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Technical Notes

The Study of the Influence of the Ceiling Structure on Acoustics in Contemporary Churches

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The paper discusses acoustic problems in the contemporary Catholic church, and presents a study of the influence of the ceiling structure on acoustics in the interior for two types of ceiling structures, i.e. the truss type and the reinforced concrete one. The investigations involved six contemporary churches: three buildings with a truss type ceiling and three buildings with a reinforced concrete ceiling. The results reveal that in churches with a truss type ceiling, acoustic parameters reach values close to recommendations. In contrast, churches with a concrete ceiling create very unfavourable acoustic conditions. The investigations rendered it possible to calculate the sound absorption coefficient α for the truss type cover.

Keywords: church acoustics; reverberation time in the church; contemporary church; church architecture.

1. Introduction

The issue of architectural acoustics in sacred buildings still lacks enough attention. While crucial acoustic decisions at the design stage are common in the case of concert halls and opera houses, in many sacred buildings acoustics is not taken into consideration at any stage. The problem is still not appreciated enough by decision making architects. When concert halls are designed, the awareness of acoustic requirements is usually very high. In contrast, in sacred buildings, where speech and music reception are equally important, acoustics are not dealt with at the design stage.

The following paper discusses the influence of the ceiling structure on acoustic conditions in the contemporary church. Publications on the issue of contemporary churches constitute a considerable part of papers devoted to church acoustics.

Investigations involved churches in Poland were followed by proposals of acoustic treatment for problematic issues (Wróblewska, Kulowski, 2007). Contemporary Catholic churches often experience too long reverberation time, which is an issue raised by authors. The example of St. Paul's Church in Bochnia shows the problem of reverberant noise, and acoustic treatment was proposed on the basis of measurements and simulations (Kosała, Kamisiński, 2011). Santa Ana's Church in Moratalaz, Madrid, underwent investigations and appropriate acoustic treatment which were developed to decrease too long reverberation time (Buenoě *et al.*, 2012). For Maria Regina Della Pace Church in Perugia, erected in 1993, where the reverberation time RT = 4.4 s, acoustic treatment was suggested on the basis of simulations in the RAMSETE programme (Buratti *et al.*, 2006). Other investigations also involved Italian churches with problematic acoustics, and they were followed by development of appropriate acoustic treatment (Quartieri *et al.* 2009; 2010; Gagliano *et al.*, 2015). Two Croatian churches were described due to considerably excessive reverberation time since it amounted to 6.9 s in one church, and the value of RT = 10.5 s was registered in the other (Horvat *et al.*, 2011). The influence of the 20th century architecture was analyzed in terms of its influence on acoustics of two churches in Porto, Portugal (Carvalho *et al.*, 2012).

Literature also discusses contemporary churches where the problem of excessive reverberation time does not occur. Acoustic investigations of Sao Carlom Borromen Church in Curitiba, Brazil, revealed that RT for the frequency of 500 Hz was below recommended values (de Sant'Ana, Zannin, 2011). In contrast, very good acoustic conditions were registered in a church, in Fatima, whose internal volume is equal to $V = 130\,000$ m^3 (Carvalho, Silva, 2010).

A new method of acoustic assessment of sacred buildings, which involved global index of acoustic quality, was presented, and application of the method in Roman Catholic churches, including contemporary churches, was described (Engel, Kosała, 2005; 2007; 2013).

The issue of acoustics in the contemporary church, which ensued as a result of the Second Vatican Council, was raised too (Soeta *et al.*, 2012).

Pews may be the element of the contemporary church that facilitates improvement of acoustic conditions. Sound absorption by service participants seated in pews underwent investigations, which took place both in the laboratory and in situ in six churches (Martellotta *et al.*, 2011). The issue of pews and their impact on interior acoustics was raised by different authors (Desarnaulds *et al.*, 2002; Cirillo *et al.*, 2007; Martellotta, Cirillo, 2009; Carvalho, Pino, 2012).

The aforementioned publications analyzed various aspects of acoustic conditions. However, the influence of the ceiling structure has not been taken into consideration so far. The following article addresses the issue. Over a dozen churches in Poznań, a city situated in western Poland, underwent acoustic investigations. Churches erected in the 1980s and 1990s in Poland lacked acoustic adaptations, which resulted in excessive reverberation time. Comparative analyses rendered it possible to notice two prevalent types of ceiling structures applied in churches: a truss type and a reinforced concrete one. Initially, the investigations involved two churches representative of the two types (Sygulska, 2016). The following publication presents results of investigations in six churches: three buildings for each type, to show dependencies between the ceiling structure and acoustic conditions in the interior.

2. The issue of excessive reverberation in contemporary churches

It is hard to imagine a functional place of worship with awe-inspiring architecture without good acoustics; such an interior would not, and could not, be considered a well-designed liturgical space. Still, many of contemporary sacred buildings do not fulfil the basic requirement, i.e. acoustics. The most serious acoustic issue that occurs in Polish contemporary sacred architecture (but also in other European countries) is too long reverberation time, which results in problematic reverberant noise. If there is also hard floor (made of stone or concrete), which is characteristic of churches, sounds such as thuds and bangs are particularly noisy and resonant. Such noises are usually caused by footsteps and chairs being moved, and when amplified by an echo, they cause additional disturbance. As a result, realization of the primary function of a place of religious worship, i.e. liturgy, is hard to perform.

Optimal acoustic conditions in a church can be defined as a balance between requirements for speech and for music. In the Catholic church, speech is very important. Conducting a liturgy becomes problematic due to the main common problem, i.e. understanding speech, and the church as a facility loses its functionality. It should also be highlighted that since 1965, when Latin was replaced by native languages after the Second Vatican Council, requirements concerning speech intelligibility have been particularly important. However, to achieve favourable acoustic conditions one should not aim at very short reverberation time recommended for interiors designed for speech (e.g. cinemas, conference halls or classrooms) as in the Catholic liturgy organ music is very important too. The pipe organ accompanies liturgy and is inseparably linked to the church interior. As official church documents state, 'The pipe organ is to be held in high esteem in the Latin Church, since it is its traditional instrument, the sound of which can add a wonderful splendour to the Church's ceremonies and powerfully lift up men's minds to God and higher things' (Musicam Sacram, Instruction on Music in the Liturgy). Also, a considerable number of churches boast high end instruments which are regularly used to perform concerts. Except for organ music, the expected longer reverberation time is also influenced by the reception of sacrum in relation to sound. Clearly noticeable reverberance is thus inherent in the tradition of sacred buildings, and it gives one a sense of being in a sacred place. Interesting conclusions in that matter are presented by (Carvalho, Nascimento, 2011). Therefore, the problem of designing acoustics of a church consists in striking a balance to ensure speech intelligibility on the one hand and create favourable conditions for organ music on the other. It is all the more challenging due to the fact that the required acoustic parameters for speech are entirely different from recommendations for rooms suitable for organ music performances.

In comparison with historical churches, contemporary sacred architecture encounters serious problems. Among contemporary churches prevail aisleless types; details are scarce, traditional materials (typically stone, glass, cement and lime plaster, and concrete) used in the construction are highly sound-reflective, which causes reverberation time to exceed recommended values (even those recommended for organ music). Also, acoustic materials which could help to achieve correct acoustics in a given interior (and which would not influence the decor) are often neglected.

In the 1980s and 1990s, acoustics were hardly ever taken into account in construction of churches, and even if the acoustic effect was satisfactory, it was, in most cases, accidental. The investigations carried out by the author revealed that the decisive factor which renders it possible to achieve acceptable acoustic conditions is the ceiling structure. The aim of the publication is to analyze how interior acoustics are influenced by two main types of ceiling used in the contemporary architecture, i.e. reinforced concrete and truss type covers.

3. Acoustic investigations

The investigations involved over ten churches in Poznań. Six of them are presented in the following publication and they include three churches with a reinforced concrete ceiling, while ceilings of the other three represent the truss type. The selected buildings were erected in the 1980s and 1990s, and their internal volumes range from 4800 m^3 to 7500 m^3.

