International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 8 Issue 02 Series. II || Feb 2019 || PP 17-37

Effect of steam boiler explosion on boiler room and adjacent buildings structure

Mohamed F. Ibrahim[1], Hisham A. El-Arabaty[2], Ibrahim S. Moharram[3]
[1] *(Structural Engineering Department, Faculty of Engineering/ Ain-Shams University, Cairo, Egypt)*
[2] *(Structural Engineering Department, Faculty of Engineering/ Ain-Shams University, Cairo, Egypt)*
[3] *(Structural Engineering Department, Faculty of Engineering/ Ain-Shams University, Cairo, Egypt)*
Corresponding Author:Hisham A. El-Arabaty

Abstract: *This research study is directed towards the study of the effect of a possible Steam Boiler explosion in an industrial facility. The study includes evaluation of the equivalent TNT charge from the ignition of the fuel used in operating the boiler, and utilizes 3-D models on LS-DYNA software package for the computation of the effect of this explosion on the surrounding air and structure. Special empahsis is placed on investigation of various common regulations related to boiler houses in factories throughout Egypt. The effect of construction of a lightweight steel roof for the boiler room, and the use of vents in the room walls is studied in detail. In addition, models of a typical 5-storey industrial building adjacent to the boiler room are used to investigate the effect of the separation distance between the building and the boiler room on the expected magnitude of damage in the building. The concept of construction of the boiler room below ground is also studied in detail, and the analysis results are used to discuss common regulations for construction of boiler houses in Egypt, and to provide recommendations for improvement of these regulations.*
KEYWORDS: *Steam boiler explosion, TNT, boiler room, LS-DYNA*

Date of Submission: 03-02-2019 Date of acceptance: 19-02-2019

I. Introduction

A Steam Boiler explosion within or immediately nearby a building can cause catastrophic damage on the building's external and internal structural frames, collapsing of walls. In addition, major catastrophes resulting from gas-chemical explosions result in large dynamic loads, greater than the original design loads, of many structures. The objective of this paper is to assess the existing methods of structural analysis and design to resist blast loads due to steam boiler internal explosion.

Several accidents have occurred in recent years due to steam boiler explosion such as St Mary's Hospital in New Jersey- United States in (2006) and MedicineFactory in Paris - France in (2007), photos of the destructive damage is shown in Figure (1)

a. St Mary's Hospital, Passaic, USA, (2006) b. Medicine Industry, Paris, France, (2007)
Figure (1): Practical Accidents of Steam Boiler explosion

The analysis and design of structures subjected to Steam Boiler explosion require a detailed understanding of blast phenomena and the dynamic response of various structural elements. This paper presents an in-depth explanation of the nature of Boilers explosions. Excellent details are provided by the "Gas Explosion Handbook" , published by Gexon Company in (2007). The mechanism of the gas clouds, ignition,

heat of release rate, pool fire, combustion and blast waves in free air are outlined, and an introduction to the different methods for the equivalent estimate of blast loads and structural response is presented.
From a physical point of view, blasting demolition consists of two dynamic stages: The first stage is the wave propagation and development of fracture network in the structure upon detonation of explosives, and the second stage is the collapse of the structure, weakened by dynamic fracture, due to the gravitational effect. Several studies on structural demolition by blasting has mainly handled the second stage [Mattern S, et al (2006), Isobe (2006)].

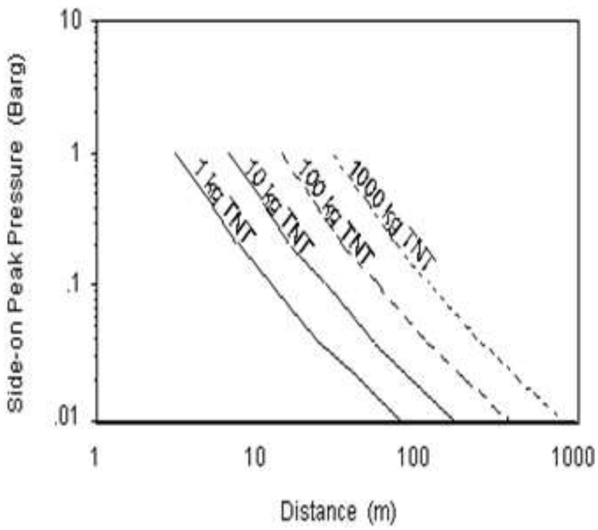
In this research, estimation of the equivalent TNT charge is performed for different fuels, and Boiler internal explosion is analyzed using LS-DYNA FE program, in which the amount of explosive, presence or absence of air, and confinement effects are investigated.

II. TNT- Equivalence Method

Once a boiler explosion accident takes place, not only is the boiler itself destroyed, but also other equipment and buildings around the boiler are damaged. Due to the complexity of overpressure generated from the boiler explosion and lack of systematic experimental data, it is common to describe the boiler explosion in terms of an equivalent TNT charge.

The diagram for TNT detonations has been used for estimation of blasts from gas explosions, even though there are differences between the blasts from a gas explosion and a TNT detonation, Shepherd et al., (1991), Van den Berg, (1985).

In a gas explosion, the local pressure may reach values as high as several bars. The blast pressure for TNT explosions is much higher closer to the charge. Such near-field data are therefore irrelevant for gas explosions.



Figure(2): Peakexplosionpressure (side-on)vs.distanceforTNT groundburst. [GasExplosionHandBook(2007)]

TNT equivalence method is widely used for gas explosions. The TNT equivalence method applies pressure-distance curves for TNT explosions to gas explosions and the equivalent TNT charge is estimated from the energy content in the exploding gas cloud (figure 2).

For typical hydrocarbons, such as methane, propane, butane etc., the heat of combustion is 10 times higher than the heat of reaction of TNT.The relation between the mass of hydrocarbons WHC and the equivalent TNT charge

$$W_{TNT} \approx 10 * \eta * W_{HC} \qquad (1)$$

Where,
η is a yield factor (η = 3%-5%), based on experience, Gugan, (1978).

The data can be scaled through a normalized length scale (Hopkinson scaling) R*

$$R^* = R/W^{1/3} \qquad (2)$$

Where,
R [m] is the distance from the centre of the explosive source and
W [kg] is the mass of the explosive source.

In order to estimate consequences of gas explosions, the geometrical conditions (i.e. confinement and obstructions) have to be taken into account. In the original TNT equivalence method, the geometrical conditions are not taken into account.

In order to take the geometrical effects into account in the TNT equivalence method, Harris and Wickens (1989) proposed to use a yield factor of 20% (h = 0.2) and the mass of hydrocarbon, WHC, contained in Stoichiometric proportions in any severely congested region of the plant. For natural gas, assuming atmospheric pressure initially , the equivalent mass of TNT can be estimated as follows:

$W_{TNT} \approx 0.16V$ [kg] (3)

Where:

V [m3] is the smaller of either the total volume of the congested region or the volume of the gas cloud.

Equation (3) will also hold for most hydrocarbons, since the energy content per volume Stoichiometric mixture is approximately the same (~3.5MJ/ m3).Use of the equation also gives a fairly good agreement between the predicted values and the experimental results as long as the explosion pressure in the cloud is in a few bars range. Weak gas explosions (less than 0.5 bar) are not represented satisfactorily.This indicates that the TNT equivalence method can be useful as an approximation if a yield factor of 20% is used together with appropriate values for WHC or V.

III. Development of the Analytical Model

In the numerical simulations throughthepresent work,thepartial differential equations governingthe basicphysicalprinciplesof conservation of mass, momentum, and energy are employed. The equations to be solved are both time and space- dependent andnonlinearinnature. These equations,together with equationsof state (EOS) and constitutive modelsdescribingmaterialbehavior anda setof initial and boundary conditions,definethe complete system forblast simulations.
This analysis is carried outusing the commercial program LS-DYNA which is a generalpurpose finite element code for analyzingthedynamic responseof structures which hasbeen available sincethe late (1980's). Thematerial modelsinthe LSDYNA constitutivemodellibrary arediversified, and capable of accurately simulatingthe actualmaterial behaviorin the model as shown in Table 1.

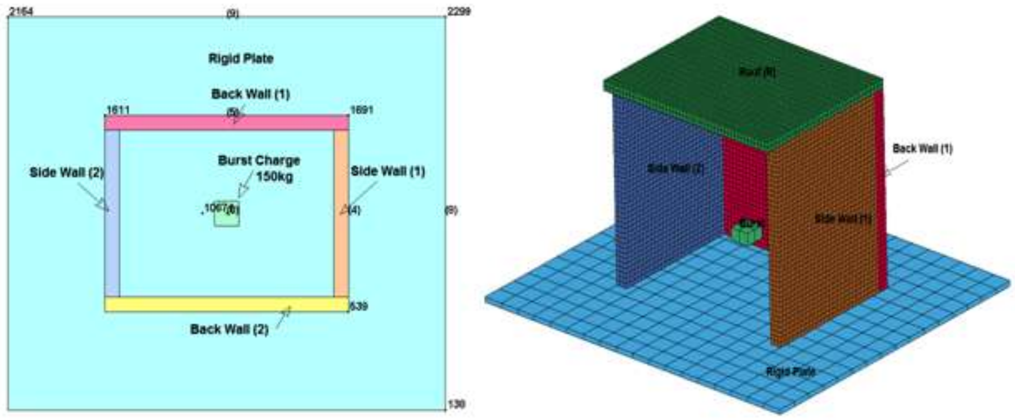
Table(1): Materialmodelsproperties.

