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Microclimatic Measurements and Laboratory Research in Historical Buildings with Medieval Wall Paintings at Croatian Adriatic Coast

Introduction

Since 2001 the *Department of Wall Paintings and Mosaics Conservation* and the *Science Laboratory* (Croatian Conservation Institute) have been systematically observing changes of microclimatic conditions in historical buildings with wall paintings and mosaics. The research is financed by the Croatian Ministry of Culture. During the last five years, microclimatic conditions were observed in seventeen historical buildings in inland and coastal parts of Croatia.[1] In addition to measuring air temperature (°C) and relative humidity (rH%), in some buildings the temperature of the walls was also measured using the electronic device *Testo data logger* and the programme *Testo Comfort Software basic*. In these fully financed projects, the types and values of water-soluble salts were defined using chemical qualitative and quantitative analyses[2] and X-ray diffraction[3]; microbiological analyses were carried out when needed.[4]

The historical buildings in Zadar, Dubrovnik and Ston with fragmentarily preserved medieval wall paintings which are presented in this paper are typical examples of the present condition of this kind of historical monument on the central and southern Adriatic coastline in Croatia. Included are the results of laboratory examinations and two-year continuous microclimatic measurements in the apse of the south nave in the Cathedral of St Stošija (St Anastasia) (Fig. 1–2) and in the room on the first floor of the belfry of St Mary's Church in a Benedictine convent in Zadar (Fig. 3–4). From Dubrovnik, results are presented from microclimatic measurements in the substructure of the Cathedral of Our Lady (Fig. 5–6) and from preliminary laboratory research in the room above the sacristy in the Franciscan monastery *Mala braća* in which microclimatic measurements have not started yet because of construction work being done on the first floor (Fig. 7–8). In addition to these monuments in urban settings, this paper discusses a valuable monument of Early Romanesque architecture, located on an isolated hill close to Ston (the small Church of St Michael) (Fig. 17–18), which represents a group of historical buildings with fragments of wall paintings at isolated locations that are hard to approach for control and maintenance.[5]

Past

Fragmentation of medieval wall paintings and its causes
"TEMPUS EDAX RERUM"

Fragmentation of the wall paintings discussed here is the result of human destructive acts and of deterioration caused by natural processes occurring over the course of time. Examples of deterioration of wall paintings caused primarily by natural processes are the wall paintings in the south apse of the Cathedral of St Anastasia and in the room on the first floor of the belfry of St Mary's Church in Zadar, as well as the paintings in the Church of St Michael near Ston on the Pelješac peninsula. In all three of these buildings the preserved fragments of wall paintings were discovered in the last century under several layers of plaster and lime coatings which were applied because of the bad condition of the walls (or possibly also as part of regular hygienic measures following plague epidemics) rather than for change of fashion.[6]

Wall paintings from the last quarter of the 13th c. (1284), discovered in 1905 in the northern apse of Zadar Cathedral, were mostly deteriorated immediately after their discovery. Looking at the problem from today's perspective, it would have been better if they had not been discovered at all, especially considering the fact that not only the valuable wall paintings but also the interesting iconographic programme that decorated that apse (*S. Thomas Becket*) were lost.[7] The actual causes of their deterioration after discovery are not known. However, judging from the fragments of wall paintings in the south apse of the cathedral, it cannot be very wrong to presume that, apart from possi-

[1] ***Zagreb***, St Mark's Church, South Portal; ***Ludbreg***, Municipal Wedding Hall; ***Ludbreg***, Batthyany Castle, Chapel of St Cross; ***Sv. Križ Začretje***, Chapel of St Anne; ***Gornja Stubica*** – Oršić Castle, Chapel of St Francis Xavier; ***Šenkovec***, Chapel of St Helena; ***Štrigova***, Church of St Jerome; ***Varaždin***, Franciscan Monastery, Pharmacy; ***Sv. Ivan na Gorici***, Church of St John; ***Oprtalj***, Church of St Helena; ***Slum***, Church of St Matthew; ***Zadar***, Cathedral of St Anastasia; ***Zadar***, Belfry of the Church of St Mary; ***Dubrovnik***, Kerša Palace; ***Dubrovnik***, Cathedral; ***Ston***, Church of St Michael; ***Pula***, Cathedral.

[2] Quantitative and qualitative chemical analyses of salts were carried out in the Science Laboratory of the Croatian Conservation Institute and in *CEMTRA*, Ltd. in Zagreb (Department for Products' Quality Control).

[3] Research of this type was carried out in the Mineralogic-Petrographic Institute of Science-Mathemathical Faculty in Zagreb.

[4] Microbiological research was carried out at the Faculty of Chemical Engineering and Technology of Zagreb University.

[5] In the meantime measurements have begun in the small Church of St John at Šilovo selo on Šipan island (Dubrovnik archipelago).

[6] Daniel V. Thompson, The materials and techniques of medieval paintings, New York, 1956, p. 72.

[7] Giusepe Bersa, L'arca e la Cappella di S. Anastasia nel duomo di Zara, in: Bollettino di Archeologia e storia dalmata XXXI, 1908, p. 11–26; – Nada Klaić and Ivo Petricioli, Zadar u srednjem vijeku II (do 1409.), (Zadar in Middle Ages, till 1409) Zadar 1976, p. 266–267. – In this apse, in semi-dome there was a depiction of Christ on the throne, holding the open book in his left hand with the sentence *"Ego sum Alpha et Omega"*, on the left side of Christ there was a depiction of St Thomas Becket in archbishop's clothes with the sign *"S. Thomas cantuarbensis"*, and St Anastasia was depicted right from Christ. A series of standing saints' figures was depicted below them. Yet in the year 1976 one could see only small fragments of Christ's figure and the throne, the lower part of St Thomas Becket's figure, and in only one head and a part of another one in central zone.

ble inadequate restoration, their condition at the time and the microclimate in the cathedral also contributed to their deterioration. After removal of several layers of lime coatings and plaster that protected the wall paintings from harm caused by crystallisation of salts on their surface and the area close to it, the destructive processes in fact continued at a faster pace, destroying the *intonaco* and the painted layers that were partly damaged earlier (Fig. 2).

