Blast load analysis of overpass columns with various cross-sections

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Abstract. The column is one of the most important elements of the bridge because its destruction can cause a collapse of the entire bridge. The aim of the research is to analyse the blast behaviour of the overpass columns on Croatian roads and highways. Based on the archive documents of design plans the most common cross-sectional shapes of the reinforced concrete column were selected. The literature provides formulas for calculation of blast pressure that depends on the distance of the explosive from the target and the amount of explosive. However, the cross-sectional shape of the column plays a significant role in retaining the pressure and impulse on the column and its distribution by column height and width. This cannot be predicted by theoretical expressions, and therefore a numerical simulation that takes into account the column geometry is required. The columns were modelled in the Ansys Autodyn hydrocode software for a supposed scenario in which an auto bomb was placed below the bridge at a distance of 2 m from the column. Based on the numerical simulations it was concluded that the circular column had the lowest pressure on the surface directly exposed to the blast load. This is due to its roundness and the angles at which the pressure was reflected. In contrast, the back surface of the circular column has the highest pressure of all the analysed columns. Generally, rectangular cross-sections have a higher pressure on the directly loaded surface. For more detailed analysis and experimental testing, a rectangular column (P6) with recesses was selected due to its high pressures on both, the front and back surfaces. Selected overpass i.e. its column was designed using the old seismic regulations and as a part of further research, its blast behaviour will be compared to the column designed using modern seismic regulations.

1. Introduction

We are witnessing an increasing frequency of terrorist attacks globally. Following the terrorist threats to bridges in California and New York (2001), greater importance is given to bridges, especially bridge columns, when designing. Damage to the columns puts the entire bridge structure at risk. Bridges are significant because of traffic, connecting certain zones of the city, and apart from their functional role they have great economic value [1].

Davis et al. (2009) state the difference in load on a circular and rectangular column, and the advantages and disadvantages of both. The cross-sectional shape plays a significant role in the magnitude of the pressure and impulse affecting the surface. Compared to the square section, the circular cross-section sustains less pressure and impulse because the pressure wave is reflected at an angle. However, the square cross-section has a larger area in comparison to the circular column of the same dimensions and can more easily resist shear at the base. Therefore, it is not clearly defined which cross-
section is better and the advantages and disadvantages of both cross-sections need to be further elaborated [1].

Bridges on Croatian roads and highways were examined and the most common columns were identified and modeled in the Ansys Autodyn software [2]. Based on the archive survey, the most commonly used cross-sections of the columns were listed. A reference column that will be analyzed in more detail and experimentally tested was selected based on the blast load maximum pressure.

2. Blast scenario
Due to the complexity of the analysis and the various parameters to take into account when analyzing the effect of the explosion on the structure, the scenario of detonation of explosives in the vehicle below the superstructure near the column is considered. According to the research conducted, this is considered as one of the most critical and common scenarios. By collapsing a component such as a column of a bridge, the bridge loses its load-bearing capacity and the entire structure is endangered. In addition to extensive material damage and traffic interruption, bridge collapse can cause a large number of casualties [3]. In the past, columns have not been designed to withstand high lateral dynamic loads and are therefore an interesting target for terrorist attacks [4]. The height of the explosive charge is determined by the height and geometry of the vehicle, and in literature [5-7] heights of 0.8, 1.0, and 1.2 m (h), which correspond to the distance of the center of the charge (located in the vehicle) from the ground level, are most commonly reported. Explosive charge (vehicle) distance from the overpass column (R = 2.0 m) was selected due to existing road barriers around the column. The scenario is shown in figure 1. Table 1 gives the estimated mass of explosives that can be placed in a single-vehicle. Mass of TNT (trinitrotoluene) explosive was selected as 100 kg and based on this value numerical simulations in Ansys Autodyn were performed [8, 9].

