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DYNAMIC RESPONSE OF MONUMENTAL CHURCH TO HIGH-ENERGY MINING TREMORS

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Abstract. *In the paper a detailed analysis of the dynamic response of a monumental masonry chapel to mining tremors typical for two main regions of mining activity in Poland (i.e. the Upper Silesian Coal Basin and the Legnica-Glogow Copper District) was presented. The representative time histories registered in both regions were used as ground motion data in the calculation of the dynamic response of the structure. The frequency contents of both selected tremors were significantly different: the dominant frequency range of the mining tremor in the Upper Silesian Coal Basin consists of lower frequencies (2-5 Hz) than in the Legnica-Glogow Copper District (5-7 Hz). The ABAQUS software was used for the dynamic calculation. The finite element model of the chapel was based on the geometry of an existing structure. Firstly, natural frequencies of the chapel were evaluated. Then, for the assessment of the influence of dominant frequencies of the mining tremor on the dynamic response of the structure, full time history analyses (THA) were carried out. The comparison of the maximal principal stresses obtained for both shocks was presented. It proved that the dynamic response of the masonry chapel was strongly dependent not only on the level of vibration amplitudes but on the dominant frequency range of the mining shock typical for the mining region as well. Finally, the response spectrum method (RSA) was applied for calculations of the dynamic response. The elastic spectrum recommended in EUROCODE 8 and the local spectral curves established for the Upper Silesian Coal Basin and the Legnica-Glogow Copper District were used. The results indicated that the EUROCODE 8 spectrum overestimated the dynamic response of the structure. Better results were obtained for the local spectra.*

1 INTRODUCTION

Historic monuments, like old masonry churches or chapels, erected in past centuries were not designed to carry modern loadings, like mining tremors resulting from intensive coal or copper exploitation processes. The evaluation of the dynamic response of engineering structures to mining tremors became a task of intensive studies in Poland [1, 2], since energy and amplitudes of vibrations caused by high-energy mining shocks are comparable with amplitudes of vibrations resulting from small earthquakes.

This paper presents the dynamic response of a monumental masonry chapel to mining tremors registered in two main mining activity regions in Poland. The main objective of the study was to compare the dynamic responses of the chapel to the mining tremors with different dominant frequency content.

Nowadays a wide range of structural analysis methods is applied in calculation of structures located in earthquake zones. In case of small seismic events or mining shocks the dynamic response of a structure is supposed to be linear. Hence, simple methods assuming linear elastic behaviour of a structure, like response spectrum method, could be introduced for calculation of the dynamic response of a structure. In this study two main evaluation methods of the dynamic response of a structure to kinematic excitation were used: the time history analysis (*THA*) based on numerical integration of equation of motion, and the response spectrum analysis (*RSA*) based on spectral curves. The following spectral curves were applied in the analyses: the elastic spectrum recommended in EUROCODE 8 [3] and the local elastic spectra established for two mining regions in Poland [4]. The assessment of applications of these spectra was conducted according to the accuracy of the obtained results.

2 THE MAIN DATA AND THE NUMERICAL MODEL OF THE CHAPEL

The analyzed masonry chapel is located in the Upper Silesian Coal Basin (USCB), which is a region of very intensive mining activity in Southern Poland. The structure (Fig. 1) was erected in 1905 for miners working in the “Gottwald” cold mine. Up to now, being rebuilt and rehabilitated (Fig. 2), it serves for prayers and sacral ceremonies.

Figure 1: Historical photo of the structure
[source: pl.wikipedia.org/wiki/Kopalnia_węgla_kamiennego_„Gottwald”].

Figure 2: Front view of the Silesia Chapel located in Upper Silesian Coal Basin [photo: Kaplica przy CH SILESIA by gothicus/en.wikigogo.org].

On the basis of existing technical documentation [5] a numerical model of the chapel was created in the ABAQUS software [6]. The chapel is a one-story building. The main dimensions are: the length – 19 m, the width – 14 m, the height – 15 m. It is founded on block foundation (Fig. 3a) that provides good behaviour of the structure located in mining areas and prevents the structure from non-uniform settlement occurring due to coal exploitation. It also reduces vibrations transmitted from the ground to the structure during mining shocks. The walls of the chapel are built of bricks on lime mortar. The structure is strengthen by a concrete plate supported by steel girders that served for a choir. The structural system of the roof consists of steel trusses. The roof of the chapel is covered by steel sheeting.