Wall paintings from the first half of the 12^{th} c. on the first floor of the belfry of St Mary's Church in Zadar were discovered through an unhappy concurrence of events, following heavy destruction of the town's centre just before the end of the Second World War. Among other buildings, the convent complex, including the church, the Capitulum Hall and the Convent, suffered damage, whereas the belfry remained unharmed. Because of strong detonations in close vicinity to the belfry, the upper plaster layers that covered the wall paintings fell off.[8] Conservation-restoration research proved that the paintings had been in fragments before they were covered with plaster and lime-coated, and that their destruction was mainly caused by natural processes of deterioration. Rainwater flowing down the openings of the belfry for centuries onto the vault and walls of the room on the first floor, together with specific microclimatic conditions, contributed to rapid deterioration of the painted layer, *intonaco* and lower plaster layers (Fig. 3).

Fig. 2. Zadar, Cathedral of St Anastasia (Sv. Stošija), south apse, wall painting, detail: typical deterioration of paint layer.

Fig. 3. Zadar, St Mary's Church, belfry, south-east wall, wall painting, detail: salt efflorescences.

▷ Fig. 5. Dubrovnik, Cathedral of Our Lady, ruins of the former Bizantine Cathedral with remains of wall paintings (second half of 11^{th} century).

▷ Fig. 6. Dubrovnik, Cathedral of Our Lady, wall paintings (see fig. 5), detail: white square shows state of conservation before cleaning in 1982–1984.

Fig. 1. Zadar, Cathedral of St Anastasia (Sv. Stošija), south apse, wall painting (c. 1284), detail.

Fif. 4. Zadar, St Mary's Church, belfry, south-east wall, wall painting (first half of 12^{th} century), detail: Christ.

Fig. 7. Dubrovnik, Franciscan Monastery *Mala braća*, room above sacristy vault, wall paintings (first half of 14th century), detail (after excavation).

In terms of the material of the *intonaco*, which consists of slaked lime and sand together with a lot of brick-powder, wall paintings from the belfry of St Mary's Church in Zadar are similar to those in the Church of St Michael near Ston. Fragmentation of the paintings in Ston, from the second half of the 11th c., is caused by capillary moisture in the foundation which completely destroyed the paintings on the lower parts of the wall, rainwater leaking through the badly maintained roof, and perhaps also the impact of airborne salts from the salt-pans near Ston (still the subject of research) (Fig. 13 and 18).

As opposed to deterioration primarily caused by natural processes, in the examples from Dubrovnik human impact caused the worst harm to the wall paintings, although it is possible that primary damages caused by natural processes hide behind the harm done by humans. Thus the actual cause of the ruin of the original Byzantine cathedral from the 6th c., with its wall paintings from the second half of the 11th c., might in fact be found primarily in the slow but continuous rise of sea level and possible flooding of its lower parts (the naves). In the 12th c. the Byzantine cathedral was pulled down, and a Romanesque cathedral was erected in its place. If data about changes in the Adriatic sea level (according to which the level rises approximately 1 mm a year) could be at least partly considered and applied to Dubrovnik, then sea level could have risen as much as 60 cm in the period from the 6th to the 12th c.[9] However, even a rise in sea level of half this much could have caused problems in that period; hence the cathedral was erected on the heaped-up area. One more fact leads to the conclusion that destruction

Fig. 8. Dubrovnik, Franciscan Monastery *Mala braća*, room above sacristy vault, detail: angel (after conservation-restauration).

[8] Croatian Conservation Institute, Archive, dossier no 59/4.

[9] G. Di Donato, R. Sabadini, L.L.A. Vermeersen, A. M. Negredo, E. Carminati, Multi-Disciplinary approach to sea-level change in the Adriatic area and in the Po-Delta: insights from modelling and stratigraphy analysis, IGBP/GAIM Report Series Report 8, EGS Vening Meinesz Conference 1: "Global and regional Sea-Level Changes and the hydrological cycle", October 4–6, 1999. Loiri-Porto San Paolo, Sardinia Italy – http://gaim.sr.unh.edu./Products/Reports/Report_8/report8.pdf – South-Western coast of England sinks 2 mm a year. Some Roman places in London had been built 5 m under the actual sea level. Features of Sea-Level Change (October 2004).

Evaluation	Chlorides (Cl^- %)	Nitrates (NO_3^- %)	Sulphates (SO_4^{2-} %)
NOT HARMFUL	< 0,03	< 0,05	< 0,01
POSSIBLY HARMFUL	0,03 – 0,10	0,05 – 0,15	0,01 – 0,25
HARMFUL	> 0,10	> 0,15	> 0,25

Fig. 9. Table showing harmfulness of salts, according to Austrian Standard B 3355-1.

Year of analyzing	1971	1973	1987	2001	2003	2004
ZADAR, Cathedral of St Anastasia		$CaCl_2$ [illegible] % [illegible] % $MgCl_2$ [illegible] % [illegible] %			Cl^- [illegible] % [illegible] %	
ZADAR, Belfry of St Mary's Church	Cl^- (plaster) [illegible] % [illegible] %		Cl^- (plaster) [illegible] % [illegible] % (pulp) [illegible] %	Cl^- (plaster) [illegible] % [illegible] %	Cl^- (plaster) [illegible] % [illegible] % [illegible] % [illegible] % [illegible] % [illegible] % [illegible] % Halite (NaCl)	
DUBROVNIK, Franciscan monastery						Cl^- (pulp) 0,01 % 0,03 % [illegible] % [illegible] %
STON, St Michael's Church					Cl^- (plaster) [illegible] % [illegible] %	

Fig. 10. Table showing laboratory analyses of chlorides (Cl^-) for Zadar, Dubrovnik and Ston.

