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INVESTIGATION OF 18-19TH CENTURY MANUALLY FORGED IRON ELEMENTS OF BUILDING STRUCTURES

PhD Theses

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1. SUMMARY OF THE RESEARCH

1.1. Introduction

The use of traditional materials and technologies, and the preservation of the original structures gain more and more importance on the field of the monument preservation and conservation. In 1996 the document *„ Preservation and conservation principles of monuments and groups of buildings in Italy"* declares this principal on national level, preferring the maintenance of the original structure and use of original-equals technologies and materials in every possible case (Karták, 2002). The Cracowian Charter (2000) favours traditional technologies and the preservation of the unhurt entirety of the sculptures and building decoration elements as well (Karták, 2002).

Following these principals, we are searching for terms of the preservation in case of manually forged iron of building structures.

On the one hand there is little information on the conditions and on the exact quality of the material of the wrought iron building structures. Ties, balk irons, handrails etc. can be statically important, but non-visible failures of the material are hazardous points of the structure, that can cause serious damages soon or later. It is recommended to analyse the mechanical properties and materials characteristics of such structures.

On the other hand the subject of this research is an important part of the construction history. Wrought iron is the most frequently occurring material of the manually forged building structures and it determines an era as well. The wrought iron is a fibrous composite consists of slag "fibres" in a metal matrix (Gordon and Knopf 2005). The characteristics of this iron-carbon alloy have significantly influenced the technological development of the smithcraft, having a great effect on the material characteristics and on the load-bearing capacity of the manually forged historical iron structures.

In this study manually forged elements of building structures are analysed with different methods, and the factors and effects are investigated, that influence the quality of the material and the mechanical properties, such as the strength, the ductility or the load-bearing capacity, from the fabrication of the base material to the different effects on the built-in structural elements. The data of the mechanical properties from the literature are compared with new measured data. Because of its common use from the 19th century the strength has greater importance than other mechanical properties as it renders the most expansive comparison. The comparison of the values measured by different ways help us to prepare a non-destructive evaluation method for the manually forged elements building structures.

1.2. Summary of the literature

The base material used for the forging has an essential influence on the later quality of the manually forged object. There are two important cutting edges between periods of the fabrication and the use of the base material, the turn between the direct and the indirect metallurgical process, and the change of the use of wrought iron to ingot iron. The first is declared by the literature, the second is not mentioned directly. Processing the data of the different sources, this change can be assumed to the period from 1880 to 1900.

On the quality of historical iron materials, there are two kinds of information sources in the literature. On the one hand the literature of the 19th century, on the other hand the 20th century measured and published data of the 19th century wrought iron bridge materials. However the bridge elements were not produced manually and we have no information on the materials of the building structures produced in the 18th century.

The materials known from the literature are steels with nearly the same composition, under 0,3 m% carbon content, but those quality disperses wildly. The strength specification of the 19th century standards are 3-4 times higher, than the allowable tensile stresses for designed structures. However the lowest measured tensile strength values are near to the allowable ones. The question repeatedly is: What are the radically low strength values caused by?

According to professionals of the time in case of ingot iron the - during the production process not eliminated - contaminants were responsible for the varying quality. In case of wrought iron this more complicated question can be answered by the examination of manual forging.

American scientists found two factors responsible for rigidity, the contamination of phosphorus and the slag caught in the material reducing the load-bearing cross sectional area. In case of sudden effects these failures may cause brittle fracture (Gordon 2005). The contamination of phosphorus does not definitely accompanied by low strength values, as it is shown from the material tests of some collapsed bridges. Despite the adequate strength the materials were lacking of ductility (Gordon 2005). The extensive slag inclusions cause lacking of ductility and lacking of strength as well. This phenomenon is not rare by wrought iron material that partly explains the dispersion of the strength values. Further research need to be carried on to find other reasons.

Some 19th century examination pointed to the fact, that relation existed between the quality of the material and the technology of the forging (Ledebur 1890). Revealing how the procedure of manual forging influences the material quality, help us to detect the characteristics of historical iron structures.

2. THE AIMS OF THE RESEARCH

I. Determine the material characteristics of 18-19th century of manually forged elements building structures:

1. proving the assumption about the cutting edges of the change in use of wrought iron and ingot iron, and presenting a relating method

1) detecting the reasons of the radical dispersion (standard deviations) of the 18-19th century manually forged materials

2) comparing the 19th century mechanical properties of iron materials with new measured values

3) detecting the factors responsible for the inhomogeneity of the manually forged materials

II. Find an evaluation method for manually forged iron building structures:

5) defining a non-destructive analysis method with its limits for “in-situ” examination cases of manually forged iron building structures

3. RESEARCH METHODS

3.1. The samples

In the study manually forged – mainly 18th and 19th century – elements off building structures were investigated with different places of origin as samples, and S235JRG2 standard steel was used as reference material. Detailed information of the samples are presented in *Table 1*.

