International Journal of Bridge Engineering (IJBE), Vol. 9, No. 2, (2021), pp. 51-62

TERRORIST ACTIONS ON LONG BRIDGES

Tassos P. Avraam[1] and George T. Michaltsos[2]

[1,2] School of Civil Engineering, National Technical University of Athens, Greece.
e-mail: michalts@central.ntua.gr, avraamt@central.ntua.gr

ABSTRACT: This paper investigates the influence of an explosive load, due to a terrorist action, on the behavior of a long bridge, and studies the explosion characteristics and their effect on the bridge. The theoretical formulation is based on a continuum approach which has been used in literature to analyze such long or suspension bridges. The analysis is carried out with the modal superposition method. The resulting differential equations are solved using the Duhamel's integral.

KEYWORDS: Long bridges, Suspension bridges, Explosive loading, Terrorist actions.

1. INTRODUCTION

A sudden explosion in the broader locality of a civil work is ever a serious event due usually in terrorist action.

In the last decades, military and state constructions around the world have been attacked by terrorists without distinction between military and civilian target. Such an action especially in bridges, which brings about the collapse of the bridge, would cause a temporary or long-term interruption of transportation and financial burdens.

Generally, the rapid release of a large amount of energy may be characterized as explosion.

Very soon, after the bombing in Nagasaki and Hiroshima, the Atomic Energy Commission of USA together with the American Military Forces, studied the phenomenon and gave the results and the first instructions and Codes [1].

Considering the power of one kiloton weapon as a "reference power", they provided information and formulas through scale relations as well as tables and diagrams for explosions with different power. We note that 1KT is the explosion produced by 1000 tons of TNT. To realize the above sizes, we mention that each one of the dropped atomic bombs on Japan in 1945, was a weapon of about 20 KT.

One of the main civilian structures targets of the future might be the long and great bridges. Their collapse would cause a temporary or long-term interruption of transportation and a significant financial burden. Therefore, it is very important to study the behavior of bridges, especially of long bridges, to loads resulting from explosions. Current building design codes and guidelines, such as U.S. Department of Defense criteria [2, 3], ASCE7 Standard [4] and the European codes [5, 6] contain guidelines and provisions for explosion resistant design and progressive collapse prevention of buildings.

Many researchers have studied the behavior of bridges under the action of explosive loads [7-17], bridges made of either steel [18, 19], or concrete [20-24] or stone structures [25]. There are also studies for blast loadings on Cable-Stayed-Bridges [26-29] or Suspension Bridges [30]. Finally, there are many studies that use FEM [31-36] and a few experimental [37].

The purpose of this paper is to investigate the influence of an explosive load, due to a terrorist action, on the behavior of a long or a suspension bridge, and studies the explosion characteristics and their effect on the bridge. The theoretical formulation is based on a continuum approach which has been used in literature to analyze such long or suspension bridges. The analysis is carried out with the modal superposition method. The resulting differential equations are solved using the Duhamel's integral.

A variety of numerical examples allows to draw important conclusions for structural design purpose, while the results have been compared with conventional solving methods.

Finally, we assume that the explosives have been placed in one or more places of the bridge while they are scheduled to explode simultaneously or with a time difference.

2 EXPLOSION LOADS

The point of the ground surface that is exactly below the explosion point is called ground zero or G.Z.

The maximum overpressure developed from a weapon of 1KT (=1000 tons of TNT) varies in relation to the distance from G.Z., according to the diagrams of figure 1 [1], where the pressure p_o is in psi and the distance in miles. We note that $1psi = 6.90KN/m^2$and $1mile = 1600m$.

The above diagrams can be expressed by the following equations [40]:

2.1 Explosion on the earth

In this case the corresponding curve has the following equation:

$$p_o = 2760 \cdot e^{-\frac{d}{70}} - 0.0314 \cdot d + 49.6 \tag{1a}$$

2.2 Explosion in the air

In this case the corresponding curve has the following equation:

$$p_o = 656 \cdot e^{-\frac{d}{120}} + 6.9 \tag{1b}$$

In the above relations d is the distance from G.Z. in meters and p_o is the pressure in dN/m^2.

