

Diagnostics of Existing Steel Structures of Winter Sport Halls

Marcela Karmazínová, Jindrich Melcher, Lubomír Vitek, Petr Cikrle

Abstract—The paper deals with the diagnostics of steel roof structure of the winter sports halls built in 1970 year. The necessity of the diagnostics has been given by the requirement to the evaluation design of this structure, which has been caused by the new situation in the field of the loadings given by the validity of the European Standards in the Czech Republic from 2010 year. Due to these changes in the normative rules, in practice existing structures are gradually subjected to the evaluation design and depending on its results to the strengthening or reconstruction, respectively. Steel roof is composed of plane truss main girders, purlins and bracings and the roof structure is supported by two arch main girders with the span of $L = 84$ m. The in situ diagnostics of the roof structure was oriented to the following parts: (i) determination and evaluation of the actual material properties of used steel and (ii) verification of the actual dimensions of the structural members. For the solution the non-destructive methods have been used for in situ measurement. For the indicative determination of steel strengths the modified method based on the determination of Rockwell's hardness has been used. For the verification of the member's dimensions (thickness of hollow sections) the ultrasound method has been used. This paper presents the results obtained using these testing methods and their evaluation, from the viewpoint of the usage for the subsequent static assessment and design evaluation of the existing structure. For the comparison, the examples of the similar evaluations realized for steel structures of the stadiums in Olomouc and Jihlava cities are briefly illustrated, too.

Keywords—Diagnostics, existing steel structure, sport hall, steel strength, indirect non-destructive methods, Rockwell's hardness, destructive methods, actual dimensions, ultrasound method.

I. INTRODUCTION

THE workplaces of the paper authors (Division of Metal and Timber Structures and Division of Structural Testing of the Faculty of Civil Engineering at the Brno University of Technology) co-operate with ACIERCON, Ltd. Company on the evaluation of existing structures, in the long term. Within the diagnostics of steel roof structural system, several constructions of sport halls in the Czech Republic have

already been investigated. The first ones were the winter stadiums in the cities of Olomouc, Jihlava and Znojmo, for example. The main aims of the diagnostics of load-carrying steel structures of these buildings were to verify the actual dimensions of structural members and to determine actual physical-mechanical properties of structural steel, to use these ones in the subsequent static assessment and evaluation of existing structure. Regarding the possibilities given by the different structural configurations and real structural conditions, the different diagnostic methods are needed to use. In the case of the winter sport stadium at Znojmo city mentioned above, non-destructive diagnostics in-situ only has been used. It was given by the fact that, because of the static reasons, no structural member or structural part could be taken from the existing roof construction.

The basic configuration and composition of load-carrying system is evident from the orientation schemes in Figs. 1-3 provided by the contracting authority.

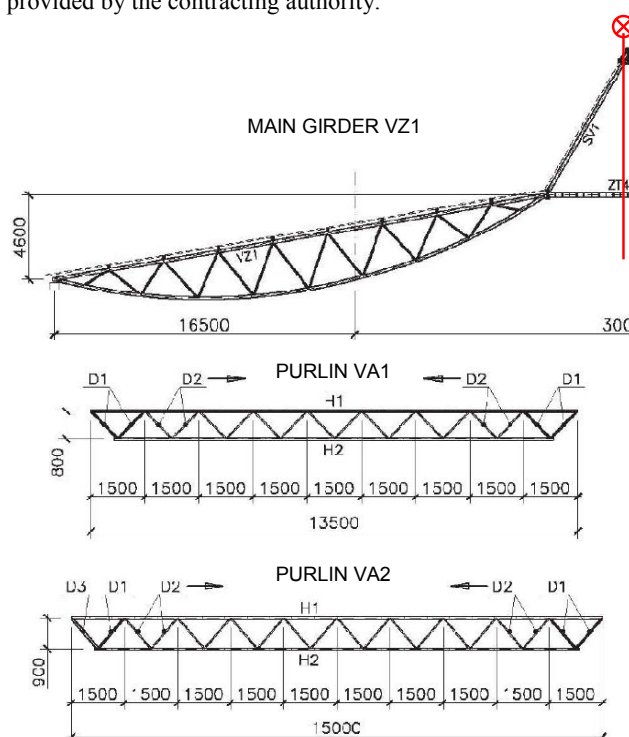


Fig. 1 Main roof girder VZ1 and purlins VA1, VA2

The roof structure is composed of plane truss main girders, purlins and bracings (see Figs. 1, 2) and the structure as a whole is supported by longitudinal arch main girders (Fig. 3).

