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FORENSIC IDENTIFICATION OF THE VEHICLE IMPACT THAT LED TO THE COLLAPSE OF THE BUSUI BRIDGE STRUCTURE

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Abstract: *This research presents a comprehensive forensic investigation into the structural failure of the Busui Bridge, a steel truss bridge in Kalimantan, Indonesia, following a catastrophic collision with a heavy vehicle. The study combines an on-site forensic audit with a simplified Finite Element Method (FEM) simulation to analyze the failure mechanism. This analysis evaluates the structural integrity of a steel truss bridge using stress data from a provided image. The maximum longitudinal stress value of 3.402×10 kN/m², which converts to 340.2 MPa, was compared against the specified properties of BJ 37 steel, namely the yield strength (f_y) of 240 MPa and the ultimate tensile strength (f_u) of 370 MPa. The results unequivocally demonstrate that the applied stress has exceeded the material's yield strength. This indicates that the bridge has entered the plastic deformation range, resulting in permanent, irreversible damage to its members and a severe compromise of its overall structural integrity. The bridge is therefore determined to be in an unsafe condition and no longer fit for its intended use.*

Keyword- Busui, Bridge, Collapse, FEM, Stress

Abstrak: Penelitian ini menyajikan penyelidikan forensik komprehensif terhadap kegagalan struktural Jembatan Busui, sebuah jembatan baja rangka di Kalimantan, Indonesia, setelah tabrakan fatal dengan kendaraan berat. Studi ini menggabungkan audit forensik di lokasi dengan simulasi Metode Elemen Hingga (FEM) yang disederhanakan untuk menganalisis mekanisme kegagalan. Analisis ini mengevaluasi integritas struktural jembatan baja rangka menggunakan data tegangan dari gambar yang disediakan. Nilai tegangan longitudinal maksimum sebesar 3.402×10 kN/m², yang setara dengan 340.2 MPa, dibandingkan dengan sifat-sifat baja BJ 37 yang ditentukan, yaitu kekuatan leleh (fy) sebesar 240 MPa dan kekuatan tarik ultimate (fu) sebesar 370 MPa. Hasilnya secara tegas menunjukkan bahwa tegangan yang diterapkan telah melebihi kekuatan leleh material. Hal ini menunjukkan bahwa jembatan telah memasuki rentang deformasi plastik, menyebabkan kerusakan permanen dan tidak dapat dibalikkan pada anggotanya serta penurunan serius pada integritas strukturalnya secara keseluruhan. Jembatan tersebut oleh karena itu dinyatakan dalam kondisi tidak aman dan tidak lagi layak untuk penggunaan yang dimaksudkan.

Kata Kunci – Busui, FEM, Jembatan, Runtuh, Tegangan

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INTRODUCTION

Civil infrastructure, particularly the intricate network of bridges, serves as the lifeblood of modern societies, facilitating economic activity, transportation, and community connectivity. However, the integrity and safety of these structures face persistent threats from a variety of factors, including age-related deterioration, natural disasters, and unexpected extreme events such as vehicular collisions. The increasing frequency of such incidents underscores a critical need for robust methodologies to not only assess damage but also to understand the fundamental mechanics of failure. In this context, forensic engineering has emerged as a crucial discipline, applying scientific and engineering principles to systematically investigate failures, determine root causes, and provide recommendations to prevent similar catastrophes in the future. The systematic collection of quantitative data from these events is vital for the development of new design standards and the improvement of reliability models for aging infrastructure (Cakir & Ulker, 2017; L. Chen et al., 2019; W. F. Chen et al., 2021a, 2021b; X. Chen et al., 2012a, 2012b; Y. Chen & Dong, 2019; Dai et al., 2020; Fakharifar et al., 2016; Gao et al., 2024a, 2024b; Liu et al., 2019; Milić et al., 2020; Reddit, 2023; Silva & Vasanelli, 2024; Usman et al., 2019; X. Zhang et al., 2022).

Figure 1. Sei Busui bridge layout

The Busui Bridge incident represents a compelling and illustrative case study of a bridge failure triggered by a seemingly common traffic accident. The sudden and complete collapse of the superstructure, while the underlying abutments remained intact, presents a clear disconnect between the magnitude of the initiating event and the severity of the structural outcome. This disproportionate failure mechanism warrants a detailed investigation that moves beyond a simple visual observation of the damage. The central problem to be addressed is to identify the specific mechanical and physical processes that translated a vehicular impact into a catastrophic structural collapse. Understanding this sequence of events is crucial for informing future risk mitigation strategies for similar structures.

