# EMPIRICAL ANALYSIS OF BLAST RESISTANCE: A COMPARATIVE STUDY OF REINFORCED CONCRETE AND STEEL-PLATE COMPOSITE WALLS

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**ABSTRACT**

*Conventional structures are not designed to resist blast loads; hence, serious damage occur when they fall victim of blast event. As a result of increase in terrorist attacks on global scale, blast resistant design is becoming a necessity to safeguard the structural integrity of our structures, most especially those structures that bear national or cultural symbolism. This study estimated the effects of blast load on building wall from charge weight of 455 kg at varying stand-off distances. The studied wall was designed as reinforced concrete (RC) and steel-plate composite (SC) elements to resist the generated blast load using SDOF system approach outlined in UFC. It was observed from results that increasing stand-off distance from 2.25m to 7m at a constant charge-weight resulted in a significant decrease in blast loads. The results also indicated that SC wall resist higher blast load than RC wall by 46%. It was concluded that SC wall performs better than RC wall under blast load of the same magnitude, and that stand – off distance plays a critical role in blast load effect. It was recommended that protective structure should be positioned at clear distance from explosion. SC section be considered for blast proof structural design and construction of structures.*

**Keywords:** Structural integrity, Blast resistant, Blast load, Stand-off distance, Building wall

## 1 INTRODUCTION

Protecting conventional structures from collapse in case of blast events is becoming one of the most critical challenges for structural engineers recently. These structures usually are not designed to resist blast loads and the magnitudes of their design loads are much lower than those generated by most blast hence is susceptible to critical damage during explosion [1]. Prior to the advent of terrorist attacks on random structures in recent years, blast resistant design is only applicable to military facilities and structures where accidental explosion is expected such as petrochemical structures and nuclear facilities. Damage to structures, loss of lives and societal panic are factors that have to be minimized if the terror threat cannot be completely stopped [2]. Terrorism is one of the most dangerous problem the world is facing recently. This problem caused the feeling of insecurity in different part of the world despite the technology advancement in different fields [1]. Terrorism is of various forms ranging from kidnapping, assassination, armed assault, bombing etc, however according to the data from National Consortium for the Study of Terrorism and Response to Terrorism (START), during the past couple of decades, attacks related to bombing outstripped one-half of the total number of terror attacks on a global basis, and Nigeria is the third most terrorised country after Iraq and Afghanistan [3]. The terror attack of 11 September 2001 on the World

Trade Centre New York, and attack on so many bridges in California have greatly influenced the methods used in design and construction of structures all over the world especially the United States U.S. [4]. These terrorist attacks are not only targeted on military facilities but also on some selected high value targets, instances are the UN building in Kabul (Afghanistan), the UN building in Abuja (Nigeria), the US embassies in Nairobi (Kenya) and Darus Salam (Tanzania) [5]. As terrorist activities are on the rise, many structures may be subjected to blast loads during service life. Nonetheless, information related to this field are mostly classified by developed nations for security reasons. Hence, the need for blast related research is growing. This study assembled important information on explosives, blast phenomena, and simplified designs approach for blast resistant structures. The performance of RC and SC walls subjected to blast load from 455kg TNT equivalent charge-weight was studied using Single degree of freedom (SDOF) approach. SDOF design of blast-resistant structure has similar approach to conventional design of structures, starting with load estimation followed by analysis and design. The most important blast wave parameters in blast load estimation include: Incident pressure ($P_{so}$), reflected pressure ($P_r$), incident impulse ($i_{so}$), reflected impulse ($i_r$), and arrival time ($t_A$) [6]. Steel–Plate Composite (SC) wall is made up of two steel sheets sandwiched with mass or reinforced concrete (Figure 1). Shear connectors such as studs are provided to anchor the steel plates. On the other hand, reinforced concrete (RC) wall is a doubly reinforced section in both faces.