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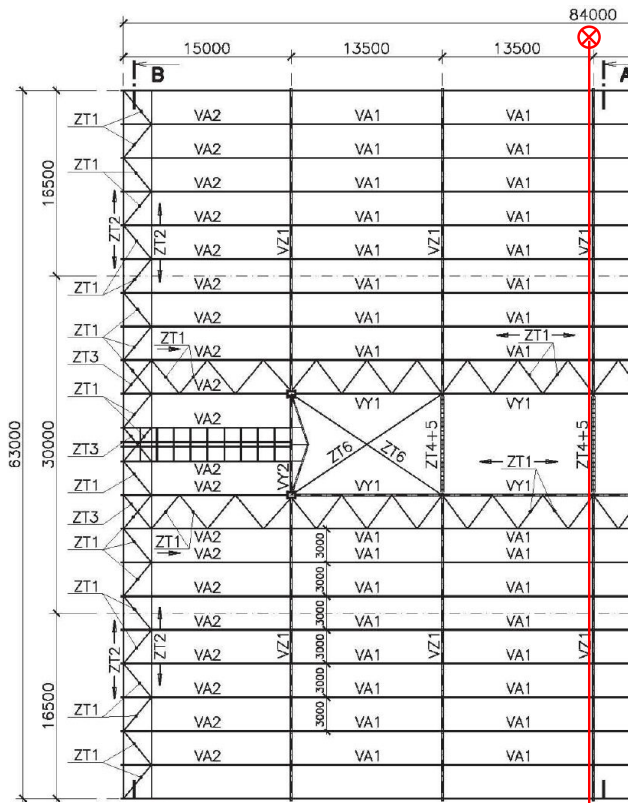


Fig. 2 Roof structural system: plan

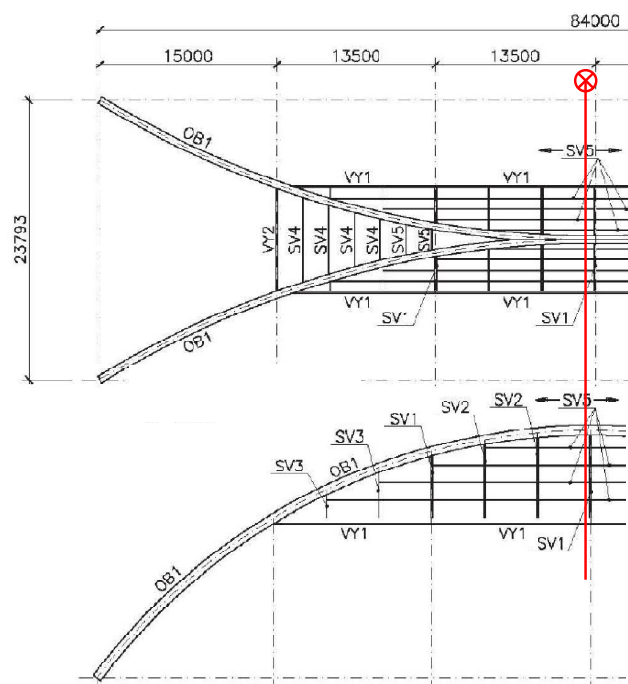


Fig. 3 Arch main girders: plan and side view

The typical cross-sections (including their dimensions) of the main structural members, that means main roof girders, purlins and arch girders, are shown in Fig. 4.