This investigation seeks to provide an expert-level analysis of the Busui Bridge failure, with objectives that include systematically documenting the findings of the on-site forensic structural audit by detailing both the pre-incident condition and the observed post-incident damage, performing a simplified Finite Element Method (FEM) analysis of the vehicle-bridge interaction to quantify the dynamic impact forces and their distribution across the structure, determining the specific failure mechanism and identifying the root cause of the disproportionate collapse through correlation of physical evidence with analytical results, and evaluating the proposed two-phase remediation plan—consisting of a temporary Bailey bridge followed by a permanent truss replacement—within the context of established civil engineering best practices for emergency response and long-term infrastructure investment.

METHOD

Forensic structural engineering is the application of engineering principles to analyze structural failures and accidents, with the goal of determining their root cause. The methodology for such an investigation is multi-faceted and rigorous. It typically begins with a thorough on-site investigation that includes the collection of physical evidence, photographic documentation, and a detailed visual inspection of the structure and its components. This is often followed by non-destructive testing (NDT) techniques, such as ultrasonic testing or radiography, to detect internal defects or material degradation that may not be apparent on the surface. Analysis of the collected evidence also includes a review of all available design documents, inspection records, and maintenance histories to identify potential pre-existing conditions or oversights. A key challenge highlighted in the literature is the need for quantitative data from failure events to inform the development of more resilient design standards. Such studies are essential for improving bridge management systems and for formulating reliability-based design limit states that account for extreme hazard events.

Finite Element Modeling of Vehicle-Bridge Interaction. Computational mechanics, particularly the Finite Element Method (FEM), has become an indispensable tool in modern civil engineering for analyzing the complex dynamic interaction between vehicles and bridges. Commercial software such as LISA FEA is frequently employed to simulate these dynamic impact events, providing a detailed understanding of a bridge's response to an extreme load. Research has identified several key parameters that significantly influence the dynamic response of a bridge, including the mass and velocity of the colliding vehicle, the lateral stiffness and mass of the bridge deck, and the contact compliance at the point of impact (Aco Wahyudi Efendi et al., 2024; L. Chen et al., 2019; Deng et al., 2019; Efendi & Weijia, 2023; Li et al., 2010; Palli et al., 2018; Sharma et al., 2018; Singh & Harsha, 2018; Z. Wang et al., 2020; H. Zhang et al., 2020).

The development of these FEM models requires meticulous attention to detail, from the representation of the vehicle's suspension systems and pneumatic tires to the geometric and material properties of the bridge structure. The models are validated through comparison with real-world experimental data, such as field tests where instrumented trucks are driven across a bridge, and the resulting displacements, strains, and accelerations are recorded. The strong correlation between numerical results and experimental data confirms the potential of this methodology for a thorough investigation of vehicle-bridge interaction, dynamic impact factors, and the ultimate loading capacity of bridges. This approach allows engineers to analyze failure mechanisms under conditions that would be impractical or unsafe to replicate in the field.

Common Failure Modes of Truss Bridges. Truss bridges are a class of structures known for their efficiency in spanning long distances by distributing forces through a network of connected triangular members. These members primarily carry axial loads, either in tension or compression. However, the stability and integrity of the entire structure are critically dependent on the integrity of its joints, which are typically reinforced by gusset plates. Gusset plates are flat metal plates that connect multiple members at a single joint, ensuring that stress is evenly spread and not concentrated at a single point plates (Cakir & Ulker, 2017; Qasim & Al-Hassani, 2018; Suleiman & Taha, 2022; Tao et al., 2018; Usman et al., 2019; Venglár et al., 2018; Venglár & Lamperová, 2021; G. X. Wang & Ding, 2019; Yilmaz et al., 2022).

