track system is modeled as a ballasted single-track configuration, including rails, sleepers, ballast, and fasteners. The mechanical and geometric properties of the components are summarized in Table 2.

Table 2. Mechanical and Geometrical Properties of the Finite Element Railway Track Model

Track component	Parameter	Value
Rail	Elastic modulus	30.55 GPa
Rail	Cross-section length	10 m
Rail	Cross-section width	4.6 m
Rail	Height	180 mm
Rail	Moment of inertia	30.55×10^6 mm⁴
Rail	Density	7850 kg/m³
Sleeper	Elastic modulus	26 MPa
Sleeper	Dimensions (L×W×H)	2600 × 220 × 230 mm
Sleeper	Poisson's ratio	0.20
Ballast	Elastic modulus	350 MPa
Ballast	Cross-section height	750 mm
Ballast	Density	1400 kg/m³
Ballast	Poisson's ratio	0.25
Rail Pad	Vertical stiffness	240000 kN/m
Rail Pad	Lateral stiffness	24000 kN/m
Fasteners	Vertical damping	248 kN·m/s
Fasteners	Lateral damping	248 kN·m/s

The impact load from the truck top is modeled as a dynamic impulse force based on the study by Oppong et al. (2021), peaking at 8,700 kN with a duration of 3 milliseconds. Figure 2 shows the impulse load profile.

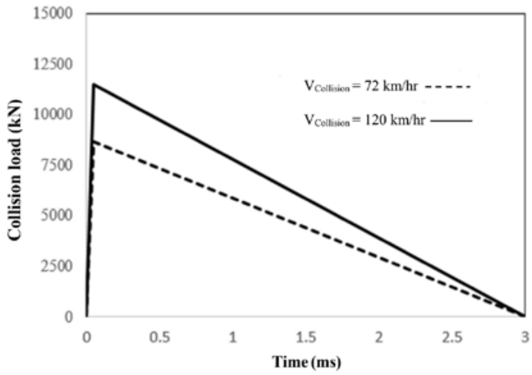

Figure 2. Collision load profile applied to the bottom of the concrete girder

Boundary conditions include fixed translational degrees of freedom at both ends of the bridge and rail model. Figure 3 depicts the 3D finite element model including the impact location and boundary conditions. Figure 4 shows the mesh configuration with an optimal mesh size of 0.2 m.

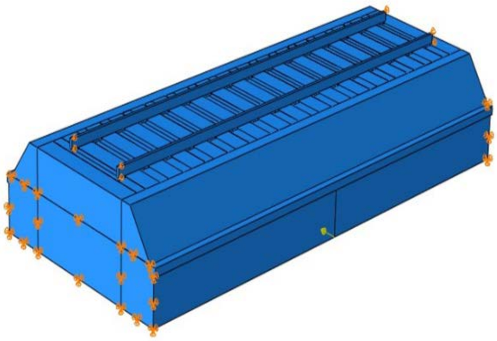

Figure 3. 3D finite element model of the bridge with impact load applied at mid-span

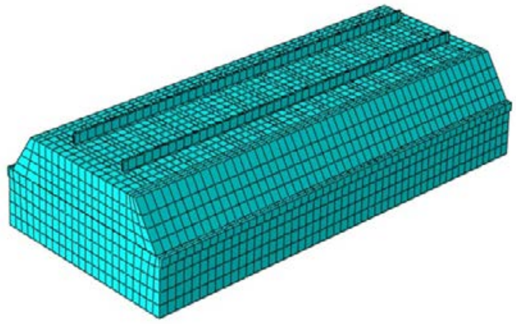

Figure 4. Mesh configuration of the finite element model under mid-span impact load

3. Results and Analysis

The results include vertical and lateral displacement graphs (Figures 5 and 6), and time-history graphs of displacements and accelerations (Figures 7 through 9).

