CHEMICAL ENGINEERING TRANSACTIONS

VOL. 48, 2016

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Eddy de Rademaeker, Peter Schmelzer

ISBN 978-88-95608-39-6; **ISSN** 2283-9216

DOI: 10.3303/CET1648071

Structural Behaviour of Multi-Storey Buildings Subjected to Internal Explosion

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Internal explosions caused by gas leaks are very common phenomena in this time and can lead to structural failures seriously compromising the static of a building, both in civil and industrial structures, and in some cases can involve the consequent entire structure' failure. The main purpose of this study is to numerically reproduce the damage effects caused by a vented explosion in a multi-storey framed reinforced concrete structure with masonry infill walls. Gas-leakage has been supposed to be situated in one room, generally that used as a kitchen. ANSYS AUTODYN® has been used to manage both the structural (Lagrangian solver) and the fluid-dynamic (Eulerian solver) issues and to make feasible their interactions. Reinforced concrete and masonry were implemented as homogenized materials and increased materials' resistances due to high strain rates were considered through the DIF coefficients. The analysis focuses on the gas mixture usually used for domestic purposes mainly consisting of methane (80% v/v) and completed by ethane, propane and n-butane. A thermodynamic and stoichiometric chemical analysis allowed for the estimation of the main parameters involved in the explosion. Results show that such a mixture has the capability to release a specific energy amounting to about 46,800 kJ/kg, theoretically exceeding that of the TNT by approximately 10 times. Finally the pressure caused by the blast wave on the walls has been evaluated.

1. Introduction

In this study explosions due to a gas leak in residential structures are examined with a focus also on the consequent structure elements collapse. These accidents are very common in Italy causing death and a huge damage in structures under blast load. For example for gas-leakage in pipes of residential structures 177 accidents took place in 2012, 144 in 2011 and 200 in 2009-2010. The increase of society economic uneasiness causes the growth of Italian individuals involved in LPG cylinders accidents. In the last years, this type of accident has been also incremented by foreign people. In addition, with reference to the statistical variance and the climatic effects, this type of accidents hasn't been reduced. This to state that the technical normative and the devices fabrication way aren't enough to eliminate the issue.

2. Explosion Chemistry

The mixture considered in this study can be characterized by the composition reported in Table 1 matching that generally used for domestic purposes.

Table 1: Gas mixture composition

Compound	Fraction	$\Delta_f \overline{G_i^0}$ [kJ mol^{-1}]
Methane	0.8	-50.5
Ethane	0.08	-32.0
Propane	0.06	-23.4
Butane	0.06	-17.0

Please cite this article as: Andreotti M., Mocellin P., Zanini M., Vianello C., Pellegrino C., Modena C., Maschio G., 2016, Structural behaviour of multi-storey buildings subjected to internal explosions, Chemical Engineering Transactions, 48, 421-426 DOI:10.3303/CET1648071

Given the thermodynamic conditions of the system, it is supposed to behave as a mixture of ideal gases starting from an initial state characterized by an atmospheric pressure and a temperature of 273 K. The thermochemical description of the domain is primarily linked to the evaluation of the maximum energy released with the reaction. The calculation has been achieved by implementing a stoichiometric reaction scheme in the gas phase that leads to the overall reaction (1):

$$CH_{1.38}H_{4.76} + 3.76(O_2 + 3.76N_2) \rightarrow 1.38CO_2 + 2.38H_2O + 14.1376N_2 \quad (1)$$

The maximum energy expresses in terms of mechanical work w is obtained considering a isochoric and adiabatic path. Assuming that vapours form ideal solutions since the contribution of the solution non ideality to the energy is small compared with the chemical reaction term, it is possible to derive eq. (2):

$$W = G^f\left(T^f, P^f, n^f\right) - G^i\left(T^i, P^i, n^i\right) - RT\left(n_{tot}^f - n_{tot}^i\right) \quad (2)$$

