# Analysis of Reinforced Concrete Structures for Accidental Blast during Launching of a Rocket

Lovepreet SINGH*[,1], Nirmal Rakeshbhai RAVALIYA[1], M. Abdul AKBAR[1]

*Corresponding Author
[1]Department of Civil Engineering,
Dr. B R Ambedkar National Institute of Technology, G.T. Road, Amritsar Bypass,
Jalandhar- 144011, Punjab, India,
lovepreets8895@gmail.com*, nirmalcivil99@gmail.com, maakbar83@yahoo.co.in

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***Abstract:*** *Despite the greatest efforts, accidents continue to happen during the process of rocket launching, either in the form of generated blast wave or the debris that flies and hits random objects. In this paper, the impact of blast loading created by a rocket launch on the tie connection and the three-hinged arch is studied using the finite element model in ABAQUS. The impact of rocket launching was modelled using the physical characteristics/geometry of the launch pad, and a blast load intensity equivalent to 20,000lbs of TNT is applied using the CONWEP module. The tie connection and three-hinged arch after validation and mesh convergence study are applied with service loads in concurrence with the blast loading. The additional impact of blast loads on the static and dynamic response of the structure is studied. The distance of the structures from the point of blast (rocket launching site) is varied, and parametric studies are carried out to arrive at detailed guidelines on the minimum safety distance that stand-alone civil infrastructure should follow in order to minimize the rocket launching impact.*

***Key Words:*** *Rocket launching, Air blast, Blast loading, Blast wave, Finite element analysis, RC structures, TNT, CONWEP*

## 1. ROCKET LAUNCHING

Rocket launching is a moment of great pride for any nation. Space research organizations mainly use it to find out important facts about space and the solar system. They explore space for valuable metals, rare objects, precious materials, medical research purposes, etc., and hence for the nation's service. Rockets are extensively used for launching satellites, human spaceflight, and space exploration. Thus, the number of launches has been growing at an average rate of about 8% per year during the past decade [1]. Rockets are also used as a missile in several military operations to propel warheads to their targets.

On the other hand, with the rapid growth of space industry, gases and debris released through rocket exhaust increasingly accumulate in the atmosphere. A large amount of explosive material is required to launch a rocket, which produces booster emission of gases such as carbon dioxide, oxides of aluminium and nitrogen, hydrogen chloride, soot, etc., which has a significant impact on the environment [2]. If a sudden accident happens in the air, it can cause damage to structures and people by the blast wind, debris, and fires. For instance, during the moon race, a soviet N-1 rocket exploded seconds after lift-off with an approximate yield of 1kt of trinitrotoluene (TNT) on 3rd July 1969 Tyuratam, Russia. The residents saw an enormous bright light burst at 35km away from the exploded site, and windows were blown out of the apartment buildings by the blast waves [3].

Also, on 1st September 2016, SpaceX Falcon 9 rocket exploded in the final minutes of a simulated countdown at Cape Canaveral, U.S. (Figure 1) [4]. While economic and technical considerations are vital to the success of any space mission, it is also important that environmental considerations be included to avoid long-term environmental damage [5]. Therefore, blast and sound waves produced from explosions significantly affect people, environment, and infrastructure.

Figure 1. SpaceX Falcon 9 rocket explosion [4]

## 2. BLAST LOADING

Blast loading is a short-duration load coming under the category of impulsive loading. The response of the structure to the explosion is governed by ductility and the natural period of vibration of a structure. An explosion is described as a large-scale, rapid, and sudden release of energy. When detonated, explosives create blast (shock) waves that can result in widespread damage to the surroundings.

Examples include trinitrotoluene (TNT) and ammonium nitrate and fuel oil (ANFO). The blast wave is unsafe, mainly when one is extremely near the centre. A blast wave voyages quicker than the speed of sound and the section of the shock wave keeps moving for a couple of milliseconds. The blast impacts are manifested as a high-intensity wave that spreads outward from the source to the surrounding air. As the wave propagates, it diminishes in strength and speed (Figure 2).