The whole 3D numerical model of the chapel is presented in Fig. 3b. The model was discretized by 336194 tetrahedral 10-node finite elements provided by the ABAQUS software.

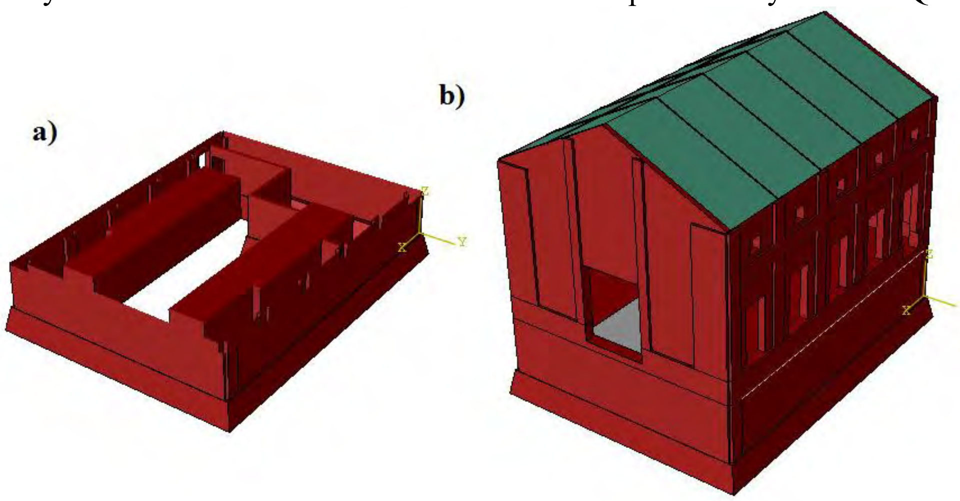

Figure 3: Numerical modeling of the chapel: a) foundation blocks, b) the whole 3D model.

The first step of the dynamic analysis was the evaluation of natural frequencies and modes of vibration of the chapel. The lowest frequencies accompanied by bending modes in two directions were: 3.28 and 4.41 Hz. The lowest frequency accompanied by torsional mode was 5.55 Hz.

3 DATA OF MINING TREMORS REGISTERED IN USCB ANE LGCD REGIONS

There are two main mining activity regions in Poland: the Upper Silesian Coal Basin (USCB) and the Legnica-Glogow Copper District (LGCD). Mining tremors registered in these regions differ as far as dominant frequency range is considered. It means that dynamic responses of to ground motion of similar energy and values of maximal amplitudes could be different for similar structures located in both mining regions. The different performance of the structure is caused by the different frequency contents of the shocks.

In case of calculations of the dynamic response of a structure to an earthquake a horizontal component of ground motion parallel to the direction of wave propagation plays central role. This component results from the Rayleigh wave propagation. Other components are usually found non-essential and they are rarely taken into account in seismic analyses. In case of mining shocks the situation is different. As the epicenter of the shock is located relatively close to an analyzed structure, different types of waves reach the structure at the same time. Typical time history of mining shock registered in a short distance from the epicenter shows that values of amplitudes in three directions are comparable.

3.1 Time histories of registered mining tremors

Figure 4 presents three components of a representative mining shock registered in the Upper Silesian Coal Basin [4]. The energy of the tremor registered in the Upper Silesian Coal Basin was about $1 \cdot 10^7$ J; the tremor was one of the strongest events ever measured in this region. Figure 5 shows three components of a selected tremor registered in the Legnica-Glogow Copper District [4]. The energy of the tremor in the Legnica-Glogow Copper District was about $5 \cdot 10^7$ J. It could be noticed that the energy of this event was 5 times bigger than the energy of the shock recorded in the Upper Silesian Coal Basin.

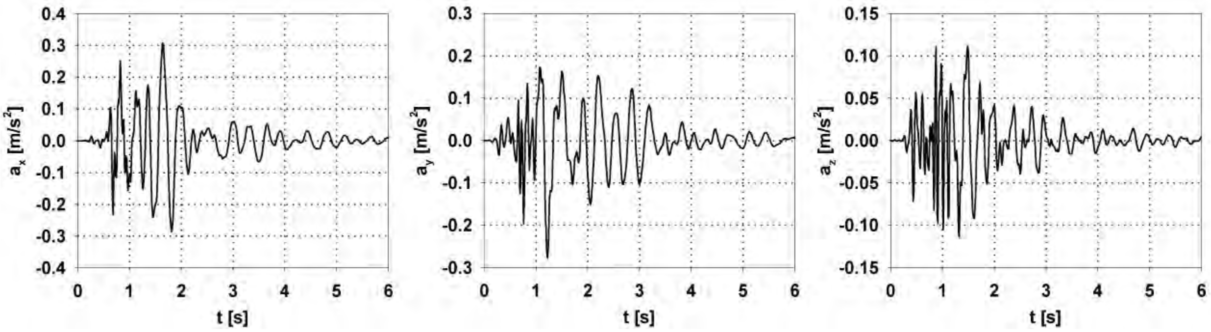

Figure 4: Time histories of ground motion accelerations registered in the USCB region in three directions: a_x, a_y – horizontal, orthogonal; a_z – vertical.