Year of analyzing	1971	1973	1987	2001	2003	2004
ZADAR, Cathedral of St Anastasia						
ZADAR, Belfry of St Mary's Church					(plaster) [illegible]% 0,06% [illegible]% [illegible]% [illegible]% 0,11% [illegible]%	
DUBROVNIK, Franciscan monastery						0,01% 0,02% 0,07% 0,12%
STON, St Michael's Church					0,0819% [illegible]% [illegible]%	

Fig. 11. Table showing laboratory analyses of nitrates (NO_3^-) for Zadar, Dubrovnik and Ston.

Fig. 12. Table showing laboratory analyses of sulphates (SO_4^{2-}) for Zadar, Dubrovnik and Ston.

Year of analyzing	1971	1973	1987	2001	2003
ZADAR, Cathedral of St Anastasia		$MgSO_4$ [illegible] % [illegible] % Na_2SO_4 0,034 %		(plaster) [illegible]% [illegible]% 0,18%	
ZADAR, Belfry of St Mary's Church	(plaster) 0,16% 0,24%		(pulp) [illegible]%	(plaster) [illegible]% [illegible]%	(plaster) [illegible]% [illegible]% [illegible]% [illegible]% [illegible]% [illegible]% Hexahydrite ($MgSO_4 \cdot 6H_2O$) Thenardite (Na_2SO_4) Gypsum ($CaSO_4 \cdot 2H_2O$) Epsomite ($MgSO_4 \cdot 7H_2O$)
DUBROVNIK, Franciscan monastery					
STON, St Michael's Church					0,005% 0,18% Thenardite (Na_2SO_4)

NaCl	30,76
KCl	0,66
$MgCl_2$	3,74
$CaSO_4$	1,64
$MgSO_4$	2,39
Other salts	0,07
Total	39,26 g/l (or 3,926%)

Fig. 13. Table showing concentration of the main salts in sea water of Mediterranean.

Date of measuring	Building	Lowest temperature (°C)	Highest temperature (°C)	Average value of temperature (°C)	Lowest relative humidity (% rH)	Highest relative humidity (% rH)	Average value of relative humidity (% rH)
3.4.–4.9.2002.	CATHEDRAL	+15,05 °C	+29,07 °C	[illegible] °C	22,10 %	81,00 %	[illegible] %
3.4.–5.9.2003.	BELFRY	+12,26 °C	+32,32 °C	[illegible] °C	30,50 %	86,00 %	[illegible] %
1.4.–15.9.2004.	CATHEDRAL	+16,21 °C	+27,00 °C	[illegible] °C	32,70%	88,00%	[illegible] %
1.4.–15.9.2004.	BELFRY	+14,49 °C	+26,95 °C	[illegible] °C	26,90 %	95,70 %	[illegible] %
22.10.2002.–3.4.2003.	CATHEDRAL	+11,17 °C	+19,77 °C	[illegible] °C	52,20%	84,60%	[illegible] %
22.10.2002.–3.4.2003.	BELFRY	+5,68 °C	+19,26 °C	[illegible] °C	34,60 %	97,40 %	[illegible] %
11.11.2003.–1.4.2004.	CATHEDRAL	+12,20 °C	+18,13 °C	[illegible] °C	28,80%	79,40%	[illegible] %
11.11.2003.–1.4.2004.	BELFRY	+8,26 °C	+17,00 °C	[illegible] °C	37,70 %	91,90 %	[illegible] %

Fig. 14. Zadar, Cathedral and Belfry: Table showing parallel measurings of temperature and relative humidity.

Date of measuring	Time of measuring	Lowest temperature (°C) & relative humidity (% rH)	Highest temperature (°C) & relative humidity (% rH)	Average value of temperature (°C)	Lowest relative humidity (% rH) & Temperature (°C)	Highest relative humidity (% rH) & Temperature (°C)	Average value of relative humidity (% rH)
31.3.2003.–30.6.2004.		+7,0 °C (85,59%)	+30,6 °C (85,11%)	+13,0 °C	60,09 %	99,71 %	79,30 %
19.2.2004.–20.2.2004.	20,00 h 0,00 h	+7,0 °C (89,59 %)					
25.8.2003.	22,00 h		+20,6 °C (85,11 %)				
12.2.2004.	14,00 h				60,09 % (+8,00 °C)		
26.2.2004.	23,00 h					99,73% (+7,7 °C)	

Date of measuring	Time of measuring		Lowest relative humidity (% rH) & temperature (°C)	Highest relative humidity (% rH) & Temperature (°C)	Average value of relative humidity (% rH)
12.2.2004	14,00 h		29,70% (+13,81 °C)		
26.2.2004	23,00 h			53,20% (+15,00 °C)	

Fig. 15. Dubrovnik, Cathedral of Our Lady (above) and Kerša palace (below): Table showing parallel measurings of temperature and relative humidity.

Fig. 16. Table showing salts and average value of temperature (°C) and relative humidity (%) and equilibrium of relative humidity for Zadar, Dubrovnik and Ston.

	SALTS	[illegible] °C	[illegible] °C	[illegible] °C	Annual average value of temperature (°C)	Annual average value of relative humidity (% rH)
ZADAR, Cathedral	$MgCl_2$? Bischofite ($MgCl_2 \cdot 6H_2O$) $CaCl_2$? Antarcticite ($CaCl_2 \cdot 6H_2O$) $MgSO_4$? (Epsomite, Hexahydrite) Na_2SO_4 ? (Thenardite) ? (Mirabilite)	33,3% rH 33,7% rH	33,3% rH 56,5 % rH	28,1 % rH 30,8 % rH 90,1 % rH 82 % rH 87,9 % rH	[illegible] °C	59,00 %
ZADAR, Belfry	Calcite $CaCO_3$ Nesquehonite $MgCO_3 \cdot 3H_2O$ Gypsum $CaSO_4 \cdot 2H_2O$ Epsomite $MgSO_4 \cdot 7H_2O$ Hexahydrite $MgSO_4 \cdot 6H_2O$ Thenardite Na_2SO_4 Halite NaCl	86,9 % rH 75,3 % rH	75,6 % rH	90,1 % rH 82 % rH 75,5% rH	[illegible] °C	69,35 %
DUBROVNIK, Cathedral					[illegible] °C	79,99 %
DUBROVNIK, Franciscan Monastery	Calcite $CaCO_3$ Hydromagnesite $Mg_5(OH(CO_3)_2)_4 \cdot 4H_2O$ Cl NO_3					
STON, St Michael's Church	Calcite $CaCO_3$ Dolomite $CaMg(CO_3)_2$ Thenardite Na_2SO_4 NO_3 Cl			82 % rH	[illegible] °C (summer)	60,38 % (summer)