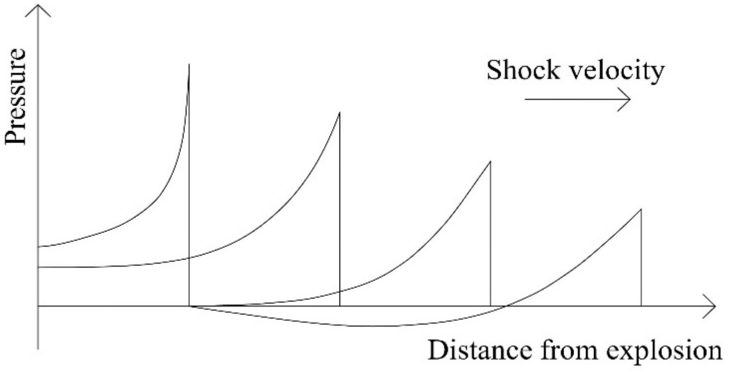



Figure 2. Blast wave propagation

**Effects of Blast Loads on Structures**

Structural behaviour during a blast relies totally upon the materials utilized in the construction of the structure. After hitting the face of the structure exposed directly to blast loading, the shock front from an explosion is instantly reflected. This impact with the structure imparts momentum to its exterior components. The corresponding kinetic energy of the moving parts should be absorbed or scattered in order for them to survive the blast without collapse. For the most part, this is accomplished by converting the moving component's kinetic energy to strain energy in the resisting elements. Typically, the resisting elements such as windows, exteriors of the structure, and support columns fail, causing partial damage through the structure's progressive collapse [6].

The structural design codes for civil infrastructure worldwide are primarily based on a linear elastic approach (i.e., the loads are within the linear proportionality limits of stress and strain) and blast loading as a type of loading to be considered in design only in its introductory stages. Hence, blast loading is typically not considered during the design of structures. Therefore, it is a new area to study while designing the critical structures near the accidental blast sites such as rocket launching sites, explosive chemical manufacturing sites, etc. In this work, the impact of the accidental explosion during rocket launch just after the take-off on two isolated civil structures (three-hinged arch and tie connection) is studied. Based on the analysis results, guidelines were developed on the minimum safe distance at which the structure should be placed if it is not designed for the blast loading.

## 3. NUMERICAL MODELLING

As part of the objective of this study, two isolated civil structures (three-hinged arch and tie connection) were modelled, and detailed finite element analysis was carried out using ABAQUS. The impact of the accidental blast during rocket launch just after the take-off was studied as a function of the height of the blast and distance of the civil infrastructure. In this study, the following assumptions were made:

(1) The height of the blast considered in this study is sufficiently high that the effect of the surface is minimal, and hence the blast can be assumed as an air blast.

(2) The rocket at the moment of the blast is still in its vertical trajectory and has not changed its direction.

(3) The waves of the blast at the instant of the accident spread uniformly outwards similar to a typical explosion without the interference of local effects.

(4) The location of the blast is a single point considered at the geometric center of the nozzles of the rocket.

Air blast of the accidental rocket explosion was modelled using the CONWEP module in ABAQUS. The CONWEP blast loading model is based on an equivalent mass of TNT explosion (assumed air blast). The air blast loading is defined by the location of the explosion, the time of detonation, and the loading surfaces. An equivalent mass of 20,000lbs of TNT with a time of detonation of 0s and a magnitude scale factor of 1 was used to develop the blast parameters required to generate the blast waves. Incident wave interactions and acoustic wave formulations were used, and the whole simulation was carried out using linear dynamic, explicit analysis. This work was carried out in two stages. In the first stage, both the isolated structures were subjected to a point load of 66.66kN (considered a factor of safety of 1.5 for the factored load of 100kN), as shown in Figure 3. The linear dynamic, explicit analysis was carried out to obtain the displacements at three nodes (represented as 1, 2, and 3), assuming three degrees of freedom for the structures (Figure 3). In the second stage, the impact of the accidental air blast during rocket launch just after the take-off at different heights and different distances on both the structures subjected to a point load of 66.66kN was analyzed. Then the corresponding displacements at these nodes were obtained. The displacements obtained at the three nodes from both analyses were compared to arrive at the minimum safe distance guidelines at which the isolated civil infrastructure should be placed if it is not designed for the blast loading.

As seen from Figure 3, the degrees of freedom considered for the arch is along the vertical direction as opposed to the horizontal degrees of freedom considered for the tie connection. Thus, the combined result will provide the effect of the direction of the degrees of freedom in determining the safe distance from the blast. The impact of the blast on the structures also depends on the height of the explosion.