A significant vulnerability in many older truss bridge designs is the lack of structural redundancy. A "fracture-critical" member is one whose failure could lead to the collapse of the entire bridge span. Gusset plates are often considered critical, non-redundant components. When subjected to an extreme, concentrated load, such as a high-velocity impact, these connections can fail in a brittle manner, initiating a cascading collapse that propagates through the structure. This failure mechanism was famously identified as the primary cause of the catastrophic collapse of the I-35W Bridge in Minneapolis, where undersized gusset plates failed under a combination of inadequate load capacity and increased weight. The observation of "torn" or "sobek" gusset plates in the forensic documentation of the Busui Bridge is a direct parallel to this well-documented vulnerability. This finding suggests that the Busui failure is not an isolated event but a manifestation of a known structural weakness in older truss designs, where a single, localized point of failure can lead to a disproportionate and catastrophic outcome (Adam & Pamadi, 2023; W. Chen, 2012; X. Chen et al., 2012a; Dai et al., 2020; Imam & Chryssanthopoulos, 2012; Milić et al., 2020; Reddit, 2023; Shi et al., 2021; Silva & Vasanelli, 2024).

Figure 2. Condition of the bridge before the incident

The forensic investigation of the Busui Bridge began with a comprehensive on-site audit to document the pre-incident condition and the extent of the damage. The inspection confirmed the bridge's existing dimensions, which were a total length of 36 m and a width of 7 m (consisting of a 6 m roadway with 0.5 m shoulders on each side). The visual examination of the substructure, specifically the abutments on both the Kuaro and Batu Aji sides, revealed no evidence of cracking, shifting, or other damage, confirming they were in good condition and had not contributed to the failure.

The primary focus of the audit was the superstructure. Extensive photographic and visual documentation was compiled, highlighting the most critical damage. This included the tearing of several gusset plates ("plat buhul") and the significant deformation of multiple diagonal members and girders, particularly on the side impacted by the vehicle. This methodical documentation of the localized damage provided the essential physical evidence needed to analyze the failure mechanism.

A simplified FEM analysis was performed to quantify the dynamic forces involved in the vehicle-bridge collision. The simulation was based on the fundamental principles of classical mechanics. The provided documentation outlined the theoretical framework for calculating the kinetic energy (E) and impact force (F) of the collision. The formulas used were:

$$E = \frac{1}{2} mv^2 \quad (1)$$

Where m is the mass of the truck in kilograms (kg) and v is the velocity in meters per second (m/s). Impact Force (F):

$$F = \frac{E}{d} \text{ (m/s)} \quad (2)$$

Where E is the kinetic energy in Joules (J) and d is the deceleration distance in meters (m).

The pre-impact velocity of the vehicle was calculated from the available kinematic data. Based on a deceleration distance (d) of 20 m and a deceleration time (t) of 2 seconds, the speed was determined to be:

$$v = \frac{d}{t} \quad (3)$$

$$v = \frac{20}{2} = 10 \text{ (m/s)}$$

This is then converted to a more common unit for traffic speed: v=10 (m/s), if 1 (m/s) = 3.6 (km/h), then if the speed is 10 (m/s), it becomes 36 (km/h). This vehicle speed simulation is based on CCTV video footage from the scene of the incident, as shown in the figure 3.

Figure 3. Vehicle speed simulation is based on CCTV video footage

The original documentation provided the formulas and the velocity calculation, but did not specify the mass of the colliding vehicle, a critical parameter for calculating kinetic energy and impact force. To address this data gap and proceed with the analysis, a standard mass for a fully loaded heavy truck was assumed to be 20,000 kg. This transparent assumption allows for a complete analysis of the incident while maintaining the scientific rigor required of a forensic study. The subsequent analysis of the impact forces was correlated with the physical damage observed during the audit to validate the simulation results.

RESULTS AND DISCUSSION

The on-site forensic audit provided critical evidence that a localized failure in the superstructure, rather than a systemic or foundation-based issue, was the cause of the collapse. As summarized in Table 1, the abutment structures on both sides of the bridge were found to be in good condition, with no observable cracks or shifting. This immediately isolated the cause of the failure to the bridge's upper structure and the initiating event.