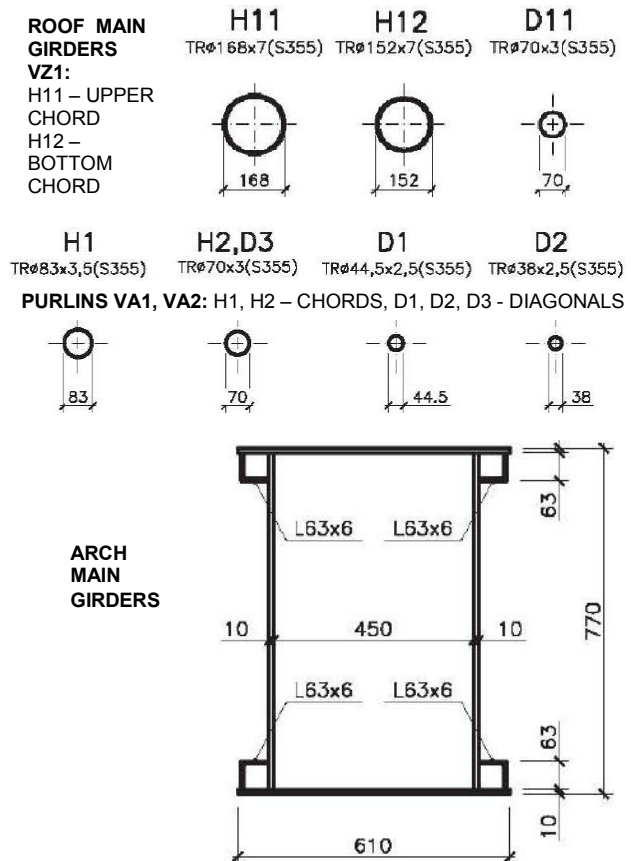


Fig. 4 Cross-sections of main structural members

The measurements mentioned below have been realized in the conjunction with the representatives of the company, both from the viewpoint of the selection of measured members of steel structure, and from the viewpoint of the provision of the lifting platforms and security mechanisms for access to the members of the structural system.

II. STEEL ULTIMATE STRENGTH DETERMINATION AND EVALUATION – NON-DESTRUCTIVE DIAGNOSTICS IN SITU

The destructive methods could not be used because of the impossibility to take specimens from existing structure for tensile testing, that the non-destructive diagnostics oriented to the indicative evaluation of strength has been used.

A. Evaluation of Existing Structures

The standard ISO 13822 Basis of Structural Design – Evaluation of Existing Structures [10] can be applied for steel structures mentioned.

Because in this case the origin material statements containing the specification of their quality were available, then the actual values of steel yield and ultimate strengths can be assumed. For the basic verification of these properties, the indirect methods not requiring the problematic sampling from the structure loaded can be used (tests according to Brinell, Vickers or Rockwell, for example). To verify properties and indicatively to determine steel strength, the suitable method

for the hardness measurement can be used; the standard ISO 13822 recommends the method using “POLDI hammer” or some method ensuring sufficient correlation between hardness and strength.

B. Selection of Testing Method

The “POLDI hammer” method recommended in [10] allows the fast assessment of the quality of metal materials inbuilt in the construction because of easily portable testing apparatus. The test is based on the comparison of the deformation caused by hammer in the known hardness specimen with deformation caused in unknown hardness tested material. However, from current viewpoint, this method is somewhat out of date, namely because of the fiddly and not too precise measurement of deformation size. It is especially difficult at high positions and, in addition, testing slender and hollow sections is problematic, too.

The next useable method is the dynamic impact method by D Leeb. The measurement is carried out by the toughened ball catapulted in the direction to the tested element. The ball strikes the surface by the defined speed or kinetic energy, respectively. The ball loses the part of its energy as a result of the surface deformation occurred. The loss of energy is greater, if the deformation is greater, i.e. the material hardness is smaller. The ball affects by the great force in the short duration of the impact. Slender and light-weight components can deform (vibrate) and then cause erroneous measurement. It can be solved by supporting back parts of the measured object, if smaller parts of the simple shape are tested. However, in the case of truss girders the vibration of the members can be difficulty corrected.

According to the structure type and the experiences of the elaborators, the universal portable apparatus for the measurement of hardness “COMPUTEST SC” (Switzerland Company “Ernst Härteprüfer SA”) using the modified Rockwell method has been chosen for testing the roof structure mentioned. The measurement is based on the exact static method enabling accurate and reliable routing of diamond edge in the measuring probe. In the measuring head the moveable sensor is placed enabling the measurement of the depth of the deformation in the range of 0–100 μm . The apparatus shows either the values of the hardness in the usual hardness units or directly tensile strength. This method is standardized by the German Standard DIN 50 157.

C. Displacement and Treatment of Tested Locations

The aim of tests performed was to verify tensile ultimate strength of steel in various members of the roof structure. The number of measured locations has been given and specified directly in situ. Because of the limited range of the lifting platform the roof bracing could not be verified. The displacement of tested locations on the roof structure and on the arches is schematically shown in Figs. 5 and 6. The composition and configuration of the load-carrying structural members is evident from Fig. 7.