3.1. Methodology of the investigations

The acoustic investigations were carried out by means of an omnidirectional sound source, a Brüel & Kjær ZE-0948 USB sound card and DIRAC programme. A sweep-signal was generated and T_{30}, EDT, t_S, C_{80}, C_{50}, D_{50}, STI and RASTI were measured. Methodology of the investigations was compliant with recommendations available in literature (Martellotta *et al.*, 2009; Engel *et al.*, 2007). The analysis included parameters which are described in literature as basic parameters used to assess acoustic properties of a religious building (Wróblewska, Kulowski, 2007). The measured parameters were compared with values recommended for churches (Wróblewska, Kulowski, 2007; Everest, 2009). The sound source was placed in front of the altar at the height of 1.5 m. Distribution of the measurement points are shown in views. In three of the investigated churches, the measuring points were determined on one side only due to the obvious symmetry of the building. In the other churches, even if only slight differences occurred, measuring points were determined on both sides of the nave. Measurements were carried out in unoccupied conditions.

3.2. Churches with reinforced concrete ceilings – description of the structure

Three of the investigated churches have reinforced concrete ceilings. They include: Church of the Sacred Heart of Jesus (HJ), St. Lawrence's Church (SL), Church of the Nativity of Our Lord (NL). Comparison of the churches (views and photos of the interiors) is shown in Table 1, while the cross-sections are presented in Fig. 1.

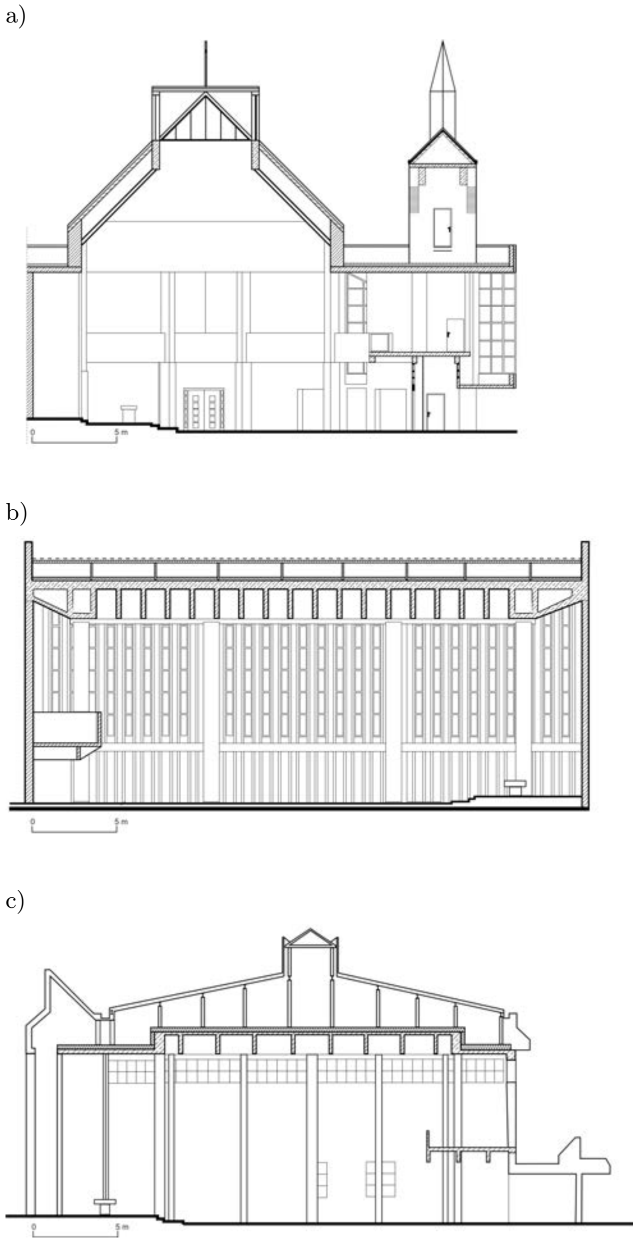
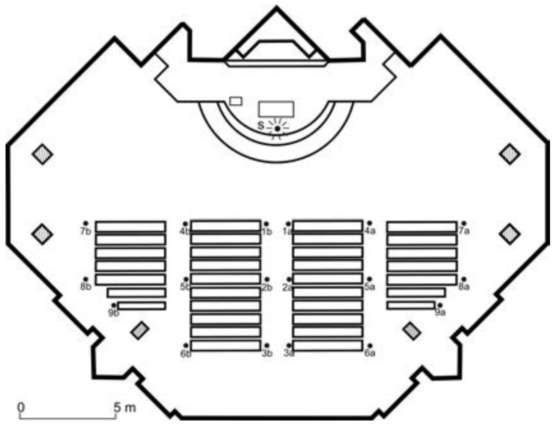


Fig. 1. Cross-sections of churches with a concrete ceiling: a) Church of the Sacred Heart of Jesus (HJ), b) St. Lawrence's Church (SL), c) Church of the Nativity of Our Lord (NL).

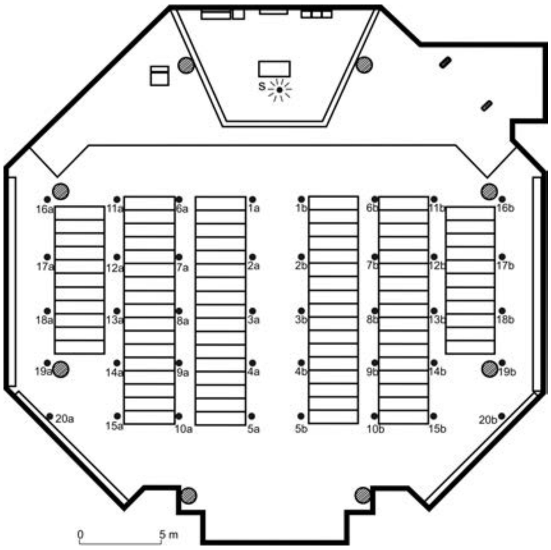
Church of the Sacred Heart of Jesus (HJ) in Suchy Las near Poznań, with an internal volume equal to 5410 m^3, was completed in 2000 (Fig. 1a). It is an aisleless central-plan church of a monolithic reinforced concrete beam and slab structure. Four reinforced concrete beams, 25 × 100 cm in cross-section, constitute edges of a truncated pyramid. The thickness of the concrete slab walls varies from 10 to 14 cm. Mineral wool, used as an insulating material, is 10 cm thick. The cover is made of copper sheets, fixed to 4 × 16 cm wooden laths. The ceiling features a square skylight, and there are bay windows in the entrance zone and in the adjacent side walls. The balcony runs along the whole nave. The church does not have an organ and an electronic instrument is used instead.

Table 1. A comparison of the churches.

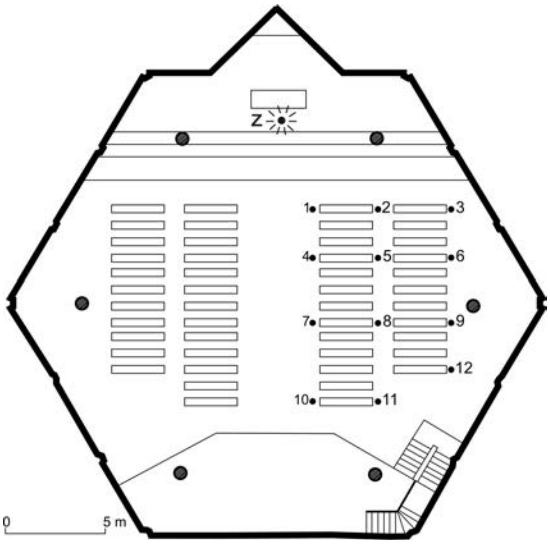
Church of the Sacred Heart of Jesus (HJ) volume 5410 m^3



St. Lawrence's Church **(SL)** volume 7500 m^3



Church of the Nativity of Our Lord (NL) volume 4800 m^3



St. Lawrence's Church (SL), with an internal volume equal to 7500 m^3, was built in years 1980–1985 (Fig. 1b). This two-storey building is a regular octagon in plan. The upper church, which was the subject of the investigation, has a coffered concrete cover. Over it, there is a 20 cm thick layer of mineral wool and an openwork of cavity brick walls of the average height equal to 90 cm, which provide support for a 15 cm thick monolithic reinforced concrete slab. The roof is covered with tar-board. The walls are made of reinforced concrete channel slabs which visually resemble pilasters, with narrow windows rhythmically distributed between them. The walls and the ceiling are covered with cement and lime plaster. A balcony with a pipe organ is situated over the entrance zone.