Table 1: Key Dimensions and Structural Condition of the Busui Bridge

Parameter	Pre-Incident State	Post-Incident State
Existing Length	36 m	Catastrophic collapse of superstructure
Existing Width	7 m (0.5m+6m+0.5m)	Not applicable due to collapse
Abutment Condition	Good, no cracks or shifting	Good, no cracks or shifting
Superstructure Condition	Undocumented	Torn gusset plates, deformed diagonals and girders

Source: AW Efendi (2024)

The documentation of the superstructure, however, revealed extensive and specific damage. The most significant finding was the "failure" and "tearing" of several gusset plates, particularly in the segments closest to the point of impact. This was accompanied by a clear change in shape ("perubahan bentuk") of the diagonal members and girders in the path of the vehicle, from the Batu Aji side of the bridge. The concentration of the damage to these specific, critical components strongly points to a localized failure mode. Based on a visual inspection, the existing abutment remains in good condition. No cracks or shifting of the abutment structure were found due to the incident, as shown in Figure 4.

Figure 4. Abutment structure inspection

The FEM simulation and kinematic analysis provided a quantitative link between the vehicular collision and the observed structural damage. The calculated velocity of the truck at the moment of impact was a relatively low 36 km/h, which is well below highway speeds. However, even at this modest speed, the dynamic forces were substantial. Based on the assumed mass of 20,000 kg for a heavy truck, the kinetic energy (E) and impact force (F) were calculated as shown in Table 2.

Table 2: Dynamic Impact Parameters and Calculated Forces

Parameter	Value	Notes
Vehicle Type	Heavy Truck	Assumed for analysis
Assumed Mass (m)	20,000 kg	Used to perform energy and force calculations
Pre-Impact Velocity (v)	10 m/s (36 km/h)	Calculated from provided kinematics
Distance of Deceleration (d)	20 m	Provided in original report
Calculated Kinetic Energy (E)	1×106 Joules	E=21 (20,000kg)(10m/s)2
Calculated Impact Force (F)	5×104 Newtons	F=20m1×106J

Source: AW Efendi (2024)

The truck has a mass of 45 tons (45,000 kg), and its speed varies between 40–100 km/h, converted into meters per second using the factor 1 km/h = 0.27778 m/s. The deceleration distance (d) is assumed to be 1 meter for impact force calculations. Based on these assumptions, the kinetic energy and impact force for a 45-ton truck traveling at different speeds were calculated, as shown in the table. For instance, at a speed of 40 km/h, the kinetic energy is 2,777,822 Joules and the corresponding impact force is 2,777.82 kN. To determine the vehicle's speed after braking for a distance of 5 meters, the kinematic equation:

$$v^2 = u^2 + 2.a.s \quad (4)$$

Where,
v = is the final velocity (m/s),
u = is the initial velocity (m/s),
a = is the average acceleration (m/s²), and
s = is the braking distance (m).

With an initial speed of 40 km/h (11.11 m/s), an acceleration of -10 m/s² due to braking, and a braking distance of 5 m, the final speed is calculated as

$$v = \sqrt{11.11^2 + 2(-10)(5)}$$

Which equals approximately 4.84 m/s or 17.42 km/h. Therefore, after braking for 5 meters, the vehicle's speed reduces to about 17.42 km/h, as shown in Figure 5.


Figure 5. Simulation of heavy vehicle collision on the diagonal side of the bridge superstructure

The analysis demonstrates that the kinetic energy of a heavy truck, even at a low speed, is significant. When this energy is transferred to a structural component over a short deceleration distance, it generates an immense impact force. This force was concentrated on a diagonal member, a component integral to the truss's load-carrying function. The correlation between the calculated impact force and the observed physical damage—particularly the torn gusset plates—provides strong support for the conclusion that the dynamic load was the direct trigger for the collapse, as shown in Figure 6.

Figure 6. Superstructure damage to the sei busui bridge

The Busui Bridge failure is a powerful, real-world illustration of a progressive or "disproportionate" collapse, where a small-scale, localized event triggers a widespread and catastrophic failure. The forensic evidence and dynamic analysis collectively suggest a clear failure mechanism. The vehicle impact was not a glancing blow, but a direct collision with a diagonal member of the truss, which was a critical, non-redundant component of the bridge's load-bearing system. This impact initiated a brittle failure at the gusset plate connection. The gusset plates, designed to distribute forces at the joints, were unable to withstand the concentrated dynamic load. Once these critical connections failed (tore), the structural integrity of the entire truss segment was compromised. The inability of the remaining members to redistribute the load led to a cascading collapse of the entire superstructure.

