Dynamic Response of Bowstring-arch Highway Bridge Subjected to Above and Below Deck Close-range Large Explosion

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Abstract. Explosion incidents that are unforeseen can lead to the occurrence of extreme loads, resulting in the generation of remarkably high stress levels within the materials comprising various structures. This can cause significant damage to crucial elements and potentially trigger a disproportionate collapse or even initiate a progressive collapse. Bridge structures, which serve as vital lifelines for cosmopolitan areas and strategic bordering environments, hold immense economic and political significance. The failure of these structures can have severe consequences with far-reaching implications. The use of a steel bowstring-arch bridge is a practical choice for congested crossings and remote border areas where spans are short. However, the current design codes for bridges do not take into account high-strain loadings such as blasts or impacts, nor do they provide recommendations for preventing these occurrences during construction or throughout the lifespan of the bridge. Explosive incidents cause greater damage in terms of material damage and loss compared to earthquakes. There has been limited investigation into how steel-concrete bridges respond to explosions in the past. This study examines the numerical analysis of a bowstring-arch highway girder bridge made of steel and concrete. The bridge is supported at both ends and is subjected to close-range concentric explosions above and below the deck at the center and end of the bridge. To model the bridge and predict its behavior, the authors utilized the Abaqus software suite. For the analysis, a significant quantity of TNT weighing 1.63-tonne has been positioned at the midpoint of the bridge and is defined using the Eulerian-Lagrangian scheme. The transmission of the explosive shockwaves within the bridge material under the given loading circumstances is illustrated and elucidated. The behavior of the bridge is examined in relation to plastic deformations, primary stress, displacement, size of the crater, and overall energy of damage.

1. Introduction

In recent years, the occurrence of blasting incidents has posed a growing danger to urban infrastructure [1-3]. Both terrorist attacks and the presence of transport vehicles carrying explosive and flammable substances have resulted in structures being exposed to potential blast loads [4-5]. The security of the international community is significantly threatened by acts of terrorism and accidental explosions. Particularly in densely populated areas, the failure of bridges can have devastating consequences, leading to substantial economic losses and other related damages. These incidents have highlighted the critical role that bridges play in facilitating urban traffic flow [6-10]. Bridge engineers have prioritized the evaluation of bridge resistance to explosions and damage caused by blasts, particularly in light of the events of 9/11 [8-10]. Nevertheless, the inclusion of significant measures for preventing explosions in design codes for non-military bridges, whether official or non-governmental, is seldom encountered. In recent times, steel-concrete composite bridges have become increasingly popular in urban construction due to their numerous advantages, such as their high construction speed and ability to

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withstand heavy loads [8]. However, there is a lack of research on the impact of explosions on steel-concrete composite bridges. Therefore, it is crucial to investigate the stress and failure mechanisms of these bridges when subjected to blast loads. When considering the performance of a bowstring-arch highway bridge under blast loading, it is essential to understand the mechanism by which the bridge responds to the blastwave. The blastwave generated by an explosion exerts high-pressure loads on the structure, leading to potential damage [8-15]. The response of the bridge to this blastwave is critical in determining its structural integrity and the level of damage sustained. The mechanism of how the bridge interacts with the blastwave directly influences the extent of damage and the effectiveness of its response. The blastwave impact on a bowstring-arch highway bridge can result in various forms of damage, such as structural deformation, fractures, or even collapse [8]. Understanding the specific modes of damage and their implications is crucial for designing effective protective measures and mitigating potential risks. By comprehending the damage mechanisms induced by blast loading, engineers can develop strategies to enhance the bridge's resilience and improve its ability to withstand such extreme events [16-24, 44].

In response to blast loading, the bowstring-arch highway bridge must exhibit a robust and efficient response to minimize damage and ensure structural stability [7, 8-10, 25-28]. This necessitates a comprehensive understanding of the bridge's dynamic behavior under blast loading conditions. By studying the response of the bridge, engineers can develop effective design strategies for strengthening the structure and implementing measures to enhance its ability to withstand blast loading. Consequently, a thorough analysis of the mechanism, blastwave impact, damage modes, and response of bowstring-arch highway bridges under blast loading is essential in ensuring their structural integrity and resilience against potential threats [25-28]. Many researchers [8, 24, 29-32, 44] focused on the structural performance of concrete piers or slabs under blasting loads. Research on the response of bridges to explosive forces is considerably less extensive compared to studies conducted on buildings. The impact of blasts on bridge elements was examined by [34], who also proposed a methodology for enhancing bridge security through design and retrofitting. Another noteworthy finding, highlighted by [35], was the significant influence of bridge geometry and clearance on the magnitude of blast loads beneath the deck. In their study, [36] examined the dynamic reaction of concrete piers when subjected to close-in blasts. They discovered that the failure mode of the pier body was determined by the arrangement of longitudinal reinforcement bars. To gain a better understanding of blast-loaded concrete bridge columns, both experimental and computational research were conducted by [37] as well as [38-39]. The research identified the crucial design factors, such as the shape of the column’s cross-section, that have the greatest impact on the effectiveness of blast-loaded reinforced concrete bridge columns. Based on these findings, design guidelines have been established to enhance the performance of bridge columns when facing blast hazards.