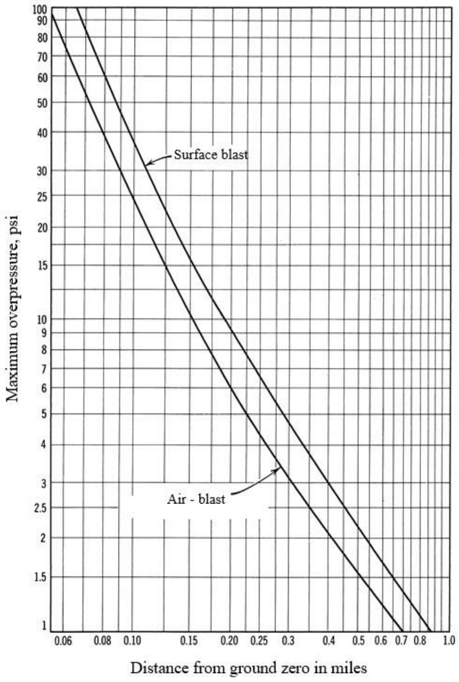
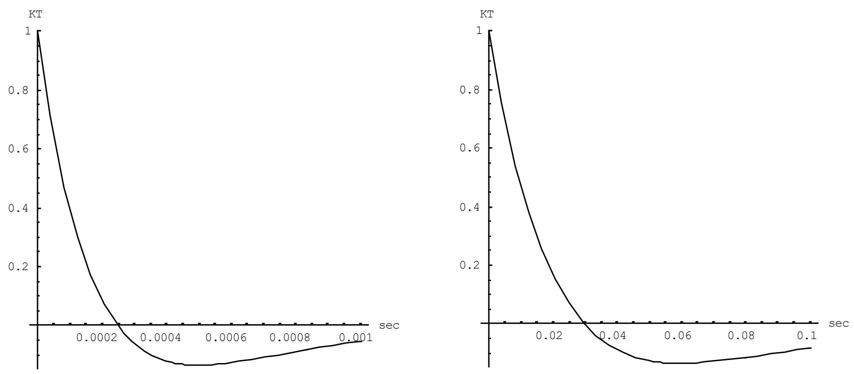


Figure 1. Maximum overpressure in relation to distance from G.Z.

This paper studies terrorist actions on bridges. For a deck width of 12m and assuming that the explosives are placed at the left or the right end of the deck (i.e. 0.10 or 12m from the end) the time functions given by [1] are shown in figures 2a.



2a. Left End ($d = 0.10m$) 2b. Right End ($d = 10m$)

Figure 2. Explosion's time function

The above diagrams show that the action of the explosion lasts less than 0.028 sec.

Therefore, the action of an explosion, very close to the point of the explosion, can be considered as an instantaneous action at time t_i (time at which the explosion occurs) and thus -can be expressed by the Dirac Function $\delta(t-t_i)$, where t_i is the ignition time of the explosive load.

3 ACTION ON A LONG BRIDGE

Let us assume (without restriction of the generality) the one-span long bridge of figure 3, with a cross-section of double symmetry (i.e. $z_M = 0$).
The equations of motion are:

$$\left.\begin{array}{l} EI_y w'''' + c\dot{w} + m\ddot{w} = \sum_i P_i \delta(x-\alpha_i)\delta(t-t_i) \\ EI_\omega \theta'''' - GI_d\theta'' + c\dot{\theta} + I_{px}\ddot{\theta} = e \cdot \sum_i P_i \delta(x-\alpha_i)\delta(t-t_i) \end{array}\right\} \quad \text{(2a,b)}$$

where P_i the explosion load at $x = \alpha_i$ and t_i the ignition time of the explosive load P_i.