Table 1. The samples

	Sample	**Sign**	**Assumed age**	**Size**
1.	Forgách-Walla curia (Budapest, 2. district), window grill	F1	late 19th century	470x 13x 13 mm
2.	Gyula fortress, peaces of ties to hang brown meat	Gy1/1	18th century	1025x 65x 27 mm
3.		Gy1/2		970x 65x 25 mm
4.		Gy1/3		992x 65x 25 mm
5.	Hatvan, sugarworks, wall tie (looped back peace)	H1/1	1889	370x 50x 7 mm
6.	Hatvan, sugarworks, wall tie (perpendicular element)	H1/2		520x 55x 10 mm
7.	Hatvan, sugarworks, wall tie (medium peace)	H1/3		983x 11x 60 mm
8.	gate hinge with unknown origin (straight, decorated)	ie1	18th century	3x 35-40 mm
9.	Máriabesnyő (Gödöllő), roman catholic parish church, altar screen element	M1/1	1768-71	630x 28x 8 mm
10.		M1/2		435x 27x 8 mm
11.	Pilis, Lutheran church, gate hinge (cross-shaped, decorated)	P1	1784	360x 35x 3 mm and 200x 35x 3 mm
12.	Sándor-palace (Budapest, I. district), wall tie	Sp1	1805	140x 31x 11 mm
13.	Zsámbék, late Zichy-castle, balk iron (looped element, hooked)	Zs1/1	round 1905	l=810 mm d=24 mm (hook: 110 mm)
14.	Zsámbék, late Zichy-castle, balk iron (perpendicular element)	Zs1/2		l=410 d=24 mm
15.	Zsámbék, late Zichy-castle, balk iron arch tie	Zs2/1	1710	850x 25x 25 mm
16.		Zs2/2		839x 25x 25 mm
17.	S235JRG2 reference material	U1	2004	19x 19 mm steel bars

3.2. Investigations

On the one hand the material characteristics, the mechanical properties and the failures of the 18-19th century elements of building structures were investigated, on the other hand during the procedures of manual forging the change of the mechanical properties of modern material samples were examined in this study.

Tensile strength and ductility was determined with standard tensile tests. Preparing a non-destructive "in-situ" investigation method, hardness (L_D value) was measured with Equotip-2 mobile digital hardometer on the surface of the samples.

For the comparison of the different examination methods prism-shaped test-pieces were taken from the middle of the samples. On the surface of these prismatic test-pieces – constituted an intermediate plane of the original samples – hardness values were measured with Equotip-2 mobile digital hardometer and a manual Brinell-hardometer, the so called Poldi hammer. Having finished the hardness tests, standard test-pieces were taken from the prismatic samples for tensile tests. The results of the tensile tests were compared with the strength values estimated from the results of the hardness tests.

Gaining realistic information about the load-bearing capacity of the structures, on pieces of the samples hole-cross-sectional tensile tests were carried out.

The test methods used usually for homogeneous steels – with adequate circumspection – are applicable for getting information about the quality and actual condition of the inhomogeneous material of the 18-19th century manually forged building structures.

The test of new (modern) materials aimed the determination of the changes of mechanical properties during the procedures of manual forging.

The metallographical, X-ray and back-wall echo ultrasonic tests determined the type of the base-material (wrought iron or ingot iron), and revealed the inner structure and the failures of the samples.

3.3. The measured parameters

The data measured, calculated and estimated by various methods is summarised in *Table 2.*