Mat. No.	MaterialTitle	Bricks	ThinShells	ThickShells	StrainRateEffects	Failure	EquationofState	ThermalEffects	Notes; GnGeneral Composites FlFluids FmFoam HyHydro-dyn Mt Metal PlPlastic Rb Rubber SlSoil/Conc

5	SoilandFoam	Y							Fm,Sl
8	HighExplosiveBurn	Y					Y		Hy
9	NullMaterial	Y				Y	Y	Y	Fl,Hy
20	Rigid	Y	Y	Y					
84	WinfrithConcretereinforcement	Y							

IV. Description of the boiler room Model

Elements of the FE model of the "Closed Room" are the Back walls (1), Side walls (2), Roof (R) and the ground rigid plate (RP), A charge weight representing the boiler explosion is placed at the middle of the room as shown in (Figure 3). In this model, a charge of TNT (150kg) is located around (1.1m) from ground surface. The distance to the Back walls is 1.70m, and the height of the RC Back walls is 4.0m, and its length is 5.0m. The RC Side walls are 4.0m high, and 3.4 m long. The thickness of all RC walls is 0.30m, and the RC roof slabthickness is 0.20 m.A rigid plate with dimensions (8.0mx9.0m) is used to model the room floor.



Figure(3):3DModelof boiler room –Plan&PerspectiveView.

For the current study a standard boiler of 2000kg (2.0 ton) capacity was selected. This type of boiler is very widely used in Egyptian factories and all around the world. Estimating the Pressure Increase Attributable to a Confined Explosion, The combustion process raises the temperature of a gaseous system and that, in turn, increases the pressure of the system by expanding the gases ZALOSH, (1995).

By comparing the two types of fuels and its equivalent TNT weight for the same Boiler type and same Boiler room and under same environment conditions a quick summary represented in Table 2.

Table(2): SummaryofDifferentTypesofFuelsProperties.

Fuel	Fuel Consumption	Density (kg/m3)	Massof spilledFuel (kg)	Burning Time(min)	WTNT (kg)
Diesel(Liquid Gas)	146(kg/hr)	918	7.298	0.27	14.59
NaturalGas (Propane)	164(Nm3/hr)	0.70	14.77	7.69	152.19

The average pressure curve on the Boiler wall compared in several cases and with several charges varied from TNT 100Kg, 150Kg, 300Kg & 600Kg. Average pressure values in both cases the single wall and the closed room with air and without air to know several effects and considerations. The studied cases are as follows :

- Single Wall with Air using normal walls.
- Single Wall with Air using rigid walls.
- Single Wall without Air using normal walls.
- Single Wall without Air using rigid walls.
- Closed Boiler Room with air using normal walls.

- Closed Boiler Room with air using rigid walls.
- Closed Boiler Room without air using normal walls.
- Closed Boiler Room without air using rigid walls.

All the above cases have been studied under different charges and with different and variable parameters in materials and walls distances. To keep the cases of different files easy in reading, tracking and monitoring a system of filing numbers system developed on the base of the following symbols as shown below:

SW; Single Wall, CR; Closed Room,

A; With Air NA; Without Air,

N; Normal wall stiffness, original thickness. R; Rigid Walls, high stiffness.

The summary of the different cases analyzed is presented in detail in Table 3.The cases for the 150 kg TNT charge are highlighted, as they are considered to be a practical value case as shown in Table 3.

Table(3): SummaryofDifferentCasesParameters.

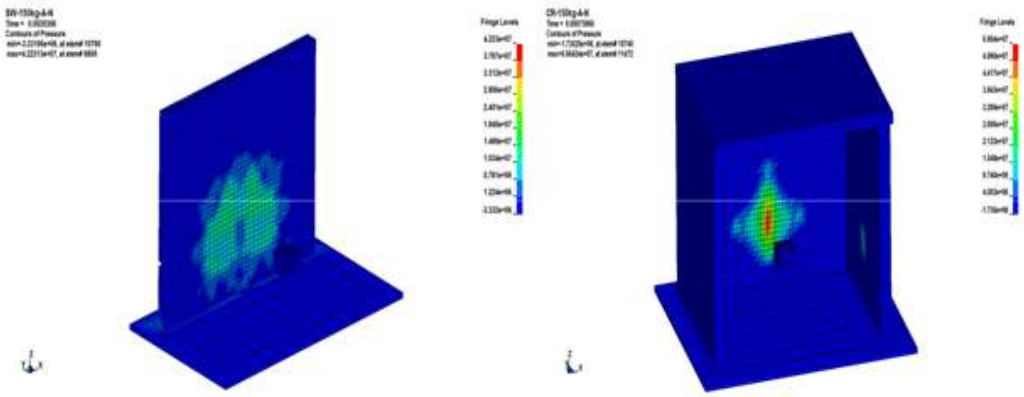
No	WallsCase reference	File Charge TNT-Kg	Caseof Air	WallsStiffness	TitleFilename
1	SW	100kg	A	Normal	SW-100kg-A-N
2	SW	150kg	A	Normal	SW-150kg-A-N
3	SW	300kg	A	Normal	SW-300kg-A-N
4	SW	600kg	A	Normal	SW-600kg-A-N
5	SW	100kg	NA	Normal	SW-100kg-NA-N
6	SW	150kg	NA	Normal	SW-150kg-NA-N
7	SW	300kg	NA	Normal	SW-300kg-NA-N
8	SW	600kg	NA	Normal	SW-600kg-NA-N
9	SW	100kg	A	Rigid	SW-100kg-A-R
10	SW	150kg	A	Rigid	SW-150kg-A-R
11	SW	300kg	A	Rigid	SW-300kg-A-R
12	SW	600kg	A	Rigid	SW-600kg-A-R
13	SW	100kg	NA	Rigid	SW-100kg-NA-R
14	SW	150kg	NA	Rigid	SW-150kg-NA-R
15	SW	300kg	NA	Rigid	SW-300kg-NA-R
16	SW	600kg	NA	Rigid	SW-600kg-NA-R
17	CR	100kg	A	Normal	CR-100kg-A-N
18	CR	150kg	A	Normal	CR-150kg-A-N
19	CR	300kg	A	Normal	CR-300kg-A-N
20	CR	600kg	A	Normal	CR-600kg-A-N
21	CR	100kg	NA	Normal	CR-100kg-NA-N
22	CR	150kg	NA	Normal	CR-150kg-NA-N
23	CR	300kg	NA	Normal	CR-300kg-NA-N
24	CR	600kg	NA	Normal	CR-600kg-NA-N
25	CR	100kg	A	Rigid	CR-100kg-A-R
26	CR	150kg	A	Rigid	CR-150kg-A-R
27	CR	300kg	A	Rigid	CR-300kg-A-R
28	CR	600kg	A	Rigid	CR-600kg-A-R

29	CR	100kg	NA	Rigid	CR-100kg-NA-R
30	CR	150kg	NA	Rigid	CR-150kg-NA-R
31	CR	300kg	NA	Rigid	CR-300kg-NA-R
32	CR	600kg	NA	Rigid	CR-600kg-NA-R

V. Analysis results of single wall and closed room Explosion Models

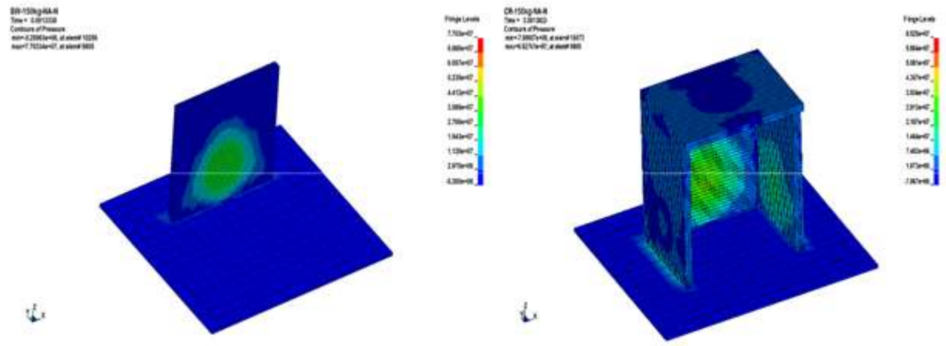
The analysis results shown below are for the case of 150 kg TNT equivalent charge. Figures 4 to 7 illustrate the pressure variation on the wall closest to the explosion, for the cases of Single Wall, and Closed Room.