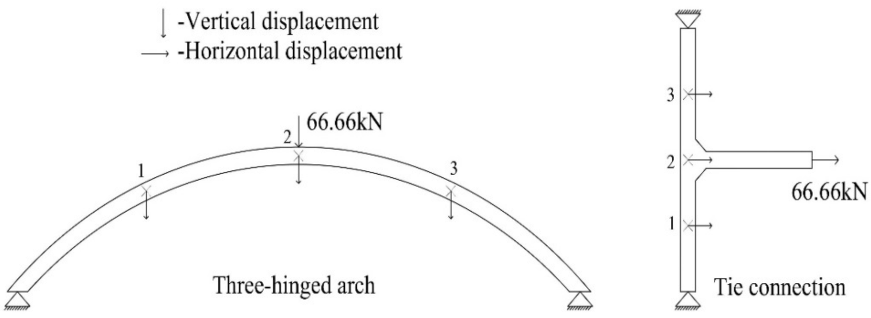



Figure 3. Degrees of freedom considered in the analysis

For the three-hinged arch, the impact of air blast was analyzed by fixing the height of the blast at 48m (four times higher than the launch pad's height as per [7]) and varying the horizontal distance (100m, 200m, 300m, 400m, 500m, 600m, 700m, and 800m) from the point of explosion to the structure. For the tie connection, the same impact was analyzed when the horizontal distance from the point of blast to the structure was fixed as 100m and varying the blast height (48m, 100m, 150m, 200m, and 250m). The pictorial representation of the accidental air blast during the rocket launch and generation of blast waves after the explosion, including isolated civil structures, is shown in Figure 4.

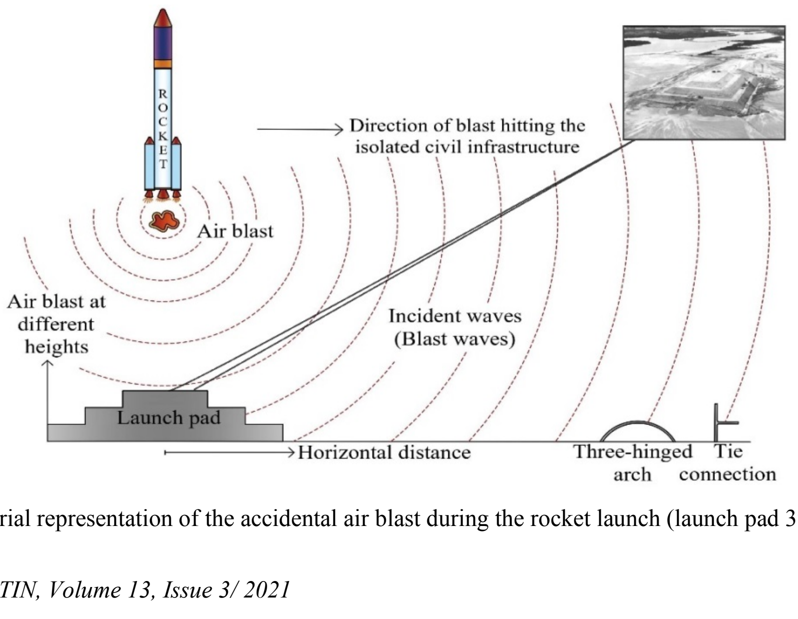



Figure 4. Pictorial representation of the accidental air blast during the rocket launch (launch pad 39A in inset [7])

### Three-Hinged Arch

The geometric model of the Reinforced Cement Concrete (RCC) three-hinged arch was taken from the Indian code SP 34(S&T) (1987), with lead as the resilient material to fill the gap at the crown of the arch [8]. The arch member's tracing was performed using AutoCAD to get the notch proportions in relation to other dimensions for the resilient fill and derive its equation. The three-hinged arch of span 15m and rise at the central crown point of 3.097m finalised based on the equation and subjected to 100kN point load including the factor of safety (1.5) at its geometric center.

The grade of concrete and grade of steel used in the design are M25 and Fe500, respectively. The design for bending and shear was performed using spreadsheet following the design philosophy of Limit State Method (LSM) based on the Indian codes, IS 456 (2000) and SP 16 (1980) [9, 10].