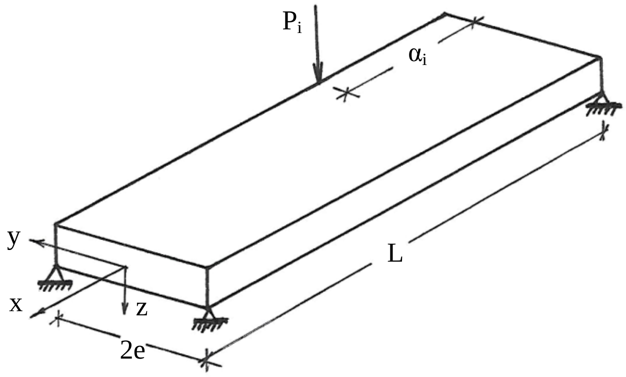


Figure 3. Long bridge with cross-section of double symmetry

3.1 The shape functions

In order to solve the equations of motion (2a,b), we have to know the shape functions of the free vibrating one-span bridge.

3.1.1 Vertical free motion

The shape functions and the eigenfrequencies are given by the following expressions:

$$X_n(x) = c_{1n} \cdot sin\frac{n\pi x}{\ell} \quad \text{(3a)}$$

$$\omega_{zn}^2 = \frac{n^4\pi^4 EI_y}{m\ell^4} \quad , \quad n = 1,2,3,\ldots. \quad \text{(3b)}$$

3.1.2 Torsional free motion

The Shape functions are:

$$\left.\begin{aligned} &\Phi_n(x) = c_{1n} \cdot \left(\sin\lambda_{1n}x - \frac{\sin\lambda_{1n}\ell}{\sinh\lambda_{2n}\ell} \cdot \sinh\lambda_{2n}x \right) \\ &\text{where:} \quad \lambda_1 = \sqrt{-\frac{GI_d}{2EI_\omega} + \sqrt{\left(\frac{GI_d}{2EI_\omega}\right)^2 + \frac{I_{px}\omega_\theta^2}{EI_\omega}}} \\ &\text{and} \quad \lambda_2 = \sqrt{\frac{GI_d}{2EI_\omega} + \sqrt{\left(\frac{GI_d}{2EI_\omega}\right)^2 + \frac{I_{px}\omega_\theta^2}{EI_\omega}}} \end{aligned}\right\} \quad (3c)$$

While the eigenfrequencies are given by the expression:

$$\omega_{\theta n}^2 = \frac{n^4\pi^4 EI_\omega}{I_{px}\ell^4} + \frac{n^2\pi^2 GI_d}{I_{px}\ell^2} \quad , \quad n = 1,2,3,\ldots. \quad (3d)$$

3.2 Solution of equ. (2a)

In order to solve equation (2a) we are searching for a solution of separate variables under the form:

$$w(x,t) = \sum_n X_n(x) \cdot T_n(t) \quad (4a)$$

where T_n are the time functions under determination and X_n are functions arbitrarily chosen, which satisfy the boundary conditions. As such functions we choose the shape functions of the bridge given by equation (3a). Introducing (4a) into (2a) we get:

$$EI_y \sum_n X_n'''' T_n + c\sum_n X_n \dot{T}_n + m\sum_n X_n \ddot{T}_n = \sum_i P_i \delta(x-\alpha_i)\delta(t-t_i) \quad (4b)$$

Remembering that X_n satisfies the equation of free motion $EI_y X_n'''' - m\omega_{zn}^2 X_n = 0$, equation (4b) becomes:

$$m\sum_n X_n \ddot{T}_n + c\sum_n X_n \dot{T}_n + m\sum_n \omega_{zn}^2 X_n T_n = \sum_i P_i \delta(x-\alpha_i)\delta(t-t_i) \quad (4c)$$

Multiplying the above by X_k and integrating from 0 to L we obtain:

$$\ddot{T}_k + \frac{c}{m}\dot{T}_k + \omega_{zk}^2 T_k = \frac{1}{m\int_0^L X_k^2 dx} \cdot \sum_i P_i X_k(\alpha_i)\delta(t-t_i) \quad (4d)$$