Church of the Nativity of Our Lord (NL) with an internal volume equal to 4800 m^3 (Fig. 1c). Load bearing elements of the ceiling and roof are made of monolithic reinforced concrete. The church was built in years 1995–2009, in the shape of a hexahedron, and its walls are covered in plaster. The hefty reinforced concrete ceiling with a motive referring to the star shape is the church's characteristic feature and represents a coffered type. Its structure is supported by four walls and by six pillars for additional support. The ceiling is covered with a 20 cm thick layer of mineral wool, and over it there is a ventilated space. A light steel structure supports the roof, covered with copper sheets. The height of the ventilated space varies from 2 to 4 m. The church does not have a pipe organ; an electronic instrument is used instead.

3.3. Churches with a truss type ceiling – description of the structure

The churches of the truss type include Church of the Blessed Virgin Mary Mother of the Church (VM), The Name of Mary Church (NM), Christ the Redeemer Church (CR). A comparison of the investigated churches is presented in Table 2, while the cross-sections are shown in Fig. 2.

Church of the **Blessed Virgin Mary Mother of the Church (VM)** was built in years 1978–1986 (Fig. 2a). This aisleless temple, with an internal volume equal to 6700 m^3, has smooth plastered walls made of circular sectors, most of which are arranged alternately, with concave and convex sides facing the interior. Spaces between the sectors are narrow and glazed. The structure of the roof is made of ten steel trusses, with a span of 24 m and a mean height about 2 m. The spacing between the trusses is 2.8 m. Reinforced concrete ribbed slabs, insulated with polystyrene, are supported by the trusses. Tar-board constitutes the outer cover. The ceiling is made of painted thin aluminum channel tiles, suspended and fixed to the bottom chord of the truss. Polystyrene boards (5 cm thick) are distributed on the channel sheets, and they are covered with foil. From the interior, the channels resemble tiles because their back surfaces can be seen. The pipe organ is situated on one side in the choir loft.

Christ the Redeemer Church (CR) was erected in 1983 (Fig. 2b). Its internal volume is

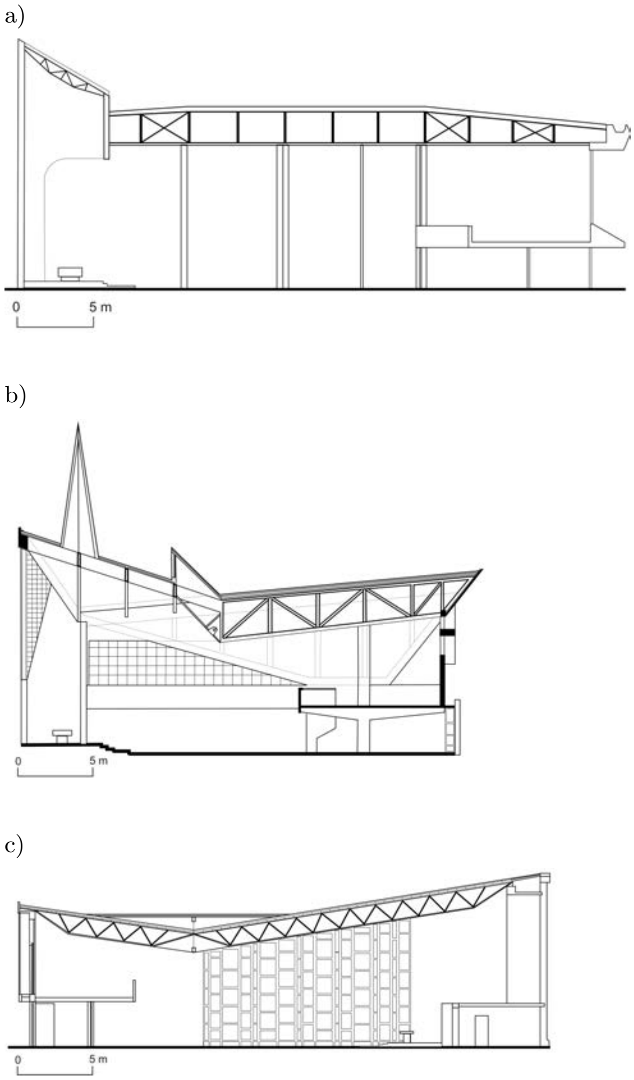


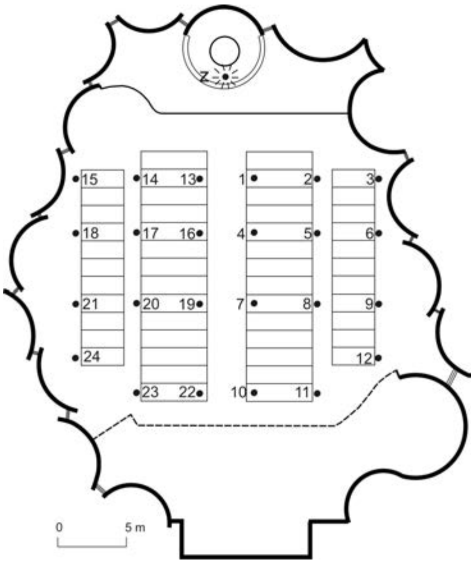
Fig. 2. Cross-sections of the churches of the truss type: a) Church of the Blessed Virgin Mary Mother of the Church (VM), b) Christ the Redeemer Church (CR), c) The Name of Mary Church (NM).

6700 m^3. The church is rectangular in plan; it is an aisleless building with narrow arcades on the sides. The structure of the ceiling is a system of 2 to 3 m high trusses crossing one another. Four trusses, which are supported by pilasters, are symmetrically located about the axis of the church. The fifth truss goes through the centre to symmetrically fork before the presbytery zone towards the pilasters which provide support for it. The 2 cm thick wood panelled ceiling is mounted to the trusses and bracings, forming a heavily sculpted coffered system, which is a distinctive feature of the church's architecture. Ribbed slabs, insulated with polystyrene, rest on the top member of the truss. The outer cover is made of aluminum sheets. The church uses an electronic instrument.

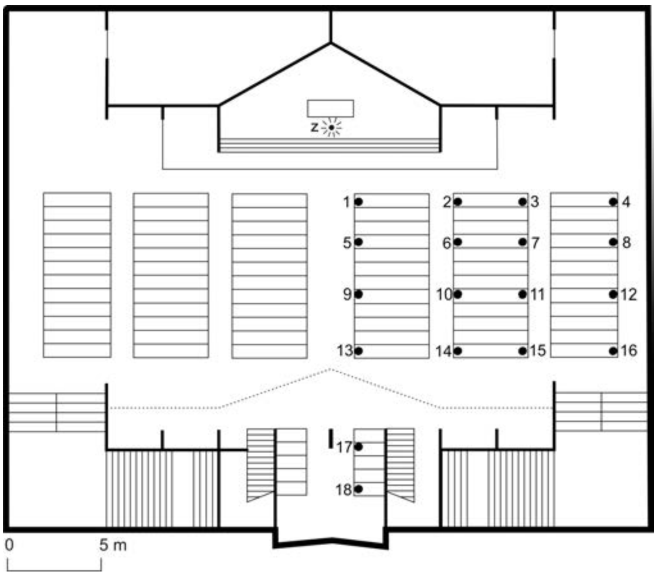
The current shape of **Name of Mary Church (NM)** (Fig. 2c) dates back to 1982. This rectangular-

Table 2. A comparison of the investigated churches.

