Research of the Existing Post-tensioned Roof Trusses and their Reliability

Petr Mynarcik[1*], Vladislav Bures[2], Marek Johanides[3], Pavel Dobes[4], David Mikolasek[5], Miroslav Vacek[6], Martin Patrman[7]

[1*] Faculty of Civil Engineering, VSB Technical university of Ostrava, Ludvika Podeste 1875/17, Ostrava – Poruba, Czech Republic; email: petr.mynarcik@vsb.cz; ORCID https://orcid.org/0000-0002-9758-342X
[2] Faculty of Art and Architecture, Technical University of Liberec, Studentska 1402/2, Liberec, Czech Republic; email: vladislav.bures@tul.cz
[3] Faculty of Civil Engineering, VSB Technical university of Ostrava, Ludvika Podeste 1875/17, Ostrava – Poruba, Czech Republic; email: marek.johanides@vsb.cz; ORCID https://orcid.org/0000-0003-4295-4761
[4] Faculty of Civil Engineering, VSB Technical university of Ostrava, Ludvika Podeste 1875/17, Ostrava – Poruba, Czech Republic; email: pavel.dobes1@vsb.cz; ORCID https://orcid.org/0000-0003-1005-3715
[5] Faculty of Civil Engineering, VSB Technical university of Ostrava, Ludvika Podeste 1875/17, Ostrava – Poruba, Czech Republic; email: miroslav.vacek@vsb.cz; ORCID https://orcid.org/0000-0002-9197-856X
[6] Faculty of Civil Engineering, VSB Technical university of Ostrava, Ludvika Podeste 1875/17, Ostrava – Poruba, Czech Republic; email: david.mikolasek@vsb.cz; ORCID https://orcid.org/0000-0003-2175-8913
[7] Faculty of Art and Architecture, Technical University of Liberec, Studentska 1402/2, Liberec, Czech Republic; email: martin.patrman@tul.cz

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Abstract

The issue of insufficient reliability and, in some cases, the failure of post-tensioned bridge structures, footbridges, and roof trusses, particularly in industrial halls, is one of the current and serious problems of the construction industry in the Czech Republic. The most well-known failures of these structures include the collapse of the Morandi Bridge near Genoa, Italy, in August 2018, and the collapse of the Troja footbridge in Prague in December 2017. Less known are the failures of post-tensioned truss roof structures that occurred in the Czech Republic and Slovakia. Especially in the Czech Republic, there were failures in Tachov (2010 and 2018), Sluknov (December 2023), and Karlovy Vary (March 2024). A common feature of all these failures was the corrosion of the prestressing reinforcement in inadequately grouted cable ducts. Roof structures of this type have been used in more than 100 buildings that are still in operation in the Czech Republic. In response to this situation, the company Rada Building s.r.o., in cooperation with academic institutions, developed a method to reinforce trusses threatened by corrosion using an external steel structure. The company carries out the reinforcement work during normal operation in the hall below the trusses. Research on post-tensioned truss structures and the possibilities of their static securing is being conducted in cooperation with the Faculty of Civil Engineering at VSB – Technical University of Ostrava, the Faculty of Art and Architecture at the Technical University of Liberec, and the company Rada Building, s.r.o. The ambition of the research is to analyze the condition of as many trusses as possible embedded in buildings in the Czech Republic and Slovakia using building structure diagnostic methods and to evaluate these surveys. Furthermore, the research aims to verify the actual behavior of such structures through tests on real trusses taken from demolished buildings. VSB – TU Ostrava has several trusses available, and load tests are currently being carried out on them. An important and final part of the research is to find the optimal diagnostic method that would improve the ability to predict the risk of roof failures in operational buildings and to optimize the methods for securing these structures to ensure full static reliability with the lowest possible costs and minimal impact on the building.