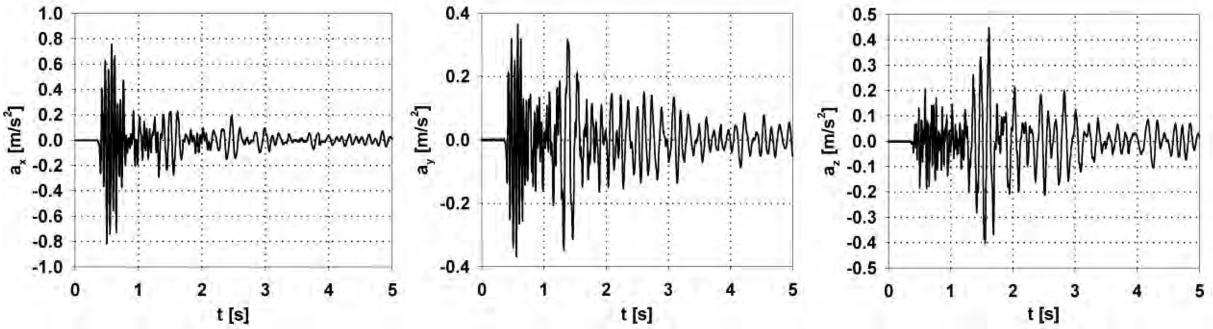

Figure 5: Time histories of ground motion accelerations registered in the LGCD region in three directions: a_x, a_y – horizontal, orthogonal; a_z – vertical.

It could be observed in Figs 4 and 5 that the maximal amplitudes of accelerations in horizontal directions are greater than the maximal vertical amplitudes. But still the values of the vertical and horizontal component are comparable. Hence, all three components of ground vibrations resulting from the mining tremors have to be considered in the dynamic analysis.

Figure 6a presents the frequency spectrum of the horizontal component in direction X of the mining shock from the Upper Silesian Coal Basin. The dominant frequencies of the shock in horizontal direction X are located in the range from 1.6 to 4.8 Hz with a noticeable peak at 3.5 Hz. In horizontal direction Y and in vertical direction Z a similar range of dominant frequencies can be observed. Figure 6b shows the frequency spectrum of the horizontal component in direction X of the mining shock from the Legnica-Glogow Copper District. The amplitudes show maxima at the dominant frequencies of about 7 and 20 Hz.

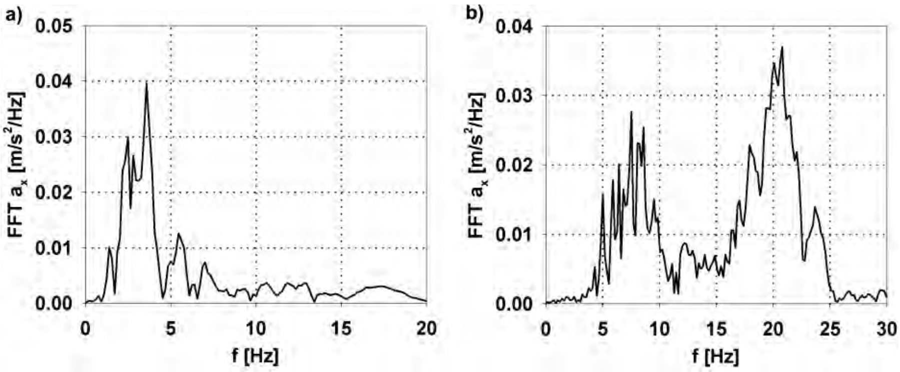

Figure 6: The frequency spectra of the mining shock registered in horizontal direction X in: a) the USCB region, b) the LGCD region.

The presented frequency spectra registered in both analyzed mining regions differ from each other as far as the dominant frequency range is concerned. The range of the dominant frequencies of the mining tremor from the LGCD region generally consists of higher frequencies than in the range of the dominant frequencies of the shock from the USCB region.