Figure 1. skeletal frame of an SC element

## 1.1 Explosion and Blast Phenomena

An explosion is an extremely fast chemical reaction that takes place within few milliseconds, where very hot gases are generated. A very large expansion of these gases will force the air around the explosion event to be compressed and form a blast wave. The blast wave travels due to the disequilibrium between the very hot wave and the undisturbed air around the explosion centre. As the wave moves away from the explosion centre, the duration of the shock increases and its amplitude decreases. The pressure at the tail falls below the atmospheric pressure as a result of over-expansion at the explosion centre. This produces a negative/suction phase, which follows the positive pulse [6]. When a blast wave hits a solid surface, it bounces back transmitting energy to the solid surface from the blast wave. Due to this transferred energy, the surface will exert a force to the air local to it. By Newton's third law, the air will exert equal force on the surface and pressure will be locally increased above the incident pressure. Thus, incident wave is reinforced and reflected due to its interaction with hard surface [6]. It is common practice to scale known parameters in blast load estimation. The scaling rule is the cube root or Hopkinson-Cranz law. According to cube root law, similar blast wave are produced at identical scaled distances when two explosives charges of the same explosive but of different sizes are detonated in the same atmosphere.

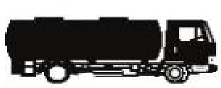
$$Z = \frac{R}{\sqrt[3]{W}} \tag{1}$$

where, Z is scaled distance, R detonation distance from a target, W mass of explosive.

### 1.2 Trinitrotoluene (TNT)

Trinitrotoluene known as TNT, is an artificial chemical compound that is highly explosive, solid, yellowish and odourless which can dissolve in or absorbs water. This property allows it to be used in wet environment. TNT is the most commonly used explosives for industrial and military purposes. Its usage for military purposes has gained momentum during World War I and became the most dominant explosives in military. It has a melting point of about 810ºC, (this is below its detonation temperature) which makes it easy to be poured in to shells after melting [7]. According [8], the equation and charts used for the estimation of blast load parameters are based on experimental studies with TNT explosive. Various materials are used by terrorists to produce explosives. Table 1 presents TNT equivalence in Kg of the explosive amount contained in various containers.

Table 1. TNT equivalence in Kg of the explosive amount contained in various containers

| Explosion source | Amount TNT | Limit for damage to eardrum[1] | Slight damage to residential houses[2] | Limit for window damage[3] |
|---|---|---|---|---|
| Pipe Bomb  | 2.3 Kg | - | 21 m (8 kPa, 26 Pas) | 259 m (0.3 kPa, 2 Pas) |
| Suitcase Bomb  | 3 Kg | - | 46 m (8 kPa, 26 Pas) | 564 m (0.2 kPa, 4 Pas) |
| Small passenger car  | 227 Kg | 30 m (44 kPa, 370Pas) | 98 m (8 kPa, 120 Pas) | 457 m (1 kPa, 25 Pas) |
| Big passenger medium car  | 455 Kg | 38 m (44 kPa, 460Pas) | 122 m (8 kPa, 150 Pas) | 534 m (1 kPa, 34 Pas) |
| Van/Minivan  | 1818 Kg | 61 m (43 kPa, 720Pas) | 195 m (8 kPa, 240 Pas) | 838 m (1 kPa, 54 Pas) |
| Small truck  | 4545 Kg | 91 m (37 kPa, 900Pas) | 263 m (8 kPa, 330 Pas) | 1143 m (1 kPa, 73 Pas) |
| Truck without trailer  | 13636 Kg | 137 m (34 kPa, 1250Pas) | 375 m (8 kPa, 480 Pas) | 1982 m (1 kPa, 87 Pas) |
| Truck with trailer  | 27273 Kg | 183 m (31 kPa, 1490Pas) | 475 m (8 kPa, 600 Pas) | 2135 m (1 kPa, 130 Pas) |

Legend* 1) Lethal air blast range, 2) Building evacuation distance, 3) Outdoor evacuation distance [9]

## 2 METHODOLOGY

### 2.1 Load estimation and design of members

In carrying out the blast load analysis the procedure below was followed. The expected charge weight, type and detonation distance were established. Using information in (a) above, the blast wave parameters were determined. These include Peaked incident and reflected pressures ($P_{so}$, $P_r$), Incident and reflected impulses ($i_{so}$, $i_r$). Wave front velocity and wavelength ($L_W$). Arrival time ($T_A$). Duration of positive phase ($t_o$). The idealised pressure diagrams were constructed for different parts of the structure based on the information in (b). The structural response and design by simplified member by member analysis technique as outlined in [8], was followed to determine suitable reinforced concrete section. Likewise, the Steel-plate (SC) composite wall was modelled as a simply supported element subjected to blast load and analysed using the provisions of [10] and [8] approach. The resistance-deflection parameters were assumed to be elasto-plastic in which the elastic stiffness $K_1$ and elastic resistance $R_y$ were calculated from equations 2 and 3 respectively.