Then, the arch was checked for safety in compression using Working Stress Method (WSM) based on IS 456 (2000) Annex B [9]. The stability (buckling) check was performed approximately using the Boussinesq equation assuming the arch to be circular [11].

In the arch, the main reinforcing bars cross each other at an angle of 60°, so that it behaves as an internal hinge at the crown, and the stirrups were drawn in AutoCAD (as the stirrup length and spacing were not uniform throughout the arch length) and then imported to ABAQUS. All the reinforcement was embedded in concrete, and a tie constraint was provided between concrete and lead (resilient fill).

The final dimensions for the notch portion to fill the resilient material (lead) corresponding to the depth of 400mm of the arch was 110mm×140mm.

The three-hinged parabolic arch of cross-section 200mm×400mm with span 15m and rise 3.097m, and two numbers of 20mm diameter bars at both top and bottom face and 2 legged 8mm diameter stirrups at 260mm c/c spacing used to confine these bars were modelled in ABAQUS (Figure 5- the reinforcement and the concrete portions shown separately for clarity). For the resilient fill (lead), the density of 11343kg/m$^3$, the modulus of elasticity of 14GPa, and the Poisson's ratio of 0.42 used [12], and the other parameters selected for modelling are given in Table 1.

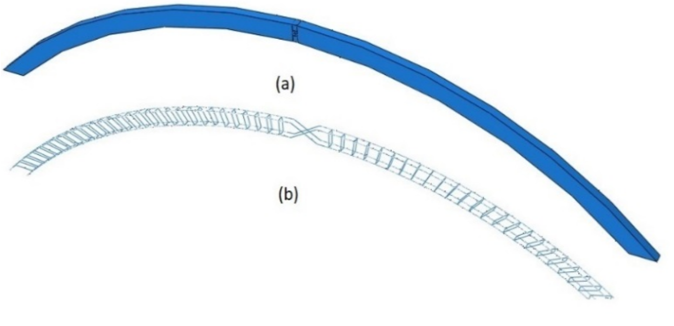



Figure 5. ABAQUS modelling of (a) arch with lead at the crown, and (b) reinforcement

Mesh convergence study was carried out for the arch by varying the mesh size. The work was validated with the vertical reaction at the supports and the shear force developed at the crown. Theoretical vertical reaction at each support, when the arch is subjected to a point load of 100kN at the crown and due to its self-weight, is 66.1328kN and that obtained through ABAQUS analysis is 66.08kN (difference of 0.08%). The theoretical jump in shear force at crown is 100kN, and the results obtained through ABAQUS analysis is 105.875kN (5.88% difference).

### Tie Connection

The details and geometric model of RCC tie connection were taken from the Indian code SP 34(S&T) (1987) [8], and tracing for the proportions including notch dimensions was performed using AutoCAD. A notch of length 150mm at the junction of vertical and horizontal member (Figure 3) at an angle of 45° based on the proportions in relation to other dimensions was provided to reduce the effect of stress concentration at the joint. A horizontal pressure load equivalent to 100kN (including factor of safety of 1.5) is applied at the end face of the horizontal member. Height of the vertical member was taken as 6m (twice the typical storey height of 3m), and the design for flexure and shear was performed using spreadsheet following the LSM philosophy based on the Indian codes, IS 456 (2000) and SP 16 (1980) [9, 10]. The horizontal member of the tie connection was designed for tension using WSM philosophy based on IS 456 (2000) Annex G. For the vertical member, a cross-section of 380mm×400mm with four tension bars and two compression bars of 22mm diameter, and that for the horizontal member, a square cross-section of 380mm with four tension bars of 16mm diameter and two compression bars of 12mm diameter was used for modelling in ABAQUS. The stirrups of 2 legged 8mm diameter at 240mm c/c spacing were used for the whole geometry. The reinforcement and the concrete portions are shown separately for clarity in Figure 6. The reinforcement provided for the tie connection was embedded in the concrete. All other parameters used for modelling the tie connection are the same as those used for the three-hinged arch (Table 1).