In eq. (2), G stands for the Gibbs free energy, n for the number of moles while the superscripts i, f are referred respectively to the initial and final state. In eq. (2) the total specific Gibbs free energy should consider the variation in the number of mole through the reaction through eq. (3):

$$G(T, P, n) = \sum_{NC,i} n_i \overline{G_i}(T, P, x) = \sum_{NC,i} n_i \left(\Delta_f \overline{G_i^0} + RT\ ln\ x_i\right) \quad (3)$$

The application of these approach leads to the estimation of the total work that can be extracted from the system and equals to -4.49E+04 kJ kg^{-1}. The TNT equivalency amounts to about 24 kg considered a value for the TNT heat of decomposition of -4570 kJ kg^{-1} (Mannan, 2012) that has been then suitable scaled as indicated by some authors (Rasbash, 1969).

3. Structure Modeling

The geometry of the model consists of the room interested by the explosion and the air volume occupied by the building as indicated in fig. 1. For the air, a 3D Euler FCT (Higher Order Euler processor) sub grid has been used. The ground level is supposed to be rigid and the air flow out is allowed in the other borders.
The model is composed by the reinforced concrete structure and the masonry walls while the soil has been simulated by using a rigid floor. The reinforced concrete structure is a frame structure composed by columns, beams and slabs. The mechanical properties of the different bodies involved in the model are described in section 4. The mesh used is more discretized for Eulerian elements to best match the spherical trend of the expansion wave and the pressure results while larger elements are involved in the description of the Lagrangian elements. The columns, beams and slabs are modeled with 3D solid elements, solved through the Lagrangian processor. In addition the room walls are filled in masonry walls and are supposed to be perfectly joined to the reinforced concrete frame. Common nodes are therefore used to transfer structural loads.
So the model is a reinforced concrete structure frame that is a commonly used technique for seismic resistance building analysis. Lagrange elements are used for the structural part while the Euler type elements are dedicated to the fluid description. The latter progressively remapped to follow the development of the explosion front.
Fixed constraints in all directions have been implemented in the slab in contact with the ground. The fluid domain also extends to a meter externally of the room walls allowing for a correct pressure profiles detection at the points Gauges even in the case of high strain of structure elements. The structure is composed respectively of: 4 pillars, 4 beams, concrete-brick floor at the ground level (simplified with a concrete slab corresponding to one area carrier) and 4 infill walls.
All the individual parts are connected to each other through bonded contact surfaces that is a perfect connection managing the mesh even without a perfect alignment between the various meshed elements. This type of connections between masonry and frame it's the worst situation that can be encountered providing a greater degree of confinement. This despite the fact that cushioning elements assume a behavior to the plate thus increasing the maximum stresses tolerable in this configuration. An explicit solver has been used to build a mesh as regular as possible to avoid excessive deformation patterns.

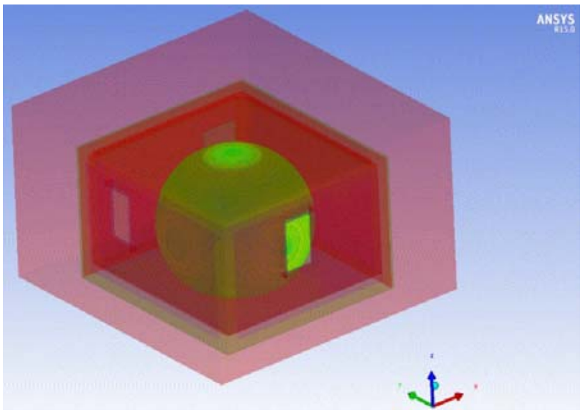

Figure 1: schematic representation of geometry modeled.

4. Materials

4.1 Air

Air is described as an ideal gas substance as indicated in eq. (4) not needing resistance and failure patterns modeling:

$$p = (\gamma - 1)\rho e \tag{4}$$

where γ is the specific heats ratio c_p/c_v, ρ is the air density and e is the specific internal energy. The latter is assumed to be equal to $2.068 \cdot 10^5 J/kg$ through eq. (5):

$$e = \frac{RT}{\gamma - 1} \tag{5}$$

where $R = 287.1 \frac{J}{kgK}$ is the specific gas constant.