of the Byzantine cathedral could have been caused by the rise in the sea level: the floor of the Romanesque cathedral was placed at a much higher point in relation to the floor of the former cathedral, whose walls were demolished to a height of somewhat more than 2 m above the floor. The main reason for that could have been an effort to avoid possible flooding in the future[10] (Fig. 5–6).

An example of fragmentation of wall paintings from the first half of the 14th c. where damage was mainly caused by human impact involves the paintings preserved on the walls above the vault of the sacristy in the Franciscan monastery *Mala braća* in Dubrovnik. The initial damage to the wall paintings occurred on the eastern wall of the sacristy after a chapel with an altar was added there at the end of the 15th c. Soon after replacing the original wooden beam in the sacristy with a vault made of stone and tufa, the wall paintings above the vault, which were damaged but still visible, were buried under rubble material. What happened to the wall paintings in the sacristy remains unknown; the results of preliminary conservation-restoration probing were negative (Fig. 7–8).

Present

Summary of results of microclimatic measurements and laboratory analyses

"NATURA NON FACIT SALTUS"

The primary aim of the research on the condition of the wall paintings in the buildings mentioned was to discover the causes of their rapid deterioration and to evaluate the role of the microclimate in these processes. The following steps concern analyses of the results and establishment of acceptable solutions for stabilising microclimatic conditions in rooms with wall paintings.

Laboratory research had been carried out sporadically over longer periods of time in some buildings, and results from the last few years, e.g. in Ston, prompted the beginning of systematic microclimatic measurements.

The analyses of salts carried out so far showed that *carbonates* (CO_3^{2-}) and *hydrogen carbonates* (HCO_3^-) are found in samples from Zadar (the belfry of St Mary's Church), Dubrovnik (the Franciscan monastery *Mala braća*) and Ston (Church of St Michael). *Calcite* ($CaCO_3$) was identified by X-ray diffraction in all three buildings; in addition *nesquehonite* ($MgCO_3 \cdot 3H_2O$) was found in Zadar, *hydromagnesite* ($Mg_5/OH(CO_3)_2/_2 \cdot 4H_2O$) in Dubrovnik and *dolomite* ($CaMg(CO_3)_2$) in Ston.

Chlorides (Cl^-) were identified in harmful concentrations in samples from all the buildings analysed. The concentration of chlorides is lower than 0.21% in Dubrovnik, and higher in Ston, where it reaches 0.38%. However, it should be emphasised that the samples taken from Ston were from new plaster. In both buildings in Zadar the concentration of salts is much higher; in the cathedral it reaches 1.21%, and in two samples taken from the belfry the defined concentrations were 3.5% and 5.8%. *Halite* (NaCl) was identified by X-ray diffraction (Fig. 9 and 10).

Nitrates (NO_3^-) were found in harmful concentrations in the belfry of St Mary's Church in Zadar and in the Church of St Michael in Ston. The highest concentration in Zadar was 0.83% and in Ston was 0.390%. Possibly harmful concentrations of nitrates were also found in the Franciscan monastery *Mala braća* in Dubrovnik (0.12%) (Fig. 9 and 11).

The harmful contents of soluble *sulphates* (SO_4^{2-}) were defined by evaporation in both buildings in Zadar; they were absent in Dubrovnik, but present in possibly harmful concentrations in Ston. *Thenardite* (Na_2SO_4) was found in the belfry of St Mary's Church in Zadar and in the Church of St Michael in Ston; in addition *gypsum* ($CaSO_4 \cdot 2H_2O$), *hexahydrite* ($MgSO_4 \cdot 6H_2O$) and *epsomite* ($MgSO_4 \cdot 7H_2O$) were identified (Fig. 9–12).

The summary of periodic laboratory analyses of salts in plasters from the two churches in Zadar carried out so far showed a gradual growth of *chlorides* (Cl^-) and *sulphates* (SO_4^{2-}) from 1973 to 2001. In the Cathedral of St Anastasia *chlorides* ($CaCl_2$ and $MgCl_2$) and *sulphates* ($MgSO_4$) measured less than 1.00% in 1973; in 2001, analyses showed that both chlorides and sulphates had increased to more than 1.00%. Analyses from 1971 proved that concentrations of *chlorides* (Cl^-) in the belfry of St Mary's Church were harmful (1.02% and 0.57%), and concentrations of *sulphates* (SO_4^{2-}) were possibly harmful (0.16% and 0.24%). Analyses in 2001 showed a slight increase of *chlorides* (0.74% and 1.05%) and a significant increase of *sulphates* (3.28% and 2.30%). A number of stone samples from the wall on the first floor of the belfry of St Mary's Church were also analysed in 2003. At that time, all analysed samples had harmful concentrations of *chlorides* (Cl^-) and *sulphates* (SO_4^{2-}), and five of seven samples measured had harmful concentrations of *nitrates* (NO_3^-).

Preliminary research on water-soluble salts and microbiological investigations were carried out on the recently discovered fragments of wall paintings in the room above the vault of the sacristy in the Franciscan monastery *Mala braća* in Dubrovnik. In the analyses of water-soluble salts carried out so far, possibly harmful concentrations of *chlorides* (Cl^-) were found in one, and harmful concentrations in two, of four analysed samples; *nitrates* (NO_3^-) were also found in possibly harmful concentrations. The carbonates *calcite* ($CaCO_3$) and *hydromagnesite* ($Mg_5/OH(CO_3)_2/_2 \cdot 4H_2O$) were defined by X-ray diffraction.