Case2-SW-150kg-A-N Case18–CR–150kg-A-N



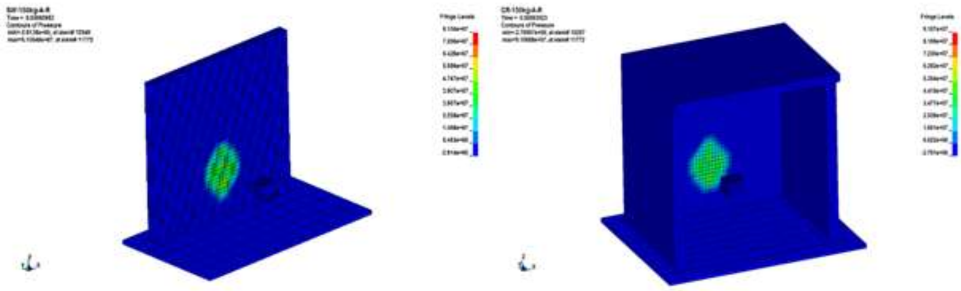
Figure(4):SW-150kg-A-N&CR-150kg-A-N

Case6-SW-150kg-NA-N Case22–CR–150kg-NA-N



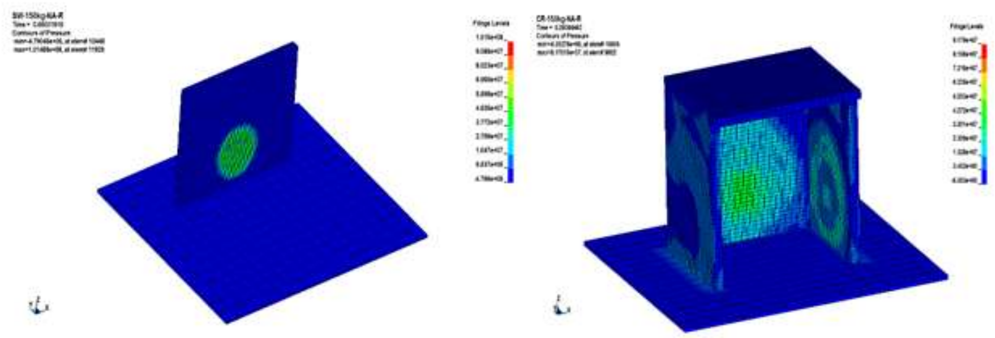
Figure(5): SW-150kg-NA-N&CR-150kg-NA-N

Case10-SW-150kg-A-R Case26–CR–150kg-A-R



Figure(6):SW-150kg-A-R&CR-150kg-A-R

Case14-SW-150kg-NA-R Case30–CR–150kg-NA-R



Figure(7):SW-150kg-NA-R&CR-150kg-NA-R

Results of the different cases are tabulated below, SW schedule with all cases results are shown in Table 4.a, while CR schedule, with all cases results are shown in Table 4.b. The failure pattern for the closed room is shown in figure 8.

Table(4.a): CollationofPressureResults–DifferentcasesforSingleWall.

BW

SeveralpressurevaluesofSolidelementshavetakenatlevel1.20maboveground facingthecharge.

4.0m=13'

(SW)=		
(CR)=		
(A)=		
(NA)=	NoAir	
(N)=	Normalstiffness	
(R)=	Rigid	

	Title	Charge TNT-Kg	MaximumPressure-Pr(Pa)							Maximum Pressure
NO.	Filename		T=0.40	T=0.60	T=0.80	T=1.0	T=2.0	T=3.0	T=4.0	
1	SW-100kg-A-N	100	0.00E+00	1.90E+07	1.50E+07	1.50E+07	1.00E+07	5.00E+06	0.00E+00	1.90E+07
2	SW-150kg-A-N	150	0.00E+00	4.10E+07	3.00E+07	3.50E+07	2.00E+07	1.00E+07	5.00E+06	4.10E+07
3	SW-300kg-A-N	300	0.00E+00	7.50E+07	7.00E+07	6.50E+07	5.00E+06	0.00E+00	0.00E+00	7.50E+07
4	SW-600kg-A-N	600	0.00E+00	2.20E+08	9.00E+07	6.00E+07	0.00E+00	0.00E+00	0.00E+00	2.20E+08
5	SW-100kg-NA-N	100	4.00E+07	3.90E+07	4.00E+07	4.10E+07	2.00E+07	5.00E+06	0.00E+00	4.10E+07
6	SW-150kg-NA-N	150	7.70E+07	4.50E+07	4.50E+07	4.50E+07	2.00E+07	5.00E+06	0.00E+00	7.70E+07
7	SW-300kg-NA-N	300	1.00E+08	5.00E+07	5.50E+07	6.00E+07	5.00E+06	0.00E+00	0.00E+00	1.00E+08
8	SW-600kg-NA-N	600	8.00E+07	1.85E+08	1.00E+08	9.00E+07	0.00E+00	0.00E+00	0.00E+00	1.85E+08
9	SW-100kg-A-R	100	0.00E+00	2.10E+07	2.80E+07	1.50E+07	7.00E+06	4.00E+06	2.00E+06	2.80E+07
10	SW-150kg-A-R	150	0.00E+00	5.75E+07	4.30E+07	4.30E+07	1.10E+07	5.00E+06	0.00E+00	5.75E+07

11	SW-300kg-A-R	300	0.00E+00	1.00E+08	6.00E+07	7.00E+07	2.00E+07	1.00E+07	0.00E+00	1.00E+08
12	SW-600kg-A-R	600	0.00E+00	2.20E+08	1.00E+08	7.00E+07	1.00E+07	0.00E+00	0.00E+00	2.20E+08
13	SW-100kg-NA-R	100	5.80E+07	4.00E+07	4.00E+07	4.00E+07	1.50E+07	5.00E+06	0.00E+00	5.80E+07
14	SW-150kg-NA-R	150	9.00E+07	4.30E+07	4.70E+07	5.00E+07	1.50E+07	1.00E+07	0.00E+00	9.00E+07
15	SW-300kg-NA-R	300	1.20E+08	5.00E+07	6.00E+07	6.50E+07	2.00E+07	0.00E+00	0.00E+00	1.20E+08
16	SW-600kg-NA-R	600	2.40E+08	1.00E+08	1.10E+08	1.20E+08	5.00E+07	0.00E+00	0.00E+00	2.40E+08

Table (4.b): Collation of Pressure Results – Different cases for Closed Room.

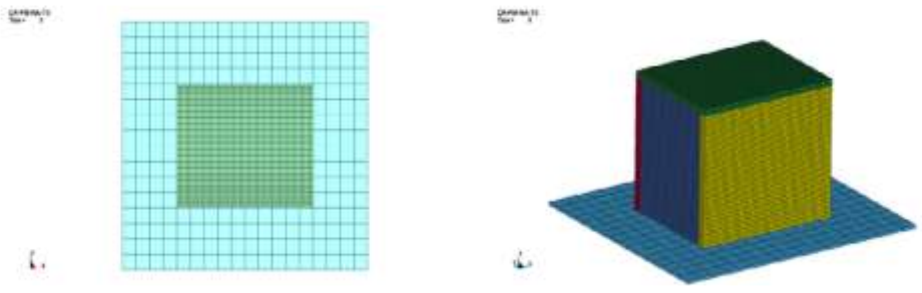
BW

SeveralpressurevaluesofSolidelementshavetakenatlevel1.20mabovegroundfacingthecharge.

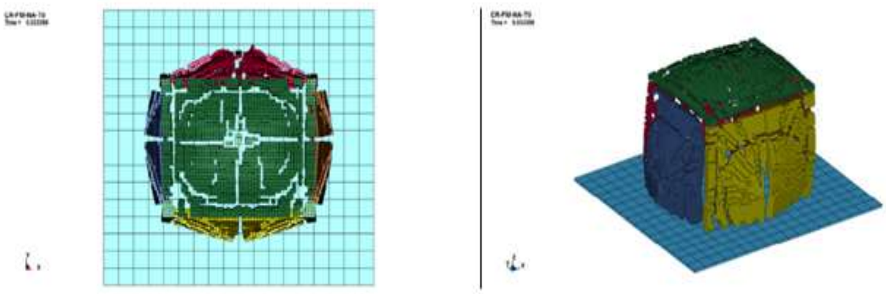
(SW)=	SingleWall
(CR)=	ClosedRoom
(A)=	Air
(NA)=	NoAir
(N)=	Normalstiffness
(R)=	Rigid

	Title	Charge TNT-Kg	MaximumPressure-Pr(Pa)							Maximum Pressure
NO.	Filename		T=0.40	T=0.60	T=0.80	T=1.0	T=2.0	T=3.0	T=4.0	
17	CR-100kg-A-N	100	0.00E+00	2.60E+07	1.80E+07	1.50E+07	1.20E+07	5.00E+06	3.00E+06	2.60E+07
18	CR-150kg-A-N	150	0.00E+00	5.50E+07	3.00E+07	3.50E+07	2.00E+07	1.00E+07	0.00E+00	5.50E+07
19	CR-300kg-A-N	300	0.00E+00	5.00E+07	8.80E+07	7.00E+07	0.00E+00	0.00E+00	0.00E+00	8.80E+07
20	CR-600kg-A-N	600	0.00E+00	2.00E+08	6.00E+07	5.00E+07	0.00E+00	0.00E+00	0.00E+00	2.00E+08
21	CR-100kg-NA-N	100	3.30E+07	2.00E+07	2.50E+07	3.00E+07	1.80E+07	5.00E+06	0.00E+00	3.30E+07
22	CR-150kg-NA-N	150	4.29E+07	3.50E+07	3.60E+07	3.80E+07	1.80E+07	2.00E+06	0.00E+00	4.29E+07
23	CR-300kg-NA-N	300	7.80E+07	4.00E+07	4.50E+07	4.25E+07	1.50E+07	0.00E+00	0.00E+00	7.80E+07
24	CR-600kg-NA-N	600	1.15E+08	8.00E+07	1.00E+08	5.00E+07	0.00E+00	0.00E+00	0.00E+00	1.15E+08
25	CR-100kg-A-R	100	0.00E+00	1.80E+07	2.80E+07	1.80E+07	5.00E+06	1.00E+06	0.00E+00	2.80E+07
26	CR-150kg-A-R	150	0.00E+00	6.60E+07	4.80E+07	4.90E+07	1.50E+07	5.00E+05	0.00E+00	6.60E+07
27	CR-300kg-A-R	300	0.00E+00	6.00E+07	1.00E+08	7.00E+07	3.00E+07	0.00E+00	0.00E+00	1.00E+08