Keywords: *post-tensioned structures, corrosion of the tendons, diagnostics, evaluation*

1. Introduction

This paper is dedicated to trusses, focusing especially on post-tensioned roof trusses that were used primarily in the Czech Republic and Slovakia for roofing industrial halls, mainly with modular spans of 18 and 24 meters. There are also trusses of this type with a span of 30 meters in archival records; however, these trusses have not yet been identified in any of the conducted building surveys. The trusses were predominantly used between the years 1960 and 1975 [1].

All from the mentioned types of trusses were originally manufactured in three (18 meters) or four (24 meters) segments for transportation reasons and were subsequently bonded together on-site with post-tensioning tendons. The post-tensioning tendons were later placed on-site into ducts installed during the truss casting process, and after tensioning the tendons, the ducts were supposed to be grouted with a grout mixture.

A common characteristic of these structures are deficiencies in the grouting of the ducts with post-tensioning reinforcement, resulting into inadequate protection of the post-tensioned reinforcement against corrosion. This issue has already led to repeated roof collapses of industrial halls in the Czech Republic. The first part of the paper presents the various types of trusses and their brief characteristics; the next part discusses methods for diagnosing corrosion of the post-tensioned reinforcement. The core of the paper is the evaluation of the performed diagnostic surveys and the assessment of the risks that the existence of these structures poses.

Trusses can be identified on-site mainly by the doubled verticals at the joints of the individual truss segments, roughly in thirds (18 meters) or quarters (24 meters) of the span.

2. Types of the Diagnosed Roof Trusses

2.1 Trusses SPP 6-18/6 a 12-18/6

The most common types of trusses that have been used and are still functioning in a large number of primarily industrial halls are the trusses of types SPP 6-18/6 and SPP 12-18/6 with a modular span of 18 meters. They were placed axial distances of 6 meters. All these trusses have the same shape; however SPP 12-18/6 (1969) is the newer version of the older SPP 6-18/6 (1961) truss for updated load requirements.

The SPP 6-18/6 (1961) trusses were cast from 400-grade concrete (nowadays C28/35) and were designed for a dead load from the weight of the roof covering of 2.10 kN/m² and for a snow load of 0.75 kN/m².

The SPP 12-18/6 (1969) trusses were cast from 500-grade concrete (nowadays C35/45) and were designed for a dead load from the weight of the roof covering of 2.50 kN/m² and for a snow load of 1.00 kN/m².

Fig. 1. Post-tensioned roof truss beam SPP12-18/6

The truss was prestressed with four prestressing tendons, each 4 x 12øP4.5. Two tendons were anchored at the left end of the upper chord of the truss and at the right end of the lower chord of the truss. The other two tendons were anchored symmetrically at the right end of the upper chord of the truss and at the left end of the lower chord of the truss. This means that both outer tensioned descending diagonals were reinforced with two prestressing tendons, and the tensioned lower chord was reinforced with a total of four prestressing tendons. Additionally, the upper chord of the truss was prestressed with one 7øP4.5 cable for assembly purposes, but it was expected that the prestressing force of this cable would disappear over time due to prestress losses therefore it was not considered in the truss calculations. The arrangement and the geometry of the prestressing tendons tracing is shown in Figure 2.