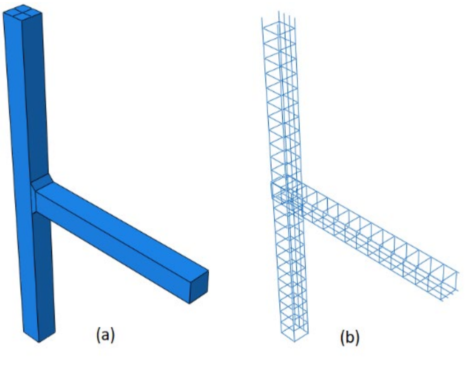



Figure 6. ABAQUS modelling of (a) tie connection with notch, and (b) reinforcement

Table 1. Parameters used in modelling

| Property | Value |
|---|---|
| Density of concrete | 2400kg/m$^3$ |
| Modulus of elasticity of concrete | 25000MPa (5000$\sqrt{f_{ck}}$ [9], $f_{ck} =$ grade of concrete = 25MPa) |
| Poisson's ratio of concrete | 0.233 |
| Density of steel | 8050kg/m$^3$ |
| Modulus of elasticity of steel | 210000MPa |
| Poisson's ratio of steel | 0.3 |
| Boundary condition | Point hinge support at the center of the face (Figure 3) |
| Method of analysis | Dynamic, explicit |
| Element types | C3D8R, an 8-node linear brick, reduced integration, hourglass control element for concrete and lead. T3D2, a 2-node linear, 3D truss element for reinforcement and stirrups [13] |

Convergence study was carried out for the tie connection by varying the mesh size. The work was validated with the horizontal displacement at the junction of the vertical and the horizontal member.

The theoretical values for the same using the double integration method is 7.231mm (calculated at the center of the vertical member including an assumed load dispersion of 45°) and obtained by ABAQUS analysis is 7.634mm (difference of 5.57%).

## 4. RESULTS AND DISCUSSIONS

**Without Blast Loading (First Stage)**

Both the structures were subjected to 66.66kN point load (as equivalent pressure load for the tie connection), and the peak displacements at nodes 1, 2, and 3 (Figure 3) were calculated after the linear dynamic, explicit analysis.

For the three-hinged arch, at nodes 1 and 3, the vertical downward displacement of 0.73mm and 0.80mm was observed, and at node 2, a comparatively higher displacement of about 11.44mm was observed.

For the tie connection, horizontal displacements 6.32mm, 9.22mm, and 6.60mm were observed at nodes 1, 2, and 3, respectively.

**With Blast Loading (Second Stage)**

In this stage, the additional air blast load of an equivalent mass of TNT of 20,000lbs was applied with the static load of 66.66kN, and displacements were calculated at the three nodes.

For the three-hinged arch, the vertical downward displacements were observed by varying the horizontal distance from the point of the explosion at a height of 48m to the center of the structure and that for the tie connection, results for the horizontal displacements, varying the height of the blast (48m, 100m, 150m, 200m, and 250m) at a distance of 100m, were observed.

The top surface of the arch and the side surface of the vertical member of the tie connection (the blast loading surfaces) were exposed to blast loading. At node 2, for the three-hinged arch, the peak displacements of 10.54mm, 11.99mm, and 11.44mm were observed at a distance of 100m, 200m, and 300m, respectively.

The same displacement of 11.44mm was observed when the blast happened beyond 300m, which was the same as that obtained for the first stage which indicates that the effect of the blast was not significant beyond this length.

After 300m, the node 2 acts as a stiff joint, and there was not any additional impact due to the blast loading.

The graphical representation of the displacements at node 2 at different distances for 2s is presented in Figure 7(a).

For the tie connection, the peak displacements of 11.03mm, 9.44mm, and 9.22mm were observed at the height of 48m, 100m, and 150m, respectively.

The same displacement value of 9.22mm as obtained in the first stage was observed when the height of the blast exceeded 150m. The displacements at node 2 at different heights for 2s is presented in Figure 7(b).