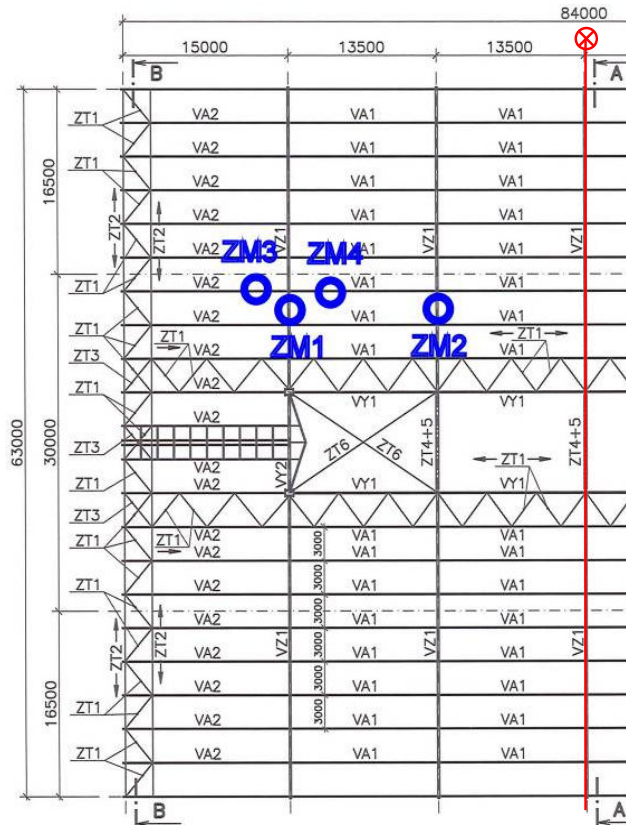


Fig. 5 Tested locations: main roof girders VZ1 – locations ZM1, ZM2, roof purlins VA1, VA2 – locations ZM3, ZM4

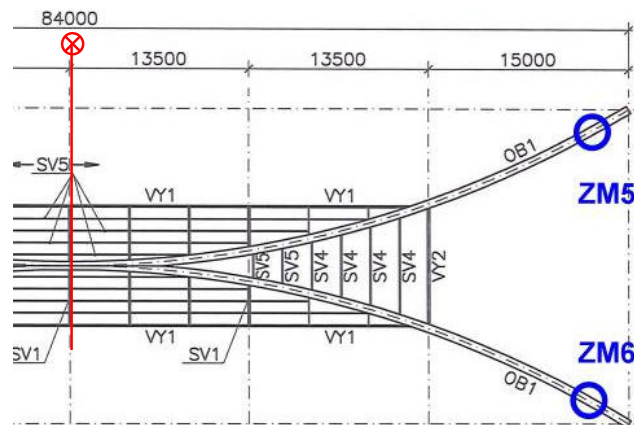


Fig. 6 Tested locations: arch main girders OB1 – locations ZM5, ZM6

Before the measurement by “COMPUTEST SC” apparatus it was necessary to remove paint layers and to prepare surface (see Fig. 8 (a) left). The distance of the measuring tip has always been calibrated using the special dipstick (see Fig. 8 (a) right). For measuring on the rounded surface the V-shaped product (see Fig. 8 (b)) has been used; on the flat surface the three-point magnetic product (see Fig. 8 (c)) has been applied.



Fig. 7 Part of tested structure: truss main roof girders, truss purlins, bracings, arch main girders



(a)



(b)



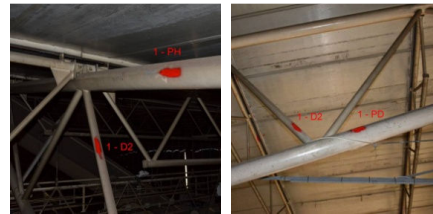
(c)

Fig. 8 Measurement by “COMPUTEST SC” apparatus: (a) prepared tested location on rounded surface (left), calibration of measuring tip distance on rounded surface (right); (b) measurement on rounded surface using V-shaped product; (c) measurement on flat surface using three-point magnetic product

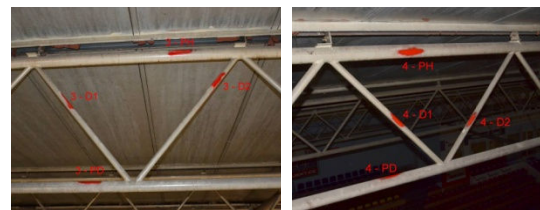
D. Tests of Steel Tensile Strength

The tests of steel tensile strength have been verified in the different members of the roof structure and arches. Based on the documentation, all tested members should be made of the same material – steel of the grade S 355, in accordance to the standard EN 10027 [11]- [13]. The members of the horizontal bracings only should be made of the different material, but these members have not been tested because of the limited range of the lifting platform (see above).