The solution of the above equation is given by the Duhamel's integral:

$$T_k(t) = \frac{1}{m\bar{\omega}_{zk}\int_0^L X_k^2 dx} \cdot \sum_i \int_0^t P_i X_k(\alpha_i) \cdot e^{-\beta(t-\tau)} \sin[\bar{\omega}_{zk}(t-\tau)] \cdot \delta(\tau - t_i) d\tau$$

or finally:

$$\left.\begin{aligned} &T_k(t) = \frac{1}{m\bar{\omega}_{zk}\int_0^L X_k^2 dx} \cdot \sum_i P_i X_k(\alpha_i) \cdot e^{-\beta(t-t_i)} \sin[\bar{\omega}_{zk}(t-t_i)] \\ &with \quad \bar{\omega}_{zk} = \sqrt{\omega_{zk}^2 - \beta^2} \quad and \quad \beta = \frac{c}{2m} \end{aligned}\right\} \quad (4e)$$

3.3 Solution of equ. (2b)

In order to solve equation (2a) we are searching for a solution of separate variables under the form:

$$\theta(x,t) = \sum_n \Phi_n(x) \cdot G_n(t) \tag{5a}$$

Where G_n are the time functions under determination and $\Phi_n$are functions arbitrarily chosen, which satisfy the boundary conditions. As such functions we choose the shape functions of the bridge given by equations (3c). Introducing (5a) into (2b) and following a procedure like this one of §3.2, we finally find:

$$\left.\begin{aligned} &G_k(t) = \frac{1}{I_{px}\bar{\omega}_{\theta k}\int_0^L G_k^2 dx} \cdot e \cdot \sum_i P_i \Phi_k(\alpha_i) \cdot e^{-\beta(t-t_i)}\, sin[\,\bar{\omega}_{\theta k}(t-t_i)] \\ &with \quad \bar{\omega}_{\theta k} = \sqrt{\omega_{\theta k}^2 - \beta^2} \quad and \quad \beta = \frac{c}{2m} \end{aligned}\right\} \tag{5b}$$

4 NUMERICAL EXAMPLES AND DISCUSSION

In this section, a numerical investigation based on the equations obtained in the previous paragraphs has been developed. The main goal of the presented examples is to study the influence of explosions of different intensities which occur at different places on a long bridge as well as on a suspension bridge.

Explosive Loads

The usual intensity of explosions from terrorist actions ranges from 0.05 to 0.10 KT (or 50 to 100 tons of TNT). Rarely, in particularly significant terrorist actions explosions with power up to 0.30 KT (~300 tons of TNT) can be used.

In this paper we will study explosions loads with power 0.1, 0.3, and 1 KT (100, 300, and 1000 tons of TNT), placed at one or more places and exploding with time difference 0.1, 0.2, or 0.5 sec.

Long Bridge

We consider a one-span bridge of length $L = 100m$, mass per unit length $m = 800kg/m$, $2e = 12.50m$, $I_y = 0.50m^4$, $I_z = 8{,}00m^4$, $I_d = 0.05m^4$, $I_\omega = 0.25m^6$, and $I_{px} = 10200kgsec^2$. The bridge is made of homogeneous and isotropic material with modulus of elasticity $E = 2.1 \cdot 10^{10} dN/m^2$. The acceptable deformations are: L /200 for the vertical motion and 10^o (or 0.1745 rad) for the torsional motion

4.1 The long bridges

4.1.1. Vertical motion

Applying the formulae of §3.2 we get the following plots:

The plots of figure 4, show that the produced vertical deformations for explosive placed at $x = L/2$ and power 1 KT are not acceptable.

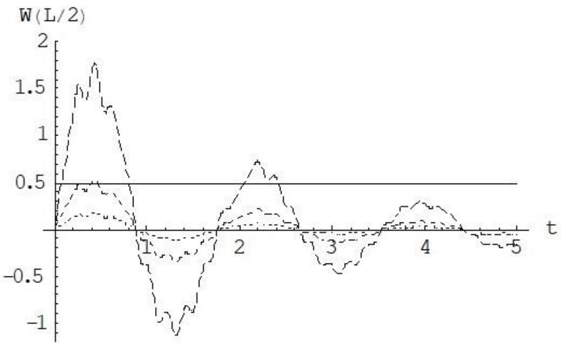


Figure 4. The vertical motion of the middle of the bridge for explosives placed at x=L/2 and explosion power of 1KT (_), 0.3KT (- - -), and 0.1KT (…..)