Based on laboratory analyses of plaster samples and crystallised salts from the Church of St Michael in Ston carried out so far, it could be concluded that certain types of harmful salts are determined by the very structure of the wall paintings' support, the use of slaked lime of dolomite origin. This could then explain the presence of *magnesium sulphate* in several forms (*epsomite, hexahidrit*). Nevertheless, its appearance can be related to airborne salts that could make their way from the sea in wind-driven rain. The identification of *halite* (NaCl) and harmful concentrations of *chlorides* in all the buildings analysed also lead to the same conclusion (Fig. 13).

[10] Based upon analyses of results of archaeological research it is supposed that the sea level in Dubrovnik rose approximately 2 metres in the last 2000 years; at the same time the ground level of the coast sank approximately 1 metre, so the total rise of sea level is approximately 3 metres. Antun Ničetić, Povijest dubrovačke luke, Dubrovnik 1996, p. 23.

Fig. 17. Ston, Church of St Michael, interior, wall paintings (second half of 11th century), detail.

Fig. 19. Zadar, Cathedral of St Anastasia (Sv. Stošija), south apse, wall paintings (1971).

The two-year average of **microclimatic measurements** in two buildings in Zadar proved that there were also larger aberrations in their microclimatic conditions. Measurements in the south nave apse of Saint Anastasia's Cathedral showed that +23.19 °C was the average air temperature in the spring-summer period, and the average relative air humidity was 64.17%. In the autumn-winter period +15.45 °C was the average air temperature, and the average relative air humidity was 56.62%. Measurements carried out at the same time on the first floor of the belfry of St Mary's Church showed a microclimate similar to that in the cathedral during the spring-summer period – the average air temperature inside the belfry was +22.56 °C, and the relative air humidity was 68.49%. However, in the autumn-winter period the average air temperature inside the belfry was +12.02 °C, while the relative air humidity was 70.22%. The difference in the autumn-winter period appeared partly due to central heating in the cathedral, and in the belfry of St Mary's Church probably due to insufficiently sealed openings between the belfry and the Capitulum Hall, from which heated air flows into the belfry and condenses on the walls of the first floor room (Fig. 14).

Fig. 18. Ston, Church of St Michael, wall paintings (see fig. 17), detail: salt incrustation.

Measurements over one year in the substructure of the Cathedral of Our Lady in Dubrovnik showed air temperature oscillations from +7.0 °C in February to +20.6 °C in August. The relative air humidity oscillated between 60.9% and 99.71% during the year. Both extreme points of relative air humidity were measured in February, at an interval of two weeks, while the air temperature oscillated between +8.0 °C and +7.7 °C, i.e. 0.3 °C (Fig. 15 above). The results of measuring air temperature (°C) and relative air humidity (rH) in Kerša Palace, located approximately 300 m from the cathedral in Dubrovnik, should be mentioned for comparison (Fig. 15 below). The temperature was measured in an unheated room on the first floor of the palace, with windows to the west. On the same day that the lowest percent of 60.09% relative air humidity with an air temperature of

+8.00 °C was measured in the cathedral (February 12, 2004 at 14:00 h), the measurements in Kerša Palace showed a relative air humidity of 29.70% and an air temperature of 13.81 °C. On the day with the highest percent of relative air humidity in the cathedral in the year (99.71%) and an air temperature of 7.7 °C (February 26, 2004 at 23:00 h), the measurements in Kerša Palace showed 83.20% relative air humidity and an air temperature of 15.08 °C. Measurements are just going to begin in the room above the sacristy vault in the Franciscan monastery *Mala braća* in Dubrovnik.

In the Church of St Michael near Ston on the Pelješac peninsula, preliminary analyses of water-soluble salts have been carried out, and microclimatic measurements were started in the summer of 2004. Their results relate only to part of the summer and early autumn period of the year 2004. During the measurement period the lowest air temperature was +18.30 °C and the highest was +29.82 °C, while relative air humidity oscillated between 27.60% and 80.90%.

Future

Possible solutions for the microclimate in the conservation and presentation of wall paintings
"TEMPORA MUTANTUR (NOS ET MUTAMUR IN ILLIS)"

Based on these reflections, it can be concluded that the problem of increasing fragmentation of the support of the painted layer in the south apse of *Saint Anastasia's Cathedral* in Zadar could be solved in a manner similar to one suggested some thirty years ago: either by taking the wall paintings off the wall, conserving both the wall and the wall paintings, and returning the wall paintings *in situ*; or by trying to stabilise the microclimate in the apse of the south nave, after which certain conservation-restoration procedures can be applied to the wall paintings without taking them off the wall. Considering the fact that both actions require stabilisation, it seems safer to preserve the wall paintings and carry out all procedures needed to conserve them without removing them. However, on the other hand, if these actions are not undertaken as soon as possible, it could be too late for the wall paintings, and so the first solution mentioned should not be incautiously refused (Fig. 19–20). One of the ideas for improving microclimatic conditions in the south apse is to install a glass partition between the apse and the nave, so that the apse would be isolated and an adequate microclimate would be easier to establish (Fig. 21).

The discovery of large quantities of water-soluble salts in the stone and in analysed plaster samples after all the necessary steps had been taken to prevent rainwater flowing along the openings at higher floors of *the belfry of St Mary's Church* led to the conclusion that solving the problem of harmful effects of salts should also include stabilising microclimatic conditions in the room in which the wall paintings were located and in the rooms that surround it directly (the stairway and the narrow passage between the ground-level entrance and the stairway) (Fig. 22). In view of the results from temperature (°C) and relative humidity (%rH) measurements carried out so far on the first floor of the belfry, a detailed study of stabilisation of its microclimate is planned. This study anticipates that the first floor room should be closed off by a glass partition towards the

Fig. 20. Zadar, Cathedral of St Anastasia (Sv. Stošija), south apse, wall paintings (2004).