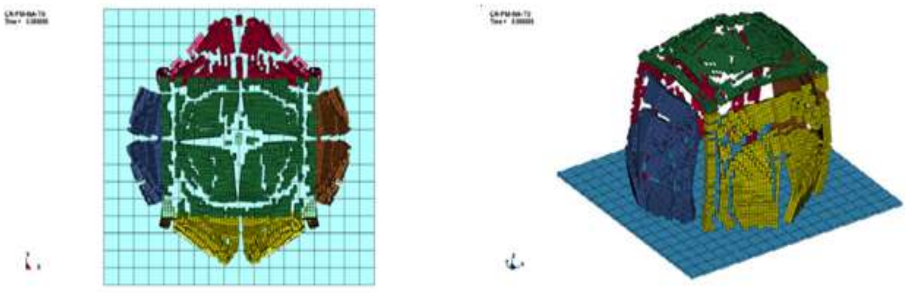
28	**CR-600kg-A-R**	**600**	**0.00E+00**	**1.20E+08**	**1.00E+08**	**1.00E+07**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**1.20E+08**
29	**CR-100kg-NA-R**	**100**	**6.60E+07**	**5.00E+07**	**5.60E+07**	**5.90E+07**	**1.00E+07**	**0.00E+00**	**0.00E+00**	**6.60E+07**
30	**CR-150kg-NA-R**	**150**	**1.00E+08**	**6.60E+07**	**4.00E+07**	**1.00E+06**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**1.00E+08**
31	**CR-300kg-NA-R**	**300**	**1.22E+08**	**7.50E+07**	**5.00E+07**	**5.50E+07**	**1.00E+07**	**0.00E+00**	**0.00E+00**	**1.22E+08**
32	**CR-600kg-NA-R**	**600**	**1.90E+08**	**1.50E+08**	**1.00E+08**	**7.50E+07**	**7.00E+07**	**0.00E+00**	**0.00E+00**	**1.90E+08**



Time=0sec



Time= 0.033sec



Time= 0.066sec

Time=0.10sec

Figure (8): Series of images showing the failure and debris scatter of Closed Room -150Kg TNT Equivalent charge.

A number of observations can be deduced from the results presented in this section:

- Use of Rigid elements to model the boiler walls resulted in a pronounced difference from the more realistic model utilizing flexible elements matching the actual wall properties. Differeneces of up to 47 % are noted in case of Sinle Wall. This indicates that use of Rigid Wall assumption in computation of blast effect is inaccurate.
- The results also indicate that increasing the flexibility of the structure subjected to the blast can produce a desirable reduction in the acting pressure value, which reduces the expected damage.
- The assumption of “No air” which is sometimes used by analysts in blast computations is found to be highly misleading. Comparing the maximum pressure in cases 5 & 1 for a single wall, the difference is around 116%. While this difference decreases with the increase of charge quantity, these results indicate the necessity of modeling air in the analysis in order to reach realistic estimates of the blast pressure.
- Comparison of the results of cases (1 & 17), and (2 & 18) shows differences in the range of 30 to 40 % in the incident pressure on the walls. This means that the confinement of the air and the blast effect inside the room produces an increase in incident pressure on the walls.
- The importance of considering confinement in the analysis is therefore highlighted in order to reach accurate results in blast analysis.
- In addition, the increases in pressure caused by confinement leads to the desirability of allowing paths for release of pressure. Several common proposals for this release are investigated in the following sections.

VI. Effect of lightweight roof construction

Common regulations in industrial areas throughout Egypt specify that the boiler house roof should be a light structure. In this section, the effect of this light roof on the confinement of blast in the boiler room is investigated. Figure 9 below shows a boiler house with a light steel roof.

Figure (9) Boiler Room Light Steel Roof.

The current study considers the Boiler room under an equivalent charge of 150kg TNT. A model is prepared for a typical boiler room with a concrete ceiling and without ceiling. The second model (without ceiling) represents the case of the lightweight roof, as this roof will not provide much resistance to the explosion wave. A comparison of results is shown in figures 10 to 14 below.

WITH ROOF WITHOUT ROOF

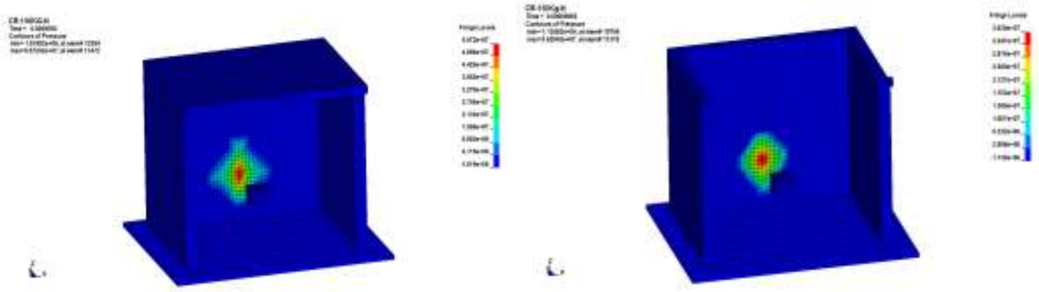


Figure (10) Room with and without roof - 150kg TNT–Pressure at time = 0.0006sec.

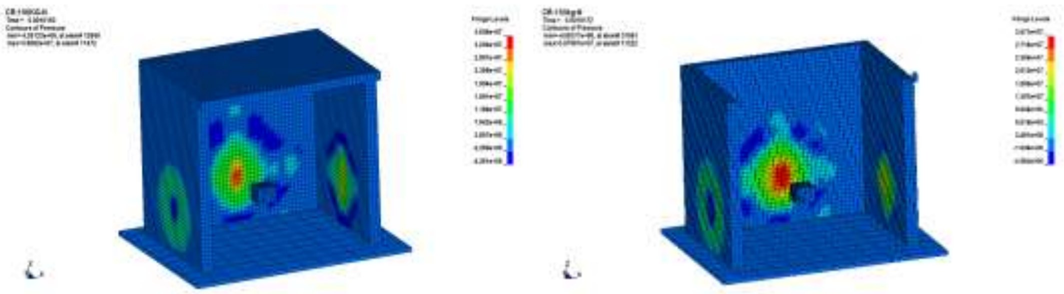


Figure (11) Room with and without roof 150kg TNT–Pressure at time = 0.001sec.

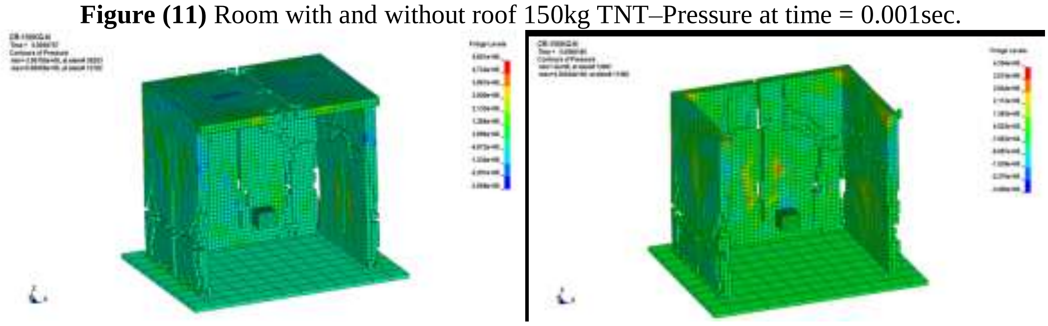


Figure (12) Room with and without roof 150kg TNT–Pressure at time state T0= 0.0066sec.

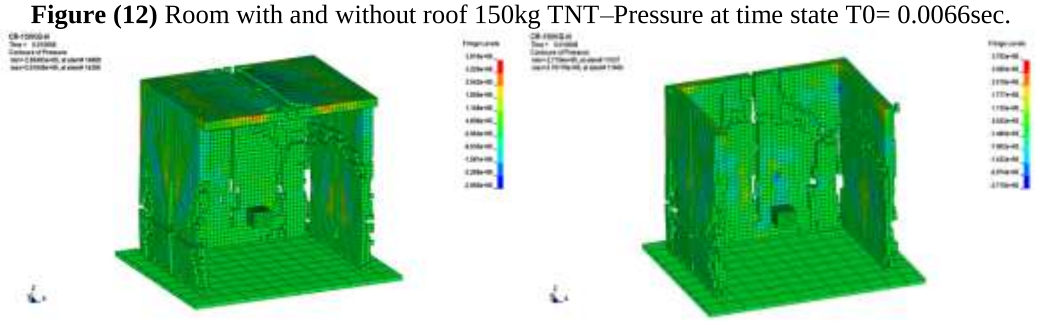


Figure (13) Room with and without roof 150kg TNT–Pressure at time = 0.01sec.

