3D FEM ANALYSIS OF PRECAST CONCRETE APARTMENT BUILDINGS UNDER MINING TREMORS – A CASE STUDY

Piotr Berkowski1(*), Jacek Barański1

1Faculty of Civil Engineering, Wrocław University of Technology, Wrocław, Poland
1(*)Email: piotr.berkowski@pwr.edu.pl

ABSTRACT

This work presents results of analysis of precast concrete multi-storey buildings under excitation caused by paraseismic tremors. 3D FEM model of the whole building as well as for specific connections in joints were applied. Results of numerical analysis were compared with destructions observed in real buildings subjected to mining tremors.

Keywords: precast concrete buildings, mining tremors, computer modelling.

INTRODUCTION

Issues related to the study of behaviour, durability and exploitation safety of buildings constructed using different types of precast systems subjected to seismic influences are extremely important in countries where earthquakes are frequent natural disasters (Magliulo et al., 2014, Aldemir et al., 2012, Biondini et al., 2010). A crucial problem is in this case a proper modelling, using modern computer methods, not only of entire precast buildings (Miedzialowski et al., 2007, Astarlioglu et al., 2004), but also of the connections between their structural elements (Chittiprolu et al., 2014, Negro et al., 2012).

Although Poland is beyond the reach of earthquakes there are regions where paraseismic vibrations associated with underground coal or copper ore mining are quite frequent (Tatara, 2012). One of the negative phenomena, in addition to terrain deformation, caused especially by underground exploitation of copper ore deposits, are rock-shocks and their effect in the form of vibrations on the surface and objects situated on it. Mining caused tremors have a local nature and not a regional one as it is the case of earthquakes. These shocks also differ from earthquakes by their irregularity, resulting in acceleration and frequency which are variable at the time. However, the most significant difference is the duration of the intensive phase of vibrations: for earthquakes this time is determined on an average of 20 seconds or more, while in the case of mining tremors these times do not exceed few seconds. In addition, duration of this phase in the epicentre region is relatively short for paraseismic tremors. Natural geological conditions in the areas of copper ore mining in Poland favour the accumulation of elastic energy in rocks. Rocks laying on ore deposits accumulate the energy, and release it during cracking. Also a great depth of residual deposits, extending from 600 to 1200 m, is a factor contributing to the accumulation of large amounts of energy in rocks. A significant impact on the formation of shocks also has conducted pillar-chamber system of exploitation. In the last few years in the areas of copper ore mining were annually recorded approx. 40 shocks of energy higher than E07 J, approx. 5 with energy around E08 J, and even some with energy higher than E09 J. The analyze made (Tatara, 2012) have also shown that there was an average of 5 shocks per year with a maximum horizontal vibration acceleration of more than 1000 mm/s² (for a frequencies band to 10 Hz).
Taking into account influence of these phenomena plays currently a very important role in the assessment of technical wear (Wodyński et al., 2008), as well as in design of strengthening of buildings located in the areas of copper underground mining in Poland. Information about the parameters describing the above phenomenon used in the design process are developed by specialized research units and mining supervision organizations, which provide values of these parameters based on years of observations and continuous measurements (Tatara, 2012, Stolecki, 2011).

DESCRIPTION OF ANALYZED PRECAST APARTMENT BUILDING SYSTEMS

Use of large-panel construction technology for apartment buildings started in Western Europe in the early 50s. In Poland, the first buildings were erected in 1957, but on a large scale this technology was used from the late 60s. Widespread use of precast elements for construction of multi-familiar buildings and also for service public ones contributed to design of many different constructional systems (Dzierżewicz et al., 2010). The differences between various systems were: modular dimensions, thickness of elements (bearing and curtain walls and slabs), materials used for fabrication, thermal insulation and structural system. With regard to precast apartment or office buildings in terms of construction their layout can be divided into the following types: wall, skeletal and mixed systems (Fig. 1), while real buildings are presented in Figs 2 and 3.