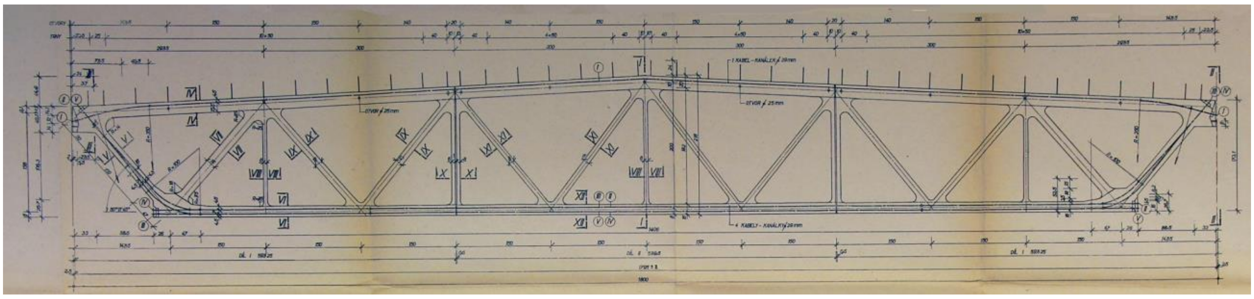


Fig. 2. Post-tensioned roof truss beam SPP 12-18/6 – tendons arrangement

2.2 Trusses V18, V18a (1961), VS 18/6 (1963)

The trusses developed by Priemstav n.p. Bratislava in 1961 were designed for a modular span of 18 meters and placed at axial distances of 6 meters. The trusses were prestressed with a total number of four continuous, twice-bent prestressing tendons, passing through the outer tensioned diagonals and the lower chord of the truss. The truss, made of 400-grade concrete (nowadays C28/35), was designed for a dead load from the weight of the roof covering of 2.03 kN/m² and for a snow load of 0.75 kN/m².

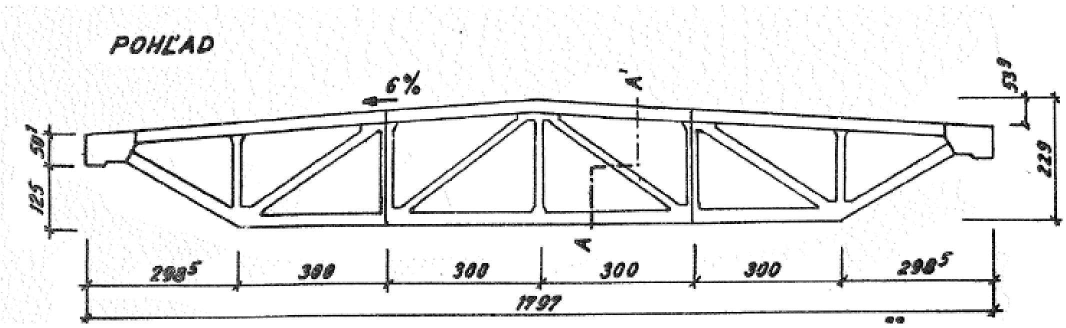


Fig. 3. Post-tensioned roof truss beam V18, VS 18/6

2.3 Trusses SPP 9-24/6 a SPP 14-24/6

These two types of structurally identical trusses were designed for a theoretical span of 24 meters, placed at axial distances of 6 meters. They differ in their manufacturer, concrete grade, and load design.

The SPP 9-24/6 trusses were manufactured by ZIPP n.p. Bratislava from 1966. They were cast from 400-grade concrete (nowadays C28/35) and were designed for a dead load from the weight of the roof covering of 2.10 kN/m² and for a snow load of 0.75 kN/m².

The SPP 14-24/6 trusses were designed at the Study and Typification Institute in Prague in 1966. The trusses were cast from 500-grade concrete (nowadays C35/45) and were designed for a dead load from the weight of the roof covering of 2.50 kN/m² and for a snow load of 1.00 kN/m².

The trusses were prestressed with a total number of two continuous, twice-bent prestressing tendons 24øP4.5, passing through the outer tensioned diagonals and the lower chord of the truss. Additionally, the lower chord was reinforced with a third prestressing tendon 24øP4.5, anchored at both ends of the lower truss chord.