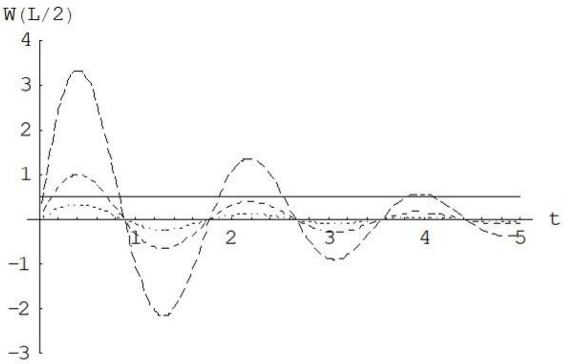


Figure 5. The vertical motion of the middle of the bridge for explosives placed at x=L/4, x=L/2, x=3L/4 and explosions power of 1KT (_), 0.3KT (- - -), and 0.1KT (…..)

The plots of figure 5, show that the produced vertical deformations for explosives placed at $x = L/4$, $x = L/2$, and $x = 3L/4$ are acceptable only for explosives' power 0.1 KT.

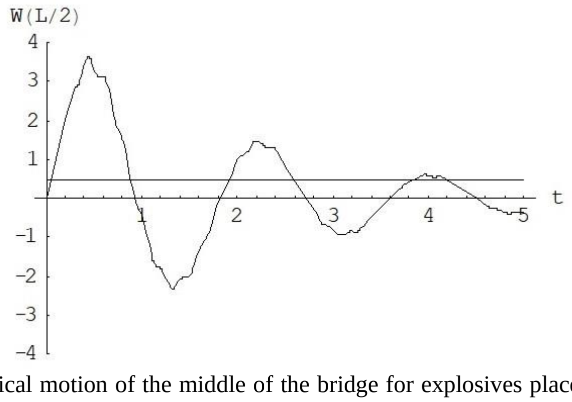


Figure 6. The vertical motion of the middle of the bridge for explosives placed at x=L/4, x=L/2, x=3L/4 but fired at different times and explosions power of 1KT.

In the plots of figure 6, we see the vertical motion of the middle of the bridge for explosives placed at $x = L/2$, and $x = L/4$, $x = 3L/4$, but the two last fired 0.1 sec later than the first one. Comparing the deformations of fig.6 to those of fig.5 we observe an increase of the deformations of about 12%.

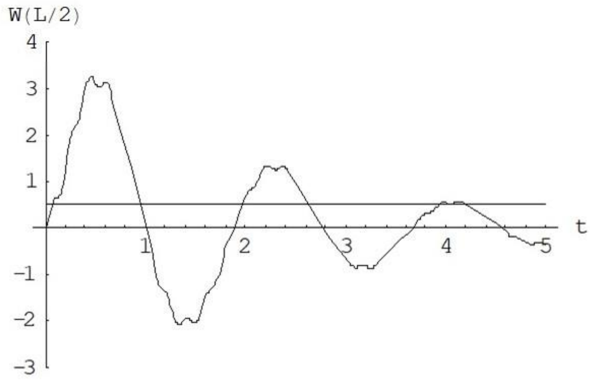


Figure 7. The vertical motion of the middle of the bridge for explosives placed at x=L/4, x=L/2, x=3L/4 but fired at different times and explosions power of 1KT.

In the plots of figure 7, we see the vertical motion of the middle of the bridge for explosives placed at $x = L/2$, and $x = L/4$, $x = 3L/4$, but the two last fired 0.2 sec later than the first one. Comparing the deformations of fig.7 to those of fig.5 we observe small differences.