Although there have been some discoveries and suggestions regarding structures such as bridges that are exposed to explosive forces, the research on how bowstring girder highway bridges behave under blasting loads is still quite limited. The purpose of this study is to thoroughly examine a steel-concrete bowstring bridge in order to identify the patterns of damage and accurately forecast the propagation of explosive waves. To achieve this, a computer program called Abaqus [33] is employed to create a 3D computer model of the bridge. The uniqueness of this work lies in its ability to predict the dynamic response of the bridge when subjected to close-range blast loading from above and below the deck.

2. Model Setup and Material Modeling

The research incorporates a range of materials like concrete, steel, air, and the explosive TNT [1, 33]. To guarantee accurate and reliable evaluation of structures exposed to explosive forces, it is essential to meticulously choose suitable material models that effectively depict the properties of concrete and steel r/f, while considering their combinations. In this study, the JCP model is utilized to examine the components of steel [33]. This extensively used approach offers a precise representation of the strength and highest pressures encountered by steel, while taking into account the impact of strain rate.

In general, the precision of the particular FEA is greatly influenced by the size of the mesh [1, 26-27]. To guarantee a dependable structural response to blast loads, a smaller mesh size is usually necessary. However, due to the restricted range of a typical explosion, it is not feasible to simulate every element of a bridge using an extremely tiny mesh size. The JWL-EOS is employed for simulating the properties of the high explosive substance [1], while the Ideal Gas EOS is utilized to represent the characteristics of the surrounding atmosphere. To recreate a scenario where there is non-reflective infinite air, a flow out boundary condition, known as the flow out boundary condition, is assigned to all surfaces within the air domain. This guarantees that the air behaves as if it is exiting the system without any reflections [1, 33].
**Fig. 1.** Numerical Model.

- Constitutive Material Models Employed for Different Materials/Parts:
  1. Steel: Johnson-Cook Plasticity (JCP) Damage
  2. Concrete: Concrete Damage Plasticity (CDP)
  3. TNT: Jones-Wilkins-Lee Equation of State (JWL-EOS)
  4. Air: Ideal Gas EOS

(a) 3D Coupled Eulerian-Lagrangian Finite Element Model
(b) Lagrangian Structure of Interest

**Fig. 2.** Considered scenarios of explosion.

(a) B-Center-Above
(b) B-Center-Below
(c) B-End-Above
(d) B-End-Below
The 3-D model of the Bowstring-arch bridge, shown in Figure 1, was developed utilizing the Eulerian-Lagrangian method in Abaqus, along with the FEM [33]. The model comprises of three primary components, each discretized using an explicit element with 8 nodes measuring 20 mm: (1) the Lagrangian domain, which represents the bridge itself, (2) the explosive material (TNT), and (3) the Eulerian domain, which represents the air. A significant mass of 1.63-tonne was positioned at the center of the bridge at a blast height of 1.5m. In Abaqus [33], a total of four models were created (Figure 2): two models are exposed to above and below deck close-in explosion at the center, while the remaining two models are subjected to above and below deck close-in explosion at the end, with a blast height of 1.50m. Supports are strategically positioned at the ends of the bridge to ensure stability. When assembling the various parts of the bridge, default connections and tie-constraints are considered. E250 steel grade, in accordance with the specifications outlined in IS 2062 [8], is utilized for the construction of the bridge. Detailed information regarding the properties of the materials used can be found in reference [1-2, 8]. The bottom surface of the Eulerian domain is completely fixed, while the remaining five surfaces are equipped with non-reflecting conditions, as explained in [2, 8].
The assessment of a building exposed to an explosion presents a distinct scenario [1]. A focused and high-pressure force is exerted on a restricted region for a short duration, which can range from microseconds to milliseconds. In this particular research, the blast under investigation lasts for 2 milliseconds.

The steel-concrete bowstring-arch highway girder bridge remains a favored option for numerous transportation infrastructure undertakings [8]. This particular bridge design integrates the robustness and longevity of steel with the stability and adaptability of concrete. Its distinctive bowstring-arch configuration enhances the structure's visual allure and augments its ability to bear heavy loads.

The damage mechanism of bowstring-arch highway bridges under close-range blast loading involves a combination of factors such as shock wave propagation, structural deformation, and material response [8]. The initial shock wave from the blast exerts dynamic pressure on the bridge structure, leading to localized plastic deformation and fracture in critical components. The interaction between the shock wave and the bridge's structural elements results in complex stress waves and dynamic amplification, leading to severe damage in vulnerable areas [1, 8]. Due to the absence of any current experimental prototypes for bridges of this kind, it was not viable to compare the computer-generated forecasts with actual data from the real world. Nonetheless, the authors' previous research [1-8, 19-21, 25-28, 40-43] has examined the dependability of Abaqus in precisely projecting the dynamic reaction of infrastructures.