3.2 Local elastic response spectra for USCB and LGCD regions

The horizontal elastic response spectrum recommended by EUROCODE 8 and the local elastic response spectra established for the USCB and LGCD regions are presented in Figs 7 and 8, respectively.

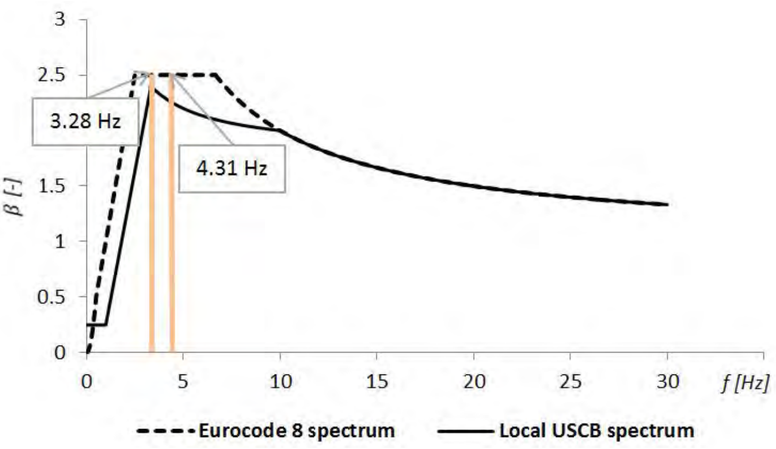

Figure 7: The shapes of the horizontal response spectrum recommended in EUROCODE 8 and the local spectrum established for the USCB region with two lowest natural frequencies.

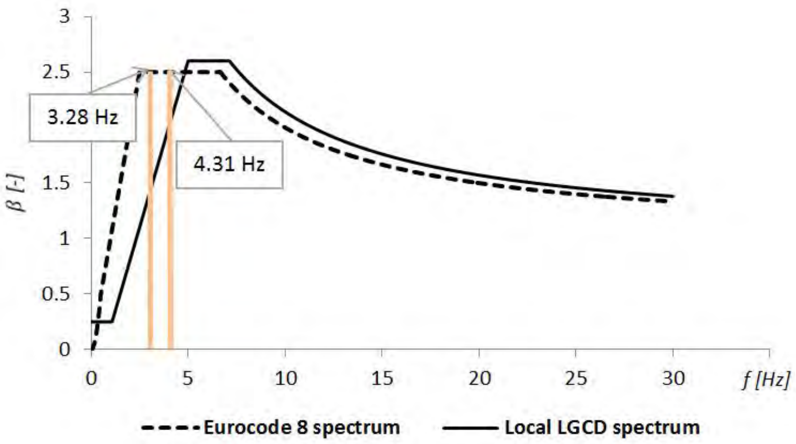

Figure 8: The shapes of the horizontal response spectrum recommended in EUROCODE 8 and the local spectrum established for the LGCD region with two lowest natural frequencies.

The proposed local spectra are based on studies of a selected set of ground motion data resulting from mining tremors in both regions [4]. Figs 7 and 8 also localize the lowest natural frequencies of the chapel on the investigated spectral curves.

4 DYNAMIC RESPONSES OF THE CHAPEL TO MINING TREMORS FROM DIFFERENT MINING REGIONS OBTAINED WITH *THA* AND *RSA* METHOD

The dynamic responses of the chapel to the selected mining shocks were evaluated for the whole model, but in the comparative analysis of the obtained responses maximal general stresses were compared for selected points presented in Fig. 9.

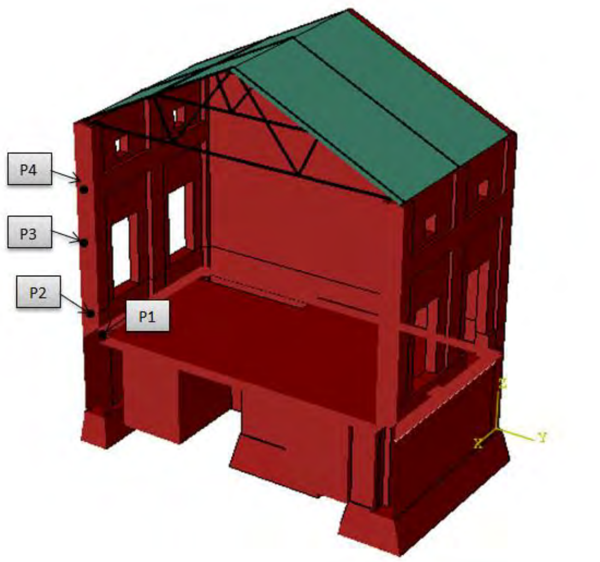

Figure 9: Location of points selected for dynamic analysis.