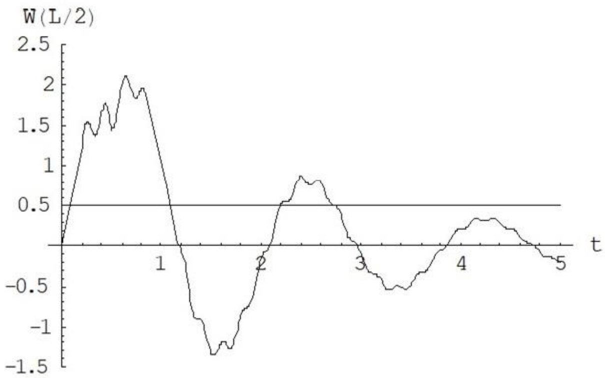


Figure 8. The vertical motion of the middle of the bridge for explosives placed at x=L/4, x=L/2, x=3L/4 but fired at different times and explosions power of 1KT.

In the plots of figure 8, we see the vertical motion of the middle of the bridge for explosives placed at $x = L/2$, and $x = L/4$, $x = 3L/4$, but the two last fired 0.5 sec later than the first one. Comparing the deformations of fig.8 to those of fig.5 we observe decrease of deformations.

4.1.2. Torsional motion

Applying the formulae of §3.3 we get the following plots:

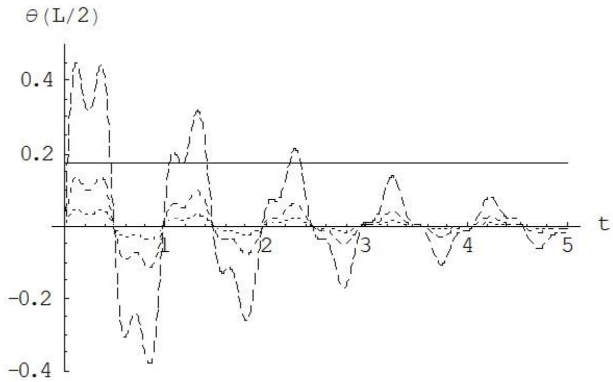


Figure 9. The torsional motion of the middle of the bridge for explosives placed at x=L/2 and explosion power of 1KT (_ _), 0.3KT (- - -), and 0.1KT (…..)

The plots of figure 9, show that the produced torsional deformations for explosive placed at $x = L/2$and power 1 KT are not acceptable.

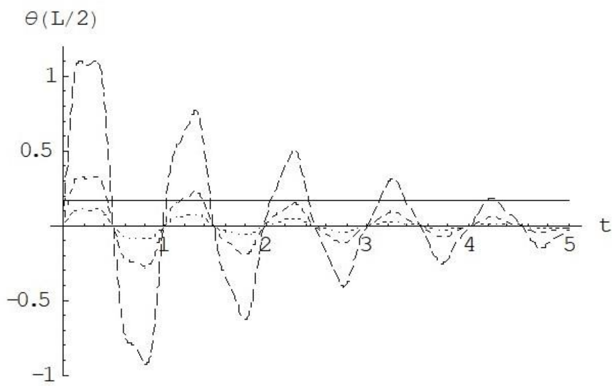


Figure 10. The torsional motion of the middle of the bridge for explosives placed at x=L/4, x=L/2, x=3L/4 and explosions power of 1KT (_), 0.3KT (- - -), and 0.1KT (…..)

The plots of figure 10, show that the produced torsional deformations for explosives placed at $x = L/4$, $x = L/2$, and $x = 3L/4$ are acceptable only for explosives' power 0.1 KT.

5. CONCLUSIONS

In this paper, a simple approach is presented to study the response of a long bridge to stress due to terrorist acts. There are papers, as for example in [36], where the behavior of a bridge has been studied, where explosives have been placed on critical elements of a bridge (such as bars). It has been shown that at least in suspension bridges this has a local influence-effect. Because of the static operation, these conclusions cannot be applied to one span long bridges.

The usual explosions due to terrorist activity amount to maximum power of 0.05 to 0.30 KT. However, we have seen explosions from terrorist acts of power more than 0.3 KT. In unusual rare cases we have explosions of power 0.8 to 1 KT, mainly in emblematic constructions.

In this paper explosions of 0.1, 0.3, and 1 KT (i.e. 100, 300, and 1000 TNT power) placed at different places on the deck of the bridge have been studied.

On the basis of the representative long bridges model analyzed herein, the following conclusions can be drawn.