Capitulum Hall and the stairway isolated from the hall by a glass door. The partitioning of the Capitulum Hall by means of a glass wall in front of the belfry in the line of two semi-columns is also being taken into consideration. The plan also anticipates stabilisation of the microclimate in the narrow passage between the belfry, the church and the attic of the Capitulum Hall, which leads to the stairway to the upper belfry floors. One of the most delicate questions in the microclimate project

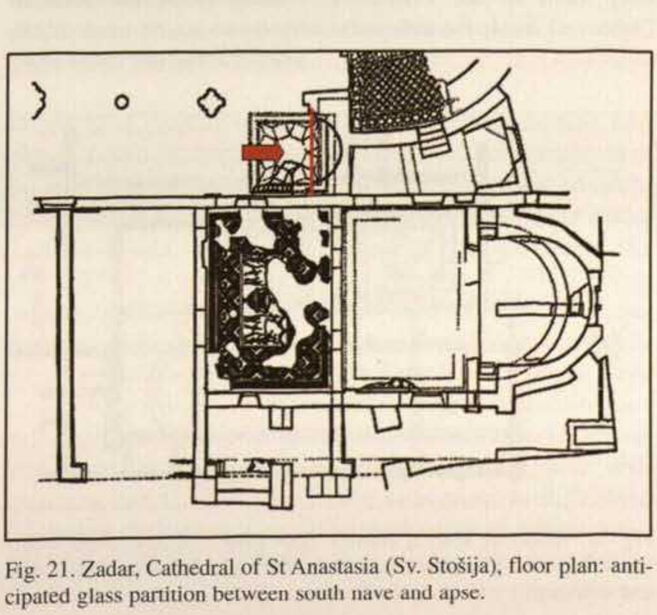

Fig. 21. Zadar, Cathedral of St Anastasia (Sv. Stošija), floor plan: anticipated glass partition between south nave and apse.

will involve selecting the stable value for the temperature and relative humidity in the room on the first floor of the belfry, considering the fact that analyses of salts showed that the analysed salts are of different *equilibrium relative humidity* (Fig. 16).[11]

In the two historical buildings in Dubrovnik the discovery of fragmentary remains of wall paintings that had been preserved for centuries under heaps of rubble material (in the Franciscan monastery) or earth (in the cathedral) produced problems about how to conserve and present them. The measurements of temperature (°C) and relative humidity (%rH) taken in the substructure of the *Cathedral of Our Lady in Dubrovnik*, showed that the actual microclimatic conditions did not harm the discovered fragments of wall paintings, at least not visibly (Fig. 6), so the results of these measurements will be direct indicators for the architects as they work out how to present these discoveries to the public. The Baroque cathedral was seismically retrofitted in the 1980s. The findings of older architectural layers of the cathedral were preserved by means of constructive interventions, and they can be seen under the present floor of thick concrete block. On the insulation board attached to its lower side there are visible condensed water drops that are dripping all the time (Fig. 5). In the substructure space there are also visible puddles of water (i.e., sea level is higher than ground level at these locations in the space under the cathedral). However, in general there are no damages visible on the wall paintings, although it should be emphasised that water-soluble salt samples were not analysed during microclimatic measurements, so the possible harm that could occur due to significant lowering of humidity is not predictable. The *ideal project* for presentation of the room under the cathedral and in front of it, made in the spring of 2004, involves a plan to present these older substructures to the public as a museum. The project specifies the "lack of space in walking areas and the necessity of maintaining a special climate" and researchers therefore suggest visits in groups of not more than twenty people. Visits to the museum are planned to last 10–20 minutes and to include not more than a thousand visitors a day.

The recent accidental discovery of wall-painting fragments from the 14th century under the present floor above the sacristy vault in the Franciscan monastery *Mala braća* in Dubrovnik made the comprehensive construction work on the

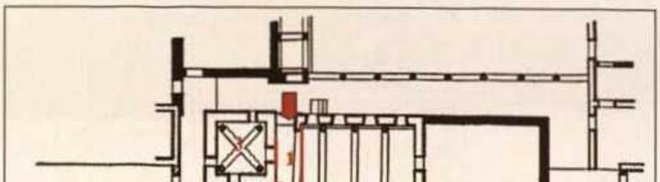

Fig. 22. Zadar, St Mary's Church, floor plan: anticipated glass partitions between belfry and capitulum hall as between capitulum hall and stairway.

first floor of the eastern monastery wing even more complicated. After discovery of the fragments, the question of their conservation and protection arose. In view of the fact that six rooms, three of them with a bathroom, were being planned above the sacristy, the initial plan was to take the paintings off the wall, put them on a new support and display them on the walls of the cloister. However, this was not accepted by conservators and restorers, who insisted on protection of the wall paintings *in situ*. The project now anticipates controlling the condition of the wall paintings by means of several openings in the floors of the newly built rooms above. Research carried out so far included X-ray diffraction of samples of crystallised salts on the surface of the wall paintings; qualitative and quantitative chemical investigations of salt samples from pulps and microbiological research on samples of fungi from cellulose pulps. Their results warned of potential problems to be expected soon if a stabile microclimate is not established in the new small space sandwiched between the vault and the floor (Fig. 23–24). Microclimatic measurements in the interposed space above the sacristy vault are therefore planned for after termination of the construction work, which will close the space off completely. The project anticipates using tubes built into the walls which will connect the space with the wall paintings to the attic and provide passive ventilation. In case such ventilation is not adequate, the tubes could be used for additional active ventilation (bringing in air with a certain temperature and humidity). Video-controls will be used for the long-term control of the wall paintings' condition.