This mode of failure provides a compelling case study for modern bridge design philosophy. Contemporary standards, such as those in the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications, define vehicular collision as an "Extreme Conditions" load case. The primary objective of designing for such an event is to prevent the loss of an entire span, even if the impacted components are damaged. The fact that the Busui Bridge collapsed demonstrates that its design, typical of older infrastructure, did not possess the inherent robustness or redundancy to survive such an event. The failure was a direct consequence of a fundamental vulnerability in the structural system's ability to withstand a single, concentrated dynamic load without triggering a complete collapse.

The forensic audit report and subsequent engineering evaluation propose a two-phase remediation plan that represents a prudent and well-established engineering approach. This strategy elegantly balances the immediate need for a functional crossing with the long-term goal of building a durable, resilient replacement.

The short-term solution involves the installation of a temporary Bailey bridge. This is a strategic choice for emergency situations. Bailey bridges are prefabricated, modular steel structures that are renowned for their ability to be rapidly assembled and deployed with minimal heavy equipment, making them ideal for disaster relief and emergency infrastructure projects. They provide a rapid lifeline to restore traffic flow, minimize economic disruption, and reconnect the community. The implementation steps for this temporary solution are practical and focused on speed, including the quick evacuation of the damaged vehicle and the preparation of the site, such as ground surveys and coordination for utility relocation.

The long-term solution involves the construction of a new, permanent truss bridge. This approach prioritizes durability, increased load capacity, and lower long-term maintenance costs over the expediency of the temporary structure. The proposed implementation steps are more extensive, involving a detailed inspection of the existing abutments, a plan for repair if needed, and the fabrication and modification of a new steel truss. The new bridge is specified as a 35 m span, a slight but significant reduction from the original 36 m length. This discrepancy suggests a deliberate engineering decision, possibly to optimize the new design's structural performance, account for new abutment geometry, or improve overall constructability. The two-phase plan effectively addresses both immediate public safety and long-term infrastructure investment, serving as a best-practice model for responding to such failures.

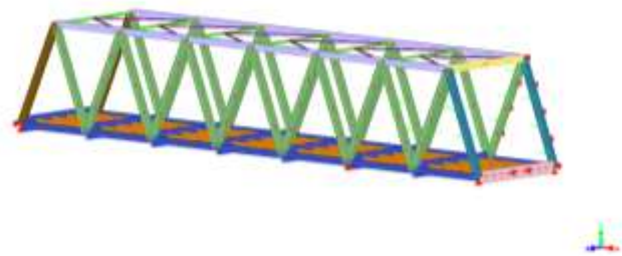

Figure 7. 3D Modeling FEM of Busui Bridge

Based on the provided image, the bridge structure is currently in a critical and unsafe condition, having exceeded its material's yield strength, which indicates it has undergone permanent, irreversible deformation. The analysis of the stress legend reveals that the maximum longitudinal stress, concentrated in the blue and red areas, reaches a peak value of 3.402×108 kN/m2. To properly evaluate this against the properties of BJ 37 steel, it is essential to convert the stress units from kN/m2 to the more commonly used MPa, where 1 MPa is equivalent to 1000 kN/m2 Thus, the maximum stress is calculated as 3.402×108 kN/m2 divided by 1000, resulting in a stress value of 340.2 MPa. Comparing this calculated stress to the given material properties, specifically the yield strength (fy) of 240 MPa and the ultimate tensile strength (fu) of 370 MPa, it becomes unequivocally clear that the maximum stress of 340.2 MPa significantly surpasses the yield strength of the steel, as shown in Figure 8.

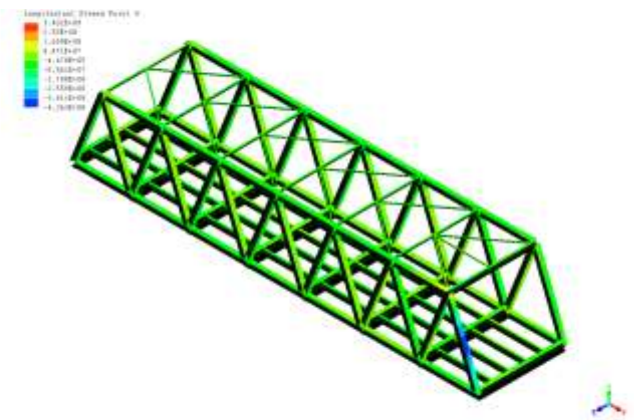

Figure 8. Stress on the bridge superstructure occurring after being impacted by heavy vehicles.