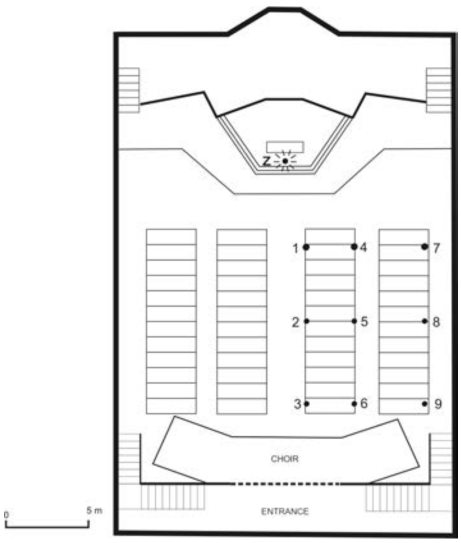
Church of the Blessed Virgin Mary Mother of the Church (VM), volume 6700 m^3




Christ the Redeemer Church (CR), volume 6700 m^3




The Name of Mary Church (NM), volume 5100 m^3




plan church has an internal volume of 5100 m^3. The walls are covered in cement and lime plaster and textured plaster with a mottled effect. The side walls are mostly glazed. The church has a big pipe organ. The pipes are located both in the presbytery and on the back wall. The roof is covered with concrete channel slabs which rest on the top member of the truss. The ceiling, made of solid larch wood panels, is suspended on the bottom member. On the ceiling, covered with foil, there is a 20 cm thick layer of glass wool. The structure of the church is based on three types of truss. One of the girders, with a 21 m span towards the transverse direction and 2.35 m in the middle, functions as a binder and provides support for two other types of trusses (located every 3 m). The height of the trusses is 1.2 m; their spans are 10 m and 21 m respectively. Figure 5 shows the view of the church along with the distribution of measurement points and the position of the sound source.

4. Results

Values of the investigated parameters are shown in Tables 3–5 and on graphs in Figs 3–5. Table 3 presents results for parameters T_{30}, EDT, and t_S. It was assumed that mean values of reverberation time for all the measurement points for individual octave bands cannot vary by more than (JND) which is defined by the Polish standard PN-EN ISO 3382-1 and amounts to 5%. The measured reverberation time T_{30} confirms a high level of reverberance in Polish contemporary religious buildings. On the basis of (Everest, 2009), Table 3 shows recommended values for reverberation time. The bottom value refers to churches where speech prevails; the top value refers to churches where organ music is performed. There is an evident difference between T_{30} values depending on the type of structure (Fig. 3). For all the churches with a truss type cover, T_{30} is within the recommended values. In most cases, however, they are very close to the top value. The most favourable values were registered in NM, where T_{30} = 1.8 s, which is a moderate value as the recommended value ranges from 1.3 to 2.8 s. In VM, there is an evident rise of reverberation time for mid-range frequencies (T_{30} for 500–1000 is 3.2 s), which can be subjectively perceived as excessive reverberance of the interior. In contrast, all the churches with a reinforced concrete ceiling registered reverberation time values which considerably exceeded recommendations. The mean value of T_{30} in these buildings oscillated between 5.0 and 5.9, while the recommended value should not exceed 2.9 s for the biggest of them. Thus, strong reverberant noise will be a distinctive feature of these interiors. Frequency characteristics of reverberation time for the two groups of churches differ a lot (Fig. 3). In all the churches with a concrete ceiling, reverberation time considerably rises for low frequencies. In the investigated buildings, the mean value of T_{30} amounts to 6.8 s for frequencies 125–250 Hz. In contrast, in the churches with a truss type ceiling frequency characteristic is almost flat. Churches with reinforced concrete covers are characterized by a considerable drop in reverberation time in relation to the drop in the frequency. Over 1000 Hz, reverberation time rapidly decreases to reach results similar to those in buildings with truss type covers, which is mainly caused by air absorbing sound. The product 4 mV seen in the denominator of the Knudsen formula (1) shows that a big internal volume of an interior will cause greater sound absorption by air.

Table 3. Comparison of the investigated parameters T_{30}, EDT, and t_S.

Name of the church	T_{30} [s]			EDT [s]		t_S [ms]	
	mean	500–1000 [Hz]	recommended mean	mean	500–1000 [Hz]	mean	recommended
Church of the Sacred Heart of Jesus (HJ)	5.91	6.1	1.3–2.8	5.8	6.0	408	70–120
St. Lawrence's Church (SL)	5.50	6.2	1.4–2.9	5.3	6.2	376	70–120
Church of the Nativity of Our Lord (NL)	5.0	5.4	1.3–2.7	4.9	5.4	367	70–120
Church of the Blessed Virgin Mary Mother of the Church (VM)	2.70	3.2	1.4–2.8	2.6	3.2	196	70–120
Christ the Redeemer Church (CR)	2.50	2.6	1.4–2.8	2.4	2.6	175	70–120
The Name of Mary Church (NM)	1.80	2.1	1.3–2.8	1.8	2.1	125	70–120

Table 4. Comparison of clarity index C_{80} and C_{50}.

Name of the church	C_{80} [dB]					C_{50} [dB]		
	first row	recommended	last row	recommended	general recommendations	mean	range of variation	recommended
Church of the Sacred Heart of Jesus (HJ)	−3.5 to −7.05	> 0	−8.2 to −8.7	> 2	−3 to 6	−8.000	−3.42 to −10.64	> −2
St. Lawrence's Church (SL)	−2.45 to −6.81	> 0	−6.35 to −8.49	> 2	−3 to 6	−7.856	−2.74 to −10.4	> −2
Church of the Nativity of Our Lord (NL)	−4.49 to −5.59	> 0	−8.04 to −8.38	> 2	−3 to 6	−8.590	−5.83 to −10.46	> −2
Church of the Blessed Virgin Mary Mother of the Church (VM)	−0.42 to −5.29	> 0	−4.17 to −6.38	> 2	−3 to 6	−6.200	−1.2 to −10.0	> −2
Christ the Redeemer Church (CR)	−0.4 to −3.27	> 0	−2.45 to −4.73	> 2	−3 to 6	−5.000	−2.6 to −6.87	> −2
The Name of Mary Church (NM)	1.4 to 0.16	> 0	−1.09 to −2.84	> 2	−3 to 6	−2.250	0.53 to −4.35	> −2

Table 5. Comparison D_{50}, STI and RASTI.

Name of the church	D_{50}	STI female		STI male		RASTI	
	mean	first row	last row	first row	last row	first row	last row
Church of the Sacred Heart of Jesus (HJ)	0.135	0.43 to 0.31	0.28 to 0.27	0.41 to 0.30	0.27 to 0.26	0.36 to 0.26	0.23 to 0.22
St. Lawrence's Church (SL)	0.160	0.44 to 0.30	0.33 to 0.29	0.43 to 0.29	0.32 to 0.28	0.39 to 0.24	0.28 to 0.23
Church of the Nativity of Our Lord (NL)	0.120	0.32 to 0.30	0.28	0.32 to 0.3	0.28 to 0.27	0.32 to 0.28	0.29 to 0.27
Church of the Blessed Virgin Mary Mother of the Church (VM)	0.240	0.49 to 0.36	0.39 to 0.37	0.49 to 0.36	0.38 to 0.36	0.44 to 0.33	0.35 to 0.32
Christ the Redeemer Church (CR)	0.270	0.47 to 0.39	0.43 to 0.38	0.47 to 0.39	0.43 to 0.38	0.42 to 0.39	0.42 to 0.33
The Name of Mary Church (NM)	0.380	0.55 to 0.50	0.49 to 0.44	0.55 to 0.50	0.49 to 0.43	0.53 to 0.47	0.45 to 0.38