Table 2. The data obtained by various methods

				1.	2.	3.	4.	5.	6.	7.
	Sign	**Sample**		**Tensile test[1]**			**From hardness test results estimated strength [N/mm^2]**			**Whole cross-sectional tensile tests (measured strength) [N/mm^2]**
				Yield stress [N/mm^2]	**Measured strength [N/mm^2]**	**Elongation [%]**	**Equotip, surface (average)**	**Equotip intermediate plane (average)**	**Poldi hammer**	
1.	Gy1	Gyula fortress, ties (wrought iron)	***aver.***	***231,4***	***354***	***36,0***	***497,6***	***365,7***	***346***	183
2.			***s. dev.***	***25,1***	***68,4***	***12,8***	***100,7***	***10,3***	***8***	
3.			min	191	269	23,3	386	357	338	
4.			max	261	524	40,5	702	377	354	
5.	H1	Hatvan, sugarworks, wall tie (ingot iron)	***aver.***	***294,6***	***391,4***	***26,3***	***447,9***	***380***	***398***	317
6.			***s. dev.***	***0,4***	***12,5***	***2,5***	***40,7***	***31,6***	***24,3***	
7.			min	294	383	23,7	386	347	370	
8.			max	295	406	28,7	499	410	414	
9.	ie1	gate hinge with unknown origin (wrought iron)	***aver.***	n.d.	n.d.	n.d.	***335,3***	n.d.	n.d.	n.d.
10.			***s. dev.***				***33,2***			
11.			min				300			
12.			max				367			
13.	M1	Máriabesnyő, altar screen element (wrought iron)	***aver.***	***373,1***	***465,3***	***18,8***	***303,8***	***437***	***415,3***	*n.d.*
14.			***s. dev.***	***26,8***	***23***	***0,4***	***25,3***	***10,6***	***48,2***	
15.			min	344	439	18,4	277	429	370	355
16.			max	397	482	19,1	347	449	466	390
17.	P1	Pilis, gate hinge (wrought iron)	***aver.***	n.d.	n.d.	n.d.	***281***	n.d.	n.d.	n.d.
18.	Sp1	Sándor-palace, wall tie (wrought iron)	***aver.***	n.d.	***339,8***	***24,7***	*n.d.*	n.d.	n.d.	n.d.
19.			***s. dev.***		***27,5***	***12***				
20.			min		308	11,2	n.d.			
21.			max		357	34,3				
22.	Zs1	Zsámbék, balk iron (ingot iron)	***aver.***	***286,8***	***364,8***	***38,8***	***350***	***340***	***346,***	n.d.
23.			***s. dev.***	***10,5***	***1,95***	***0,6***	***15,7***	***7***	***24,3***	
24.			min	278	363	38,4	327	333	330	
25.			max	298	367	39,5	360	347	374	
26.	Zs2	Zsámbék arch tie (wrought iron)	***aver.***	***179,3***	***303,2***	***36,8***	***497,4***	***393***	***380***	*n.d.*
27.			***s. dev.***	***13,6***	***8,6***	***4,8***	***30,6***	***17,3***	***22,7***	
28.			min	174	295	31,2	449	373	354	269
29.			max	195	312	39,6	549	403	396	384
30.	U1	S235JRG2 reference-material	***aver.***	***284,1***	***422,6***	***36,5***	n.d.	***409,7***	***383,3***	n.d.
31.			***s. dev.***	***9,1***	***1,86***	***0,4***		***23,1***	***8,3***	
32.			min	275	421	36,2		393	374	
33.			max	293	425	36,9		436	390	

n. d.=no data; s. dev.=standard deviation; aver.=average

4. NEW SCIENTIFIC RESULTS

In this chapter the theses are typeset with cursive, the explanations are typeset with normal characters.

1. Thesis: *In consideration of the historical processing of metallurgy, building structures and structural elements it can be declared, that the manually forged building structures in Hungary were manufactured from wrought iron before 1880 and ingot iron after 1910. Between 1880 and 1910 both materials were used.*

Relying upon the results of our investigations the age of manually forged elements of building structures and the application of different materials can be determined by X-ray and back-wall echo analysis.

The strength of the material used for manually forged iron structural elements strongly influenced by the type of the base material (wrought iron or ingot iron). It is possible to reveal the type of the iron with X-ray or back-wall echo ultrasonic tests. The inhomogeneous structure of the material with slag stringers in the metal matrix means wrought iron, the homogeneous material structure means ingot iron.

Studying the literature it can be stated, that from the beginning of the 18th century to the 1830-ies the iron used for building structures was wrought iron produced by direct metallurgical technology or refined from crude iron (indirect method). Between the 1830-ies and the 1850-ies the new puddle iron technology spread worldwide (Remport, 1995).

The further developments of the iron-industry (1856 Bessemer process, 1865 Siemens-Martin process, 1879 basic converter process) up to the middle of the 19th century resulted the production of the higher carbon containing ingot steel, and some years later the ingot iron (mild steel).

The first Bessemer converter in Hungary was commissioned in Resica in the year 1866. From 1876 a Martin-furnance operated here as well (Edvi, 1900). The first basic Bessemer-converters applied to the production of materials for forging were commissioned in Hungary in the 1880's. With this new procedure the disadvantageous phosphorus was eliminated. In

Salgótarján the earlier puddle-furnaces were changed to basic Bessemer-converters in 1883, the ironworks of Zolyómrező in 1886, the one in Resica in 1889 were equipped with basic Martin-furnaces (Maurer, 1892).

The change of the applied material of the structural elements from wrought iron to ingot iron was fulfilled slowly. The application of the bloomery (wrought) iron was driven back to the 19th century in middle-Europe, but puddled and refined wrought iron types were available as construction material further on.

Round 1870 - in consequence of the technical level of the iron-industry - ingot iron (mild steel) still not appeared, only ingot steel (with relative higher carbon content) was produced (Ledebur, 1890). From the 1880-ies wrought iron progressively lost importance, while ingot iron gained more and more.

Round 1890 the two kinds of iron were used approximately in the same amount as construction material (Ledebur, 1890). The 1890 edition of the *Breymann Baukonstrutionslehre* reported the competition of the two materials on the market (Breymann, 1890).

