Attempt at Numerical Representation of Gas Explosion in a Large Panel Building

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Abstract. Analysis of the construction market in Poland and its trends in the recent years indicates a resurgence of prefabricated technology in residential construction. The main period of prefabrication development in Poland was in the 1970s, when it was referred to as large panel. According to a report by Building Research Institute, buildings constructed with large panels are characterized by their high durability and any damage occurring in the buildings built using the technology can be divided into two groups. The first is damage similar to that occurring in traditional construction, such as damage to partition walls, roof covering or installations. The other is damage related to the prefabrication technology itself, i.e. the production of elements (material damage) and their assembly (damage at connections). Other potential threats include mining activity in the case of buildings located in mining areas and gas explosions related to the gas systems present in this type of building. This paper, therefore, attempts to recreate the process and consequences of an explosion in a closed room of a multi-family building using a numerical model. The simulations are based on: literature data (concerning calculating and applying explosion actions) and own experience in assessing the response of a concrete structure described using an elastic-plastic-damage (e-p-d) model. The result of the analyses included indication of areas directly affected by risk of loss of stability (with potential expansion of disaster area). The paper also presents the effect of “expulsion” of an external wall due to explosion. It was found that structure failure states obtained in the analyses are fully compatible in qualitative sense with observed real construction disasters caused by explosions. Real quantitative trustworthiness should result from laboratory tests of materials from which the buildings under analysis are built of.

1. Introduction

Residential construction using precast elements in Europe (figure 1) is not as common in recent years as it was previously. It is generally agreed that main development period of prefabrication technology in residential construction (figure 2) was in 1970s; it was referred to as large panel building. These systems were varied in their possibilities to shape the building or complexes; they dealt with production of all components of buildings: floor slabs, load-bearing walls, partitions, stairs and elevator shafts. Currently prefabricated technology is both a challenge and an opportunity to further develop modern residential construction [2]. That is why recent years in Poland see a resurgence of
prefabricated technology in residential multi-family construction and in construction of public buildings. This is also indicated by analyses of the Polish construction market and its trends in recent years.

![Figure 1. Strijkizjer [6], a complex of large panel buildings [own photograph], precast walls and balconies [1]](image)

![Figure 2. Examples of incorrect installation of elements in large panel buildings: a) lack of proper verticality of wall elements, c) incorrectly shaped movement joint, d) bent anchor bolt e) incorrect filling of the gap between wall elements, f) cracks and loss of material in the finish layer of triple-layered external walls in large panel construction [7]](image)

Even though large panel buildings are currently built using newer systems and are not affected by the problem of 3Ds (dirty, dangerous, difficult) [4], and contemporary prefabrication utilizes modern, durable connections and flexible systems accommodating high aesthetic requirements and allowing to erect custom building shapes with diverse characters and functions [5], analyses are still being carried out on the subject of safety of the existing large panel buildings.
In its paper “Assessment of Safety and Durability of Buildings Erected Using Industrialised Methods” (“Ocena bezpieczeństwa i trwałości budynków wykonanych metodami uprzemysłowionymi”) the Building Research Institute ran diagnostics for c. 300 large panel buildings erected using general (WK-70, Szczecin i WUF-T) and local systems (WWP, Dąbrowa) located in provinces: Masovian, Lodz, Silesian and Lower Silesian (areas affected by mining). In the technical condition report [8] it was stated that buildings constructed with large panels are characteristic for their high durability and any damage occurring in the buildings built using the technology can be divided into two groups. The first is damage similar to that occurring in traditional construction, such as damage to partition walls, roof covering or installations. The other is damage related to the prefabrication technology itself, i.e. the production of elements (material damage) and their assembly (damage at connections). Typical damage in large panel buildings (figure 2) are the result of systemic and usage defects [9-12]. Paper [13] describes rules of diagnostics for large panel building and potential preventive measures.

In the light of the above the only potential threat to the safety of large panel buildings is mining activity in the case of buildings located in mining areas [14-23] and explosions of gas [24,25] related to the fact that largest panel buildings are equipped with a gas system. Even though the latter make up only 5% of all disasters in the past twenty years, their consequences are often subject to media coverage [26]. Examples of such disasters include explosions of gas in Gdańsk in 1995, in Astrachań in 2012 or Magnitogorsk in the Chelyabinsk Oblast in Russia last year (2018).

Considering the above, research was launched independently in order to seek a method to recreate an explosion inside a large panel building using a FEM numerical model.