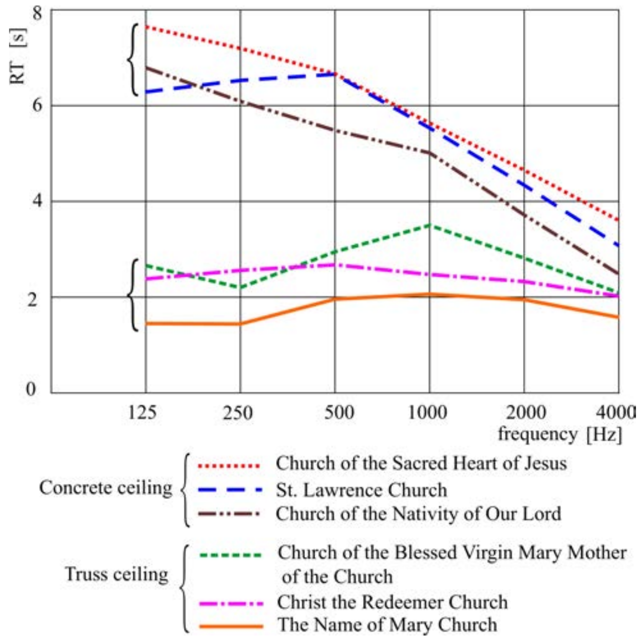


Fig. 3. Reverberation time in the frequency function – comparison of the investigated churches.

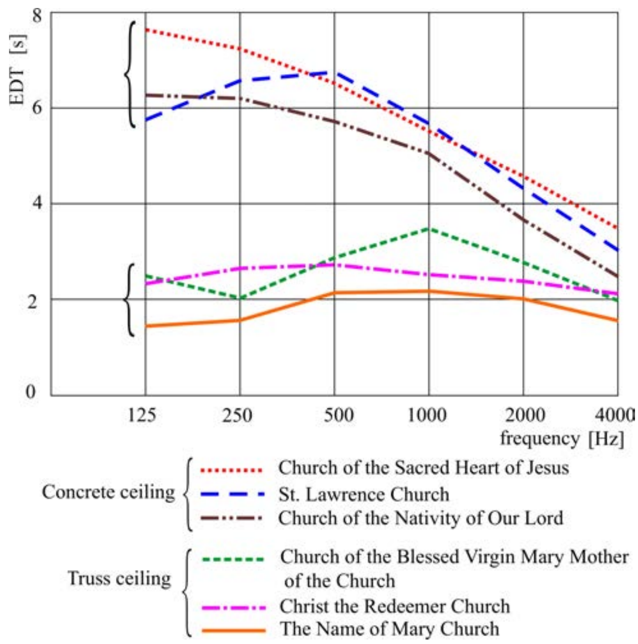


Fig. 4. Early Decay Time EDT – comparison of the churches.

The mean EDT value for the investigated churches is slightly lower than the mean T_{30} value, and for one of the investigated churches, i.e. NM, it takes the same value. For the 500–1000 Hz band, with the exclusion of HJ, T_{30} and EDT values are identical. Characteristics of frequencies for the two parameters in all the investigated churches are very similar. Figure 4 presents characteristics of frequencies for EDT for the churches.

Values of parameter center time t_S in all the churches exceed recommended values. It should be highlighted that the parameter is particularly unfavourable in buildings with a concrete ceiling. The mean value t_S in the buildings ranges from 367 ms to 408 ms (in HJ), while the extreme recommended value is 120 ms (Wróblewska, Kulowski, 2007). The values considerably exceed the permissible value for organ music, which is 180 ms.

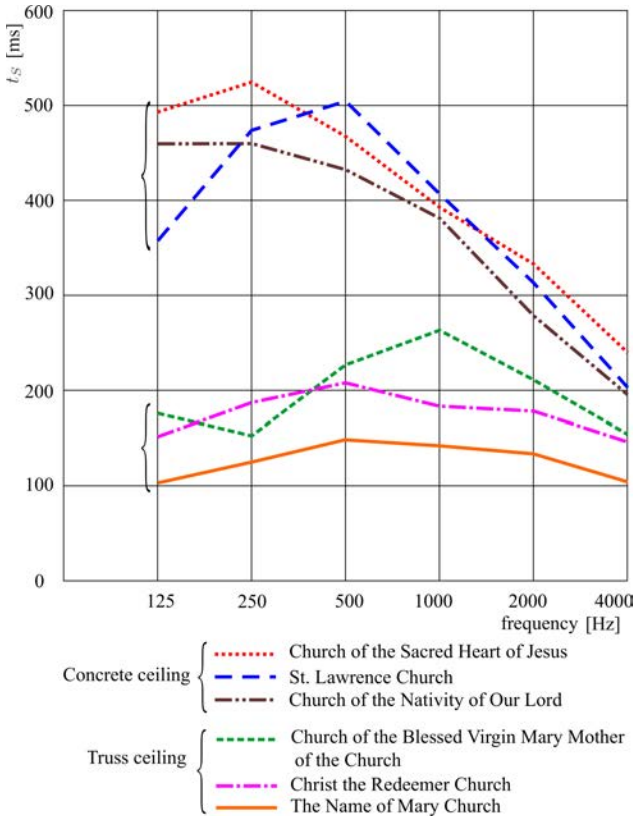


Fig. 5. Center Time t_S – comparison of the churches.

Table 4 presents parameters C_X. Clarity C_{80} does not reach recommended values in any of the churches (the recommended values are based on the data available in (Wróblewska, Kulowski, 2007). Church NM with a truss type ceiling registered the most favourable values: C_{80} is within recommended values for the first rows, while the back rows reach values lower than the recommended ones. However, when compared with general recommendations, the values are acceptable in all the measurement points. Similarly to the parameters discussed earlier, churches with a concrete ceiling registered less favourable C_{80} values than the truss type churches. In the buildings of the first type, the parameter exceeds −8.0 dB for the back rows, which is an acceptable value only for churches with an internal volume over 15 000 m^3.

The parameter C_{50} reaches better values in churches with a truss type ceiling than in churches with a concrete one. For the front part of the nave, the interiors of VM and NM register values within the recommended range, while values are slightly below recommendations in the back rows. In NM, measurement points in the middle of the row are the least favourable, while in VM, they are points 18, 21 and 24 due to the lack of favourable side reflections. In CR, only the first row registered acceptable results, while in the remaining measurement points the values are exceeded, thus reaching the least favourable values for the furthest points. In the churches with a concrete ceiling, the parameter does not meet recommendations in any point, and reaches particularly unfavourable values in the back part of the nave, i.e. over −10 for all the three buildings discussed here.

Table 5 presents parameters D_{50}, STI and RASTI. In compliance with recommendations, D_{50} for churches irrespective of their internal volume ranges from 0.4 to 0.6. Speech intelligibility over 85% occurs when $D_{50} = 0.34$ (Cremer, Müller, 1982), which occurs only in NM, where $D_{50} = 0.38$. In the churches with a concrete ceiling, the parameter registers low values: D_{50} oscillates between 0.12 and 0.16, while in the truss type churches, it exceeds 0.2.

STI and RASTI have more favourable values in the churches with a truss type ceiling. The best results were obtained in the first rows in churches VM and NM. In the churches with a concrete ceiling, certain measurement points in the last rows are particularly unfavourable, where the values are below 0.3. In SL, speech intelligibility is particularly problematic. STI is more favourable only for measurement points 1a and 1b, situated in the first rows close to the sound source. The remaining measurement points in the first rows reach values similar to those registered in measurement points in rows situated further from the sound source.