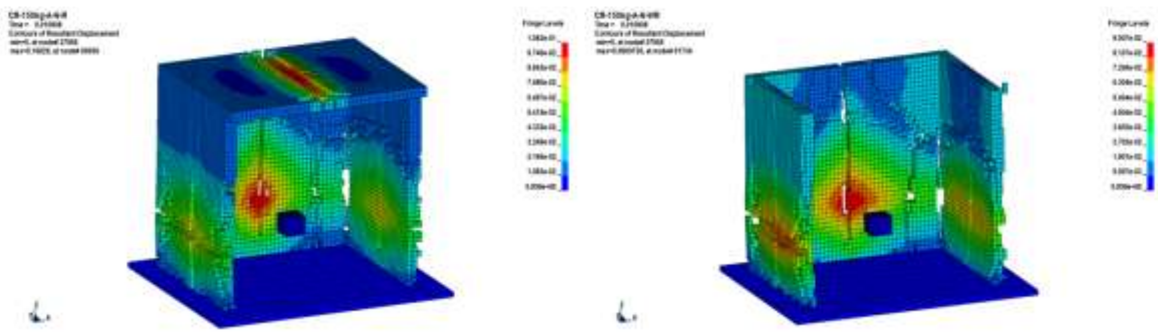


Figure (14) Room with and without roof 150kg TNT- Debris Scatter &Displacement at Time = 0.01sec.

The above results show a reduction in incident pressure on the wall of about 30% (43 MPa for the room with concrete roof, reduced to 30 MPa when the roof is removed) . The maximum displacement to the contrary increased from 0.085 m to 0.110 m. However, this increase can be explained by the modified statical system for the light roof case where the walls act as 3-sided panels, instead of 4-sided panels.

This reduction is caused by the release provided by the light roof, as its speedy damage in case of explosion provides a release for the blast wave, and reduces the confinement of the room, thus leading to reduced values of pressure on the walls, and a subsequent reduction in the expected damage, as seen in the damage patterns illustrated in figure 14.

The effect of adding vents to the boiler room is studied by comparing the results of 2 models, both of which resemble concrete wall and roof boiler rooms, the first without any vents, and the second with vents. Figure 15 shows a practical case of a boiler room with vents.

Figure (15) Boiler room with vents

Figures 16 to 20 illustrate the analysis results for the 2 models. Pressures on the walls of the boiler room can be seen in figures 16 to 19 for successive time steps, while the displacements and debris scatter are shown in figure 20, for the 2 cases.

WITHOUT VENTS WITH VENTS

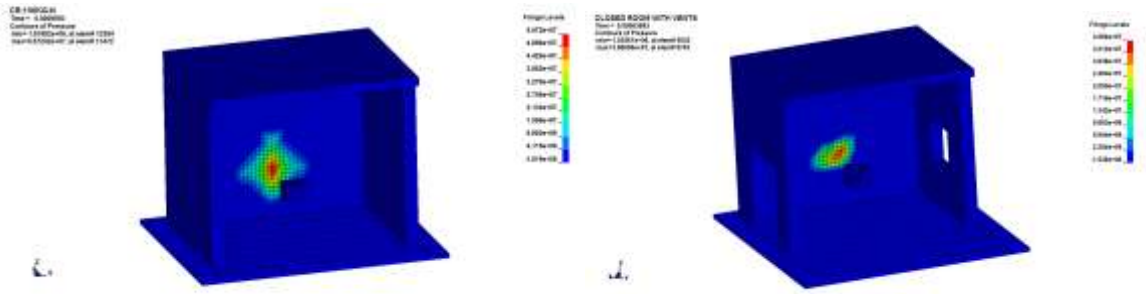
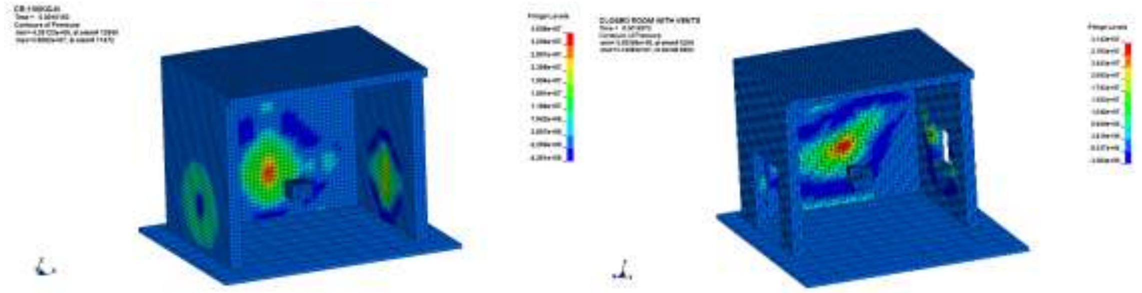
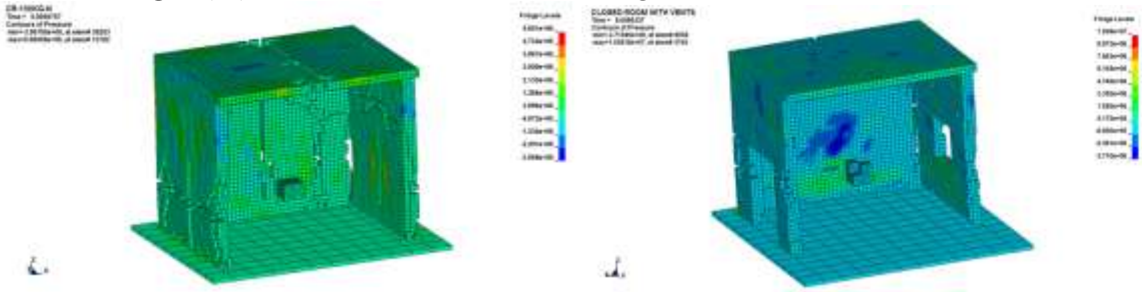


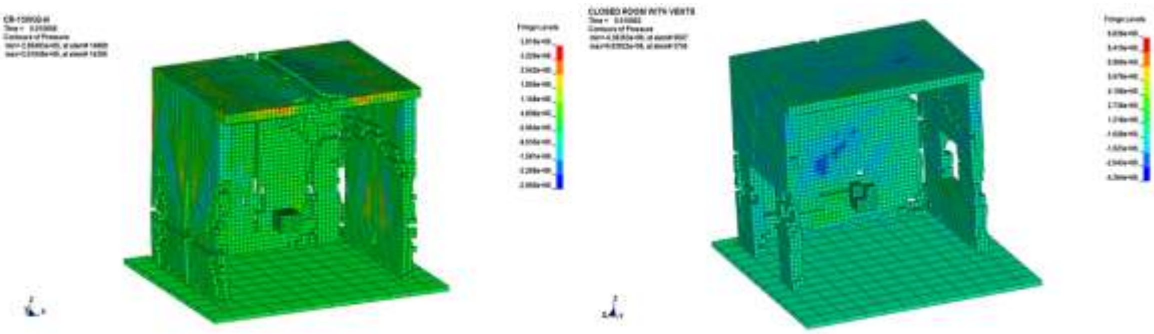
Figure (16) Room with and without Vents 150kg TNT–Pressure at time = 0.0006sec.



Figure(17) Room with and without Vents 150kg TNT–Pressure at time = 0.001sec.

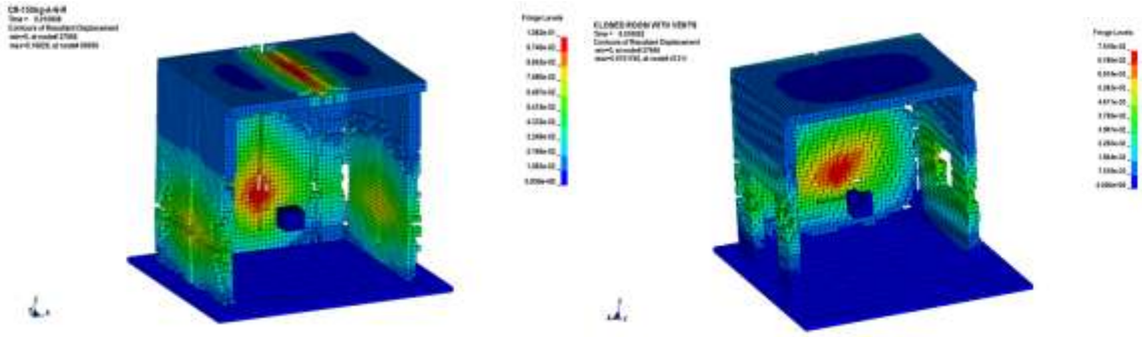


Figure(18) Room with and without Vents 150kg TNT–Pressure at time = 0.0066sec.



Figure(19) Room with and without Vents 150kg TNT–Pressure at time = 0.01sec.

WITHOUT VENTS WITH VENTS



Figure(20) Room with and without Vents 150kg TNT-
Debris Scatter & Displacement at Time = 0.01sec.