1. In general, the vertical and torsional deformations seem to be the critical, while the lateral ones are negligible.
2. For the very long bridges of one span.

Vertical deformations due to explosions with explosives placed only in the middle of the bridge span and power greater than 1 KT are not acceptable.

Explosions due to explosives placed in the middle and quarters of the bridge which have a power greater than 0.3 KT cause vertical deformations which are not acceptable.

If the explosives placed in the middle and quarters of the bridge are fired at different times, they could cause greater deformations up to 15%.

As for the torsional deformations due to explosions caused by explosives placed in the middle of the bridge of power greater than 1 KT they are not acceptable, as well as deformations caused by an explosion of explosives placed in the middle and quarters of the bridge and power greater than 0.3 KT are also unacceptable.

REFERENCES

1. USAEC “The effects of Nuclear Weapons”, 1957, 1973+, 1986, Printing Office, Washington D.C.
2. U.S. Department of the Army Technical Manual: TM5-1300, Structures to resist the effects of accidental explosions. United States Department of the Army, Navy and Air Force, USA, 1990
3. U.S. Department of Defense Unified Facilities Criteria, DoD Minimum antiterrorism standards for buildings, 2002.
4. American Society of Civil Engineers, Minimum design loads for buildings and other structures, 2002.
5. EN 1990:2002 Eurocode - Basis of structural design, 2002.
6. prEN 1991-1-7, Eurocode 1 - Action on structures, General actions - Accidental actions European Standard.
7. Cowper, G.R. and Symonds, P.S.: Strain hardening and strain rate effect in the impact loading of cantilever beams. Brown University, Division of Applied Mathematics report, 1957; 28
8. Baker W.E., Cox P.A., Westine P.S., Kulesz J.J. and Strehlow R.A.: Explosion hazard and Evaluation. Elsevier. New York, USA, 1985.
9. Ghali, A., & Tadros, G. (1997). Bridge progressive collapse vulnerability. Journal of the Structural Engineering,123(2), 227–231.
10. Manual of steel construction: Load & resistance factor design. American Institute Steel Construction, 2001.