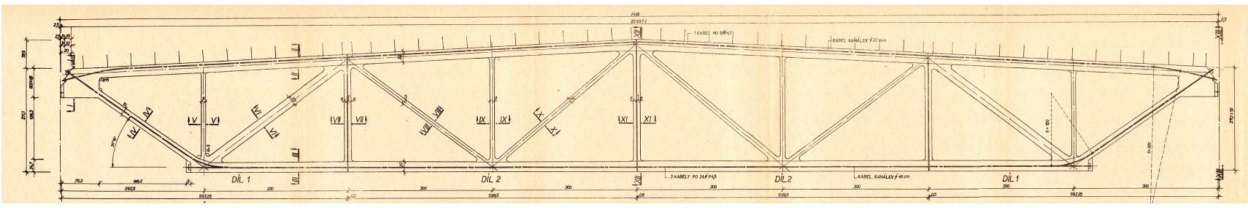


Fig. 4. Post-tensioned roof truss beam SPP 14-24/6 – tendons arrangement

2.4 Trusses VS 24/6

The trusses developed by Priemstav n.p. Bratislava in 1963 were designed for a modular span of 24 meters and placed at axial distances of 6 meters. The trusses were prestressed with a total number of four continuous, twice-bent prestressing tendons, passing through the outer tensioned diagonals and the lower chord of the truss. Additionally, the lower chord was reinforced with two more prestressing tendons, anchored at both ends of the lower truss chord. These trusses were made of 400-grade concrete (nowadays C28/35) and were designed for a dead load from the weight of the roof covering of 2.03 kN/m² and for a snow load of 0.75 kN/m².