Fig.1 Structural systems of precast apartment and public service buildings

Fig.2 Typical precast large-panel apartment buildings: wall system
Analyzing the structural layout of buildings of one of the most popular systems, the so-called “WWP” system (Wrocław Precast Large-Panel Building System) (Fig. 2), one should pay particular attention to errors in the design and then to the construction ones. First of all it is about connections between prefabricated elements (Fig. 4). Most of them raise serious objections due to their strength and possible lack of proper execution. Another shortcoming at the time when these large-panel buildings were erected is that their design was the same despite they were constructed in a completely different areas, especially irrespective of geological conditions and possibility of influence of loads specific to the mining areas.

**Fig. 3** Examples of precast apartment buildings: mixed system

**Fig. 4.** Horizontal and vertical joint between internal walls and slabs in large-panel system

**COMPUTER MODEL OF LARGE-PANEL BUILDINGS’ HORIZONTAL JOINTS**

One of the most important elements of the computer analysis of precast large-panel apartment buildings is the appropriate definition of model of joints between their structural elements. In order to consider the influence of the technical condition of joints between construction elements of such buildings on the behaviour of these joints under various loads, the creation of a suitable computer model of joints using FEM was proposed (Barański et al., 2003, 2010).
The exact 2D model of the joint (Fig. 5), which was implemented first, corresponds with a geometrically typical horizontal joint (Fig. 4) used in a “WWP” system (Dzierżewicz et al. 2010). It is a section of the structure in which precast reinforced concrete elements such as a floor slab and an upper and a lower walls can be distinguished and also joint filling such as concrete and "lining" of the wall elements such as cement mortar can be identified.

Due to its complexity the model from Fig. 5 would cause some difficulties in application during the analysis of the entire building, which could be treated as both a plain and spatial structure. Therefore the above model was used to designate the characteristics of the replacement joint which would permit easier modelling.

The implementation of a simplified model of the horizontal joint in the form shown in Fig. 6, which uses models of constraints that are used in non-linear analysis of concrete structures in Lusas software (Lusas, 2014) was proposed. In this model the upper element, namely the vertical upper wall plate, is connected to the rest of the system by a set of elastic constraints with characteristics corresponding to the behaviour of the model presented earlier.
In order for such a simplified model (Fig. 6) to as far as possible reflect the operation of the exact FEM model (Fig. 5) it was necessary to determine the stiffness of the elastic constraints used in JOINT type elements. For this purpose, simulated numerical calculations based on the material non-linear analysis of the model of a typical horizontal joint used in “WWP” buildings (Figs 4 and 5) were carried out. For the defined model of a material and its features, as in Table 1, FEM calculations were carried out in order to designate the stiffness of the elastic constraints used in JOINT type elements for the simplified model of a joint (Fig. 6).

**Table 1 Properties of element materials for the analysed joint**

<table>
<thead>
<tr>
<th>Value</th>
<th>Precast element concrete</th>
<th>Fulfilment concrete</th>
<th>Lining mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ [MPa]</td>
<td>3.00e07</td>
<td>2.31e07</td>
<td>4.50e06</td>
</tr>
<tr>
<td>ν</td>
<td>0.167</td>
<td>0.167</td>
<td>0.200</td>
</tr>
<tr>
<td>$\rho$ [kN/m$^3$]</td>
<td>25</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>$f_t$ [kN/m$^2$]</td>
<td>900</td>
<td>750</td>
<td>100</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>0.004</td>
<td>0.003</td>
<td>0.00001</td>
</tr>
</tbody>
</table>

In order to verify the compatibility of such a defined model of a joint with its accurate FEM projection, the course of horizontal displacements for a wide range of loads was tested for both systems. The results showed good accordance between the yield results (Barański et al., 2003).

By using the joint model which was described above it is also possible to carry out simulations of changes of joint stiffness and the assessment of the impact of such changes on the behaviour of a structure. By changing the values of stiffness of elastic constraints it is possible to go from rigid joints (monolithic) to hinge joints which reflect the damaged (degraded) joints.

**COMPUTER ANALYSIS MODELS OF PRECAST APARTMENT BUILDINGS UNDER THE EFFECT OF DIFFERENT TYPES OF LOADS**

The proposed computer models of “WWP” system buildings were applied in analysis of these buildings for different load types as self-weight, settlement and wind, as well as for various degrees of horizontal joint degradation, with the aim to determine the mode of their eigen-vibrations.