In total 22 tested locations have been verified on the upper chords PH, bottom chords PD and diagonals D: 8 measured locations on 2 main roof girders – upper chord, bottom chord, 2 diagonals; 8 measured locations on 2 roof purlins – upper chord, bottom chord, 2 diagonals; 6 measured locations on 2 arches – upper flange, bottom flange, 2 webs. Individual tested locations are documented in Fig. 9.



(a)



(b)



(c)

Fig. 9 Tested locations: (a) truss main roof girders; (b) truss roof purlins; (c) arch main girders

E. Test Results and Evaluation of Steel Tensile Strength

Test results obtained directly from the tests as particular values of steel ultimate tensile strength, have been statistically evaluated, that means characteristic values of tensile strength have been determined (see also [1]–[3]).

According to the statistical principles, mean values of the ultimate strength f_{um} and standard deviations have been determined by statistical procedures from the test data. Respecting the recommendation of EN 1990 (Annex D) [15], the variation coefficients have been considered as “unknown” and the values have been statistically determined from the test data (see Table I). The characteristic ultimate strength has been calculated according to the formula:

$$f_{uk} = f_{um} (1 - k_n \cdot v_{fu}); \quad f_{ud} = f_{um} (1 - k_{d,n} \cdot v_{fu}), \quad (1)$$

where $k_n = 1.74$ for 8 tests and $k_n = 1.77$ for 6 tests (in the case of arches) and “unknown” variation coefficient (see Annex D of EN 1990). The results have been separated to three individual sets. The characteristic values of ultimate strengths based on the principles above are listed in Table I.

TABLE I
VALUES OF STEEL ULTIMATE STRENGTH f_u

Tested members	Mean value f_{um} [MPa]	Standard deviation s_{fu} [MPa]	Variation coefficient v_{fu} [---]	Character. value f_{uk} [MPa]
Roof girders	567	21.1	0.037	530
Roof purlins	586	30.7	0.052	533
Arches	535	28.3	0.053	485

The results of the tests in situ shown the assumed material quality of steels used for the members of the roof structure of winter sports stadium in the city of Znojmo: material of all members of main roof girders and purlins is steel S 355 (with nominal ultimate strength of 510 MPa). Ultimate strengths of the material steel arches were a little lower. The results can be influenced by the higher dispersion of the values and by the lower number of tested locations. The combination of both these factors caused decreasing in the characteristic value of the tensile strength compared to the mean value by 50 MPa (the mean ultimate strength is 535 MPa and the characteristic ultimate strength is 485 MPa).

III. STRUCTURAL MEMBERS ACTUAL DIMENSIONS VERIFICATION – NON-DESTRUCTIVE DIAGNOSTICS IN SITU

Based on the client requirements, the non-destructive verification of the thicknesses of selected members of steel load-carrying roof structure has been performed [6]. Within this control the thickness of 22 significant locations of load-carrying structure has been measured using ultrasound method.

A. Description of Ultrasound Method

The measurement of the thickness of the wall of selected steel members of load-carrying structure was realized using the ultrasound defectoscopy apparatus named “PosiTector UTG”, which is the instrument with the simple manipulation,

high technical parameters and very high operating resistance. The measurement accuracy is ± 0.03 mm in the range from 1 mm to 125 mm. For the measurement the direct piezoelectric probe with the nominal frequency of 10 MHz; the impulse reflection method has been applied. The principle of the ultrasound method is based on the periodical mechanical oscillations, which are transmitted by the ultrasound probe to the tested material, where they are spreading by the constant speed. When the oscillations stumble upon the material non-homogeneity or upon the opposite side of tested subject, then they are reflected back with the lower energy; this process is recorded by ultrasound probe and after it is displayed on the screen of the evaluating apparatus. Time since sending ultrasound signal up to its returning back is proportional to the distance of non-homogeneity or of the opposite side. Ultrasound method is suitable for the measurement of thickness of steel structures and products.