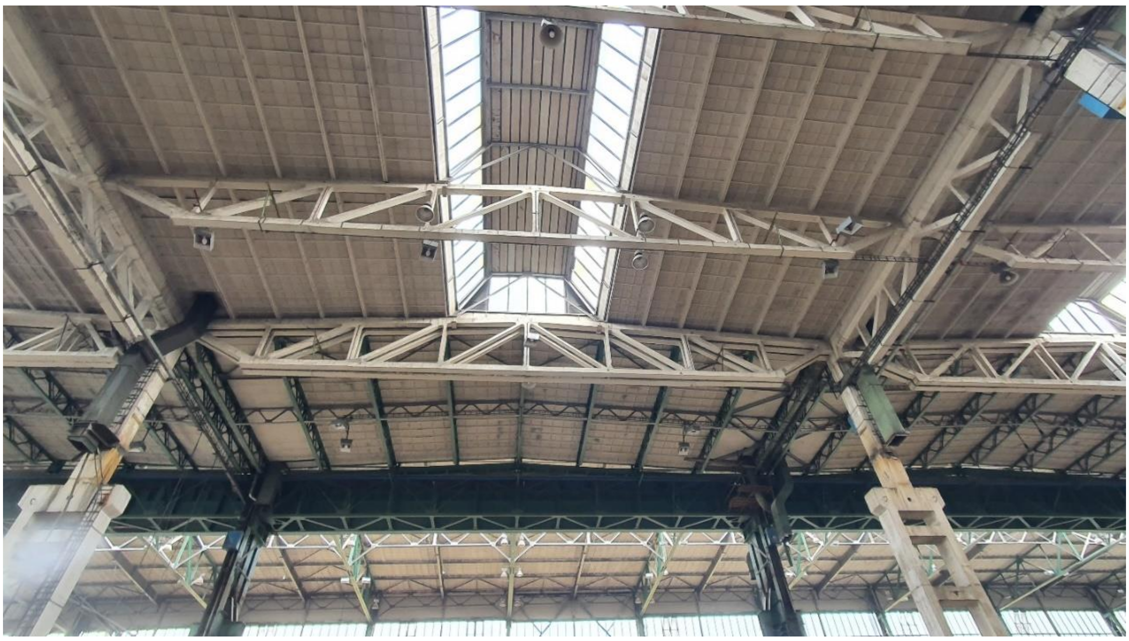


Fig. 5. Post-tensioned roof truss beam VS 24/6

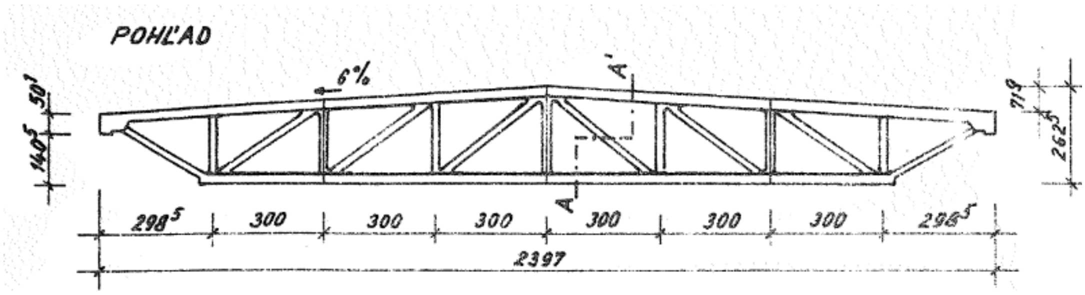


Fig. 6. Post-tensioned roof truss beam VS 24/6

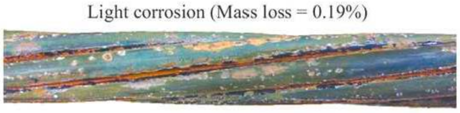
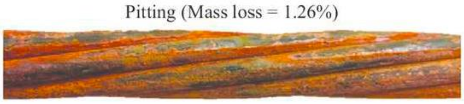
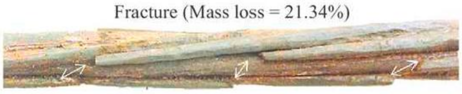
3. Diagnostics methods of the tendons corrosion

The primary diagnostic method is an endoscopic examination of the prestressing reinforcement. The prestressing reinforcement (most commonly consisting of 12øP4.5 tendons) is placed in ducts with a typical diameter of 29 mm. The exact position of the ducts is determined using a D-tect 150 SV reinforcement detector and marked on the surface of the examined truss member. Then, the duct is carefully drilled with a 6 mm diameter drill bit, and after verifying the duct's position, the hole is enlarged up to a diameter of 10 mm. The condition of the duct together with the prestressing reinforcement is inspected using a Laserliner Videoinspector 3D or, if necessary, an Olympus IPLEX IV9620GL videoscope.

Fig. 7. Endoskopic survey of the truss tendons

The survey assesses the condition of the duct grouting, and in the case of partial or completely missing grouting, it evaluates the degree of corrosion of the prestressing reinforcement. The visual assessment of the corrosion level is typically performed according to TABLE 1, adapted from [4].

Tab. 1. Rating scale depending on the corrosion attack of the tendon surface according to [4]

No corrosion (Mass loss = 0.0%) 	Without corrosion	Grade 1
Light corrosion (Mass loss = 0.19%) 	Slight surface corrosion locally, especially in the gaps between the wires, weakening up to 0.19 %	Grade 2
Pitting (Mass loss = 1.26%) 	Moderately developed surface corrosion weakening up to 1.26 %	Grade 3
Heavy Pitting (Mass loss = 2.72%) 	More intensive corrosion with a transition to a pitted form, weakening up to 2.72 %	Grade 4
Cross section loss (Mass loss = 8.38%) 	Intensive corrosion with the formation of peeling off scales, weakening up to 8.38 %	Grade 5
Fracture (Mass loss = 21.34%) 	Significant weakening with breaks of some wires, weakening about up to 21.34%	Grade 6

Examples of photographs taken during the endoscopic survey of ducts with prestressing reinforcement in trusses are shown in the following images:

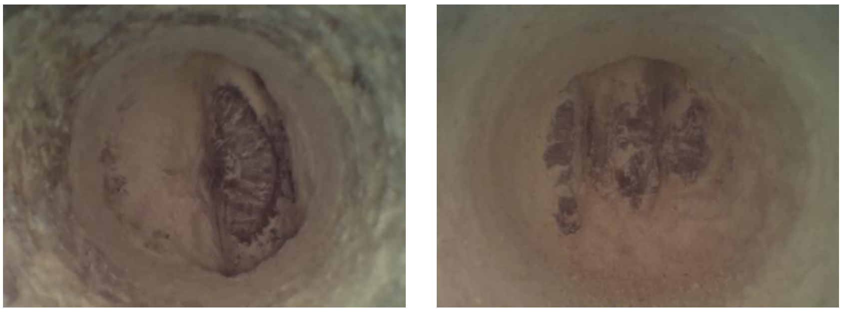


Fig. 8. Tendon ducts are fully grouted - G

Fig. 9. Tendon ducts without grouting, tendons without corrosion – corrosion grade 1