In the case of dynamic loads it is also necessary to determine the frequency of eigen-vibrations for the structure of interest. On their basis load coefficients are determined, which aim to simplify the course of calculations by converting the dynamic load into an equivalent static load. In order to determine the frequencies of normal eigen-vibrations simplified procedures of their calculations are usually used. They are correct for simple cases, i.e. systems with simple schemes and operating in ideal conditions. In reality, the frequency of building vibrations often differs from those designated by formulas. This is so, not only because of the simplifications, but also due to the real condition of a structure. Basically, the only correct way is the experimental assessment made for existing buildings. For complex systems, if there is no possibility to make measurements, the use of computer simulation is an alternative method. The following example illustrates how the condition of joints affects frequency values and the modes of eigen-vibrations of the analysed building. It should be
emphasized that it is the modes of eigen-vibrations that decide about the behaviour of a structure during the occurrence of dynamic loads. The calculations were restricted to the designation of some initial values of frequency. Selected eigen-vibrations for the 3D building model with monolithic joints and with degraded joints are presented in Figs 7 and 8.

In Table 2 the values of frequencies of eigen-vibrations for both cases with their corresponding eigen-values are summarized.

![Fig.7 The first mode of eigen-vibrations: a) ideal joints; b) degraded joints](image1)

![Fig.8 The second mode of eigen-vibrations: a) ideal joints; b) degraded joints](image2)

<table>
<thead>
<tr>
<th>Mode of vibrations</th>
<th>Ideal joints</th>
<th>Degraded joints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eigen-value</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>1</td>
<td>31.1462</td>
<td>0.88823</td>
</tr>
<tr>
<td>2</td>
<td>70.2144</td>
<td>1.33362</td>
</tr>
</tbody>
</table>

The comparison of the results shows that the initial normal mode frequencies for the same building can vary by an order of magnitude for various states of joints.
EXAMPLE OF DYNAMIC ANALYSIS OF PRECAST APARTMENT BUILDING UNDER INFLUENCE OF MINING TREMORS

The developed finite element model for defining precast housing building constructions was then used for computational verification of their behaviour under the influence of paraseismic tremors occurring very often in areas where copper ore is mined in underground mines. Buildings constructed in this area in the initial period of implementation of such construction systems, i.e. in the late 60s of the 20th century, were not specially designed to consider influences of this type, as intensive mining operations were not envisaged in their close vicinity – exploitation was to be carried out outside of the so-called “safety pillars” around cities. However, along with the exploitation of deeper located deposits and the decision to also carry out exploitation in the close vicinity of the “safety pillars”, paraseismic phenomena began to increasingly affect the technical condition of precast large-panel buildings.

The developed methodology of defining precast large-panel buildings was used in the dynamic FEM analysis of a precast building erected with the so-called “WBL big-block” technology (Figs 9 and 10) in order to identify the most strenuous points of the construction and prove the correctness of the applied model by comparing computer simulated damage to that really occurred in the assessed building.

In the this computer analysis the FEM model, which was used to determine the distribution of internal forces (stresses) and the behaviour of a tall precast building (Figs 9 and 10) under the influence of paraseismic tremors, was verified. For the structural calculations, Lusas software (Lusas, 2014) was again used. The system of structural elements of the model geometrically corresponds to the real arrangement of the building made in the “WBL big-block” technology.
The response of a construction system to the given load is needed for the strength analysis and the assessment of safety of such a building object. Such a response depends on many factors: the mass of a system, the static scheme, the stiffness of elements, the value of damping and the driving force.

Such data was obtained on the basis of previously saved records of tremors in the form of accelerograms (Fig. 11). A commonly used method of testing the structure’s response to tremors is the RSM (Response Spectrum Method) (Lusas, 2014) (Fig. 12). The knowledge of characteristics of the driving forces, which most commonly are ground acceleration amplitudes with frequencies corresponding to them, is required to find a solution to this problem.