The most accurate measurement is ensured by the probes with higher frequency, but for the usual probes with the nominal frequency of 5 MHz the reading error is about 0.3 mm. This error could be only eliminated by very high quality of material surface at the measured point, which is not usually real in practice. So it is important to measure the thickness in one point several times. Thus, the reading is more accurate, if the nominal frequency of the probe is higher. However, the usage of the probes with the higher frequency is limited by the material ability to conduct sound and by the quality of surface where the probe is touched. The thickness of the gap between the probe and material surface also very influences the accuracy of reading. On the other hand, the probes with the lower nominal frequency of $f = 4 \pm 5$ MHz are not so sensitive to the change of thickness of the gap between the probe and tested material, therefore they are mostly used for the thickness measuring. This is also in the case of our measuring, because the surface, to what the probe has been touched, was not perfectly planar. Each non-planarity of the surface under the probe is shown by four time higher error of reading. Thus, for the gap of 0.08 mm the error of reading is 0.32 mm, i.e. 0.4 mm after rounding to tenths. So that, in this case the read thickness is by 0.4 mm higher, and it can be only influenced by the better surface preparing, to obtain zero gap between the probe and material surface on the small area of the diameter of $\varnothing 10$ mm. The error of reading because of the surface non-planarity under the probe can be eliminated by the good preparation of material surface.

For the calibration of ultrasound apparatus two basic gauge blocks K1 and K2 (see the standards EN ISO 2400 [16] and EN ISO 7963 [17]) have been applied. The block K1 is made of steel with following parameters: the speed of the propagation of longitudinal waves is $c_L = 5\,920 \pm 30$ ms⁻¹, the speed of propagation of transverse waves is $c_T = 3\,255 \pm 20$ ms⁻¹, the attenuation is $\alpha = 0.05$ dBmm, the density is $\rho = 7.85 \cdot 10^3$ kgm⁻³. The gauge block K2 is also made of steel with the same acoustic properties as the first one. This second type of the gauge is preferred in for the measuring in situ, for its smaller dimensions and weight.

B. Results of Thicknesses Measurement

The measurement of cross-sections thicknesses have been performed in the same locations as the verification of tensile strength. In total 22 measured locations have been verified; only two locations on the upper flanges of the arches have not been tested.

Before measuring the colour layers have been removed and the surface has been aligned to be the smoothest (see Figs. 8 (a) or (b), for example). On each measuring base of the area of 30×30 mm, minimally 3 measurements of the wall thickness have been always performed and subsequently the mean values have been calculated. The results of the measurement of the thickness t of steel members are listed in Table II.

TABLE II
MEASURED THICKNESSES OF VERIFIED MEMBERS

Member type	Thickness mean value t_m [mm]
Roof girders	chords 7.57
	diagonals 3.56
Roof purlins	chords 3.48
	diagonals 2.79
Arches	flanges 10.46
	web 10.49

Using ultrasound device mentioned above, the thicknesses of the walls of selected statically important structural members of the roof structure and arch main girders of the winter sport stadium in the city of Znojmo have been verified. Applying 10 MHz ultrasound probe and precise preparation of the verified members surface the measuring accuracy of ± 0.3 mm has been achieved. Based on the results of ultrasound measurement and available documentation of the roof structural system, it can be deduced, that the actual thicknesses of particular selected members, which have been measured, correspond with the thicknesses mentioned in drawing documentation.

IV. OTHER RELATED EXAMPLES

A. Steel Ultimate Strength Determination and Evaluation – Non-Destructive Diagnostics in Situ

Similarly as in the paragraph II, steel ultimate strength has been determined in the case of steel roof structure of the winter sport stadium at the city of Jihlava [4], [5], [9].

This roof structure is composed of plane girders – garland truss main roof girders with ties, parabolic truss purlins and bracing system (see Fig. 10). The stadium was built at the turn of the 60th and 70th years of the 20th century. The width and length of the roof structure in the plan are 60×100 m.

According to the available documentation, the material of the purlins chords and bracings members (Zt) should be steel of the grade of 11 353 (the expected design ultimate strength is $f_{ud} = 350$ MPa), as well as steel of purlins diagonals (Vd). Further, according to that documentation, the material of main truss girders chords is the same steel of the grade of 11 523 ($f_{ud} = 520$ MPa), while the material of tube diagonals is steel 11 373 ($f_{ud} = 370$ MPa). For purlins, bracings and main girders suitable locations have been selected to be covered almost of

important members for the measurement (see Fig. 11). The following total numbers of locations have been measured: 7 locations on the chords (VP) and 7 locations on the diagonals (VT) of main girders, 6 locations on the chords (Ve) and 2 locations on the diagonals (Vd) of purlins and 3 locations on the members of bracings (Zt).