4.2 TNT

The explosive substance is modeled through the JWL approach proposing a dedicated empirical EoS for explosive materials. These equations are implemented in many hydrocodes (for example LS-DYNA, AUTODYN) and have the form reported in eq.(6):

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{6}$$

where the coefficients A, B, R_1, R_2 and ω depend on the composition of the explosive, the variable $V = v/v_0$ is the expansion of the explosive products and E the detonation energy per unit volume. For the TNT, when its expansion ratio reaches 10 times the starting value, the description is switched to the ideal gas approach.

Table 2: TNT Equation of State Parameters

Parameter	Value
Density	1,630
A (GPa)	371.2
B (GPa)	3.231
R_1	4.15
R_2	0.95
Adiabatic constant, ω	0.30
Detonation velocity, D (m/s)	6,930
Energy per unit volume, E_0 (GPa)	7
CJ pressure, P_{CJ} (GPa)	21

4.3 Reinforced Concrete

The equation of state considers the pressure p a function of density ρ with an approximation based on the Hooke's law as indicated in eq.(7):

$$p = K\mu \quad (7)$$

where $\mu = \left(\frac{\rho}{\rho_0}\right) - 1$ is the compression, ρ_0 is the reference density and K is the material Bulk Modulus.
Reinforced concrete elements can be modeled as a combination of joined elements of concrete and steel with the assumption of perfect contact. However the modeling of an extended structure based on this approach is prohibitive because of a huge amount of elements required. In addition the computational burden of a dynamic explicit solver is directly proportional to the amount of mesh elements.
This problem has been overcome by implementing a homogenized elastic-plastic material to simulate the behavior of reinforced concrete that is present in columns, beams and slabs. Pillars and beams section has been considered to be equal to 30x30 cm with an armature equals to 1% of the area.
The tensile strength is considered like the steel strength and compressive strength as that of the concrete.
The increase in the mechanical properties due to the high strain rate has been considered. The law has been studied in CEB Model Code 2010 that is able to describe the variations in compressive, tensile strength and in elastic modulus. The implementation of the right materials properties has been ensured by firstly performing a run concerning static properties and then involving the dynamic increase factor in the mechanical properties values.
Compressive strength is described by using eq. (8-9) as reported in some works (fib, 2013)

$$f_{cm}^{dyn} = f_{cm}\left(\frac{\dot{\varepsilon_c}}{\dot{\varepsilon_{c0}}}\right)^{0.014} \quad per\ \dot{\varepsilon_c} \leq 30s^{-1} \quad (8)$$

$$f_{cm}^{dyn} = f_{cm} \cdot 0.012 \cdot \left(\frac{\dot{\varepsilon_c}}{\dot{\varepsilon_{c0}}}\right)^{\frac{1}{3}} \quad per\ \dot{\varepsilon_c} > 30s^{-1} \quad (9)$$

With $\dot{\varepsilon_{c0}} = 30 \cdot 10^{-6}\ s^{-1}$.
While for tensile strength (fib, 2013) eq. (10-11) have been implemented:

$$f_{cm}^{dyn} = f_{cm}\left(\frac{\dot{\varepsilon_{ct}}}{\dot{\varepsilon_{ct0}}}\right)^{0.018} \quad per\ \dot{\varepsilon_{ct}} \leq 10s^{-1} \quad (10)$$

$$f_{cm}^{dyn} = f_{cm} \cdot 0.0062 \cdot \left(\frac{\dot{\varepsilon_{ct}}}{\dot{\varepsilon_{ct0}}}\right)^{\frac{1}{3}} \quad per\ \dot{\varepsilon_{ct}} > 10s^{-1} \quad (11)$$

With $\dot{\varepsilon_{ct0}} = 1 \cdot 10^{-6}\ s^{-1}$.
Finally the elastic modulus (fib, 2013) is described as indicated in eq.(12):

$$E_{cm}^{dyn} = E_{cm}\left(\frac{\dot{\varepsilon_{ct}}}{\dot{\varepsilon_{ct0}}}\right)^{0.026} \quad con\ \dot{\varepsilon_c} = 30 \cdot 10^{-6}\ s^{-1} \quad (12)$$