2. Gas explosions

2.1. Statistics regarding construction disasters in Poland caused by gas explosions
Disasters caused by gas explosion constitute about 5% of all disasters in Poland in the past twenty years; a third (in 2008–2014) were caused by natural gas. Natural gas is a fuel consisting of gaseous hydrocarbons (ethane, methane, propane), liquid hydrocarbons and a certain amount of carbon dioxide, nitrogen, hydrogen, hydrogen sulfide and noble gases (argon, helium). At concentrations of 4.9% to 15.4% it creates an explosive mixture with air [27]. It is estimated that in a typical poorly ventilated kitchen, an explosive mixture is created 5-6 hours after opening a gas stove valve or a leak appearing, after which a minor spark is enough to initiate an explosion [26].

![Figure 3. Types of buildings affected by disasters caused by gas explosion in 2008–2014 according to [26].](image)
Based on data presented in [26] it was determined that in 1995-2014 the 70% of the most destructive disasters related to gas explosion affected residential buildings. In 2008-2014 residential building disasters caused by gas explosion constituted 76% of cases, out of which 26% were multi-family buildings (figure 3). In about 50% of disasters natural gas was the cause.

While these disasters do not occur often, their death toll is high. In 2008–2014 57 people died as a result of gas explosion and 330 were injured [26], which corresponds to 14% and 26% of all construction disasters respectively (on average, 23% of disaster victims were involved in gas explosions).

![Comparison of number victims of construction disasters and victims of gas explosion accidents in years 1995–2014, according to [27].](image)

**Figure 4.** Comparison of number victims of construction disasters and victims of gas explosion accidents in years 1995–2014, according to [27].

2.2. Examples of construction disasters involving large panel buildings

2.2.1. Construction disaster in Gdańsk in 1995. On 17 April 1995 at 5:50 a gas explosion occurred in a residential building at al. Wojska Polskiego 39 in Strzyża quarter of Gdańsk [28]. The 11-storey building had been built in 1972 using large panel technology in a local system labelled MBY-110Z “Gdańsk Set” [29]. The building had a single stairwell, its volume was 14.275 m$^3$ and the built-up area under it 436.562 m$^2$ (usable space – 3,461.7 m$^2$); it housed 77 flats.

The building was severely damaged in the explosion – figure 5a–c. Three bottom storeys completely collapsed – figure 5d.

A committee led by the Chief Inspector of Construction Supervision, having considered the technical condition of the building, made the decision to demolish its remaining part (figure 5e); the decision was carried out on 18 April 1995 [26].

22 people were killed in the disaster; 1 person died of shock suddenly on 18 April [30]. Another 12 people were injured.
2.2.2. Construction disaster in Magnitogorsk in 2018. On 31 December 2018 at 6:12 local time (2:12 in Poland) gas exploded in a multi-family building at 164 Prospekt Karla Marksa in Magnitogorsk, in the Chelyabinsk Oblast in Russia [33]. The nine-storey apartment block consisting of twelve segments had been built in 1973 using large panel technology. It housed 623 flats [33] which were home to 120 people [32].

The explosion, which likely occurred in a flat on the building’s first floor, caused part of the building to collapse (figure 6). As a result, 48 flats located between the sixth and seventh stairwell were partly or completely destroyed [33]. Due to bad technical condition and the hazard of collapse it was decided that another two stairwells would be dismantled [34].

In total, 39 people were killed in the disaster and six were transported to hospitals, one of them being a 10-month-old boy [34].

Figure 5. The documentation of the disaster in Gdańsk: a, b, c) damage caused by gas explosion [28, 31], d) general cross-section of the building before and after the explosion [29], e) demolition of the remaining part of the building [28].

Figure 6. Documentation of the construction disaster in Magnitogorsk [34]
3. Methodology

3.1. Computational model of a building

The analysis used a multi-family building with concrete floors and walls (internal and external). C25/30 concrete was assumed for calculations. Concrete wall thickness is 0.20 m. Concrete floor slabs (0.20 m thick) should be considered to be continuous. Modelling large panel buildings was analysed e.g. in [35–37]. The subject of the research was a numerical model of a real building presented in figure 7.

For the purposes of description of building elements an elastic-plastic-damage (e-p-d) model [38] for concrete. This is dictated by the fact that the assessment of the safety of a structure loaded with explosion is based on analysis of the damage to walls and floors in the explosion area, measured with the degree of the material’s degradation – which poses a hazard of localised loss of stability in subsequent calculation scenarios. The usefulness of the e-p-d model in building structure analysis has been confirmed e.g. in [39-41]. Its applicability in analysing deformation and failure of buildings’ structures under varying loads has been analysed e.g. in [39,40,42,43] among others. Calculations were performed using ABAQUS/Standard software.

Characteristic functions describing evolution of strength parameters (for concrete) in relation to strain are shown in figure 8a. Figure 8b presents functions describing development of material degradation resulting from progress of plastic strains.