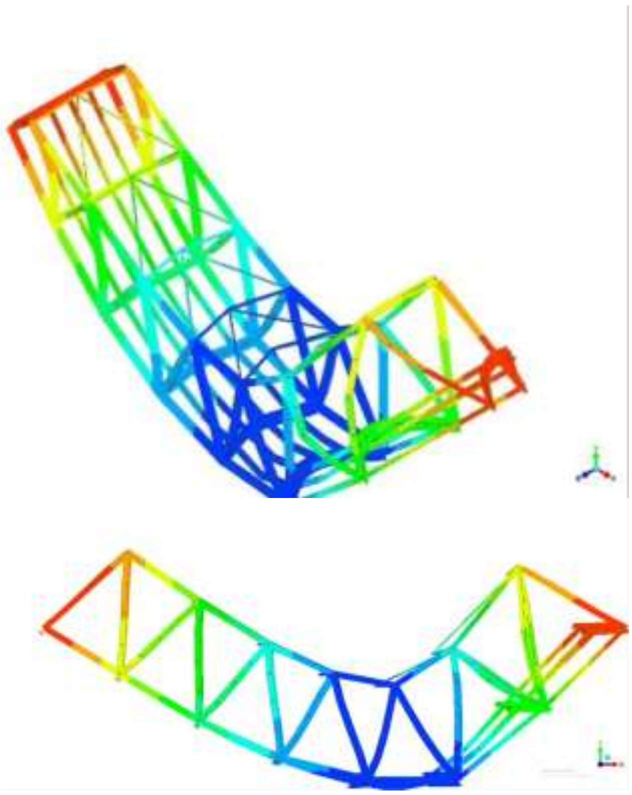

Figure 9. Deformation of the bridge caused by being hit by heavy vehicles.

This is a pivotal point in structural analysis, as the yield point represents the transition from the elastic region, where a material can deform and subsequently return to its original shape once the load is removed, to the plastic region, as shown in Figure 9, where deformation becomes permanent. The image visually confirms this state, as the high-stress areas (depicted in dark blue and red) indicate specific members within the truss have yielded. When a steel component enters the plastic region, it loses its ability to function as a fully elastic member, meaning it has lost a substantial portion of its structural integrity and safety factor. This condition is not an immediate catastrophic failure, as the ultimate tensile strength of 370 MPa has not yet been reached, but it signifies that the bridge superstructure is no longer capable of operating as designed. The permanent change in shape and geometry of the steel truss, as described in the prompt, means the bridge has been fundamentally compromised; even if the load were to be removed, the deformed members would not spring back to their original position. Consequently, the bridge is no longer structurally sound or safe for its intended use, as its load-bearing capacity has been severely diminished, making it susceptible to future collapse under normal operating conditions. The stresses observed are a clear and dangerous indicator of a structural failure that requires immediate and urgent intervention, such as demolition and replacement or extensive

CONCLUSIONS

The forensic investigation of the Busui Bridge failure confirms that a relatively low-speed vehicular impact on a critical non-redundant structural member triggered a catastrophic and disproportionate collapse. The core of the failure mechanism was the brittle tearing of the gusset plate connections, which were unable to absorb the concentrated dynamic energy from the collision. This failure mode provides a compelling case study that validates the importance of modern design standards which prioritize structural redundancy and survivability under extreme event loads. The incident demonstrates the inherent vulnerability of older infrastructure that may not have been designed to withstand such unpredictable, high-energy events.

Based on the detailed stress analysis, it is concluded that the bridge structure is in a critical state of failure. The maximum longitudinal stress observed in the image surpasses the yield strength of the steel, causing permanent deformation in the affected members. This irreversible plastic deformation signifies that the bridge has lost its elastic integrity and can no longer be considered structurally sound. While the ultimate tensile strength has not yet been reached, the bridge is no longer operating within its intended safety parameters and is at high risk of future catastrophic failure under normal loading conditions. Immediate action is required to remove the bridge from service and undertake extensive remediation, such as complete replacement or substantial repair of the compromised sections, to prevent a potential collapse.

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