5. Discussion

5.1. Historical church vs contemporary church

Roofing in contemporary churches is commonly either of the truss type or of the reinforced concrete type. The application of steel structures and then reinforced concrete in religious architecture became a common practice after changes in the spatial layout of the church, which followed the Second Vatican Council. Formal documents stress the importance of unity; thus, religious architecture aims to shape such a space that highlights unity of the congregation. It was only natural to create a one-space interior, which is the most common solution in contemporary sacred buildings. Steel truss structures or reinforced concrete roofs render it possible to cover wide spans without application of additional support, and to put these intentions into practice. Such solutions are now used in contemporary churches regardless of their volume, while historical churches with wide spans have numerous subspaces, created by aisles, transepts and chapels. In the past, constructive capabilities rendered it possible to erect aisleless churches with small spans only. Figure 6 shows cross-sections of historical churches, presenting the layout with aisles for the basilica, the hall church and the aisleless church.

The above-mentioned changes in the spatial layout as well as changes in the structure had a huge impact on acoustic conditions of the interior. Numerous subspaces in historical churches facilitate decrease in reverberance. Also, a historical aisleless church, due to limitations of construction capabilities, has a small span between the walls in comparison with contemporary solutions. Thus, excessive reverberation, which increases along with the increase of the internal volume of the interior, or the issue of echo, which results from the span between smooth walls, would not cause such problems as in the contemporary sacred architecture. Vast spaces of contemporary churches increase reverberation time, and occurrences of clearly audible echo are quite common. There are also other factors that have a negative influence on the acoustics, and they are linked to the minimalistic interior design and types of finishes. Therefore, in comparison to historical churches, contemporary sacred architecture faces a number of issues.

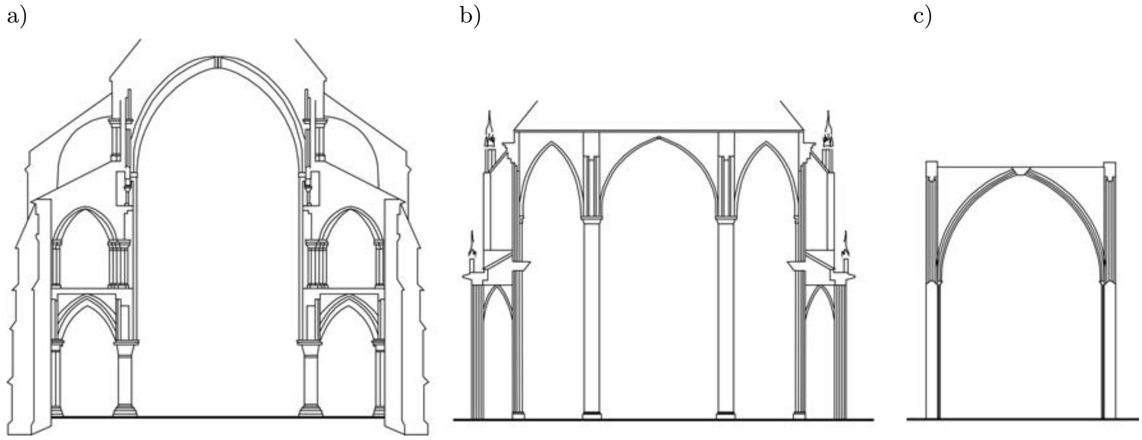


Fig. 6. Cross-sections of historical churches: a) basilica, b) hall church, c) aisleless church (Author's own drawing, on the basis of (Koch, 1996)).

5.2. Comparison of the influence of the truss structure and the reinforced concrete structure on acoustics of an interior

The investigated churches fall into two categories according to their layout as they represent either central-plan or longitudinal plan buildings. All central-plan buildings have a concrete cover, while all buildings in longitudinal plan have truss covers. Therefore, the assumed type of solution results from the layout designed by the architect. In terms of construction, central plans are the easiest to put into practice using *in situ* concrete slabs. In contrast, for longitudinal plans, the easiest way is to use trusses due to the rectangular shape of the view. Acoustically, churches with a truss type cover and a concrete cover belong to two different categories.

Materials used as finishes are similar in all the investigated churches. Table 6 shows a comparison of the areas of the churches and the corresponding finishes.

Plaster is used as a finishing material for walls in all the churches. In most of the interiors, considerable parts of the walls are glazed. Church NM slightly differs from the rest as it features more wood than in the other churches. The entrance wall of the nave features wooden strips, and the interior of the church houses more pipes than the other churches, where there are either no pipe organs (three churches) or they constitute a small part of the church's equipment. In all the churches, the floors are covered with smooth stone tiles. A small area is carpeted in the presbytery but is omitted in terms of the internal volume due to its insignificance. The pews in five of the churches are of similar light wooden construction, with thin upholstered seats (omitted in terms of the internal volume). In NM, the pews are heftier and have thicker upholstered seats in comparison with the other churches. The only significant differences between the churches lie in the ceiling construction. As it was mentioned before, the ceilings fall into two categories, i.e. the reinforced concrete type and the truss type. Churches SL and NL, which belong to the first category, feature coffered ceilings, and in HJ, the ceiling is smooth. In the churches with truss type covers, either wooden strips (in VM and NM) or aluminum tiles CR are fixed to the bottom member of the truss.

Irrespective of their internal volume, which ranges from 4800 m^3 to 7500 m^3, churches with a concrete cover considerably exceeded recommended values of all acoustic parameters. In NL, the ceiling is made of reinforced concrete in the form of a grid, which makes hexagonal coffers (Table 1), and, along with smooth plastered walls, creates a highly reverberant space. Reverberation time is too big due to the finishes, which lack suitable absorptive properties. The reverberation time T_{30} = 5.0 s, while recommendations for churches in this internal volume range are from 1.3 s to 1.7 s for churches where speech prevails, and from 1.7 s to 2.7 s for churches where organ music plays an important part (Everest, 2009). The ceiling is sculpted,

Table 6. Comparison of the areas of the churches together with finishes.

Name of the church	Ceiling [m^2]			Walls [m^2]				Total floor area [m^2]	Pews [m^2]	
	concrete	truss		plaster	glass	wood	pipes	stone floor	wood	wood + cushion
		wood	aluminum tiles							
Church of the Sacred Heart of Jesus (HJ) V = 5410 m^3	540	–	–	625	56	22	–	470	80	–
St. Lawrence's Church (SL) V = 7500 m^3	900	–	–	1060	200	20	10	900	230	–
Church of the Nativity of Our Lord (NL) V = 4800 m^3	476	–	–	672	120	28	–	476	101	–
Church of the Blessed Virgin Mary Mother of the Church (VM) V = 6700 m^3	10	–	850	936	95	37	12	860	260	–
Christ the Redeemer Church (CR) V = 6700 m^3	–	980	–	975	160	45	–	891	206	–
The Name of Mary Church (NM) V = 5100 m^3	–	680	–	560	220	108	80	640	–	140

which facilitates sound diffusion in the interior, but due to the finishes and smooth walls sound absorption is small.

Particularly unfavorable conditions occur in church HJ. In terms of volume, the church is much smaller than SL; still, reverberation time in the interior reaches less favourable values. In HJ, where V = 5400 m^3, T_{30} = 5.9 s, while reverberation time for frequencies 125–250 Hz amounts to 7.4 s. In contrast, in SL, where V = 7500 m^3, T_{30} = 5.5 s, the reverberation time for frequencies 125–250 Hz amounts to 6.4 s. Despite its much smaller volume than SL, HJ has longer reverberation time, the reason for which is the smooth concrete ceiling generating strong reflections, while in SL, 1.7 m deep concrete coffers have sound diffusing properties.

Churches with truss type covers evince good acoustic conditions. Reverberation time, the most important parameter used in assessment of acoustic conditions in religious interiors, reaches particularly favourable recommended values.

Church CR is an interesting example of a construction system – trusses that cross each other make a coffer system covered with wooden panels. Regardless of the fact that the truss structure has absorptive properties, the shape of the ceiling in the form of deep wooden coffers is an additional factor facilitating sound diffusion.

VM exemplifies an interesting case of a ceiling covered with tiles resembling ceramics, which gives an overall impression of solidity. On the basis of visual perception, the viewer expects long reverberation time. However, the visual impression does not correspond to the audible one as the interior has subjectively moderate reverberance. The reason is the finishing material, i.e. thin aluminum tiles mounted to the bottom chord of the truss. The tiles are light, which enables the sound to penetrate into the space of the truss (Fig. 7).