11. Paik J.K. and Thayamballi, A.K.: Ultimate Limit State Design of Steel-Plated Structures. John Wiley & Sons Hoboken, NJ, USA, 2003.
12. Ray, J. C., Armstrong, B. J., & Slawson, T. R. (2003). Air blast environment beneath a bridge overpass (pp. 63–68). Transportation Research Record 1827, Transportation Research Board, Washington, DC.
13. Marchand, K., Williamson, E. B., & Winget, D. G. (2004). Analysis of blast loads on bridge substructures. In Proceedings of the structures and materials (pp. 151–160). Southampton: Wit Press.
14. Anwarul Islam, A. K. M., & Yazdani, N. (2008). Performance of AASHTO girder bridges under blast loading. *Engineering Structures*,*30*(7), 1922–1937.
15. Kiger, S. A., Salim H. A., & Ibrahim, A. (2010). Bridge vulnerability assessment and mitigation against explosions. Midwest Transportation Consortium. Iowa State University.
16. Williamson, E. B., Oguzhan, B., Williams, G. D., & Davis, C. E. (2010). Blast-resistant highway bridges: design and detailing guidelines. TRB's National Cooperative Highway Research Program (NCHRP) Report 645.
17. Bi, K., Ren, W. X., Cheng, P. F., & Hao, H. (2015). Domino-type progressive collapse analysis of a multi-span simply-supported bridge: A case study. Engineering Structures,90, 172–182.
18. Baylot, J. T., Ray, J. C., & Hall, R. L. (2003). Prediction method for response of steel bridge beams and girders to blast and fragment loads (pp. 69–74). Transportation Research Record 1827, Transportation Research Board, Washington, DC.
19. Miyachi, K., Nakamura, S., & Manda, A. (2012). Progressive collapse analysis of steel truss bridges and evaluation of ductility. Journal of Constructional Steel Research,78, 192–200.
20. Baker, W.E.: Explosions in Air. University of Texas Press. Austin, Texas, USA, 1973.
21. Scott, B.D., Park, R., and Priestley, M. J. N.: Stress-Strain behavior of concrete confined by overlapping hoops at low and high strain rates. ACI J. 1982;79(1):13-27
22. Soroushian, P., Choi, K. and Alhamad, A.: Dynamic constitutive behavior of concrete. ACI J. 1987, 83 (2): 251 -258
23. CEB-FIP model code 1990. Comite´ Euro-international du Be´ton. Trow-bridge. Redwood books. Wiltshire, UK, 1993
24. Malvar, L. J. and Crawford, J. E.: Dynamic increase factors for concrete. Twenty-Eighth DDESB Seminar, Orlando, FL, USA, 1998
25. Xu, Z., Lu, X., Guan, H., Lu, X., & Ren, A. (2013). Progressive-collapse simulation and critical region identification of a stone arch bridge. Journal of Performance of Constructed Facilities,27, 43–52.
26. Son, J., & Astaneh-Asl, A. (2009). Blast protection of cable-stayed and suspension bridges. In Proceedings of the TCLEE conference on lifeline earthquake engineering in a Multihazard environment (pp. 1–12). Reston, VA: ASCE.
27. Hao, H., & Tang, E. K. C. (2010). Numerical simulation of a cable-stayed bridge response to blast loads, Part II: Damage prediction and FRP strengthening. Engineering Structures,32(10), 3193–3205.
28. Cai, J., Xu, Y., Zhuang, L., Feng, J., & Zhang, J. (2012). Comparison of various procedures for progressive collapse analysis of cable-stayed bridges. *Journal of Zhejiang University-Science A (Applied Physics & Engineering)*,*13*(5), 323–334.
29. Hashemi, S. K., Bradford, M. A., & Valipour, H. R. (2016). Dynamic response of cable-stayed bridge under blast load. Engineering Structures,127, 719–736.
30. Sherbaph, M. (2013). Study and investigation of the effects of the explosion on suspension bridges. MSc dissertation, University of Tabriz, Department of Civil Engineering (In Persian)
31. Ray, J. C. (2006). Validation of numerical modeling and analysis of steel bridge towers subjected to blast loadings. In Proceedings of the structures congress and expositions (pp. 1–10). Reston, VA: ASCE.
32. Tang, E. K. C., & Hao, H. (2010). Numerical simulation of a cable-stayed bridge response to blast loads, Part I: Model development and response calculations. Engineering

Structures,32(10), 3180–3192.

33. Ibarhim, A., Salim, H., & Rahman, N. A. (2012). Progressive collapse of post-tensioned box girder bridges under blast loads using applied element method. In *Structures congress* (pp. 2291–2300). Reston, VA: ASCE.
34. Tian, L., & Huang, F. (2013). Numerical simulation for progressive collapse of continuous girder bridge subjected to ship collision based on three-stage simulation method. Advanced Materials Research,790, 362–366. https://doi.org/10.4028/www.scientific.net/AMR.790.36.
35. Tian, L., & Huang, F. (2014). Numerical simulation for progressive collapse of continuous girder bridge subjected to ship impact. Transactions of Tianjin University, 20, 250–256. https://doi.org/10.1007/s12209-014-2216-8.
36. Farahmand-Tabar, S., Barghian, M., & Vahabzadeh M., Investigation of the Progressive Collapse in a Suspension Bridge under the Explosive Load., Int. Journal of Steel Structures, 2019, 19(6): 2039-2050.
37. Fujikura, S., & Bruneau, M. (2011). Experimental investigation of seismically resistant bridge piers under blast loading. Journal of Bridge Engineering,10(1061), 63–71.
38. Wawranek A., Steinhard O., Theory und berechnung der Stahlbrücken, 1958, Springer Verlag, Berlin
39. Michaltsos G.T. and Raftoyiannis, I.G., (2012), “Bridges’ Dynamics”, e-Book, Bentham Sciences Publ., UAE
40. Michaltsos G.T. and Sophianopoulos D.S. (2021), “Suspension Bridges under Blast Loads: A preliminary linearized approach”, Archive of Applied Mechanics, https://doi.org/10.1007/s00419-021-01991-5