The analysis results show a clear reduction in incident pressure on the wall of about 49% (43 MPa for the room with concrete roof, reduced to 22 MPa when the roof is removed) . The maximum displacement is also reduced by about 24% from 0.085 m to 0.065 m.

Similar to the case of the light roof, the This reduction is caused by the release of the blast wave in case of explosion reduces the confinement of the room, thus leading to reduced values of pressure on the walls, and minimizes the damage.

In some districts in Cairo, local authorities require light sheeting to cover one side of the boiler room, which is usually chosen facing an open area or a fence, and not an adjacent building. The results of the study above indicate that this requirement is highly useful, as it reduces the effect of explosion in case of accident on the boiler room other walls, and on any adjacent buildings in the other directions.

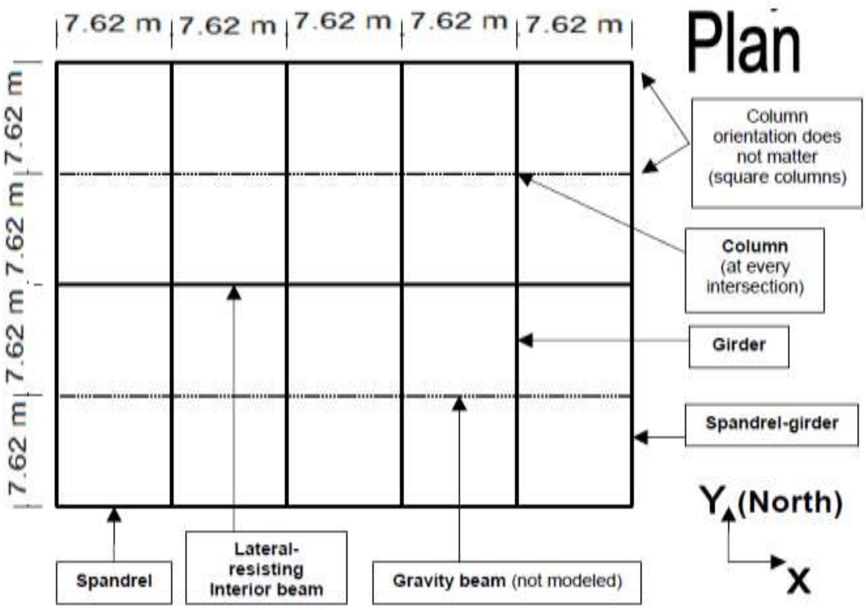
VII. Effect of boiler explosion on adjacent buildings

To study the effect of the Boiler room explosion, the hazard is not localized in the boiler room only but extends to the adjacent main Factory. Boiler Explosion has a significant effect also on the structural system of the factory presented in slabs, beams, columns and walls.

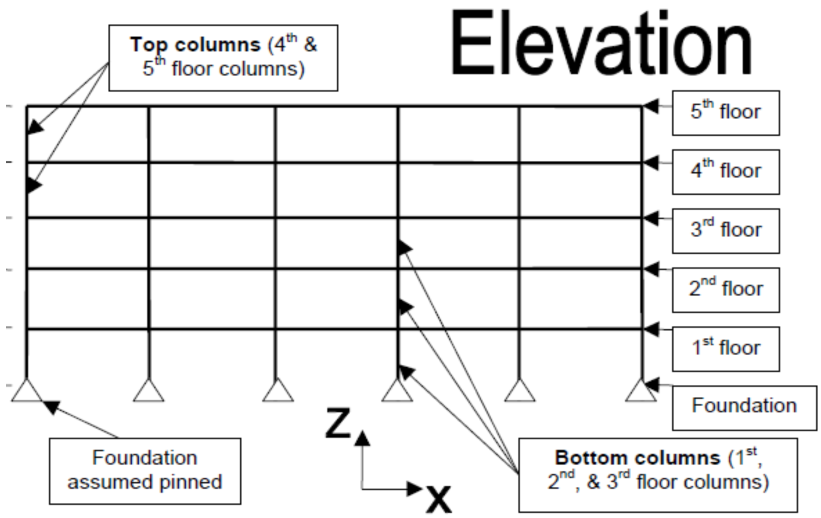
The selected model for the factory has been have been taken from UFC 4-023-03 – 25 January 2005- "DESIGN OF BUILDINGS TO RESIST PROGRESSIVE COLLAPSE", with the same dimensions, length, width, height, number of spans and also the sizes of the concrete elements as shown below.

The selected "Five Story Reinforced Concrete Factory" structure is a five-story reinforced concrete moment frame building [UFC (2005)]. It is four bays by five bays in plan, each 7.62 m x 7.62 m typical bay. The building is assmed to be an adjacent factory building to the Boiler Room.

Figure 21 shows the plan and elevation of the factory building, while the Material properties and reinforced Concrete Member Sizes and Reinforcement for the building are illustrated in tables 5 and 6 respectively.



(A)ReinforcedConcreteFactoryPlan



(B)ReinforcedConcreteFactoryElevation
Figure(21) ReinforcedConcreteBuilding

F'_c	34500kN/m²	concretestrength
F_y	413700kN/m²	rebaryieldstrength
E_c	24855578kN/m²	modulusofelasticityofconcrete
E_s	2.0E+8kN/m²	modulusofelasticityofrebar
G	10356491kN/m²	Shearmodulus
Y	0.2	Poisson'sratio

Table5. MaterialProperties

MemberGroup	Dimensions	BottomReinf.	TopReinf.
Spandrels	B=0.51m D=0.61m	0.00114m²	0.00155m²
InteriorBeams	B=0.51m D=0.61m	0.00114m²	0.00155m²
Girders	B=0.51m D=0.76m	0.00156m²	0.0029m²
Spandrel-Girders	B=0.51m D=0.76m	0.00156m²	0.0021m²
BottomColumns	0.51mx0.51m	0.0052m²	
TopColumns	0.51mx0.51m	0.0041m²	

Table6. ReinforcedConcreteMemberSizesandReinforcement

A model is developed using LS-DYNA software for the analysis of the boiler room, and adjacent factory structures under the effect of boiler explosion. All primary lateral-load resisting system of the structure is modeled using solid elements , and the soil type is assumed to be soil type (I)

Two types of models are developed based on the above criteria, first model [A] is a boiler room above ground, with different distances away from the main factory building (2m and 6m distances were selected for this study), and the second model [B] is a model of the boiler room constructed beneath the ground, so that its top roof is at ground zero level. The same distances from the building (2m & 6m) are selected for this model. Figure 22 illustrates the location of the boiler house relative to the factory building for the 2 Models.

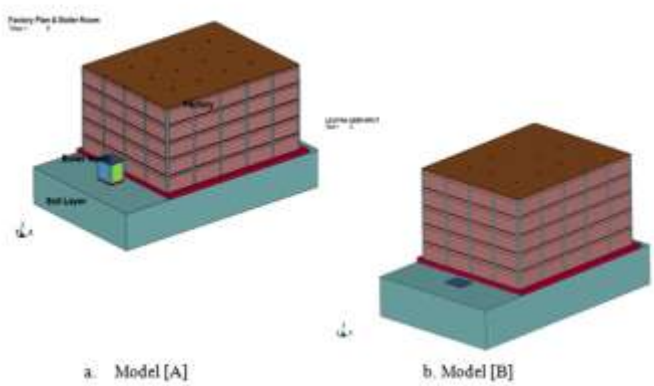
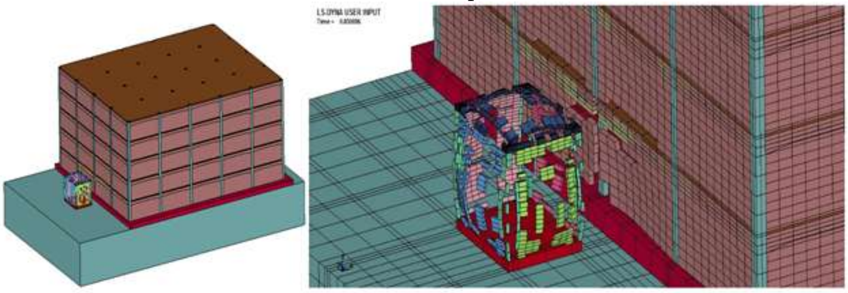
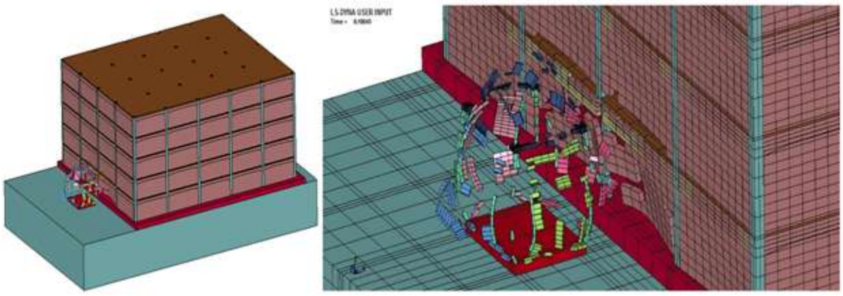


Figure (22) Factory and Boiler Room Model Perspective for Models [A] & [B].