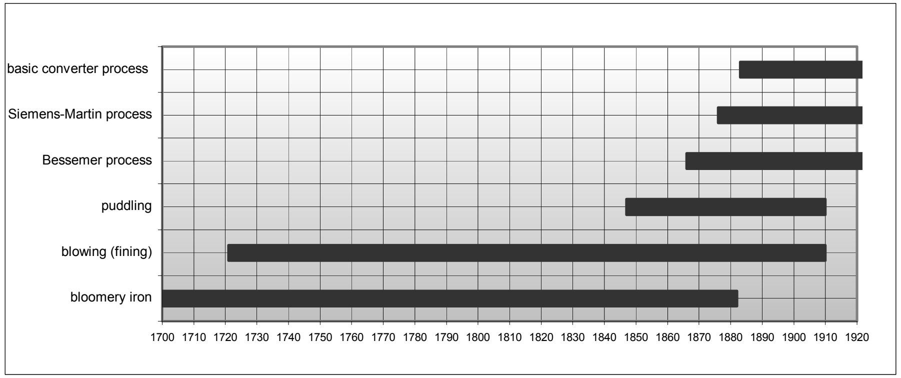


Figure 1. Fabrication methods of iron in the 18-19th century Hungary

The final lost of importance of wrought iron was in the first decade of the 20th century. It can be proved by the literature of construction industry of the era. The 1902 edition of the *Breymann Baukonstrutionslehre* mentions only ingot iron as construction material, no wrought iron (Breymann, 1902). There are few differences between the two editions. If this information had to be rewritten there should be important changes on the market of construction materials. In 1900 Edvi Illés Aladár also reported in his book about the radical decrease of the number of refining hearths and puddling furnaces (Edvi, 1900). The changes of the methods of iron production are shown in *Figure 1*.

The building data of the iron bridges show similar result. According to the investigation of some researchers in 1958-59, the material of the Hungarian iron railway bridges were prepared from wrought iron before 1890, and ingot iron after 1900 (Nemeskéri, 1958).

The hypothesis made relying upon the data of the literature was proved by the results of the X-ray and metallographical analysis of the samples of structural elements as well (*Table 3.*). The samples originated from buildings constructed round 1900 was shown homogeneous material structure that is characterises ingot iron, the ones made before 1880 were made of wrought iron.

In most cases wrought iron is characterised by the way of its production. The materials with different inner structure can be distinguished on the X-ray image that allows to making difference between variant materials.

Table 3. Structure of material of the examined samples according to the X-ray and ultrasonic tests

Sample	**Sign**	**Assumed age**	**Structure of material according to the X-ray and ultrasonic tests**
Gyula, fortress - ties	Gy1	18^{th} century	material structure with the characteristics of wrought iron
Zsámbék – arch tie	Zs2	1710	
Máriabesnyő – altar screen element	M1	1768-71	
Pilis – gate hinge	P1	1784	
Sándor-palace – wall tie	Sp1	1806	
Hatvan, sugarworks – wall tie	H1	1889	homogeneous material structure of ingot iron
Zsámbék – balk iron	Zs1	1905k.	
Forgách-Walla curia – window grill	F1	late19^{th} century	

2. Thesis: *Relying upon the result of the investigations on manually forged elements of building structures, in consequence of the effects of the forging procedures caused by the forming work and the changing of the carbon content, the quality of the material near the surface of the sample differing from the quality of the inner sectors.*

The metallogrphical tests showed the variation of the material structure in both cases of the samples originating from the Gyula fortress and the Sándor-palace. The carbon content of the coating layer near the surface in one of the cases became higher (carbonisation) (*Fig. 2.*) in the other case it became lower (decarbonisation) (*Fig. 3.*), than it was in the inner part of the samples. Accordingly the hardness value measured on the surface of the sample originates from the Sándor-palace were much lower ($L_{Dátl.}$=222), than it could be expected (L_D~320-355) relying upon the strength values (308-357 N/mm^2). The strength values of the sample originates from the Gyula fortress has significant standard deviation values (s=68,4 N/mm^2) at the tensile tests, however some of the strength values estimated from the harness values (L_D=490) measured on the surface of the sample are outliers (702 N/mm^2)

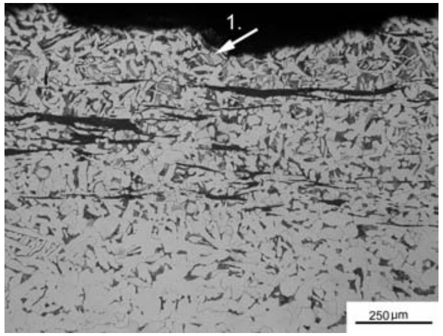


Figure 2. Carbonised part near the surface (Gyula, fortress)