![Figure 7.](image)

**Figure 7.** The FEM model of the analysed building, kinematic support of the building and the location of the room with explosion load

![Figure 8.](image)

**Figure 8.** a) Weakening/strengthening relationship and b) failure curve for concrete [40]
3.2. Modelling gas explosion
The most significant problem related to usage of natural gas (methane) are the strong explosive properties of its mixture with air [26,44]. Dynamic load assumed in the analyses corresponds to changes in uniform load acting on the walls and floors forming the constraints of the explosion area of the fuel mix, where changes in pressure $P(t)$ over time $t$ are realised in subsequent intervals according to the function in figure 9.

![Figure 9](image)

**Figure 9.** Change in gas explosion load $P(t)$ over time; characteristic points $W1$, $W2$ and $K$, which are subject to analysis, are marked on the graph.

Causing ignition and combustion of portions of the flammable mix in an enclosed space causes the pressure to increase in the entire volume occupied by the mixture. The increase of pressure and internal energy, caused by inability to transfer energy outside the space in which the reaction takes place, leads to a rise in temperature with rapid acceleration of combustion rate. The value of pressure in the space occupied by the mixture increases abruptly, approaching maximum pressure. Function $P(t)$ was constructed for the purposes of the analysis through linearisation of empirical functions described in [45–47], coupled with reduction of peak pressure value $P(t)$, resulting e.g. from local brittleness of the barrier (so called vented explosion [45,46,48,49]). The peak value of the function (in the analysed case equal to 35 kPa) depends, among others, on the volume of the space occupied by the mixture contained by walls and floors of the room.

4. Results and discussions
The aim of the analyses was to run numerical experiments simulating the process and consequences of an explosion in a closed room of a multi-family building erected using large panel technology (figure 7). Every change to the conditions of “containment” of the mixture causes decompression and change in the value of pressure on walls and floors. One such scenario was considered, caused by “expulsion” of an external wall.

Because the moment of “expulsion” of the external wall can be considered to be a random event on the $t$ axis of the $P(t)$ curve and strongly dependent on the quality of connections between elements, three scenarios were analysed (figure 10) – showing the percentage of degradation of the building’s structure sliced with a transverse plane $\alpha$ (figure 7) at the selected point in time:
- for “expulsion” at timepoint $W1$ – total damage state $d$ (figure 10a),
- for “expulsion” at timepoint $W2$ – total damage state $d$ (figure 10b),
- without wall “expulsion”, for timepoint $K$ – damage state $d$, describing tension related material damage (figure 10c).
Analysing the condition of the structure in the explosion area (figure 10) damage can be seen developing in a manner corresponding to the delay in wall “expulsion” time.

Subsequent figures allow to detail the observations of this state. The figure shows the “agreement” of the description of damage state $d_t$ with the horizontal stress $\sigma_{11}$ for timepoint W1.

![Figure 10](image)

**Figure 10.** a) Total damage state $d$ for “expulsion” at timepoint $W1$; b) total damage state $d$ for “expulsion” at timepoint $W2$; c) damage state $d$ for timepoint $K$ without wall “expulsion” (view from cross-section plane $\alpha$ from figure 7).

Figure 12 shows the state of damage $d_t$ for the structure at moment $K$ for the structure in which “expulsion” of an external wall did not take place. Comparing degradation $d_t$ of floor slabs (figure 11a and figure 12) it is noticeable that the condition of the bottom floor slab from fig 12 constitutes a hazard to the structural safety due to the extent of the damage area and its intensity.

At the same time, it can be stated that in the computational model the qualitative representation of the behaviour of a large panel building during a real internal explosion was accurate (fig 11 and 12). The real quantitative trustworthiness should result from thorough laboratory tests of materials, e.g. functions presented in figure 8 and connection quality assessment [13].
5. Conclusions
Numerical simulations used in analysis of dynamic problems related to explosions – where the destructive wave of highly compressed air propagates outwards from the epicenter of the explosion – have attempted to capture the mechanism of explosion and obtain a credible method of numerical modelling for a long time. In this work, the authors have assumed that the numerical approach will allow a credible prediction of the condition of wall structure (comprising horizontal and vertical concrete elements) resulting from an explosion inside the building.

The applied numerical approach uses elastic-plastic-damage description of the structure material, based on its recognized effectiveness in representing results of laboratory tests on structure materials in different load scenarios.

Structure failure states obtained in the analyses presented in the paper are fully consistent in the qualitative sense with the observed consequences of real explosions. Real quantitative trustworthiness should, however, result from laboratory tests of materials from which the buildings under analysis are built of.
Acknowledgment(s)
Numerical calculations were carried out partly in the Academic Computer Centre Cyfronet-AGH based on computation quota documents no MNiSW/SGI3700/PŚląska/054/2010, MNiSW/SGI3700/PŚląska/083/2007 and MNiSW/SGI3700/-PŚląska/084/2007, and partly using PL-Grid Infrastructure.

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