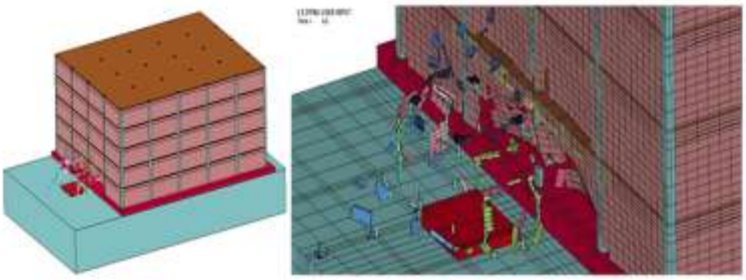
Figures 23 to 24 show a sample of the results obtained from the LS-DYNA model analysis. The results are for the case of Boiler room above ground (Model [A]), and at a distance of 2 m from the factory façade. Figure 23 shows the damage and debris scatter, while Figure 24 illustrates the acting pressure on the column facing the boiler room at different times after the explosion.



Time=0.030sec

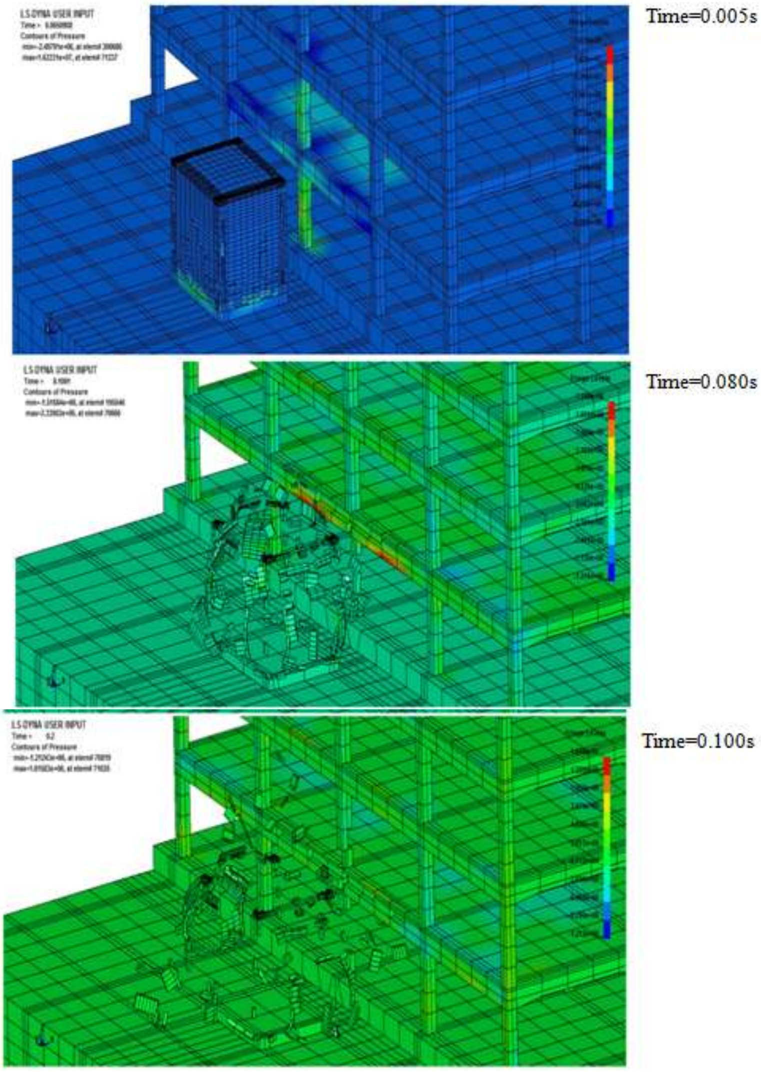


Time=0.080sec



Time=0.100sec

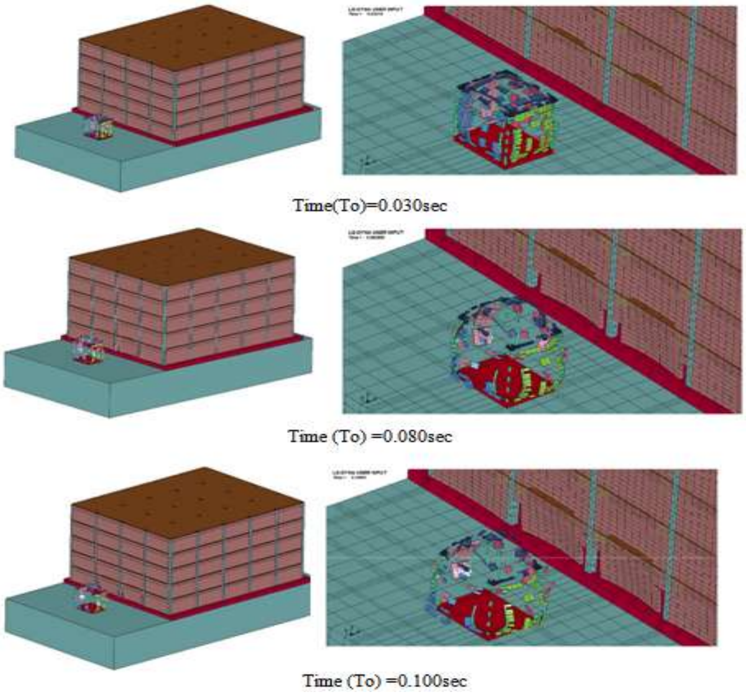
Figure(23) SeriesofimagesshowingthefailureanddebrisscatterofClosed Boiler Roomandthe



Figure(24) Seriesofimagesshowingthepressure and the damage of the Boiler Roomandthe Factorymainelevationconcretewallsandcolumns.

The extensive damage produced in the building façade, and concrete skeleton can be seen clearly in the figures. It can be noted that the concrete column facing the boiler house is totally destroyed, which indicates a serious hazard of collapse for the building.

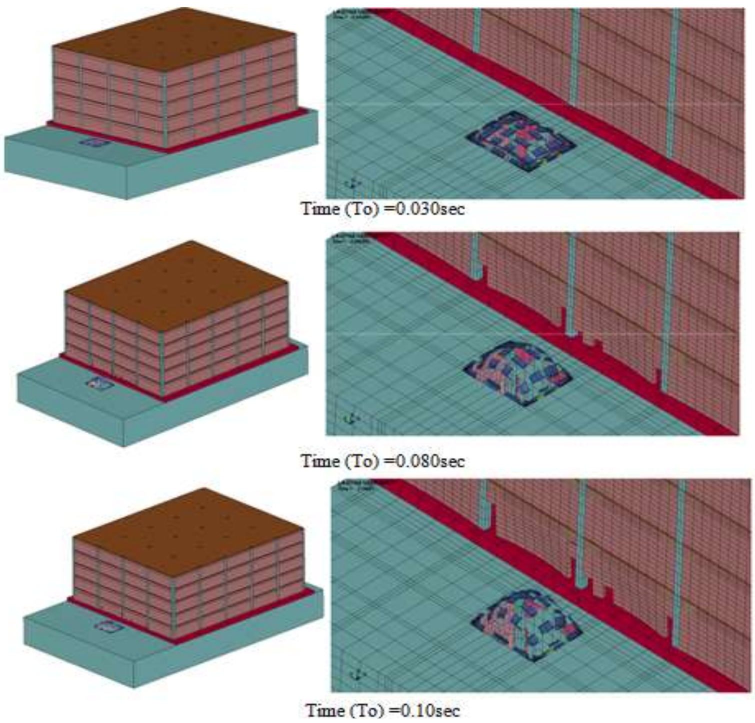
The effect of the same explosion for the case of 6m spacing between the boiler room and the factory building is shown in figure 25 below.



Figure(25) SeriesofimagesshowinthefailureanddebrisscatterofClosedRoomandthe Factorymainelevationconcretewallsandcolumns.

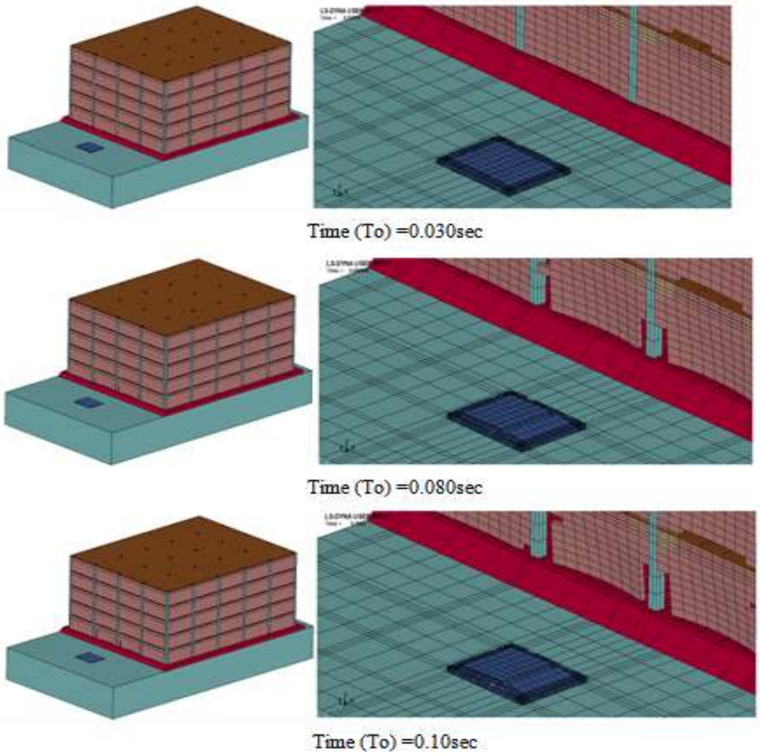
It can be noted that the damage to the building façade is limited compared to the case where the boiler room is located only 2 m away from the façade.