![Figure 1. Theoretical blast scenario.](image)

**Table 1.** Estimated quantities of explosives in various vehicles [8, 9].

| Vehicle type               | Charge mass [kg] |
|----------------------------|------------------|
| Compact car trunk          | 115              |
| Trunk of a large car       | 230              |
| Closed van                 | 680              |
| Closed truck               | 2270             |
| Truck with a trailer       | 13610            |
| Truck with two trailers    | 27220            |

3. Columns cross-sections
After reviewing the archive of bridge designs on Croatian roads and highways, the most common cross-sectional shapes of reinforced concrete columns shown in figure 2 have been selected. Circular (O) columns and rectangular columns with different notches (P1-P7) predominate. In the last two decades, rectangular columns with variable cross-sections (V) have been constructed. The cross-section increases
linearly from the bottom to the top of the column. Two columns in overpass cross-section dominate as an inter-span supports. The height of the columns can be averaged around 6 m.

![Columns Diagram](image)

**Figure 2.** Types of columns cross-sections.

4. **Numerical models**

The full-scale columns were modelled in Ansys Autodyn. The charge was placed as in the above-described scenario. The air through which the pressure of the explosion wave is propagated is modelled. The blast in air can be modelled using 1D approach. The 1D wedge mesh using axial symmetry in Autodyn is shown in the figure 3(a). Flow out boundary condition is used to eliminate the wave reflection effect. The numerical simulation stops and the data is saved when the blast wave reaches the end of the 1D air mesh. Then the results of blast pressures are remapped to the 3D simulation air surrounding as an initial state of the blast wave. Remap is performed by including symmetry in all directions [10]. Gauge points 1 to 4 are placed on the front surface of the column, where point 1 is placed at the height of 0.8 m what corresponds to the height of the explosive charge, point 2 at a height of 2 m, point 3 in the middle of the column at 3 m, and point 4 at the very top of the column at 6 m. Gauge point locations for column P6 are shown in the figure 3(b) and the locations are the same for all studied columns. The points are set to analyse the pressure distribution across the column. Gauge point 5 is the lateral point, and gauge point 6 is set to the backside, at the height of the explosive charge. The air mesh size plays a significant role in the pressure distribution [11], and in this analysis, a 50 mm element air mesh size was used. The reduction of the mesh size increases the length of the numerical calculation and it is considered that the specified mesh is sufficient to compare obtained pressures. The resulting pressures from Ansys Autodyn may differ due to the size of the air mesh from those obtained analytically using expressions from the literature. Blast pressure rises instantaneously while it takes only a few milliseconds for pressure to attenuate from maximum value to ambient pressure, so the calculation is set to 4 milliseconds, which is sufficient to obtain maximum pressure. If we are interested in the response of the structure to the effect of the explosion, the calculation should last at least 10 times longer. The column is modelled as pure concrete and reinforcement is not considered because the pressure distribution is analysed not structural response. For the sake of faster calculation symmetry is utilized so half of the column is modelled and the blast wave pressure distribution is considered to be symmetrical. The explosive is located at a height of 0.8 m.
Figure 3. (a) 1D wedge model of blast wave propagation and (b) 3D column model (P6) in Ansys Autodyne.

5. Results and discussion

At gauge point 1, maximum pressure occurs due to the pressure reflection from the ground, so the reflected pressure interacts with the initial pressure and acts together on the column. The pressure is rapidly expanding upwards and covers gauge points 2, 3 and 4. At these points, the pressure is lower as the distance from the charge increases. The angle of incidence of an explosion wave is directly related to the magnitude of the pressure; a larger angle of incidence means lower pressure. At gauge point 1, the angle of incidence is zero and the pressure is maximum. The lateral gauge point 5 and the backside gauge point 6 are also influenced by the pressure because the pressure rapidly spreads around the column. Figure 4 shows the propagation of the blast pressure wave in time around the column P6.

Figure 4. The blast wave propagation around the column P6.

After the numerical simulation of 9 columns with different cross-sections, shown on figure 2, pressure diagrams and pressure distribution along the columns height was analysed. Figure 5 shows the gauge point maximum pressures for each column. The maximum pressure is at gauge point 1 which is located directly opposite to the detonation point, while in the centre of the column at gauge point 3 there is a significant decrease in blast pressure. The lowest pressure is at gauge point 6 located on the backside of the column. We can also see that column P3 has the highest pressures in comparison to column P6, while the lowest pressures are recorded for circular column O as expected. Figure 6 shows the pressure-time distribution diagrams at gauge point 1 for all column types. Positive phase duration for all recorded pressure-time profiles is around 4 milliseconds.
Figure 5. Maximum pressure in gauge points for all types of columns.