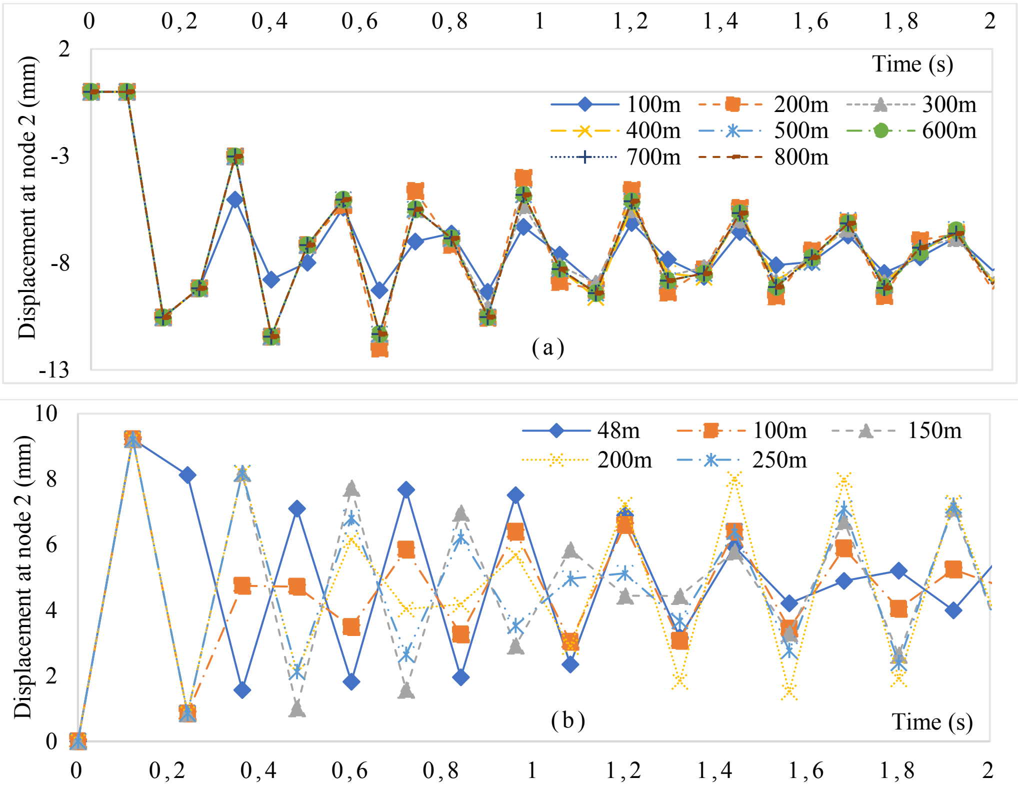



Figure 7. Displacements at node 2 for (a) the three-hinged arch at different distances, and (b) the tie connection with explosion at different heights for 2s

At nodes 1 and 3, a maximum displacement of 7.73mm and 7.77mm was observed for the three-hinged arch when the structure is at a distance of 100m followed by a sharp decrease in the displacements to 3.21mm and 3.37mm, respectively, for a distance of 200m. For larger distances, the displacements were continuously decreasing, and at 800m, it was within the safe range as obtained in the first case with displacement of 0.73mm and 0.80mm at nodes 1 and 3 respectively (Figure 8(a)).

For the tie connection, at the height of 48m, the peak displacement of 7.48mm and 8.13mm was observed at nodes 1 and 3, respectively. The displacement decreased with an increase in the height and remained constant after 150m with the displacement of 6.32mm and 6.60mm at nodes 1 and 3, respectively (Figure 8(b)).

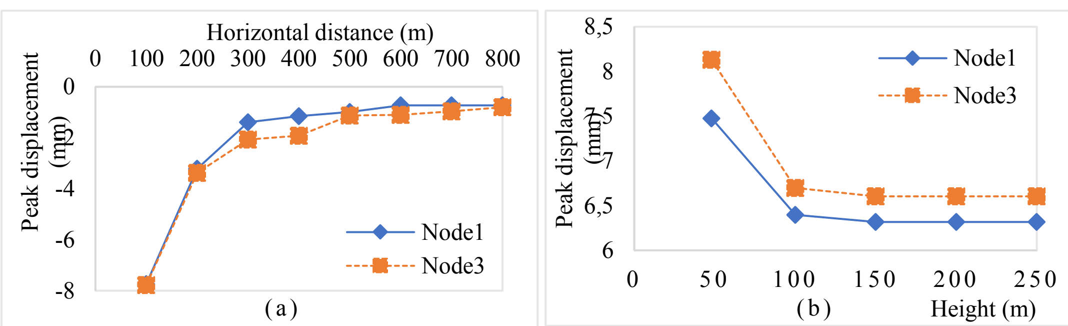
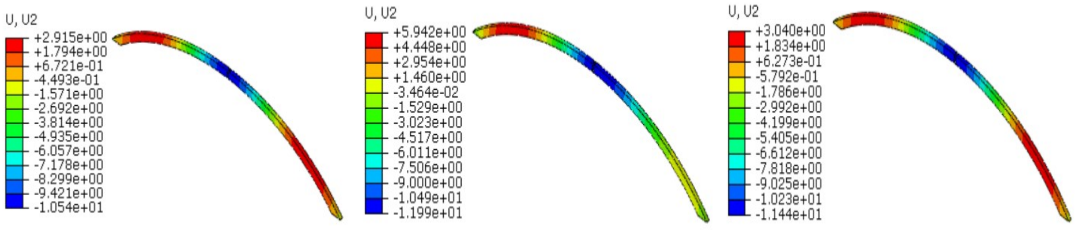