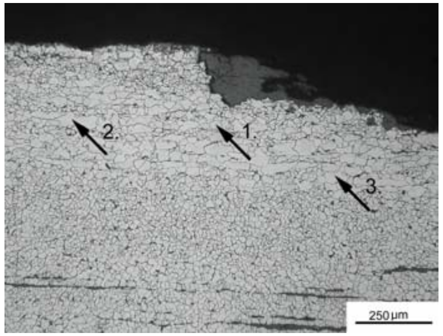


Figure 3. Decarbonised surface (Sándor-palace)

The difference of the material quality near the surface is also proved by the comparison of the hardness test values measured on the surface and on the inner plane with Equotip-2 mobile digital hardometer. In case of surface hardness tests, the test values measured close to each other showed little difference, but the test values originating from various parts of the surface of the same sample showed significant differences. The test values on intermediate planes, originating form various parts of the same sample showed much less differences (*Table 2, 4-5. column; Figure 4.*).

Comparing the surface and the intermediate plane hardness tests, there was no correlation (r=-0,1) between the values (*Figure 6.*). There was also no linear correlation between the strength values measured by tensile tests and the ones estimated from the hardness tests on the surface of the samples, while between the strength values measured by tensile tests and the ones estimated from the intermediate plane hardness tests strong correlation (r=0,86) could be found.

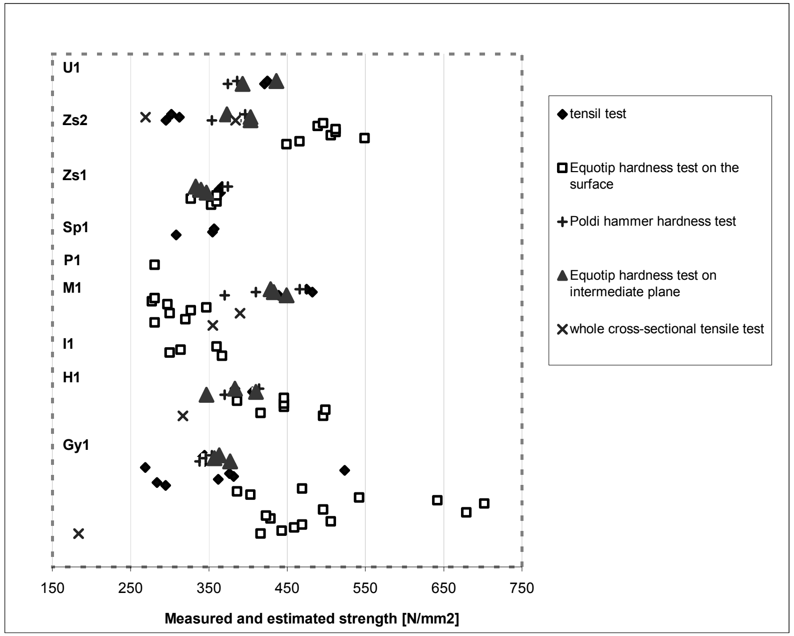


Figure 4. Strength data obtained by various methods

3. Thesis: *In case of the manually forged elements of building structures the standard deviation of the strength values of a sample can be as high as the standard deviation of all the values measured on different samples.*

Processing the strength data of 19th century wrought iron bridge materials (49 data), the average of the values is 366 N/mm^2, the standard deviation is s=32 N/mm^2. In case of 19th century wrought iron materials – used as base material for forging – the average of 21 data is 399 N/mm^2, the standard deviation is s=110 N/mm^2.

The measured and estimated strength values are presented in *Table 2.* The test results of the samples originating from the Gyula fortress particularly remarkable. The average of the tensile test results is 354 N/mm^2, the standard deviation is s=68 N/mm^2. The average of the strength values estimated from the Equotip-2 hardness test results is 498 N/mm^2, the standard deviation is s=101 N/mm^2. Consequently the standard deviation of the samples of Gyula is nearly equivalent with the standard deviation of the values of different materials collected from the professional literature (*Figure 5.*).