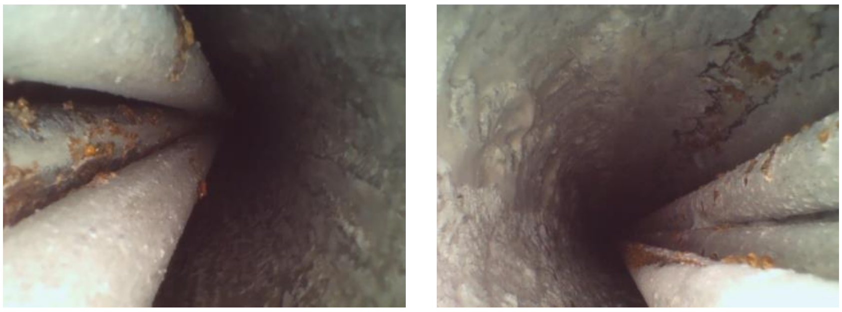


Fig. 10. Tendon ducts without grouting, local corrosion + leak marks – corrosion grade 2

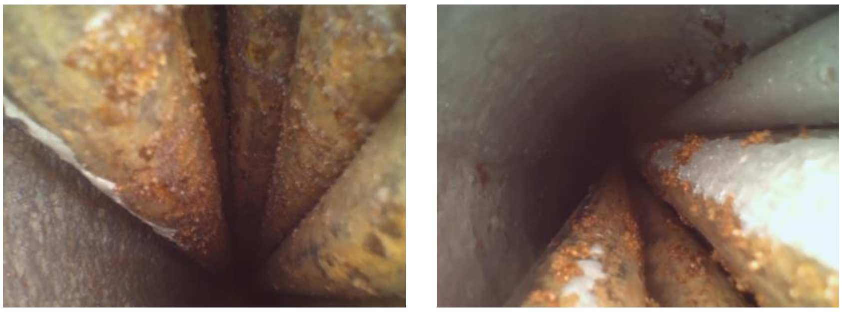


Fig. 11. Tendon ducts without grouting, surface corrosion – corrosion grade 3

Fig. 12. Tendon ducts without grouting, surface corrosion – corrosion grade 5

Fig. 13. The upper anchor in the location of the truss bedding on the column –
– total corrosion of the tendons and opposite side in the relative satisfying condition –
taken out from the collapsed truss

The diagnosis using endoscopy is currently the primary diagnostic method. Its main disadvantage is that it provides only local information about the condition of the reinforcement at a specific point and does not reveal the condition of the reinforcement outside the specific endoscopic probe. This drawback can be somewhat mitigated only by the experience of the technician performing the diagnosis and his/her assessment of critical points where endoscopic probes should be performed. For example, it has been verified that there is a lower probability of successful duct grouting and thus a higher risk of reinforcement corrosion in the outer tensioned diagonals of the truss than in the straight lower chord of the truss. The critical area is primarily the anchoring zone of the reinforcement at its placement on the column, where water gets easily into the structure and also condensation of moisture most commonly occurs.

Some companies, in addition to endoscopic examination, use larger chiseled (broken) probes with dimensions of approximately 100 x 100 mm, which allow a better direct visual assessment of the reinforcement condition. Additionally, this type of probe allows the execution of a prying test on the prestressed reinforcement using a large screwdriver, providing a rough estimate of the level of tension in the reinforcement. However, this is a somewhat controversial inspection method due to the risk of damaging the truss rod, which typically has a cross-section dimension of 160/300 mm.

Further non-destructive methods for diagnosing reinforcement corrosion, based on various physical methods, are currently in the laboratory development stage, but they are not yet practically applicable to existing structures.