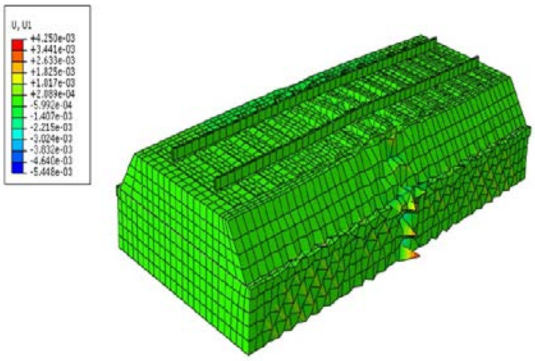

Figure 5. Lateral deformation graph of the railway bridge deck under mid-span impact load

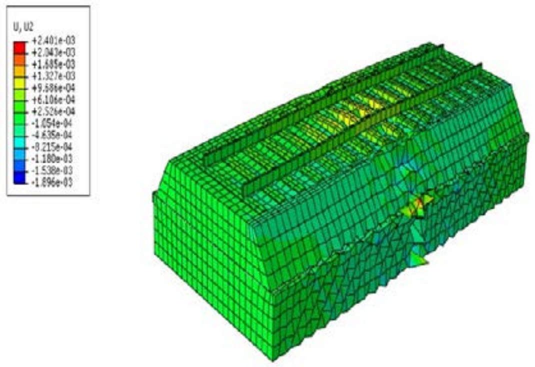

Figure 6. Vertical deformation graph of the railway bridge deck under mid-span impact load

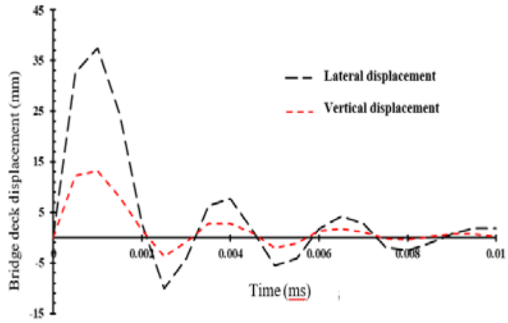

Figure 7. The bridge deck vertical and lateral displacement time history under collision load

According to Figure 7, the maximum lateral and vertical displacements of the bridge deck at the point of collision (mid-span) are approximately 37.45 mm and 13.15 mm, respectively. The magnitude of the impact force applied to the railway bridge superstructure is 8700 kN, and the duration of the applied load, as previously mentioned, is 3 milliseconds.

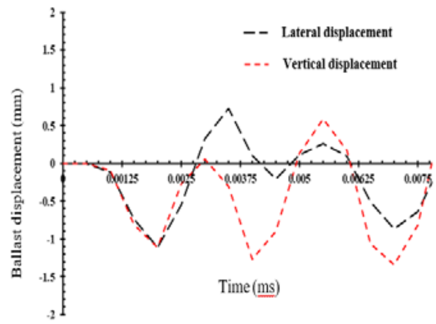

Figure 8. The ballast vertical and lateral displacement time history under collision load

According to Figure 8, the maximum lateral and vertical displacements of the ballast mass at the mid-span of the bridge, under the impact load applied to the underside of the deck, are approximately 1.0 mm and 1.3 mm, respectively.

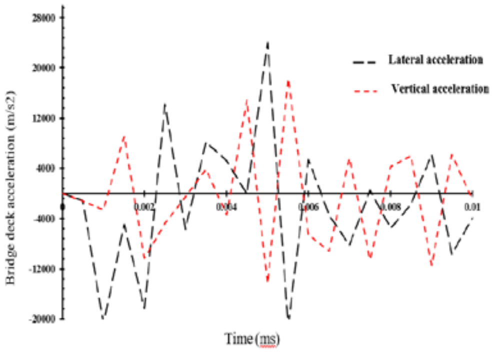

Figure 9. The bridge deck vertical and lateral acceleration time history under collision load

According to Figure 9, due to the high intensity of the impact load applied to the bridge deck, its extremely short duration, and the impulsive nature of the force, the vertical and lateral acceleration values are significantly high. The peak lateral and vertical accelerations are approximately 2600 g and 1500 g, respectively. It is worth noting that, in order to enhance the accuracy of the modeling process, all of these time-history diagrams were obtained considering vertical and lateral bridge–track interaction, implemented through spring and damping elements in the finite element model.

4. Maintenance and Repair Strategies

This section examines various strategies for maintaining and rehabilitating railway bridges subjected to over-height vehicle impact loads. The objective is to implement: 1. Preventive Measures, 2. Retrofitting Techniques, and Post-Damage Rehabilitation methods to prevent future impacts, minimize reconstruction and maintenance costs, and avoid speed reductions or line closures caused by safety concerns over damaged structures. Figure 10 illustrates a preventive system implemented in countries like the United States and Australia, using traffic signs, surveillance cameras, and laser scanners to alert road vehicle drivers at a designated distance from the railway bridge.