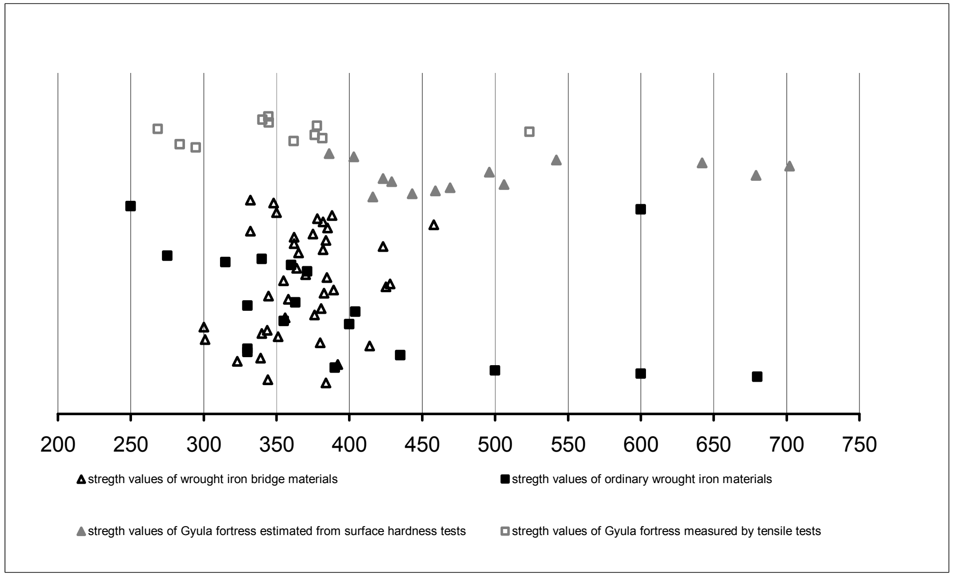


Figure 5. The strength values from the literature comparing with own test results

4. Thesis: *According to different investigations the inhomogeneity influences the load-bearing capacity of the material of manually forged elements of building structures - besides the quality of the base material – in case of wrought iron resulted by the weakening of the material in consequence of the penetrating corrosion at the slag inclusions connected to the surface and the local changes caused by the working process. In case of ingot iron the inhomogeneity influences the load-bearing capacity caused by the local changes of the working process only*

The inhomogenety of manually forged iron is resulted by three factors. One of the factor is the production of the material. It is characteristic at bloomery irons, but in consequence of the subsequent use, the fagotting of different materials (generating larger cross-sections from smaller pieces of iron by longitudinal welding) and the slag inclusions inhomogeneity of the base material characterises every kind of wrought iron. The phenomenon is known from the literature.

The second factor causing inhomogeneity is the penetrating corrosion caused by the slag inclusions connected to the surface. This effect was recognised by the whole cross-sectional tensile test of the sample originates from the Gyula fortress. The X-ray tests showed slag inclusions with connection to the surface at the place of the later fracture. The corrosion is seen on the fractured surface was deeply penetrated into the middle of the structure. Hence the strength value of the whole cross-sectional tensile test (183 N/mm^2) was much lower as the minimum strength measured by normal tensile test on standard test pieces of the same sample (284 N/mm^2).

The third factor causing inhomogeneity is the working process of the forging. On the one hand the connection of the work piece with the fire of the smith hearth, on the other hand the effect of the hot and cold forming influences the mechanical properties of the material. In case of hot forming the hardening is caused by the working, the softening is caused by recrystallization on the adequate temperature (Verő-Káldor, 1977). The hot-forming processes of the manual forging are made under unregulated circumstances. In consequence of this fact the hot-forming processes can become off partly out of the temperature range necessary for hot forming (not in austenite phase), and the hot forming accompanied by the cold-forming–like distortion of the material structure. These are usually small-scaled distortions, but those result detectable changes of the strength and the ductility. This can be concluded from the results of some 19th century study (*Table 4.*), and the change of the strength and elongation values was experienced at the tensile tests of the upset and stretched samples of the *U1* material (*Table 5.*). The characteristics of the samples produced in ironworks are influenced by the last phase of the forming work (Verő-Káldor, 1977), that results smaller changes of the mechanical properties, like in case of manual forging, where the forming processes has an effect only on the particular formed part of the sample. During the production of the manually forged elements of building structures, the work-piece is only

partly reheated, so the effects of the earlier processes remained, superimposed or weakening each other, herby changing unevenly the mechanical properties.

Table 4. The effect of the hot-working on the strength and elongation

Rate of working [%]		Strength [N/mm^2]	Elongation* [%]	Reduction in area [%]	Reference
1. probe	65	481	22	43	(Ledebur, 1890)
	85	510	21	44	
2. probe	65	486	21	43	
	90	520	20	42	
3. probe	65	477	23	41	
	95	556	18	41	

*The elongation data applied for the whole length of the test specimen (that is not published).

Table 5. Mechanical properties of the material before and after manual forging

Sign	Sample	Measured yield stress [N/mm^2]	Measured tensile strength [N/mm^2]	Measured elongation [%]
U1	standard value	265	413	36,5
	state before forging	274,9-293,1	420,9-424,6	36,2-36,9
	stretched state	308,9-353,5	449,9-457,9	35,5-36,6
	upset state	259,3-268,4	441,9-445,7	34,5-34,9

The direct connection with the fire of the smith hearth is experienced at the metallographical tests (*Figure 2. and 3.*). The strength data estimated from the hardness tests measured on the surface and on the intermediate plane show no correlation (r=0,35) (Figure 5.).