4. Summary of the experience from the diagnostic surveys

The following tables summarize the results from 24 surveys in total, partially performed by the staff of VŠB - TU Ostrava (marked in purple) and partially by the staff of Diagnostika stavebních konstrukcí s.r.o. (marked in blue). Most surveys were conducted for the SPP 6-18/6 trusses. In the following table, "G" indicates a fully grouted duct with prestressing reinforcement. Numbers 1 to 5 indicate the degree of corrosion according to TABLE 1. In most surveys, the inspection focused only on the outer tensioned diagonals, while in a few cases, probes were also made into the lower chord of the truss.

Tab. 2. Trusses SPP 6-18/6 a 12-18/6

Survey number	Probes **bottom chord** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	Probes **outer diagonal** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]
1	16	100						86	37.2	26.7	32.6	3.5		
2	16	62.5		37.5				36			47.2	38.8	14.0	
3								71	39.4		23.9	29.6	4.2	2.9
4	10	90.0				10.0		20	40.0		40.0	20.0		
5								23	30.4	4.3	43.5	8.8	13.0	
6								394	87.1	2.5	6.3	2.5	1.6	
7								82	9.8	4.9	53.7	26.6	2.4	3.6
8								53		5.7	77.4	16.9		
9								10			60.0	40.0		
10								62	27.4	12.9	48.4	9.7	1.6	
11								94	32.9	11.7	48.9	4.3	2.2	
12								28	35.7	21.4	39.3	3.6		
13								44	27.3	11.4	61.3			
14								20	45.0	20.0	30.0	5.0		
15								28	3.6		67.9	25.0	3.5	
16								18	44.4	5.3	38.9	11.1		
Σ	42	83.3		14.3		2.4		1069	47.1	7.1	33.0	10.2	2.1	0.5

Tab. 3. Trusses V18, V18a, VS 18/6

Survey number	Probes **bottom chord** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	Probes **outer diagonal** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]
1	4	75.0			25.0			56	19.6	25.0	35.7	19.7		
2								36	47.2	22.2	27.7	2.9		
3								128	12.5	14.1	35.9	29.7	7.8	
Σ	4	75.0			25.0			220	20.0	18.2	34.5	22.7	4.6	

Tab. 4. Trusses SPP9-24/6 a SPP 14-24/6

Survey number	Probes **bottom chord** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	Probes **outer diagonal** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]
1								35	60.0	2.9	20.0		11.4	5.7
2								135	63.7		23.7	4.5	8.1	
Σ								170	62.9	0.6	23.0	3.5	8.8	1.2

Tab. 5. Trusses VS 24/6

Survey number	Probes **bottom chord** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	Probes **outer diagonal** [pieces]	G [%]	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]
1	9	88.9		11.1				18	44.4	22.2	27.9	5.5		
2								10	80.0			20.0		
3								19	5.2	31.7	57.9			5.2
Σ	9	88.9		11.1				47	36.2	21.3	34.0	6.4		2.1

More than 1,500 probes were performed during the monitored surveys. Based on the evaluation of the experience from a total of 24 surveys, the following can be stated:

- The risk of insufficient grouting of prestressing reinforcement ducts is significantly higher in the outer diagonals of the truss compared to the lower chord of the truss. For the lower chord, perfect grouting of the ducts was found in approximately 80% of cases, and isolated instances of prestressing reinforcement corrosion were observed up to level 4 according to TABLE 1. In the case of the outer tensioned diagonals, the probability of perfect grouting of the prestressing reinforcement ducts is roughly half that of the lower chord, and numerous instances of prestressing reinforcement corrosion were observed up to level 5 according to TABLE 1.
- Corrosion of the prestressing reinforcement, diagnosed mainly in the outer diagonals of the truss, most frequently occurs at level 2 according to TABLE 1 (approximately 30% of all probes). In the vast majority of cases, the detected level of corrosion did not exceed level 4 according to TABLE 1. The highest recorded level of corrosion was assessed as level 5 according to TABLE 1, occurring in less than 1% of probes. No instances of level 6 corrosion were recorded according to TABLE 1.