The effect of "burying" the boiler house underground is investigated by repeating the same analysis runs for (2m & 6m) spacing between the boiler room and the adjacent building for Model [B], where the boiler room is placed underground, so that its top roof is at zero ground level. The damage and failure shape are illustrated in figure 26 for 2m spacing, and in figures ## for 6m spacing.



Figure(26) SeriesofimagesshowingthefailureanddebrisscatterofClosedRoomandthe Factory main elevation concrete walls and columns.

Case of boiler room constructed underground at 2m from factory building.



Figure(27) Seriesofimagesshowingthefailureanddebrisscatterof ClosedRoomandthe Factory main elevation concrete walls and columns.

Case of boiler room constructed underground at 6m from factory building.

Table 7 illustrates a summary of the main results obtained for the 4 cases described above, with comparisons between the cases of 2 & 6 m spacing, and cases of above-ground and below-ground construction of the boiler room.

Table 7. Summary of results for Boiler room adjacent to factory building Pressure and Velocity of Burst wave.

ComparisonSheetforBoilerRoomFacingFactory

1- SeveralpressurevaluesofSolidelementsforthecolumnfacingthe
2- SevetyVelocityvaluesofsolidsoilelementsfacingthefactory.

	Title	Charge TNT-Kg	MaximumPressure-Pr(Newton)				Maximum Pressure	Reduction percentagebetween 2.0m&6.0m	Reduction percentagebetweenabove &Below
NO.	Filename		To=0.005	To=0.008	To=0.01	To=0.1			
1	BoilerRoom@2.0m AboveGround	150	1.70E+07	1.00E+07	3.00E+06	0.00E+00	1.70E+07		
2	BoilerRoom@6.0m AboveGround	150	0.00E+00	9.00E+06	2.00E+06	0.00E+00	9.00E+06	47%	
3	BoilerRoom@2.0m BelowGround	150	5.00E+06	7.00E+06	1.50E+06	0.00E+00	7.00E+06		59%
4	BoilerRoom@6.0m BelowGround	150	0.00E+00	5.00E+06	1.00E+06	0.00E+00	5.00E+06	29%	44%

NO.	Title / Filename	Charge TNT-Kg	Maximum Velocity-Ve(m/sec) To=0.001	To=0.002	To=0.003	To=0.005	Maximum Velocity		Reduction percentagebetween 2.0m&6.0m	Reduction percentagebetweenabove &Below
1	BoilerRoom@2.0m AboveGround	150	7.90	7.00	5.00	3.00	7.90			
2	BoilerRoom@6.0m AboveGround	150	1.70	1.90	1.50	1.00	1.90		76%	
3	BoilerRoom@2.0m BelowGround	150	0.00	2.00	3.70	3.50	3.70			53%
4	BoilerRoom@6.0m BelowGround	150	0.00	0.50	1.70	1.00	1.70		54%	11%

It can be seen clearly, that for case of Model [A], the effect of increasing the spacing from 2 m to 6 m between the boiler room and the adjacent building has produced a significant reduction in both the pressure exerted on the façade columns (47% reduction), and the burst wave velocity (76% reduction). The difference in damage size, and scatter can also be observed in the analysis results.

In addition, the effect of constructing the boiler room underground produced a significant effect (59% reduction in pressure, and 53% reduction in burst wave velocity), for the case of a 2 m distance between the boiler room and the adjacent building. Lower reduction percentages are observed for the case of a 6 m distance, but the reduction in pressure is still significant.

VIII. Conclusions and Recommendations

The models developed on LS-DYNA as part of this study proved to be highly efficient in the study of the behavior of boiler explosion effects on the structure of the boiler room and adjacent buildings. A number of important conclusions can be made related to the models accuracy as follows:

- Analysis results showed that use of Rigid elements to model the boiler walls produced unrealistic results, and it is highly recommended to use the actual flexible wall properties in analysis.
- Increasing the flexibility of the structure subjected to the blast was found to produce a desirable reduction in the acting pressures, and reduce the expected damage in boiler room walls.
- The assumption of "No air" which is sometimes used by analysts in blast computations is found to be inaccurate.
- The confinement of the air and the blast effect inside the room produces an increase in incident pressure on the walls. It is therefore important to consider the confinement in the analysis model. Moreover, the presence of air is also important to consider as it was found that neglecting it could lead to a large deviation in results from the actual case.

With respect to the structural behavior of the boiler room structure, and the adjacent buildings, a number of important conclusions can be made from the analysis results as follows:

- A very important conclusion from the results obtained in this study is that construction of the boiler room below ground has a highly significant effect in reducing the effect of a boiler explosion accident as compared to the case of construction above ground. This reduction applies to the incident pressure on the adjacent building façade, the burst wave velocity, and the extent of expected damages.
- It is highly recommended that an extensive study be directed towards implementation of the concept of underground boiler room in Egypt's industrial cities, where most authorities currently require that the boiler room be constructed above ground level. The study results indicate a very high advantage in case of underground construction of the boiler room. This is more pronounced when the adjacent buildings are light steel structures, which is much weaker in resisting a possible boiler explosion accident.
- For the case of above-ground boiler houses, the current study highlights the importance of the distance between the boiler room, and the nearest factory building. While several local authorities in Egypt require a 6m minimum distance, this limitation is not strongly enforced, and in some cases, boilers are allowed to be placed at a smaller distance or within the same industrial building with a concrete wall separating it from the rest of the building. In such cases, it is recommended that designers should be required to perform an advanced analysis of the possibility of an explosion incident, and that the main Factory building facing the boiler room should be designed based on the progressive collapse failure mode.
- Providing paths for release of the blast wave is found to produce a significant effect on the boiler room confinement, and reduce the effect of an explosion on its walls and on adjacent buildings. This includes both the construction of a light roof, and providing vents in the walls. While several Cairo local authorities

require the light roof, few of them require design for the vents. It is recommended that these two design criteria become essential requirements for all industrial areas, and that a study of the vents locations and sizes be required as an integral part of the boiler house design.

References

[1]. Agardh, L., Nov., 1999. "Validation of Numerical Simulations of Structural Response via Material Sample Testing and Field Trials", 3rd Asia-Pacific Conference on Shock & Impact Loads on Structures, pp.1-14, Singapore.
[2]. A.K.Shaha, 2006.Combustion Engineering and Fuel Technology, Oxford
[3]. Agbabain M. S., 1985. "Design of Structures to Resist Nuclear Weapons", ASCE-Manuals and Reports on Engineering Practic-No.42.
[4]. Baker, W. E., 1973. "Explosion in Air", University of Texas Press, Austin, TX.
[5]. Baker, W. E., 1983. Cox, P. A., Kulesz, J. J. and Strehlow, R. A., "ExplosionHazards and Evaluation", Elsevier.
[6]. Baylot J. T., 2000. "Effect of Soil Flow Changes on Structure Loads", Journal of Structural Engineering, Vol.126, No. 12, December, pp 1434-1441.
[7]. Beshara, F.B.A. 1994, "Modeling of blast loading on aboveground structures -I.
[8]. Internal blast and ground shock", Comp.& Struct. Vol. 51, No.5.
[9]. Chengqing Wua, Hong Haob, January 2006. Numerical simulation of structural response and damage to simultaneous ground shock and air blast loads.
[10]. FEMA 426, 2003. Federal Emergency Management Agency. (Washington, DC: Federal Emergency Management Agency, December).
[11]. FEMA-356, 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency: Washington, DC.
[12]. Gas Explosion Handbook, Gexon Company, July 2007.
[13]. Johnson, D.M. et al. 2002. "Investigation of Gas Dispersion and Explosions in Offshore Modules", OTC-paper 14134, Houston 6-9.
[14]. Pierorazio, A.J., Thomas, J.K., Baker, Q.A and Ketchum, D.E 2005, An update to the Baker- Strehlow-Tang vapor cloud explosion prediction methodology flame speed table, Process Safety Progress, Volume 24, Issue 1, pages 59-65.
[15]. Technical Manual TM 5-885-1, 1986 "Fundamentals of Protective Design for
[16]. Conventional Weapons", Headquarters Department of the Army, Washington.
[17]. W.P.M. Mercx et al. 1994, Modelling and experimental research into gas explosions, Overall Report of the MERGE Project, CEC contract: STEP-CT-0111 (SSMA) Mercx.
[18]. U.S. Nuclear Regulatory, 2004. Quantitative Fire Hazard Analysis Methods for the Commission Fire Protection Inspection Program – December.
[19]. Unified facilities criteria (UFC), 2008. Structures to resist the effects of accidental explosions, December.

Hisham A. El-Arabaty" Effect of steam boiler explosion on boiler room and adjacent buildings structure" International Journal Of Engineering Science Invention (Ijesi), Vol. 08, No. 02, 2019, Pp 17-37