![Fig.11 Accelerogram of tremors caused by mining exploitation (velocity vs. time) – E = 1.70e8 J](image)

The method of applying tremor loading, results from the features of Lusas software. Frequencies of eigen-vibrations of a structure in the range of 0 to 10 Hz were calculated for this purpose. Such a range was chosen because higher frequencies of eigen-vibrations of such buildings in reality occur with a very small probability.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eigenvalue</th>
<th>Frequency Hz</th>
<th>Error norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>218.409</td>
<td>2.35210</td>
<td>0.215876e-07</td>
</tr>
<tr>
<td>2</td>
<td>324.898</td>
<td>2.86876</td>
<td>0.604087e-07</td>
</tr>
<tr>
<td>3</td>
<td>484.764</td>
<td>3.50417</td>
<td>0.717542e-07</td>
</tr>
<tr>
<td>4</td>
<td>2557.91</td>
<td>8.04939</td>
<td>0.105644e-05</td>
</tr>
</tbody>
</table>

Afterwards, from the designated spectra of ground response which are based on the records of accelerated tremors in the vicinity of a building, amplitude values in the range from 0 to 10 Hz, were also read. Damping for a structure was assumed at a level of 5%. The CQC (Complete Quadratic Combination) method was applied to estimate the response of the system. The obtained values of eigen-vibration frequencies on four first modes of vibrations are summarized in Table 3 and charts of the selected modes of eigen-vibrations are shown below (Figs 13 and 14).
The carried out calculations also included the determination of stress distribution in the elements of a building due to self-weight, wind load, kinematic coercion and the relevant combinations of these loads. The values of resultant amplitudes of horizontal components of accelerations were obtained using the RSM (Response Spectrum Method). The obtained coercions enabled the normal stresses and stresses in the directions of X, Y and Z in the load-bearing elements of an object to be determined. The analysis included a precast part of the building which is located above the ground floor.
One of the strongest tremors which occurred in the area of the analysed building foundation had an energy value equal to \( E = 1.50 \times 10^9 \) J. This tremor caused the occurrence of many damages in the form of vertical cracks in the area of contacts between precast elements in the assessed building (Fig. 15). However, for this tremor, the installed on-site measuring devices were not able to either correctly register the whole course of the tremor nor the peak values of vibration accelerations. Therefore, based on a comparative analysis of the course of dozens of previous tremors it was decided to define the load parameters from this tremor with the introduction of the so-called amplification factor. This factor is calculated as the quotient of the measured peak value of accelerations for the analysed tremor and the selected model tremor with vibration frequencies closest to the real eigen-vibrations of the assessed building. The value of such a calculated factor was equal to \( \text{AMP}_{301} = 3.01 \). The obtained distributions and stress values are shown in Figs 16, 17 and 18.

Fig. 15 Examples of damage on contacts between precast elements in the "WBL" type of building

Fig. 16 Distribution of max. Sx stresses for the tremor with energy equal to \( E = 1.50 \times 10^9 \) J
The values of tensile stresses due to kinematic coercion caused by the tremor with energy of $E = 1.50 \times 10^9$ J amounted to about 1.74 MPa (Fig. 18). Treating these stresses as characteristic, it can be assessed that they exceed the characteristic strength for concrete from which the building object is erected. The area which is considered includes ring beams, monolithic pins and also precast structures and their joints. Due to the fact that the monolithic and precast elements are reinforced, the stresses in those zones are not dangerous. Instead, they could cause cracks in the line of joints filled with mortar between precast elements which was confirmed by damage that occurred in the building.

CONCLUSIONS

The presented study shows that technical state of horizontal joints in the precast large-panel buildings constructed in the so-called „WWP“ and “WBL” systems decides on their behaviour during the occurrence of paraseismic phenomena caused by underground mining.

There were also presented results of numerical simulation of the impact of connections between structural large-panel elements on the dynamic response of precast buildings. The overworked models were used to analyze the real precast buildings that were exposed to mining tremors.
Test results and numerical modelling of large-panel buildings, treated as complex mechanical systems, are very important in assessing the technical condition of existing structures, undertaken in order to properly carry out the renovation works currently performed for precast large-panel buildings.

REFERENCES