5. Evaluation of the roof trusses based on surveys

Corrosion of prestressing reinforcement generally presents a significantly greater problem than corrosion of mild reinforcing steel for the following reasons:

- A prestressing tendon consists of a larger number of thin wires, and the loss of material due to corrosion on the surface of the wire results in an approximately four times greater reduction in cross-sectional area compared to a single reinforcing bar with the same effective cross-section. The impact of cross-sectional area reduction of a prestressing tendon, composed of 12 wires with a diameter of 4.5 mm, and a single reinforcing bar with the same cross-sectional area is shown in TABLE 6, adapted from [2].

Tab. 6. Impact of the corrosion loss on the surface of the reinforcement on the cross-sectional area

Weakening of the cross-sectional area [%]	Surface corrosion loss [mm]	
	Circular reinforcement bar Ø 15,58 mm	Tendon 12 ø P4.5 mm
2	0,0390	0,0113
2	0,0780	0,0226
2,554 %	0,1000	0,0289
5	0,1970	0,0570
8,675 %	0,3458	0,1000
10	0,3995	0,1155
20	0,8225	0,2376

- Moisture holds and spreads very well in the gaps between the individual wires of the prestressing tendons.
- When corrosion reduces more than 5% of the cross-sectional area, there is not only a reduction in the cross-sectional area of the prestressing reinforcement but also a significant decrease in the mechanical properties of the reinforcing steel, especially the yield strength. A detailed analysis of this issue was published in article [3].

The assessment of the reliability of structures with prestressing reinforcement weakened by corrosion is not yet included in any valid regulations in the field of building construction in the Czech Republic. To a reasonable extent, the standard ČSN 76 6221 "Inspections of Road Bridges" can be used for the assessment of structures, which includes the evaluation of the structural condition of the bridges depending on the corrosion of the prestressing reinforcement according to TABLE 7.

Tab. 7. Construction condition of the bridge depending on reinforcement corrosion according to [5]

Construction status of the bridge	Weakening of tendons	Tendon ducts
V – bad	up to 1 %	partially grouted
VI – very bad	up to 5 %	not grouted

Structural condition V – bad, or VI – very bad, means that restoring the reliability of the bridge will require its reconstruction (structural modifications, modernization). Corrosion of prestressing reinforcement at a level exceeding 5% reduction in cross-sectional area is assessed as a critical condition. A critical structural condition means the immediate closure of the bridge or the immediate provisional assurance of its reliability, for example by providing provisional support. Based on the comparison of TABLE 1 and TABLE 7, it can be concluded that corrosion level 4 according to TABLE 1 should be considered the limit, and corrosion level 5 already indicates a critical condition of the structure.

6. Conclusion

In the framework of a total of 24 evaluated surveys, containing 1506 evaluated probes, corrosion at level 5 according to TABLE 1 was detected in less than 1% of cases, corrosion at level 6 was never detected. At the same time, even corrosion at level 6 should not be sufficient for the collapse of the structure.

In the case of the collapse of the roof truss, from which the anchor of the prestressing reinforcement was taken according to FIGURE 13, the failure of the prestressing reinforcement occurred in close proximity to the upper anchor at the location of the truss bedding on the column. There are suspicions that in other known cases of collapse of structures of this type, failure of the anchorage areas occurred. Therefore, it seems that one of the other desirable directions of research should be the investigation of the condition of the anchorage areas and the investigation of the behavior of the truss during failure in the anchorage area of the prestressed reinforcement.

Acknowledgments

The research is carried out with the financial contribution of the company Rada Building s.r.o., which is actively involved in the research and which, based on the results of the research so far, has developed a system of additional reinforcement of the trusses. This system enables the strengthening of problematic trusses with a retrofitted steel structure, realized during full operation in the hall in such a way as to ensure the static reliability of the truss even in the event of a total failure of the original prestressed reinforcement.

Thanks also go to the company Diagnostika stavebních konstruktcí s.r.o., which provided a total of 14 Final Reports from the conducted surveys for the purposes of this research.

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