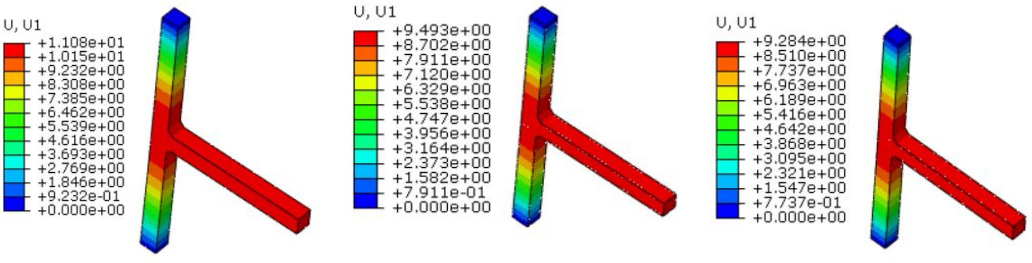

Figure 8. Peak displacement at nodes 1 and 3 for (a) the three-hinged arch, and (b) the tie connection

Displacement contour plots (maximum) for the three-hinged arch and the tie connection showing the displacement at different distances and different heights are presented in Figure 9 and Figure 10, respectively.




(a) (b) (c)

Figure 9. Vertical displacements for the three-hinged arch at (a) 100m, (b) 200m, and (c) 300m distance from the source of the explosion




(a) (b) (c)

Figure 10. Horizontal displacements for the tie connection at (a) 48m, (b) 100m, and (c) 150m height from the ground level

After comparing the results of both stages, it was observed that an isolated three-hinged arch could be constructed at a safe distance of 800m from the point of explosion if the accidental blast happened at 48m from the ground level. An isolated tie connection is secure to be constructed at a distance of 100m from the point of explosion if the explosion occurs at the height of 150m from the ground level. The results may however change if the degree of freedom considered for the tie connection is the vertical displacement of the free end as opposed to the horizontal displacement considered in this study.

## 5. CONCLUSIONS

The paper presents the results of accidental blast of a rocket take-off and the impact if can have on isolated civil infrastructure namely a three hinged arch and a tie connection. Based on the study, following conclusions were made:

- As expected, the impact of air blast on the structures decreases with an increase in horizontal distance between the source of the explosion and the structure as the intensity of blast waves decreases with increase in distance.
- An increase in the height of the explosion from the ground level imparts a comparatively less or negligible impact on the isolated civil structures as the intensity of blast waves decreases with increase in the height of blast.
- For isolated three-hinged arch, negligible impact was seen beyond a distance of 800m from the point of explosion when the blast happened at a height of 48m. Thus, the minimum safe distance to stand-alone a three hinged arch could be 800m.

- For isolated tie connection, beyond the explosion height of 150m and at a horizontal distance of 100m from the point of explosion, almost negligible impact was observed. Hence, the minimum safe distance to construct the structure could be 100m if the blast happened at 150m height from the ground level. The minimum distance may change if the degree of freedom considered is the vertical displacement.

Blast loading as a type of loading for civil infrastructure is only in its implementation stage in many country codes worldwide. Among the type of blast loads, the load of accidental blast due to rocket launching is more predictable unlike regular blast loads and hence provide a better platform to study the impact of blast loads on civil infrastructure.

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