Summary

The text presents the results of measuring temperature (°C) and relative humidity (% rH), together with the results of qualitative and quantitative chemical analyses and X-ray diffraction of water-soluble salts, and microbiological analyses that were carried out so far in a few historical buildings with remains of medieval wall paintings at central and south part of the Croatian Adriatic coast (the south nave apse of Saint Anastasia's Cathedral and the room on the first floor of the belfry of St Mary's Church in Zadar; the substructure of Cathedral of Our Lady and the room above the vault in the Franciscan Monastery *Mala bráca* in Dubrovnik; Church of St Michael near Ston at Pelješac peninsula). The researches in the buildings were carried out with the purpose to determine their microclimatic conditions and relevant factors that these conditions influence decisively, like water-soluble salts and microbiological damages, so the satisfactory conditions of protection and conservation of wall paintings could be chosen based upon these results. The laboratory researches and microclimatic measuring carried out so far showed that stabile microclimate should be provided, considering the equilibrium relative humidity (φ_R%) of present

[11] Andreas ARNOLD and Konrad ZEHNDER, Monitoring Wall Paintings affected by soluble Salts, in: The Conservation of Wall Paintings (Proceedings of a symposium organized by the Courtland Institute of Art and the Paul Getty Institute, London, July 13–16, 1987), Getty Conservation Institute 1991, pp. 103–135; Cliford PRICE, An Expert Chemical Model for determining the environmental conditions needed to prevent salt damage in porous materials, European Communites, 2000.

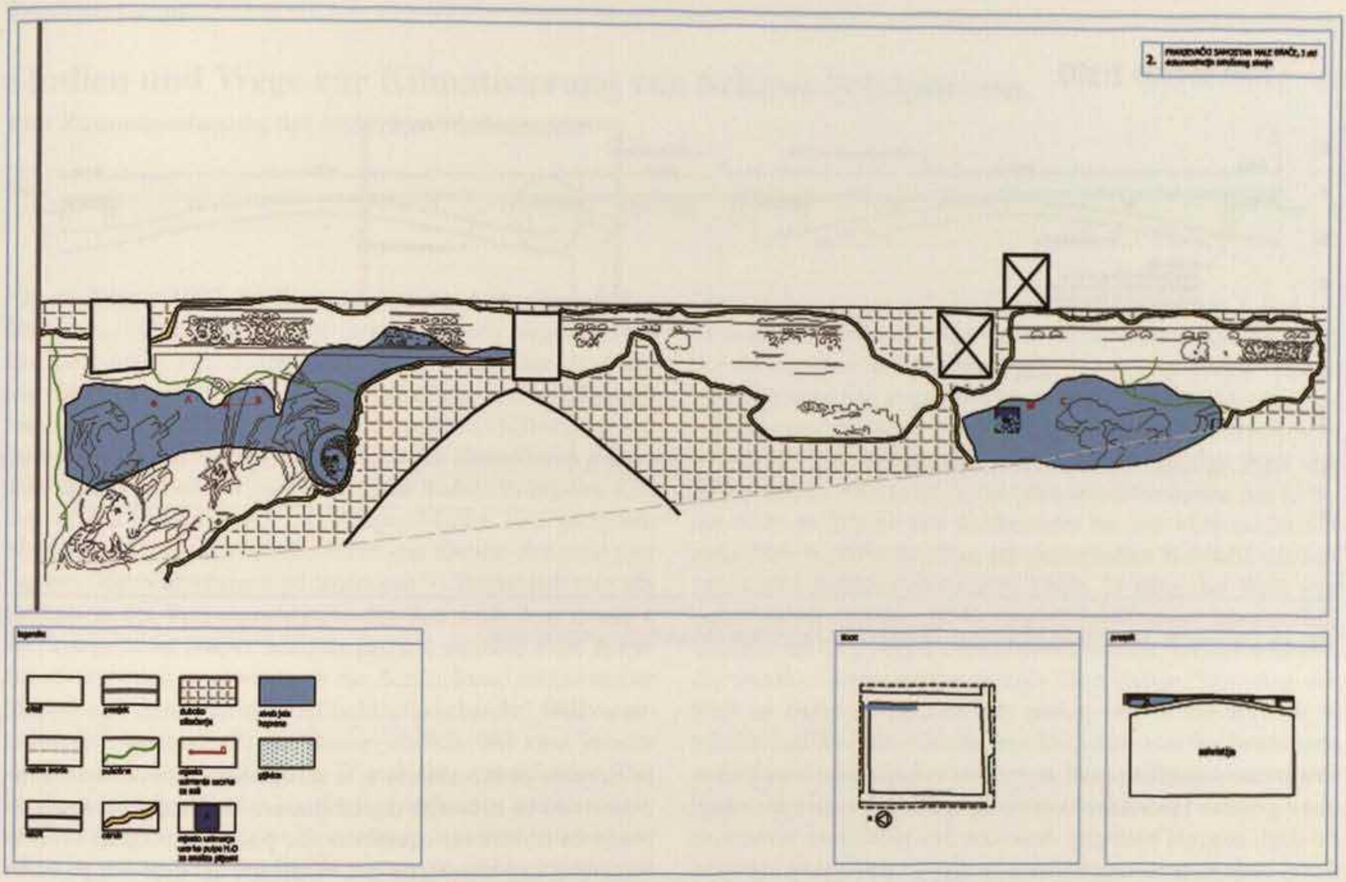

Fig. 23. Dubrovnik, Franciscan Monastery *Mala braća*, room above sacristy vault, east wall: graphic documentation of conservation-restauration works.

water-soluble salts, which is one of the basic prerequisite conditions for preserving the remained fragments of medieval wall paintings.