Of the two columns with maximum pressures, P6 was selected for further analysis because it is more frequent on Croatian highways and is designed according to old seismic regulations. Further research will deal with the blast load behaviour of the columns as they are, studying their blast vulnerability. Furthermore, the column will be designed according to modern seismic regulations, i.e. EN1998 and its blast load behaviour compared to the old column. The bottom part of both columns is exposed to maximum blast pressures. There is a significant increase in the blast pressure due to wave reflection from the ground. Obtained pressure distribution along column height indicates the possible column shear failure. Figure 7 shows the pressure distribution by column height for the selected rectangular column with recesses P6 and for the circular column O. We notice that the largest difference in pressure is in the lower half of the column, below 3 m. Pressures are significantly reduced in the upper half of the column and are almost equal in intensity.

Figure 6. Pressure-time diagrams for gauge point 1.

Pressure-time diagrams of all 6 gauge points on the column P6 are shown in figure 8. It is obvious that gauge points 1 and 2 have higher pressures than the rest of the gauge points due to their proximity to detonation point. Gauge points 3 and 4 recorded significantly reduced pressure intensities. Lateral gauge point 5 has its maximum value at the same time instance as gauge point 2 but has a significantly lower pressure values due to its position on the opposite side of the column. The pressure reaches gauge point 6 before reaching the top of the column because the path of the blast wave is shorter than for gauge point 4. Pressure recorded in gauge point 6 indicates that the blast wave envelops and interacts with modelled column.

Figure 7. Reflected pressure distribution by column height (P6 and O).

Figure 8. Reflected pressure-time diagrams for all 6 gauge points (P6).
6. Conclusion
Numerical analysis in Ansys Autodyn confirmed that the column shape plays a significant role in resistance to blast wave propagation. The circular column O has the lowest pressures, while the maximum pressures are observed on the column P3 and P6. The critical zone of the column is the lower half because, in addition to the direct pressure from the explosion, the reflected pressure from the ground also interacts with the column. Due to the high pressure at the bottom, shear failure of the column is expected.

7. References
[1] Davis C E et al. Design and detailing guidelines for bridge columns subjected to blast and other extreme loads 2009 Structures Congress 2009: Don't Mess with Structural Engineers: Expanding Our Role
[2] Ansys 2010 Ansys Autodyn Users’s Manual Canonsburg PA USA
[3] Cooper J D, Smith M C and Ernst S L, Blue ribbon panel recommendations for bridge and tunnel security
[4] Abedini M et al. 2019 Pressure–impulse (P–I) diagrams for reinforced concrete (RC) structures: a review Archives of Computational Methods in Engineering 26(3) pp 733-767
[5] Winget D G, Marchand K A and Williamson E B 2005 Analysis and design of critical bridges subjected to blast loads Journal of Structural Engineering 131(8) pp 1243-1255
[6] Fujikura S, Bruneau M and Lopez-Garcia D 2008 Experimental investigation of multihazard resistant bridge piers having concrete-filled steel tube under blast loading Journal of Bridge Engineering 13(6) pp 586-594
[7] Elsanadedy H M et al. 2011 Effect of blast loading on CFRP-Retrofitted RC columns-a numerical study Latin American journal of solids and structures 8(1) pp 55-81
[8] Draganić H and Sigmund V 2012 Blast loading on structures Technical Gazette 19(3) pp 643-65
[9] Hameed A H 2007 Dynamic behavior of reinforced concrete structure subjected to external explosion (Kufa University Jumada Elawal) 1428 p 103
[10] Shi Y, Li Z and Hao H 2008 Mesh size effect in numerical simulation of blast wave propagation and interaction with structures Transactions of Tianjin University 14(6) pp 396-402
[11] Draganić H and Varevac D 2018 Analysis of blast wave parameters depending on air mesh size Shock and Vibration 2018

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