$$R_y = \frac{8M_y}{L} \tag{2}$$

$$K_1 = r_1 . \frac{384EI_{eff}}{5L^3} \tag{3}$$

$$M_e = K_{LM}.[Lb(t_{ce} + 2t_pt_s)] \tag{4}$$

The effective mass of the element $M_e$ which was calculated from equation (4) and elastic stiffness $K_1$ were used to calculate natural frequency $\omega_n$which is subsequently used to calculate normalized total impulse I and normalized total force P, the two were then plotted in response chart of [10] and found the damage state okay. The design of an SC wall is carried out as summarised in Figure 2.

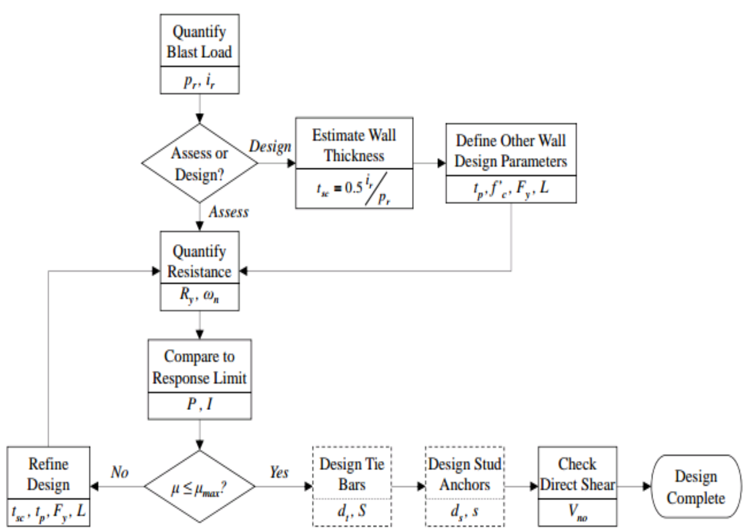



Figure 2. Process followed to design blast resistant SC wall

## 3 RESULTS AND DISCUSSION

### 3.1 Blast Load

From Table 2, it can be observed that the blast wave parameters ($P_r$, $i_r$) for a 455 kg (charge-weight) dropped significantly as the stand-off distance is increased from 2.25m to 7m, and continue to drop slowly as the stand-off distance is increased from 7m to 42m. Increasing stand-off distance beyond 42m became less significant as the pressure generated became very small. The reflected pressure $P_r$ dropped from 100,000 kN/m$^2$ to 9,000 kN/m$^2$ (i.e dropped by 91%) and reflected impulse $i_r$ dropped from 49020 kN/m$^2$-ms to 7353 kN/m$^2$-ms (i.e dropped by 85%) when the stand-off distance is increased from 2.25m to 7m. The blast load generated at 2.25m exceeded the capacity of maximum permissible thickness of both the SC and RC walls as specified by [10] and [8] respectively. RC walls of thicknesses 450 mm, 300mm, 200mm, 150mm, 125mm, 100mm and SC walls of 300 mm, 200 mm, 100 mm, 75mm, 50mm were found adequate to resist the blast loads generated at 7, 14, 21, 28, 35 and 42 meters respectively. It showed that stand-off distance plays a critical role in blast load estimation, and sets the limits for blast pressure and impulse as similarly reported by [11]. Therefore, to provide protection to personnel and equipment (acceptor system) the protective shelters (structures) need to be positioned at distance from the explosion by forcing the terrorist to detonate the bomb as far away as possible by maximizing the stand-off distance.