Firstly, to assess the influence of the frequency range of a mining shock on the dynamic response of the chapel the calculations of the dynamic responses were performed using the time histories of selected mining tremors registered in three directions in the USCB and the LGCD regions (see Figs 4 and 5, respectively). The time history analysis (*THA*) was carried out with the Hilber-Hughes-Taylor time integration algorithm provided in the ABAQUS software. Modal dynamic analysis was implemented for the solution, since the problem was assumed to be linear-elastic. A critical damping ratio of 5 % was introduced in the calculation.

Secondly, the evaluation of the dynamic response of the chapel with the response spectrum method (*RSA)* was carried out. The is only an approximate method, but it estimates the peak response of a structure to particular ground motion. The following response spectra were applied in the analysis. Firstly, the elastic spectrum recommended by EUROCODE 8 (ground type A, damping 5 %) was implemented [3]. Then, the local elastic spectra established for the USCB and the LGCD regions were used (see Figs 7 and 8, respectively). The *CQC* method for modal summation [6] was used in the calculations.

4.1 Dynamic response of the chapel to the mining tremor in the USCB region

The relation between maximal principal stresses at selected points P1-P4 (see Fig. 9) obtained from the *THA* and *RSA* methods for the mining shock from the USCB region is presented in Fig. 10. The elastic spectrum from EUROCODE 8 and the local spectrum for the USCB region were applied in both horizontal directions with the maximum ground acceleration of 0.3 and 0.28 m/s^2, respectively. Since three directions of the ground motion during the mining tremor were taken into account in *THA* method, the vertical response spectra were also taken into consideration with the maximum ground acceleration of 0.12 m/s^2. The values of the maximum ground accelerations were taken from time histories presented in Fig. 4.