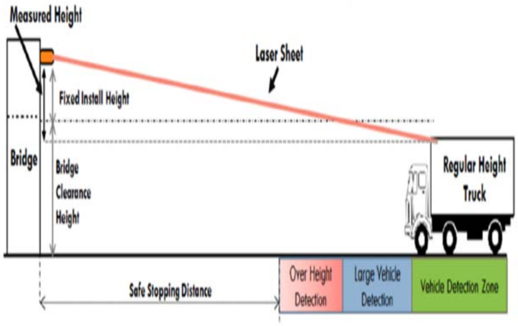

Figure 10. Use of laser scanners, traffic signage, and surveillance systems to alert

Figure 11 shows a railway bridge in Georgia, USA, previously exposed to over-height vehicle collisions. Steel deflector beams were installed between the abutments and below the girders to effectively increase the clearance envelope and reduce the probability of impact.

Figure 11. Use of steel deflector beams to increase clearance and mitigate collision risk

Both strategies illustrated in Figures 10 and 11 are categorized as preventive methods aimed at avoiding collision incidents. However, in some cases, collisions between road vehicles and the superstructure of railway bridges are unavoidable. In such situations, various retrofitting and damage repair techniques are required, some of which are discussed in the following sections of this study. Figure 12 illustrates the application of double-layer honeycomb aluminum sheets with varying densities along the collision zone, particularly in concrete bridges. This configuration effectively dissipates impact energy.

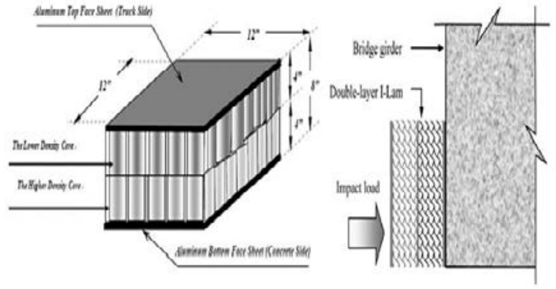

Figure 12. Application of honeycomb-structured aluminum sheets with dual-density layers along impact zones

Analyses indicate that in the case study bridge in Badrud–Spidan, this approach reduced maximum lateral displacements by approximately 40–50%. Figure 13 demonstrates the use of Energy Absorbing Materials (EAM), such as polyurethane foams, installed in the superstructure areas vulnerable to truck-top collisions. This method reduces structural vibrations and mitigates damage.

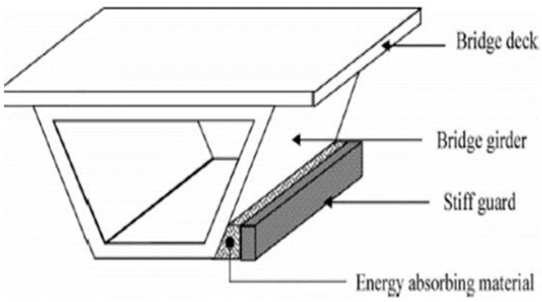

Figure 13. Application of EAMs (e.g., polyurethane foam) to dampen vibrations and minimize structural damage

Studies show that this solution can reduce localized deformation and deep cracking in the superstructure by up to 50–60%. Figure 14 presents reinforcement techniques applied after collision events, including metal jackets, polymer coatings, and Fiber Reinforced Polymer (FRP) sheets installed in vulnerable girder and deck zones.

Figure 14. Post-collision application of steel jackets, polymer coatings, and FRP sheets on concrete girders and decks

5. Conclusions

In this study, the dynamic behavior of a railway bridge located in the Badrud–Spidan region of Isfahan, Iran, under the impact load resulting from a truck top colliding with its superstructure was investigated. A three-dimensional finite element model of the bridge–track interaction system was developed using ABAQUS software, considering both vertical and lateral interactions. Time-history diagrams of acceleration and displacement—both vertical and lateral—were generated for key structural elements, such as the bridge deck and ballast. The results revealed that the maximum lateral and vertical displacements of the bridge deck at the impact location (mid-span) were approximately 37.45 mm and 13.15 mm, respectively. For the ballast mass, the corresponding maximum displacements were 1.0 mm laterally and 1.3 mm vertically. Subsequently, various strategies for preventive maintenance, retrofitting, and post-impact repair were reviewed to address bridge performance under over-height vehicle collisions. The authors' analysis of the bridge–track interaction model demonstrated that the use of honeycomb-structured aluminum sheets with varying densities along the impact zone, as well as vibration-absorbing materials such as polyurethane foam, can significantly reduce the peak dynamic responses and deformation at the contact location with the truck top.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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