Fig. 7. Ceiling in Church of the Blessed Virgin Mary Mother of the Church VM is made of aluminum tiles mounted on the bottom chord.

In NM reverberation time reaches the lowest values of all six investigated churches. The reverberation time T_{30} = 1.8 s and meets recommendations. The church features not only a sound absorbing ceiling but also a lot of wood in the form of wooden strips on the back wall and on the balustrade of the choir loft, which promotes additional sound diffusion. This, in turn, prevents echo. Elaborately designed pews with upholstered seats have an additional sound absorptive function.

5.3. Acoustic impact of the ceiling

The investigations show that acoustics in the examined interiors are considerably determined by the type of cover. In the six analyzed churches, the only considerable differences in terms of finishes concerned the ceiling. The churches with a truss type ceiling have significantly shorter reverberation time than the churches with a concrete ceiling. The difference results from absorptive properties of the truss cover. Figure 8 shows a diagram illustrating differences in construction between buildings with reinforced concrete covers and truss covers.

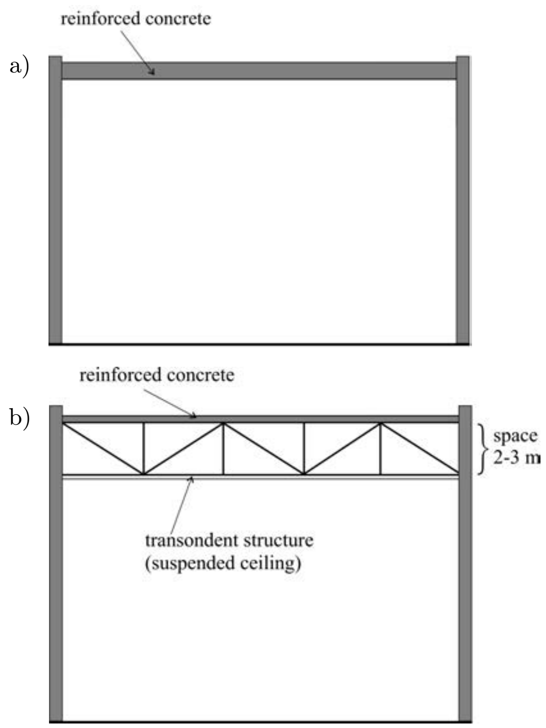


Fig. 8. Illustration of two types of covers: a) reinforced concrete type, b) truss type.

In the churches with a reinforced concrete cover, the ceiling constitutes a sound reflective surface. If such a ceiling is coffered (like in two of the churches under investigation), it is sound diffusive, however, it still has low absorption properties. Therefore, the churches with such covers have long reverberation time. RT considerably exceeds recommended values, which are particularly high for lower frequencies. In the churches with the truss type cover, wooden strips or aluminum tiles are attached to the bottom chord of the truss.

The structures enable penetration of the sound, which loses its energy in the void between the bottom and top chord of the truss. Such churches have flat frequency characteristic of reverberation time because truss ceilings ensure that low frequencies are absorbed. Most sound absorptive materials and building materials in general absorb high and mid-range frequency sounds. Sound absorptive systems and spatial absorbers are used to absorb low frequency sounds (Engel *et al.*, 2007). Therefore, the 2 to 3 meter high space between the bottom and the top chord of the truss in the churches with a truss type ceiling constitutes a broadband sound absorptive system. The top chord of the truss features concrete channel slabs or reinforced slabs, which have acoustic properties similar to reinforced concrete covers in three of the investigated churches. If a ceiling fixed on a light structure was mounted to the reinforced concrete ceilings (at a distance of about 2 m), reverberation time could be reduced (for low frequencies in particular).

5.3.1. Example of the structure of a truss type ceiling

Structures of the truss type ceilings in the investigated churches, irrespective of their individual differences, are built according to the same constructional plan – materials that allow sounds to permeate are fixed on the bottom member of the truss, with a void greater than 1 m between the top and bottom member. Figure 9 shows a constructional detail for VM. The main constructional elements of the truss (top and bottom members) are made of channel bars, and web members are also made of two channel bars welded together. Foamed polystyrene is placed on the bottom member of the truss in the form of 1 cm thick boards

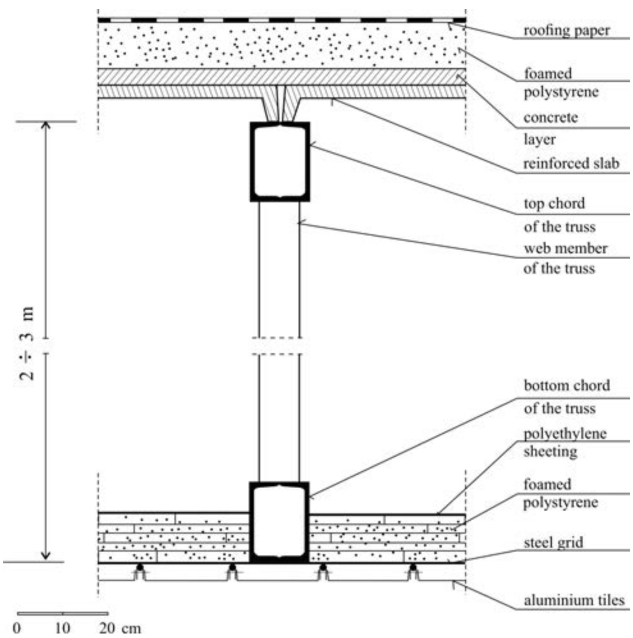


Fig. 9. Constructional detail of the ceiling in church VM.

Fig. 10. Inside the ceiling of church VM.

loosely placed on a steel frame lined with polyethylene sheeting. Along with thin aluminum tiles, the polystyrene constitutes a transondent layer. Figure 10 shows a photo of the inside of the ceiling. The foreground features vertical and cross members; reinforced slabs are placed on the top member of the truss, with polyethylene sheeting placed on the bottom member of the truss.

5.3.2. Application of the results of the investigations

It is possible to determine the absorption coefficient α for a reinforced ceiling for a newly designed church on the basis of data available in literature. However, literature does not give data on the absorption coefficient for truss type ceilings. The absorption coefficient α_x was calculated for the analyzed truss type covers on the basis of the investigations. First, the mean absorption coefficient α_{mean} in all the investigated churches was calculated on the basis of the Knudsen equation.

The Knudsen equation is as follows:

$$T = \frac{0.161\,V}{-S\ln(1-\alpha_{\text{mean}}) + 4mV}, \tag{1}$$

where T – reverberation time [s], V – internal volume [m^3], S – total surface area of room [m^2], m – air attenuation coefficient (Table 7), α_{mean} – mean absorption coefficient Eq. (2)

$$\alpha_{\text{mean}} = \frac{\sum_i \alpha_i S_i}{\sum_i S_i}. \tag{2}$$

Table 7. Air attenuation coefficient m.

Frequency [Hz]	250	500	1000	2000	4000
m [m^{-1}]	0.00009	0.00025	0.0008	0.0025	0.007

After transformations of the expression (1), the mean absorption coefficient α_{mean} is calculated from Eq. (3):

$$\alpha_{\text{mean}} = 1 - \exp\left(-\frac{0.161V}{TS} + \frac{4mV}{S}\right). \tag{3}$$

Figure 11 presents the mean absorption coefficient.