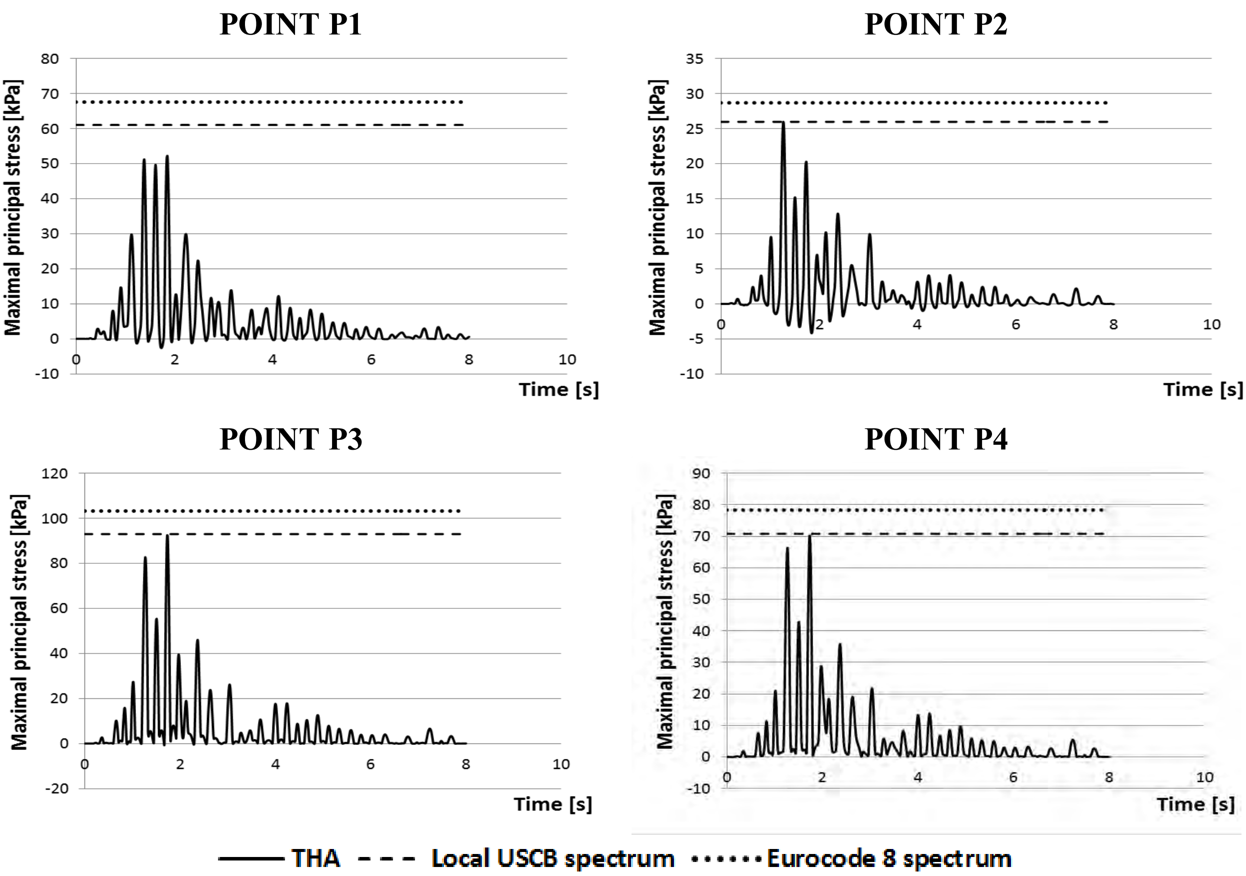

Figure 10: Relation between maximal principal stresses at points P1-P4 (see Fig. 9) obtained from *THA* and *RSA* method with the EUROCODE 8 elastic spectrum and the local USCB elastic spectrum.

In Table 1 the differences between maximal principal stresses obtained from *THA* and *RSA* method with the elastic response spectrum recommended in EUROCODE 8 are presented for all selected points P1-P4. The differences between stresses obtained from *THA* and *RSA* method with the local response spectrum established for the USCB region are summarized in Table 2.

Table 1: Differences between maximal principal stresses at all selected points (see Fig. 9) obtained from *THA* and *RSA* method with the elastic response spectrum recommended in EUROCODE 8.

Point	Maximal principal stress [kPa]		Difference
	THA	*RSA* (EC8 spectrum)	[%]
P1	52249	67603	28.9
P2	25974	28698	10.5
P3	92537	103292	11.6
P4	70231	78341	11.5

Table 2: Differences between maximal principal stresses at all selected points (see Fig. 9) obtained from *THA* and *RSA* method with the local elastic response spectrum established for the USCB region.

Point	Maximal principal stress [kPa]		Difference
	THA	*RSA* (USCB spectrum)	[%]
P1	52249	61059	16.9
P2	25974	25978	0.1
P3	92537	93032	0.5
P4	70231	70788	0.8

On the basis of the results presented in Fig. 10 as well as in Table 1 it could be noticed that the differences between maximal principal stresses obtained from the exact *THA* and the approximate *RSA* methods reached up to 29 % (see Table 1, Point P1). The results obtained from both methods differed significantly less when the local USCB elastic response spectrum was used in the analysis. They reached up to 17 % (see Table 2, Point P1).

4.2 Dynamic response of the chapel to the mining tremor in the LGCD region

The relation between maximal principal stresses at selected points P1-P4 (see Fig. 9) obtained from the *THA* and *RSA* methods for the mining shock from the LGCD region is presented in Fig. 11. The elastic spectrum from EUROCODE 8 and the local spectrum for the LGCD region were applied in both horizontal directions with the maximum ground acceleration of 0.8 and 0.36 m/s^2, respectively. The vertical response spectra were also taken into consideration with the maximum ground acceleration of 0.45 m/s^2. The values of the maximum ground accelerations were taken from time histories presented in Fig. 5.

In Table 3 the differences between maximal principal stresses obtained from *THA* and *RSA* method with the elastic response spectrum recommended in EUROCODE 8 are presented for all selected points. The differences between stresses obtained from *THA* and *RSA* method with the local response spectrum established for the LGCD region are summarized in Table 4.

On the basis of the results presented in Fig. 11 as well as in Table 3 it could be noticed that the differences between maximal principal stresses obtained from the exact *THA* and the approximate *RSA* methods reached up to 100 % (Table 3, Point P2). The results obtained from both methods differed less significantly when the local LGCD elastic response spectrum was used in the analysis. They reached up to 72 % (see Table 4).