Formula provided by Malvar et al. (fib, 2013) has been used to take into account the increase in the steel reinforcement bars resistance inside the structural reinforced concrete elements as indicated in eq. (13):

$$f_{yk}^{dyn} = f_{yk}\left(1 + \frac{6}{f_{yk}}\ln\left(\frac{\dot{\varepsilon_c}}{5 \cdot 10^{-5}}\right)\right) \quad (13)$$

Table 3: Reinforced Concrete C25/30 Properties

Parameter	Value
Density (kg/m^3)	2,500
E_{rc} (MPa)	35,155.33
v	0.25
G_{rc} (MPa)	14,062.13
B_{rc} (MPa)	23,436.89
Yield stress (kPa)	4,019.20
Principal tensile failure stress (kPa)	4,823.04
Max principal stress difference/2 (kPa)	6,600.00
Failure erosion model	

4.4 Masonry

The equation of state used for masonry is similar to that employed for the reinforced concrete. In this case also using again a homogenized material approach. The increase in the strength for high strain rates has been contemplated by referring to the formula used by some authors (Ming Wang et al., 2008):

$$DIF = c_1 + c_2 \log_{10}(\dot{\varepsilon_c}) + c_3(\log_{10}(\dot{\varepsilon_c}))^2 \quad (14)$$

The coefficients are:

- for elastic modulus

$$\leq 1.05s^{-1} \qquad c_1 = 1.0460 \quad c_2 = 0.0153 \quad c_3 = 0 \quad (15)$$
$$> 1.05s^{-1} \qquad c_1 = 1.0447 \quad c_2 = 0.0709 \quad c_3 = 0.3339 \quad (16)$$

- for compressive strength:

$$\leq 3.55s^{-1} \qquad c_1 = 1.1140 \quad c_2 = 0.0380 \quad c_3 = 0 \quad (17)$$
$$> 3.55s^{-1} \qquad c_1 = 1.1338 \quad c_2 = -0.3417 \quad c_3 = 0.6247 \quad (18)$$

- for tensile strength:
$$\leq 1.21s^{-1} \qquad c_1 = 1.0600 \quad c_2 = 0.0200 \quad c_3 = 0 \quad (19)$$
$$> 1.21s^{-1} \qquad c_1 = 1.0275 \quad c_2 = 0.3751 \quad c_3 = 0.3872 \quad (20)$$

Table 4: Masonry Properties

Parameter	Value
Density (kg/m^3)	1,000
E_{rc} (MPa)	2,046.00
v	0.25
G_{rc} (MPa)	818.40
B_{rc} (MPa)	1,364.00
Yield stress (kPa)	290.00
Slope (°)	40.00
Principal tensile failure stress (kPa)	200.00
Max principal stress difference/2 (kPa)	400.00
Failure erosion model	

5. Pressures

The pressure evolution with the height of the walls has been investigated. From this point of view maximum and minimum pressure peaks developing in some Gauges points have been connected as indicated in fig. 2.
These points are respectively located at 0, 135 and 270 cm from the ground level.
To detect pressure variations two different room sections are considered: the central part of the walls and the corner area. Results obtained are reported in fig. 2.
The maximum pressure recorded and listed are those taking place during the entire phenomenon including also the reflected pressures. It is clear that the pressure trends have a parabolic course with the maximum peak overpressure located in an intermediate height. On the contrary, the depression peak is located at the border areas. It should be noted that the a general description of the pressure trends is not feasible since turbulent induced phenomena inside the room determine a high variability in the waves generated and reflected on the surfaces. The depression is maximum at the upper floor level of the structure where the presence of the reinforced concrete beam, that is a more rigid material than masonry, makes concentred the incident pressure waves and subsequent reflected waves in these areas more soliciting the structural elements.
The pressures are highest in the central part of the wall where the rigid material plays a key role having a greater ability to deform. On the contrary where the deformation is limited by the structure constraint conditions (fix joint beam-pillar) the positive pressure magnitudes are not so large. However an increase in the negative ones is observed. Pressures developed at ground level are not significant because of the assumption of rigid plane. It should however be noted that doesn’t reflect reality. Future studies will be dedicated to a better investigation of these issues.
This is to conclude that the rigidity of a surface invested by the explosion mechanism plays a key role in the determination of the pressure values developed inside the room interested by the phenomenon.
Further studies will be required since the modeling approach is based on the TNT – equivalency methods thus implying a detonation mechanism. This approach is only preliminary and not fully applicable to situation involving combustible mixture since related to deflagrating processes. Therefore results here presented should be considered as affected by some degree of overestimation.