Fig. 10 Roof structure of winter sports stadium in Jihlava city

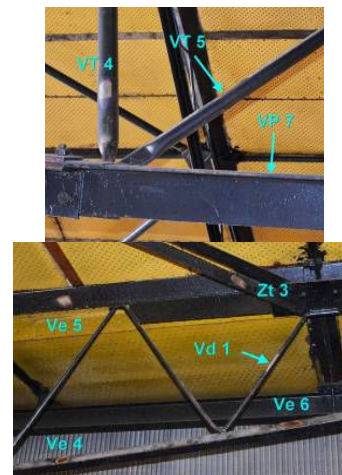


Fig. 11 Tested locations: main girders – VP, VT; purlins – Ve, Vd; bracings – Zt

Test results have been statistically evaluated according to [15] and the characteristic values of tensile strength have been determined (see Table III). Variation coefficient has been given $v_{fu} = 0.05$ (known) and fractile factors k_n have been taken from Annex D [15] for given test number.

TABLE III
VALUES OF STEEL ULTIMATE STRENGTH f_u

Tested members	Mean value f_{um} [MPa]	Standard deviation s_{fu} [MPa]	Variation coefficient v_{fu} [---]	Character value f_{uk} [MPa]
VP	583	35.0	0.05	521
VT	486	17.0	0.05	445
Ve, Zt	429	30.0	0.05	376
Vd	373	7.0	0.05	360

Material of the roof structure consisted of truss main girders, purlins and bracings can be classified as follows: steel of main girder chords can be classified like as current steel of

the grade of S 355 corresponding with steel class of 52, steel of main girder diagonals is current steel of the grade of S 235 corresponding with steel class of 37 being used in the period of structure realization; steel of purlins and bracings is current steel of the grade of S 235 corresponding with steel class 37.

B. Steel Yield and Ultimate Strengths Determination and Evaluation – Destructive Diagnostics

In the case of winter sport hall in Olomouc city [4], [7], [8], the mechanical properties of steel of the roof structure have been determined using the destructive method based on the tensile tests of the specimens manufactured from structural members taken from the existing structure.

This roof structure is the spatial truss grid consisting of steel circular tubes connected by spherical joints (see Fig. 12). The stadium was built in the 6th decade of the 20th century. The main dimensions of the roof truss grid are following: the width and length in the plan are 68×100 m, the grid height is 4 m.



Fig. 12 Roof structure of winter sports stadium in Olomouc city

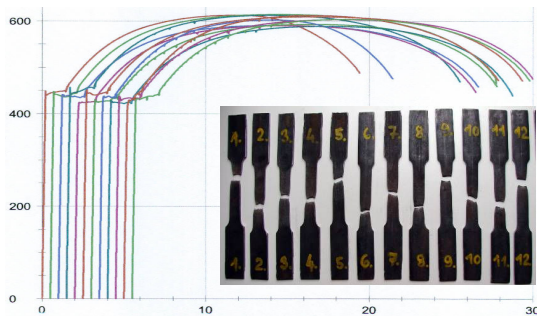


Fig. 13 Failed test specimens and corresponding tensile diagrams

TABLE IV
CHARACTERISTIC AND DESIGN VALUES: STEEL YIELD STRENGTH f_{yk}, f_{yd} ,
STEEL ULTIMATE STRENGTH f_{uk}, f_{ud}

Mean value	Standard deviation	Variation coefficient	Character. value	Design value
f_{ym} [MPa]	s_{fy} [MPa]	v_{fy} [---]	f_{yk} [MPa]	f_{yd} [MPa]
f_{um} [MPa]	s_{fu} [MPa]	v_{fu} [---]	f_{uk} [MPa]	f_{ud} [MPa]
438.8	10.5	0.05	393	368
602.8	10.0	0.05	559	506

Material tests of steel have been performed according to the methodology described in [14], [15]. For test specimens the part of the diagonal with the tube section of TR 102/3.5 approximately 800 mm long taken from the roof spatial truss

grid has been used. In total 12 test specimens for tensile tests have been manufactured from this structural member. Failed specimens and tensile diagrams are shown in Fig. 13.