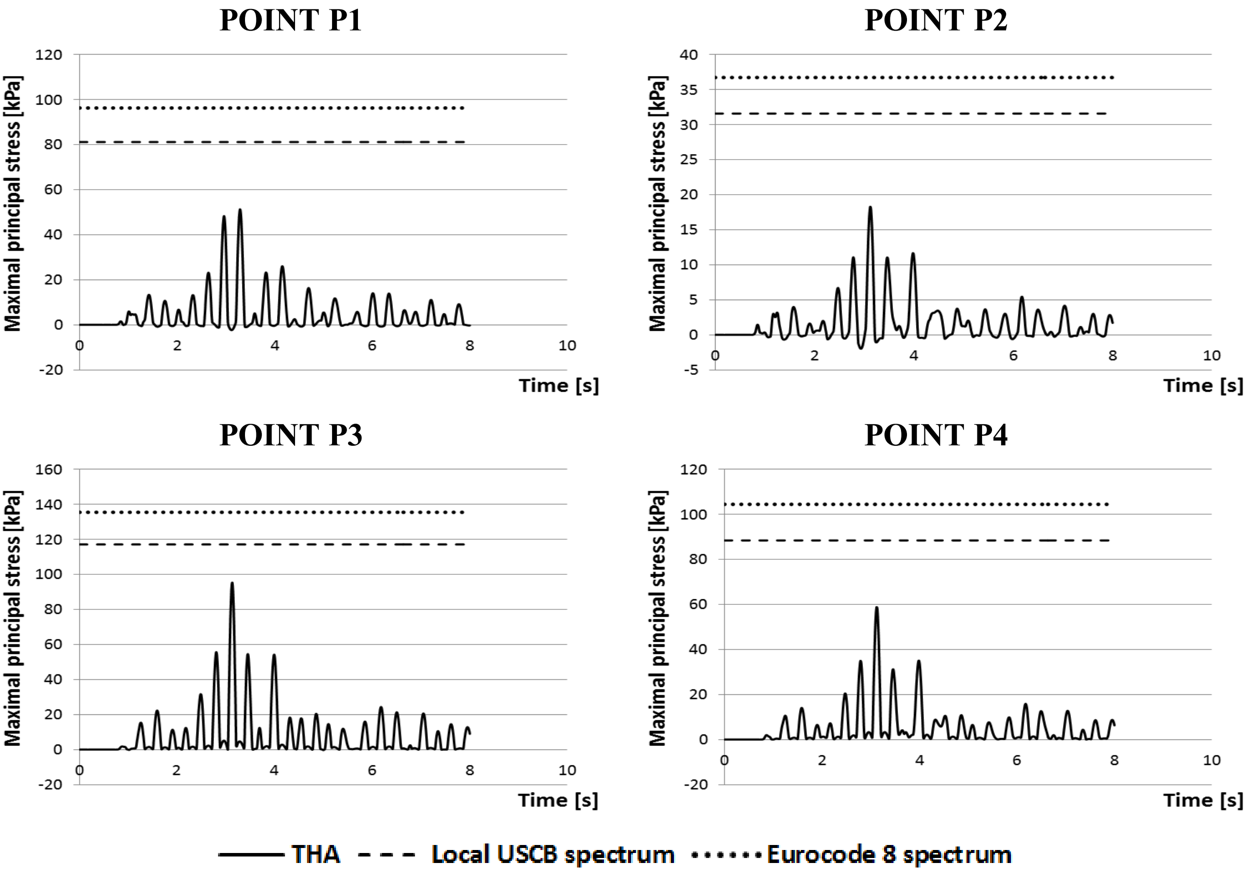

Figure 11: Relation between maximal principal stresses at points P1-P4 (see Fig. 9) obtained from *THA* and *RSA* method with the EUROCODE 8 elastic spectrum and the local LGCD elastic spectrum.

Table 3: Differences between maximal principal stresses at all selected points (see Fig. 9) obtained from *THA* and *RSA* method with the elastic response spectrum recommended in EUROCODE 8.

Point	Maximal principal stress [kPa]		Difference
	THA	*RSA* (EC8 spectrum)	[%]
P1	51324	96316	87.6
P2	18298	36732	100.7
P3	95375	135489	42.1
P4	58839	104478	77.6

Table 4: Differences between maximal principal stresses at all selected points (see Fig. 9) obtained from *THA* and *RSA* method with the local elastic response spectrum established for the LGCD region.