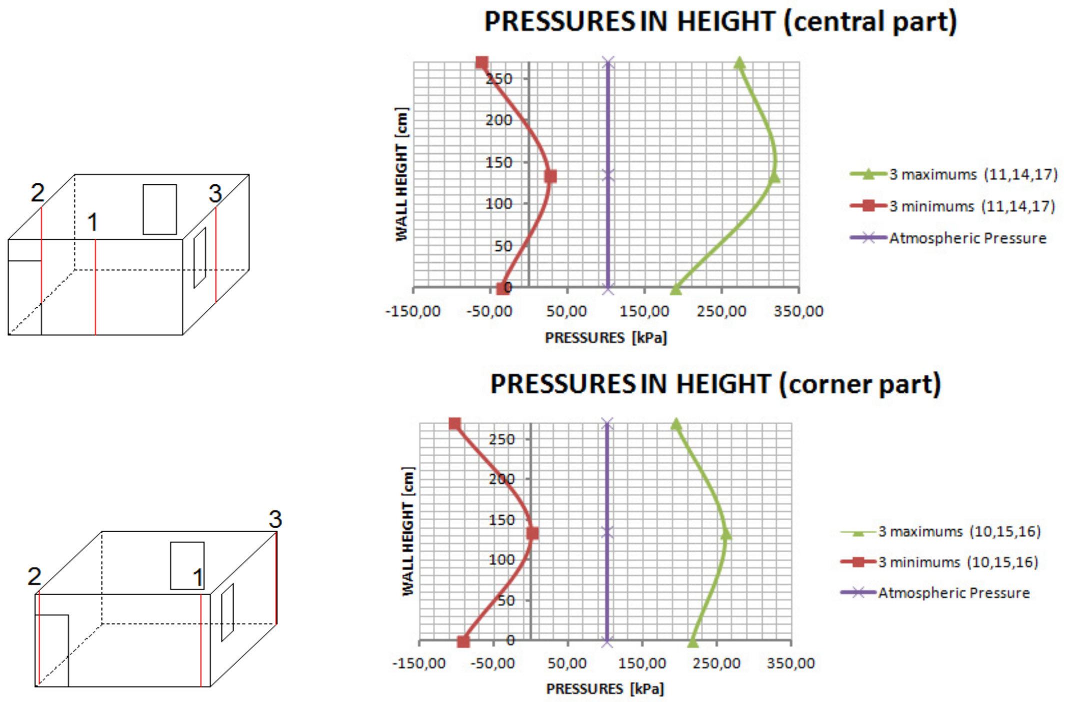

Figure 2: Pressure profiles results in characteristic points of the structure. Maximum, minimum and atmospheric values.

6. Conclusions

A domestic gas mixture explosion has been modeled with the analysis of the pressure profiles detected at the room walls. Results show that pressure profiles are not regular and does not behave in the same way throughout the different simulations. A unique formulation is therefore not feasible given that the profiles are strictly influenced by the geometry and the openings position and extension.
In addition the approximations used, such as that of the TNT – equivalency approach, play a key role in the definition of the pressure peaks trend that can be intended as an over – estimation if compared to that of a gas mixture deflagration.
Curves obtained from AUTODYN can identify an envelope diagram that is created by the configuration of mirrored peak pressures at different heights on the wall than the value of the atmospheric pressure (101.325 kPa). These diagrams shows that central elements are mainly interested by positive pressure values while corner elements are subjected to depression mechanisms.

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