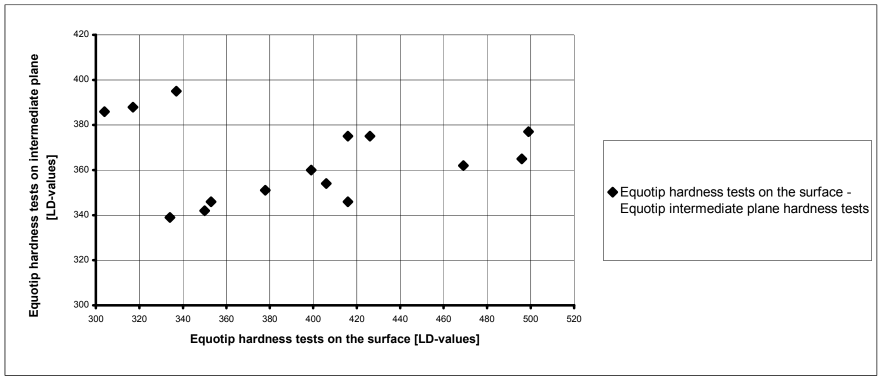


Figure 5. Searching for correlation between the strength values estimated from various harness tests

In consequence of these effects the mechanical properties measured on different locations of the same samples can wildly differ from each other, and the standard deviation value can be relatively high (*Table 2.*). The last one of the three factors appears in case of ingot iron base material as well.

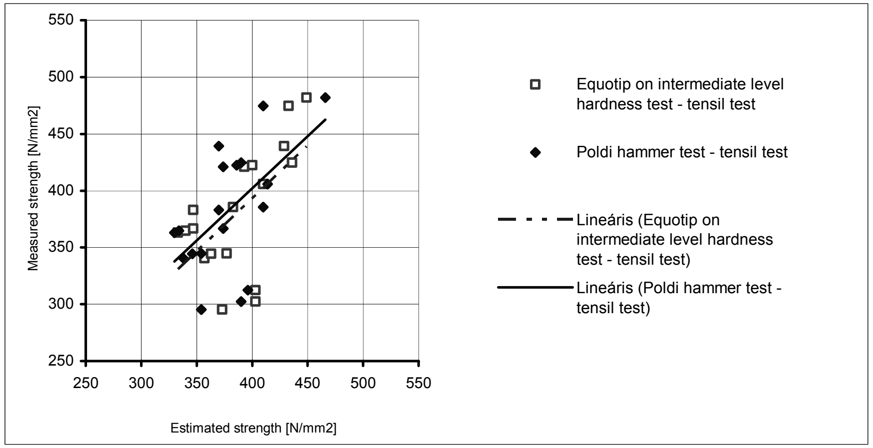
5. Thesis: *The inhomogeneity of the material of the manually forged elements of building structures significantly influences the measured values hence it is necessary to reveal the inhomogeneity causing factors and to evaluate the possible consequences of the state of the structures manufactured from such material. According to this, in case of manually forged elements of building structures, three exclusive cases can be distinguished:*

1. *If the material of the structure is homogeneous (ingot iron), the strength can be estimated from the harness test values with adequate circumspection.*
2. *If the material of the manually forged building structure element is wrought iron, the strength can not be adequately estimated, but if the material does not contain harmful contaminant materials (sulphur, phosphorus) in critical amount, the X-ray, and back-wall echo ultrasonic tests do not show any forge-welded joint or failure risking the load-bearing capacity (larger slag inclusions blocking the cross-sections) and the risk of deteriorating environment (phenomenon of penetrating corrosion) is not existing, than the structure is appropriate for the earlier existed and unmodified loads.*
3. *If the wrought iron structure contains forge-welded joints or hazardous material failures, the structure can be considered with reduced load-bearing capacity regarding to the amount and extension of the failures.*

The testing methods of steel structures are developed for testing homogeneous material samples. The material of the manually forged building structures is not homogenous. On the one hand in many cases the base material of the structural elements is inhomogeneous wrought iron, on the other hand the heating and forming processes of the forging cause several kind of inhomogeneity (hardening, carbonisation, decarbonisation) accompanied by differences of the material properties, in the different locations of the sample (*Table 2.*). These factors should be considered at the measurements and the evaluation process.

The type of the base material (ingot or wrought iron) and the places of the material failures can be revealed by X-ray and back-wall echo ultrasonic tests.

In case of ingot iron the lack of ductility is usually caused by sulphur or phosphorus contamination that can be detected by optical emission spectroscopy. The inhomogeneity of the material of manually forged elements of building structures in case of ingot iron caused by the working process, the strength of the sample can estimated from hardness test on well selected test spots of the sample. As it is already mentioned the hardness tests on the surface are not results of adequate information about the strength of the sample, but in case of ingot iron it is possible to prepare a spot a couple of millimeters under the surface, where it is possible to estimate characteristic strength values from the measured hardness values. The above statement proved by the correlation between the strength values at tensile tests and the strength values estimated from the hardness tests measured with Equotip-2 (r=0,86) and mobile Brinell (Poldi-hammer) (r=0,79) hardometers (*Figure 6.*). In case of homogeneous material the hardness test can be fulfilled on a spot that not influences the stability.