Table 2. Blast wave parameters for a 455 kg (charge-weight) at stand-off distances of 2.25m - 42m

| Parameters<br>Units | R<br>(m) | Z<br>(m/kg$^{1/3}$) | $P_{so}$<br>(kPa) | $P_r$<br>(kPa) | $i_{so}$<br>(kPa-ms) | $i_r$<br>(kPa-ms) | $L_w$<br>(m) | $t_A$<br>(ms) | $t_o$<br>(ms) |
|---|---|---|---|---|---|---|---|---|---|
| Magnitudes at centre of wall | 2.25 | 0.28 | 12000 | 100000 | 19608 | 49020 | 1.72 | 0.45 | 1.72 |
| | 7.00 | 0.86 | 1700 | 9000 | 1716 | 7353 | 1.63 | 2.86 | 9.80 |
| | 14.0 | 1.71 | 400 | 1400 | 1308 | 3433 | 3.68 | 16.40 | 10.63 |
| | 21.0 | 2.57 | 160 | 400 | 899 | 2206 | 6.13 | 22.06 | 17.97 |
| | 28.0 | 3.42 | 80 | 200 | 654 | 1471 | 7.68 | 40.85 | 28.60 |
| | 35.0 | 4.30 | 50 | 130 | 570 | 1144 | 8.17 | 57.19 | 32.68 |
| | 42.0 | 5.14 | 36 | 90 | 449 | 981 | 9.80 | 73.56 | 35.68 |

### 3.2 Comparison of Blast Load Resistance Between RC and SC Wall

From Table 3, it showed that the RC walls of thicknesses ($T_C$ = 450 mm, 300mm, 200mm, 150mm, 125mm, 100mm) were designed and found as the minimum sections to resist the blast loads at 7, 14, 21, 28, 35 and 42 (case two-case seven) respectively. The reinforcement ratio provided in the vertical and horizontal directions were little above the minimum reinforcement ratio specified by [8] for vertical and horizontal directions. The support rotations of the walls were calculated as 1.99$^o$, 1.83$^o$, 1.80$^o$, 1.92, 1.89 and 1.98$^o$ respectively, while the allowable support rotation of the chosen sections is 2$^o$ therefore the sections were adequate in flexure and shear. It can be observed from Figure 3 that SC wall sections of the same thickness as RC wall resists higher blast load indicating the suitability of SC wall for blast proof structural design and construction (Figure 3).

Table 3. Variation of section thickness of RC and SC walls with reflected pressure

| $P_r$ Magnitude (kPa) | 100,000 | 9000 | 1400 | 400 | 200 | 130 | 90 |
|---|---|---|---|---|---|---|---|
| RC Wall Thickness (mm) | NIL | 450 | 300 | 200 | 150 | 125 | 100 |
| SC Wall Thickness (mm) | NIL | 300 | 200 | 100 | 75 | 50 | 50 |

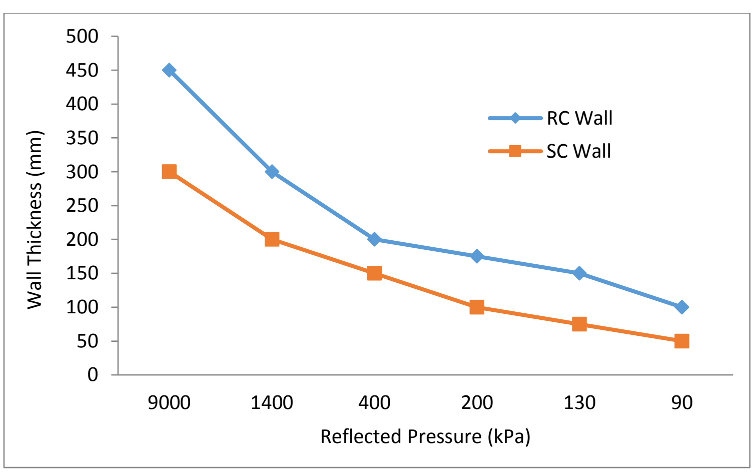



Figure 3. Variation of section thickness of RC and SC walls with reflected pressure

## 4. CONCLUSIONS

Based on the results and observations from the design of RC and SC walls, the following conclusions were drawn: Reflected pressure ($P_r$) and reflected impulse ( $i_r$) decreased with increase in Stand-off distance. The responses of RC and SC walls are a function of blast wave parameters ($P_r$ and $i_r$) which are inversely proportional to stand-off distance. Therefore, increasing stand-off distance at a constant charge-weight results in a small deflection consequently small section. SC wall section can resist the same blast load as 46% thicker RC wall on average. SDOF analysis is an easy and fast approach for estimating the response of an SDOF element subjected to blast load.

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