Point	Maximal principal stress [kPa]		Difference
	THA	*RSA* (LGCD spectrum)	[%]
P1	51324	81186	58.2
P2	18298	31592	72.7
P3	95375	117118	22.8
P4	58839	88446	50.3

4.3 Comparison of dynamic responses to tremors from the USCB and LGCD regions

Figs 10 and 11 present the time histories of maximal principal stresses in selected points obtained for the shocks from the USCB and the LGCD regions, respectively. It could be observed that the amplitudes of accelerations of the mining tremor registered in the Legnica-Glogow Copper District were almost three times greater than the amplitudes of accelerations from the Upper Silesian Coal Basin (see Figs 4 and 5). Despite of it, the values of the maximal principal stresses were greater in case of the tremor from the Upper Silesian Coal Basin. It indicates that the dynamic response of the chapel is strongly dependent on the dominant frequency range of the kinematic excitation. In case of the shock from the Upper Silesian Coal Basin the frequency band (see Fig. 6a) includes first natural frequency of the chapel associated with the mode executed by horizontal excitation. The frequency range of the shock registered in the Legnica-Glogow Copper District (see Fig. 6b) does not include the lowest frequency of the chapel.

Figure 10 presents the results obtained for the *RSA* method for the shock registered in the USCB region. The comparison of the maximum values of principal stresses obtained from *THA* and *RSA* method based on the spectral curve recommended in EUROCODE 8 is shown in Table 1, whereas the comparison of the maximum values of principal stresses obtained from *THA* and *RSA* method based on the local spectral curve is presented in Table 2. The dynamic response of the chapel was slightly overestimated if the elastic response spectrum recommended by EUROCODE 8 was introduced. Almost accurate results were obtained if the local elastic response spectrum established for the Upper Silesian Coal Basin was applied. However, the results obtained on the basis of the EUROCODE 8 spectral curve approximate the dynamic response very well, since the range of the dominant frequencies of the shock is similar to typical dominant frequencies of earthquakes.

Figure 11 presents the results obtained for the *RSA* method for the shock registered in the LGCD region. The comparison of the maximum values of principal stresses obtained from *THA* and *RSA* method based on the spectral curve recommended in EUROCODE 8 is shown in Table 3, whereas the comparison of the maximum values of principal stresses obtained from *THA* and *RSA* method based on the local spectral curve is presented in Table 4. It could be noticed that the dynamic response of the chapel was significantly overestimated if the elastic response spectrum recommended by EUROCODE 8 was introduced. More accurate results were obtained if the local spectrum established for the Legnica-Glogow Copper District was applied. The following explanation of the obtained results seems to be reasonable: the local spectrum established for the LGCD region is shifted towards higher frequencies in comparison with the spectrum recommended in EUROCODE 8 (see Fig. 8). The maximum values of accelerations in the EUROCODE 8 spectrum start from 2.5 Hz, whereas in the local spectrum – from 5.0 Hz. Therefore, for the chapel with the first natural frequency of 3.28 Hz, the value of the spectrum recommended in EUROCODE 8 is about 70 % greater than the value of the local LGCD spectrum. Due to this difference, the EUROCODE 8 spectrum overestimates even by 100 % the results obtained from *THA* method.

5 CONCLUSIONS

- The comparative analysis of the dynamic responses of the chapel to the mining shocks from different mining regions showed that the frequency range of kinematic excitation significantly influences the response of the structure. When the dominant frequency range includes basic frequencies of natural vibrations, the values of maximal stresses can be bigger than the values obtained in result of applying a kinematic excitation of even higher amplitudes but of a frequency range not including basic natural frequencies.

Hence, the dynamic performance of similar buildings located in various mining regions may differ not only due to the magnitude of amplitudes but due to the range of dominant frequencies of the shock (which is typical for a particular region) as well.

- The EUROCODE 8 spectral curve is designed for earthquakes. Since the range of dominant frequencies of the shock in the Upper Silesian Coal Basin is similar to typical dominant frequencies of earthquakes, the *RSA* method based on the EUROCODE 8 spectral curve estimates the peak response of the chapel to the shock in this region with good accuracy. Better results of approximation was obtained if that local spectrum established for the USCB region was introduced.
- The dominant frequencies of mining tremors in the Legnica-Glogow Copper District are much higher than typical frequencies of earthquakes. Hence, the application of the spectrum recommended in EUROCODE 8 significantly overestimates the dynamic response of the chapel (with relatively low natural frequencies) subjected to the shock from this region. Substantially better results of approximation can be obtained from *RSA* method, provided that local spectrum established for the LGCD region is introduced.
- The problem pertain only to structures with low natural frequencies. The dynamic response of a structure with higher natural frequencies (over 10 Hz) obtained on the basis of both EUROCODE 8 and local spectrum will be almost identical.

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