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igure 6. Correlation of the estimated and the measured strength

In case of wrought iron the lack of ductility can also be caused by slag inclusions reducing the area of the cross sections and the penetrating corrosion. All of these failures can be detected by the X-ray tests. If nothing refers to the above mentioned failures, the structures load-bearing capacity is appropriate for the earlier existing loads, although the strength of the material can not be estimated from the hardness tests in this case. Because of the inhomogeneity there is no exact relation between the mechanical properties of the different parts of the sample.

If a wrought iron structure's load-bearing capacity is reduced by forge-welded joints, corrosion or slag inclusions block the area of the cross sections, it is necessary to reveal the weakest cross section and to determine the toughness of the material. There is no general solution, because the decision about the future of the structure is influenced by the circumstances of the use (condition of the structure, loads, change of the loads etc.).

5. POSSIBILITIES OF PRACTICAL APPLICATION

In this study only a few samples were investigated, as a preliminary step ("pilot" program) of a larger volume research using more data and analysing these problems in details.

As a result of this study a new database is available about the material properties of the 18-19th century manually forged building structures that is a base of comparison for further researches.

The X-ray and back wall echo ultrasonic tests are everyday methods in other fields. Use of these methods for revealing the failures of manually forged elements of building structures, allows the preventive protection of the structures belonging to the architectural heritage.

It is important to clarify if a manually forged building structure of structural element serves as load-bearing structure or if it does have historical or artistic value.

Manually forged elements of load-bearing building structures

Investigating manually forged elements of load-bearing building structures more cases can be distinguished. The demands are different if a manually forged load-bearing building structure has an artistic character and historical value, if a load-bearing structural element has no artistic character, but the discharge of the structure change the appearance of the building, and if it can be discharged without varying the appearance of the building.

This new investigation method gives an opportunity for diagnose manually forged structures or structural elements (e.g. ties, wall ties, bulk irons). In accordance with the admitted principals of the monument protection the possible most elements of the original structure have to be preserved.

Taking into consideration the fact that the material itself does not last for ever, the possibilities of preservation are also limited. The practice of monument preservation aims to keep the building in good condition, and in order to lengthening the life-cycle of the building it is recommended to reveal and control the condition of the material of monuments.

In more European countries a monument-monitoring service system is working, and there would be a demand on such service in Hungary as well.

The new method presented here would give the opportunity to control the manually forged load-bearing building structures, that is a preventive assessment of the possible dangers, like bursting damage of arches. X-ray and complementary tests (e.g. spectroscopic, ultrasonic and hardness tests) help to determine the condition of the structure, to estimate the strength of the material and to reveal the hidden failures, that can cause rigidity and the deterioration of the structure. This method could be used for the preventive protection of the manually forged iron building structures and the whole building.

If the structure – according to the investigation – is dangerous or irreparable, the discharge of the old structure is necessary. If it does not influence the load-bearing capacity of the building negatively it is preferred to use a new structure corresponding to the original, particularly if the character of the structure closely connected with the appearance of the monument. If the stability of the monument requires, or if the application of a modern structure does not influence the character of the building, new (to the original not corresponding) salvation can be applied as well.

Manually forged iron building structures and structural elements with artistic character

Some manually forged iron building structure or structural element with artistic character are not load-bearing one (e.g. handrails, gates, fences), but there are some demand on their load-bearing capacity. In this case it is recommended to proceed like in case of load-bearing structures.

In case of manually forged irons with artistic character the results of this research can be used on one other field. If the extent of the damage made it necessary for repairing these structures, the simply change of the original elements has been the admitted method for a long time.

The X-ray tests allow to reveal the former reparations of manually forged structural elements. This can be useful at the case, if the reparation has not been documented, and the history of the structure is matter of research.

The reparation actions can be easily followed, if ingot iron was used instead of a former wrought iron element (if the reparation was applied after 1880).

The different kinds of wrought iron (with different inner structure) also can be distinguished by this method. Although in this case all the circumstances should be taken into

consideration, because different inner structure of wrought iron does not consequently means different time of manufacturing. The method will give authentic result only if the investigation of the historical background is also investigated.

6. POSSIBILE CONTINUATION OF THE RESEARCH

The extension of the measurements with investigation on more samples is an obvious continuation of the research.

In this study the relations between the material and technology was analysed. The analysis of the relation between the technology and formal appearance would be expedient as well.

The cases when a manually forged building structure element does not fulfil the requirements are not dealt with in full depth in this study. This problem partly belongs to the reconstruction of structures and partly to the restoration exercises of smithcraft. Some of the relating questions could be answered by further research.

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