Zusammenfassung

Raumklimatische Messungen und Laboruntersuchungen in Denkmälern mit mittelalterlichen Wandmalereien an der kroatischen Adriaküste

Der Beitrag referiert die Ergebnisse naturwissenschaftlicher Untersuchungen, mit denen die Schadensursachen bei einigen stark gefährdeten Zeugnissen mittelalterlicher Wandmalerei in Kroatien analysiert wurden. Es handelt sich um Denkmäler an der mittleren und südlichen Adriaküste, im einzelnen um die Südapsis der Kathedrale Sankt Anastasia und eine Obergeschoßkapelle im Glockenturm der Marienkirche von Zadar, um die Unterkirche der Kathedrale Unserer Lieben Frau in Dubrovnik und einen Raum über der Sakristei des dortigen Franziskanerklosters sowie um die Michaelskirche bei Ston auf der Halbinsel Pelješac. Verglichen wurden die Messungen von Temperatur und relativer Feuchte mit den Ergebnissen qualitativer und quantitativer Salzanalysen (X-ray-Diffraktometer) auf der einen und mikrobiologischen Analysen auf der anderen Seite. Die Untersuchungen sollten der Bestimmung der mikroklimatischen Bedingungen und der diese Bedingungen definierenden Faktoren dienen, um sowohl unter dem Aspekt der Salzbelastung wie der mikrobiologischen Schädigungen verträglichere raumklimatische Voraussetzungen für den präventiven Schutz und die Konservierung der Wandmalereien festzulegen. Laboruntersuchungen und Klimamessungen zeigten die Notwendigkeit eines stabilen Raumklimas, um die vorhandenen wasserlöslichen Salze in Lösung zu halten und die durch Auskristallisierung entstehenden Schadensprozesse zu vermeiden.

Sommario

Misurazioni ambientali e ricerche di laboratorio nei monumenti con pitture murali della costa adriatica croata

Il contributo riferisce i risultati delle ricerche scientifiche sulle pitture murali medioevali in Croatia, le quali sono attaccate ad un grave degrado causato da sali solubili. Le analisi chimiche sui sali solubili – sia quantitative che qualitative – e le analisi microbiologiche sono state eseguite su diversi monumenti storici con resti di pitture murali situati lungo la costa adriatica centrale e meridionale della Croatia. Tra questi si ricorda l'apside meridionale della Cattedrale di Sant'Anastasia e una capella superiore nella torre campanaria di Santa Maria di Zadar, della cripta della Cattedrale della Beata Vergine a Dubrovnik e dell'ambiente soprastante l'estradosso della volta nel convento francescano di *Mala braća* nella medesima città e, infine, della chiesa di San Michele presso Ston sulla penisola di Pelješac. Sono stati confrontati i dati delle misurazioni su temperatura e umidità sia con i risultati delle analisi qualitative e quantitative dei sali, sia con i dati delle analisi biologiche. Le ricerche erano

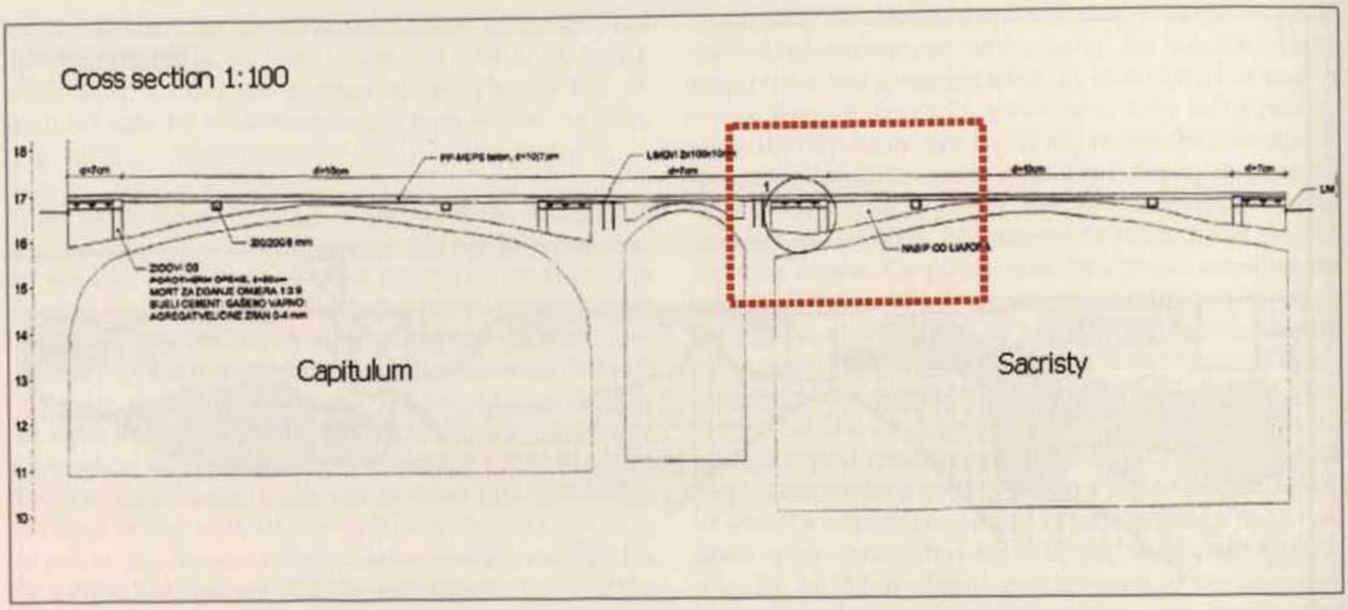

Fig. 24. Dubrovnik, Franciscan Monastery *Mala braća*, capitulum and sacristy: cross section.

finalizzate a stabilire quali particolari condizioni microclimatiche e generali favorivano la cristallizzazione dei sali e lo sviluppo degli attacchi biologici. Solo con una protezione preventiva e con corrette premesse climatiche si potevano creare le condizioni per una corretta conservazione delle pitture murali. Tutte le ricerche di laboratorio e le misurazioni climatiche hanno dimostrato la necessità di stabilizzare il clima ambientale in modo da trovare un equilibrio che possa mantenere i sali in soluzione, impedendo, così, il verificarsi del dannoso processo della cristallizzazione.

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Fig. 1–24: Fototeka, Hrvatski restauratorski Zavod, Zagreb.