3. Results

When a bridge experiences an explosion underneath it, the deck of the bridge is subjected to significant upward forces. These forces can be intensified by the buildup of pressure in the areas between the support girders and the bridge deck. As a result, the deck may detach from the support girders. Furthermore, powerful explosive forces have the capability of inducing either shear failure or membrane failure in the bridge deck. Deck failures typically occur in specific areas and result in the release of blast loads from those areas. This release of pressure can help alleviate the strain on the supporting structural components. However, if shear studs are not present (present study case), there is a risk that the deck may detach from the girders once the blast loads have dissipated, resulting in an impact force. In situations where explosions happen above the deck, the blast causes localized damage to the deck, often in the form of craters, which leads to significant plastic deformation.

The behavior of the girders is influenced by the loads transferred to them not just through the response of the deck, but also due to the impact of localized damage. Spalling refers to the occurrence of tension failure in a structural element due to the transmission of a shock wave. This wave reflects off the opposite face, alters its direction, and generates tension forces as it returns towards the center of the element. On the other hand, cratering is a compression crushing failure that takes place on the blast face and involves the removal of concrete. Taking into account the consequences of this localized...
damage, uplift forces result in significantly reduced capacities of the members due to loss of cover and the bond between steel and concrete.

![Fig. 5. Y-displacement: section cut view.](image)

Table 1. Predictions at t=2ms in the deck for the considered blasts.

<table>
<thead>
<tr>
<th>Blast location</th>
<th>Model No.</th>
<th>Y-displacement [m]</th>
<th>Shear stress [MPa]</th>
<th>Plastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above-deck</td>
<td>B-Center-Above</td>
<td>-1.24</td>
<td>37.11</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>B-End-Above</td>
<td>-0.33</td>
<td>35.11</td>
<td>0.75</td>
</tr>
<tr>
<td>Below-deck</td>
<td>B-Center-Below</td>
<td>+0.68</td>
<td>34.52</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>B-End-Below</td>
<td>+1.04</td>
<td>38.85</td>
<td>0.79</td>
</tr>
</tbody>
</table>

The consequences resulting from the explosion scenarios on the bridge are depicted in Figure 3. We have witnessed significant structural failure in both the deck and the underlying support girders at the designated blast sites. The deck has suffered damage in the form of spalling and the creation of craters.

Figure 4, the explosion that occurred at the center of the bridge, with the blast situated 1.5m above the deck, resulted in a total damage of 1950.78J. Conversely, when the blast occurred below the deck, the bridge sustained a damage of 1780.74J. In the case of a concentric explosion at the end of the bridge, also with a blast height of 1.5m above the deck, the total damage experienced by the bridge was 977.99J. However, when the blast occurred below the deck, the damage amounted to 1388.56J, which is 1.42 times greater than the damage caused by the blast above the deck.

The explosion occurring on the upper deck at the central part of the bridge leads to a significant downward displacement of the deck, reaching a maximum of 1.24m. Conversely, at the end of the bridge, the displacement is slightly lower, measuring at a maximum of 0.33m (refer to Figure 5 and Table 1). On the other hand, when the explosion happens beneath the deck at the central part of the bridge, it causes the deck to undergo an upward displacement of up to 0.68m. However, at the end of the bridge, the deck experiences a greater displacement of 1.04m.
The table provided, Table 1, lists the shear stress and plastic strain values for the concrete deck in different blast scenarios. In the case of an explosion below the deck at the bridge's end, the maximum shear stress recorded is 38.85 MPa, along with a plastic strain of 0.79.

4. Conclusion

This study investigates the impact of close-range large explosions, both above and below deck, on a single-span bowstring-arch highway bridge. It evaluates the extent of damage caused by these explosive forces, considering a significant amount of TNT weighing 1.63 tonne positioned at a blast height of 1.50m at the center and end of the bridge. The simulations conducted for this research employ Abaqus and its integrated material modeling techniques. The following conclusions can be drawn from this analysis:

- The bridge is highly vulnerable to the examined detonations, resulting in substantial destruction from a strong explosion on the platform/deck. As a result, repairing the bridge becomes extremely challenging.
- When the explosion occurs at the end of the bridge, it suffers a total damage of 977.99J. However, if the blast were to occur beneath the deck, the resulting damage would be 1388.56J, which is 1.42 times higher than the damage caused by the blast above the deck.
- Stress wave propagation within the materials of a bridge becomes more complex when there is an explosion below the deck, as opposed to an above-deck blast occurring at the center of the bridge. The blast forces lead to increased damages and stresses on both the deck and steel girder.

References

33. ABAQUS/CAE FEA program version 6.15 Concrete-damaged plasticity model, explicit solver, three-dimensional solid element library, ABAQUS DS-SIMULIA User Manual (2020)