Test results evaluation is oriented to the statistic elaboration of characteristic and design values [15] and subsequently to the determination of steel grade. Variation coefficients have been considered as “known” and the values have been taken as $v_{fy} = v_{fu} = 0.05$. Characteristic and design values of yield and ultimate strengths have been calculated as:

$$f_{yk} = f_{ym} (1 - k_n \cdot v_{fy}); \quad f_{yd} = f_{ym} (1 - k_{d,n} \cdot v_{fy}), \quad (2)$$

$$f_{uk} = f_{um} (1 - k_n \cdot v_{fu}); \quad f_{ud} = f_{um} (1 - k_{d,n} \cdot v_{fu}), \quad (3)$$

where $k_n = 1.188$ and $k_{d,n} = 1.712$ for 12 tests and variation coefficients “known” [15]. Based on characteristic and design values of steel yield and ultimate strengths statistically derived (see Table IV) including the test number consideration, it can be concluded: steel grade is S 355 (nominal yield strength of $f_y = 355$ MPa), which practically corresponds with steel series of 52 (design yield strength $f_{yd} = 360$ MPa, design ultimate strength $f_{ud} = 520$ MPa) used at the time period of the design and realization of the existing structure.

C. Structural Members Actual Dimensions Verification – Non-Destructive Diagnostics in Situ

The actual dimensions, i.e. thicknesses of tube structural members of steel roof structure of the winter sport hall at the city of Olomouc, have been determined similarly as in the paragraph III [5],[7],[8].

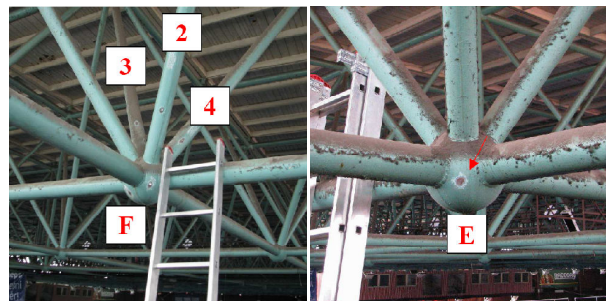


Fig. 14 Illustration of tested locations: diagonals and bottom chord spherical joints



Fig. 15 Illustration of structural members with tested locations prepared for subsequent measuring

The measurement of the thickness of selected steel tubes and spherical joints of the roof structure was realized using the ultrasound defectoscopy instrument “SONIC 1200 HR” by the company of “Staveley Instruments Inc.” (U.S.A.). The direct piezoelectric probe with the nominal frequency of 10 MHz has been used; the impulse reflection method, as well as in the case of the stadium in Znojmo city [6], has been applied. Within this verification, the thickness of 29 statically significant steel members in total has been measured (see Fig. 14, for illustration). The following members have been verified: (i) 13 diagonals – 7 tubes TR Ø102/4, 4 tubes TR Ø 127/6 and 2 tubes TR Ø 168/8; (ii) 4 bottom chord members – 2 tubes TR Ø 219/10 and 2 tubes TR Ø 219/14; (iii) 6 upper chord members – 2 tubes TR Ø 127/6, 2 tubes TR Ø 168/6 and 2 tubes TR Ø 219/10; (iv) 6 spherical joints.

On each verified member 3 measuring bases have been prepared (see illustration in Fig. 15). On each measuring base of the area of 30×30 mm, minimally 3 measurements of the thickness have been always performed and subsequently the mean values have been calculated. Applying 10 MHz ultrasound probe and precise preparation of the surface the measuring accuracy of ± 0.4 mm has been achieved. Based on the results of the measurement and available documentation of the roof structural system, it can be deducted, that the actual thicknesses of particular selected members, which have been measured, correspond with the thicknesses mentioned in drawing documentation.

TABLE V
MEASURED THICKNESSES OF VERIFIED MEMBERS

Member type		Thickness mean value t_m [mm]
Diagonals	TR Ø 102/4	3.56
	TR Ø 127/6	6.00
	TR Ø 168/8	7.85
Bottom chords	TR Ø 219/10	10.45
	TR Ø 219/14	14.05
	TR Ø 127/6	5.90
Upper chords	TR Ø 168/6	5.95
	TR Ø 219/10	10.00
Spherical joints	thickness 14 mm	14.00
	thickness 10 mm	9.50

V. CONCLUSION

Partial conclusions have been mentioned above – see paragraphs II. E, III. B, IV. A, IV. B and IV. C. The paper especially presents the usage of indirect non-destructive methods for the verification of geometrical and mechanical properties, when destructive methods cannot be applied.

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