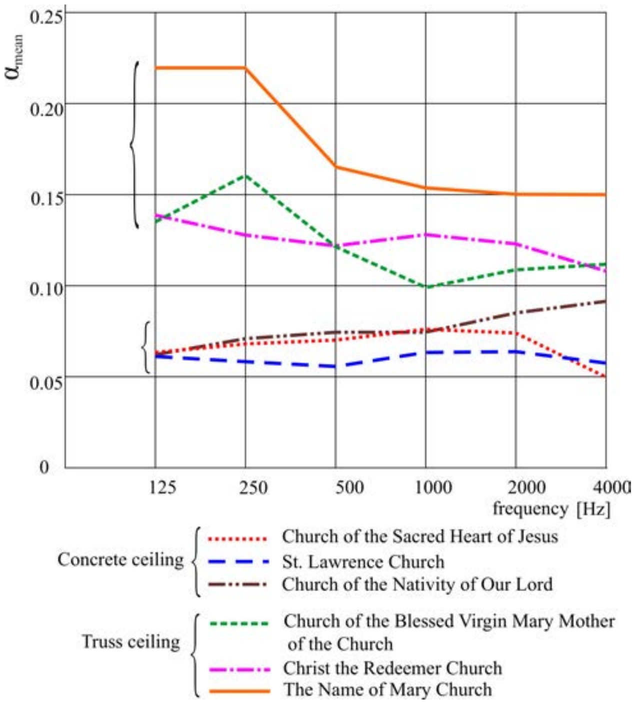


Fig. 11. Mean absorption coefficient α_{mean} in the frequency function.

It can be seen that in the churches with truss type ceilings, the value of the mean absorption coefficient is about twice as big as in the churches with reinforced covers.

The sound absorption coefficient α_x for the truss type ceiling was calculated from Eq. (4), which resulted from transformations of the expression (2)

$$\alpha_x = \frac{\alpha_{\text{mean}} S - \sum_j \alpha_j S_j}{S_x}, \tag{4}$$

where α_x – mean ceiling absorption coefficient, S_x – area of the ceiling, α_{mean} – mean absorption coefficient Eq. (2), $\sum_j \alpha_j S_j$ – total absorption of room with the exclusion of the ceiling.

The absorption coefficients α_j assumed in the calculations are presented in Table 8. The calculated absorption coefficient α_x for the churches with truss type covers are shown in Fig. 12.

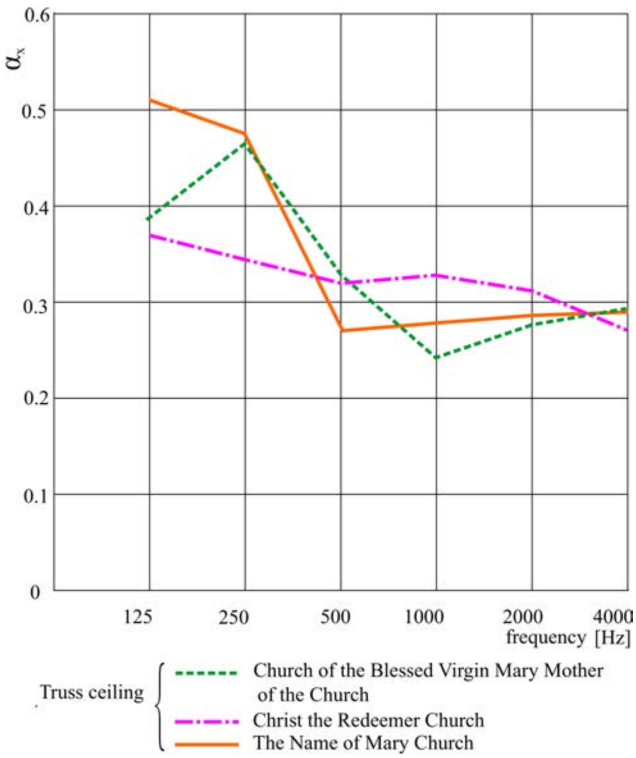


Fig. 12. Absorption coefficient α_x for the churches with the truss type cover.

Table 9 presents the mean absorption coefficient α_x for bands 500–1000 Hz and an averaged one for six octave bands. The calculated mean coefficient α_x for

Table 8. Sound absorption coefficients assumed in the calculations.

Materials	Absorption coefficient α					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Concrete slab plastered or without painting (Kulowski, 2011)	0.11	0.08	0.07	0.06	0.05	0.05
Limestone walls (Vörlander, 2008)	0.02	0.02	0.03	0.04	0.05	0.05
Hard floors, hard surfaces average (Vörlander, 2008)	0.02	0.02	0.03	0.03	0.04	0.05
10 mm soft carpet on concrete (Odeon, 2011)	0.09	0.08	0.21	0.26	0.27	0.37
Thick glass panel (Kulowski, 2011)	0.18	0.06	0.04	0.03	0.02	0.02
Double glazing, 2–3 mm glass, >30 mm gap (Vörlander, 2008)	0.15	0.05	0.03	0.03	0.02	0.02
Ordinary windows (Odeon, 2011)	0.35	0.25	0.18	0.12	0.07	0.04
Wood, 1.6 cm thick, on 4 cm wooden planks (Vörlander, 2008)	0.18	0.12	0.10	0.09	0.08	0.07
Wood boards on joists or battens (Building Bulletin, 1976)	0.15	0.20	0.10	0.10	0.10	0.10
Wooden pews unoccupied (Carvalho, Pino, 2012)	0.04	0.05	0.07	0.09	0.09	0.07
Pews with seat cushion (Carvalho, Pino, 2012)	0.12	0.30	0.41	0.34	0.29	0.31

Table 9. Mean absorption coefficient α_x.

Name of the church	$\alpha_{x(500-1000)}$	$\alpha_{x(6)}$
Church of the Blessed Virgin Mary Mother of the Church (VM) $V = 6700\ \mathrm{m}^3$	0.29	0.34
Christ the Redeemer Church (CR) $V = 6700\ \mathrm{m}^3$	0.33	0.33
The Name of Mary Church (NM) $V = 5100\ \mathrm{m}^3$	0.28	0.35
Mean value	0.30	0.34

three churches for six octave bands $\alpha_{x(6)} = 0.34$. For bands 500–1000 Hz, the coefficient $\alpha_{x(500-1000)} = 0.30$.

6. Conclusions

Introduction of steel and reinforced concrete structures into religious building construction enabled application of wide spans without intermediate supports. In the historical church, such vast spaces never occurred due to limitations of construction capabilities. Historical churches with big internal volumes have numerous subspaces due to the presence of aisles, transepts, side chapels and others, which decreases reverberation time, while architecture of the contemporary church is characterized by aisleless interiors. According to contemporary tendencies, architects prefer economical artistic expression and favour the scarcity of details in application yet often use sound reflective materials (such as glass, concrete and stone). Such solutions obviously create conditions for occurrence of reverberant noise.

In the contemporary churches in Poznań, Poland, discussed in the following paper, no intentional action was taken to create favourable acoustic conditions. Yet, depending on the assumed constructional solution, the interior is either acoustically problematic, or acoustic parameters of the interior reach values compliant with recommendations, or the parameters are at least close to the recommended values. Good acoustic conditions were registered in churches with a truss type ceiling. Such a solution was not applied intentionally to obtain correct acoustic conditions in the interior, and positive results were a matter of coincidence. In contrast, in churches with a reinforced concrete cover, the ceiling is a visually attractive form (churches NL and SL), but acoustically, it is a system hardly capable of absorbing sounds. Other finishes also have a low sound absorption coefficient. Therefore, the churches would benefit from an acoustic treatment.

The truss type cover is a system that absorbs sound in broadbands. Wooden strips or aluminum tiles have transondent properties, and energy of the sound is lost in a space of about 2 m between the top and the bottom member of the truss. The structure renders it possible to absorb low frequencies, so an interior with this particular type of cover is characterized by a flat frequency characteristic of reverberation time.

Sound absorption coefficients α can be commonly found in literature for the reinforced concrete cover. However, literature fails to give information on such data for the truss type cover. In result, the investigations facilitated calculation of the sound absorption coefficient α for truss type covers. The calculated average coefficient α_x for the three churches for six octave bands is $\alpha_{x(6)} = 0.34$, while for bands 500–1000 Hz, it amounts to $\alpha_{x(500-1000)} = 0.30$.

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