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REPAIRING AND REINFORCING LOAD BEARING ELEMENTS OF TIMBER STRUCTURES, DAMAGED BY BIO-DEGRADATION

P. Agel*, A. Lokaj**

Abstract: *Many historical timber constructions are damaged by biodegradation especially by ligniperdous insect. Sometimes the degradation is so high, that some construction members need to be replaced or reinforced. In common buildings we can use many known methods to repair damage. But in historical buildings we must mind visual aspect and Bureau of care of historical monuments. According to their demands we are not able to replace whole members also repaired timber element must look like original members. This article describes the method which can be used in such cases.*

Keywords: ***reinforcing, timber, bio-degradation, structure, element***

1. Introduction

At the reconstructions and repairs of historical roof structures it is often necessary to deals with load bearing members damaged by biodegradation. Best way to repair such structure will be to replace whole damaged member. This is often against position of Bureau of care of historical monument which we must mind when dealing with historical buildings. Main goal of the bureau is to maintain visual (historical) look of the construction.

One of many solutions of this situation is to remove damaged truss reinforce it and return back to its original place. In part 2 of the article there is detailed description of repair technology which maintains member look and its former strength.

For reliable design of load bearing member repairs it is to be to set construction principles which are based on calculation procedures and methods proved by laboratory test on appropriate samples.

2. Technology description

Method of reinforcing timber members using wooden core with higher strength can be used only for timber damaged by ligniperdous insect. Ligniperdous bugs do not cause change of wood structure as do wood-decaying funguses. Insects cause decrease of wood mass based on classical foundations (Reinprecht, 2008). If the stage of decay is not high it is possible to use reinforcing method.

In common practice it is easy to take out damaged members and replace them with new members of to repair it according to one of already known methods such as addition of timber liner, glass or carbon fibres liner etc. These repairs are often explicit so they can´t be used in historical building.

Reinforcing technology proces:

1. Survey and localization of damaged members in
2. Complete inspection and set up of stage and kind of
3. Temporary support of construction

* Ing. Petr Agel: Faculty of Civil engineering, Technical Univesity of Ostrava. Ludvika Podeste 1875/17, 708 33 Ostrava – Poruba, e-mail: petr.agel@vsb.cz
** doc. Ing. Antonín Lokaj, Ph.D.: Faculty of Civil engineering, Technical Univesity of Ostrava. Ludvika Podeste 1875/17, 708 33 Ostrava – Poruba, e-mail: antonin.lokaj@vsb.cz

4. Extraction of damaged members from construction and analysis of material characterization by not destructive methods (ultrasound scan, PILODYN etc.)
5. Design and analysis of reinforcement
6. Transport of damaged members from building site to carpenter shop
7. Timber treatment by microwaves, high temperature of another insekticide method
8. Cutting off the slots for core – place nad dimensions depends on stage of damage and kind of stress
9. Glue up the core made of timber of similar monture and higher strength (f.e. oak or beech) Fig. 1
10. Carpentry finish
11. Historical imitation coat – varnish paint with addition of dust etc.
12. Return of reinforced member to its originál place and its fixing into construction

Fig. 1: Timber members damaged by ligniperdous insect with embed reinforcing core

3. Advantages and disadvantages of reinforcing members with timber core

Indisputable advantage of reinforcing members damaged by ligniperdous insect is the fact that damaged member and reinforcing core are made of materials with similar physical characteristics. This eliminate the problems which are common for members reinforced with steel bars, carbon or glass fibers. In theses composites different volume changes can happen (thermal and moisture changes). Also the ratio between tensile strength and modulus of elasticity is different in comparison to the timber.

Another advantages:

- Glued joint between timber and core is almost rigid
- When the core is inside the cross section it is possible to maintain original look
- Fire endurance is not decreased as in another types of reinforcing
- Good availability of material and low cost of repairs

Disadvantage of this method is certainly higher work difficulty. Method is destined to historical building so it is possible to declare that time loss is acceptable according to character of repair.

4. Laboratory tests of members damaged by ligniperdous insect

For load bearing capacity tests of timber members damaged by ligniperdous insects reinforced by wooden core there were eight laboratory samples manufactured. Dimensions and strength of these members are mentioned in Tab.1. Different cross section of samples is stated in Fig.2.

Tab. 1: Timber members damaged by ligniperdous insect with embedded reinforcing core

(length of members is l=3,0 m)

	Measured valuables					Calculated valuables						
	h (mm)	h_{avg} (mm)	b (mm)	b_{avg} (mm)	m (kg)	V_{avg} (m^3)	ρ_{avg} (kg/m^3)	A_{avg} (mm^2)	$W_{y,avg}$ (mm^3)	$f_{m,d}$(Mpa)	M_{max} (kNm)	$P_{4,b}$(kN)
	145,3		113,6									
1	145,4	144,00	118,9	116,90	23,30	0,051	459,85	16833,60	404006,40	18,46	7,46	17,2
	142,4		118,2									
	133,7		112,2									
2	136,1	136,00	116	113,97	19,20	0,047	411,55	15499,47	351321,24	18,46	6,49	15,6
	139,0		113,7									
	169,0		129,5									
3	169,0	168,00	131,8	131,50	31,70	0,067	470,46	22092,00	618576,00	18,46	11,42	24,5
	166,0		133,2									
	137,3		108,9									
4	133,4	132,00	109	107,90	19,50	0,043	454,85	14242,80	313341,60	18,46	5,78	14,5
	123,9		105,8									
	145,7		135									
5	142,6	143,00	136,5	134,07	21,80	0,058	372,82	19171,53	456921,54	18,46	8,44	19,5
	140,3		130,7									
	129,7		123,8									
6	134,1	133,00	119,7	123,03	24,20	0,049	492,97	16363,43	362722,77	18,46	6,70	16,7
	134,0		125,6									
	153,0		122,3									
7	155,0	153,00	128,6	127,37	26,30	0,059	448,38	19487,10	496921,05	18,46	9,17	19,7
	150,0		131,2									
	155,0		123,6									
8	165,0	165,00	125,1	124,53	30,20	0,062	488,28	20548,00	565070,00	18,46	10,43	22,4
	175,0		124,9									

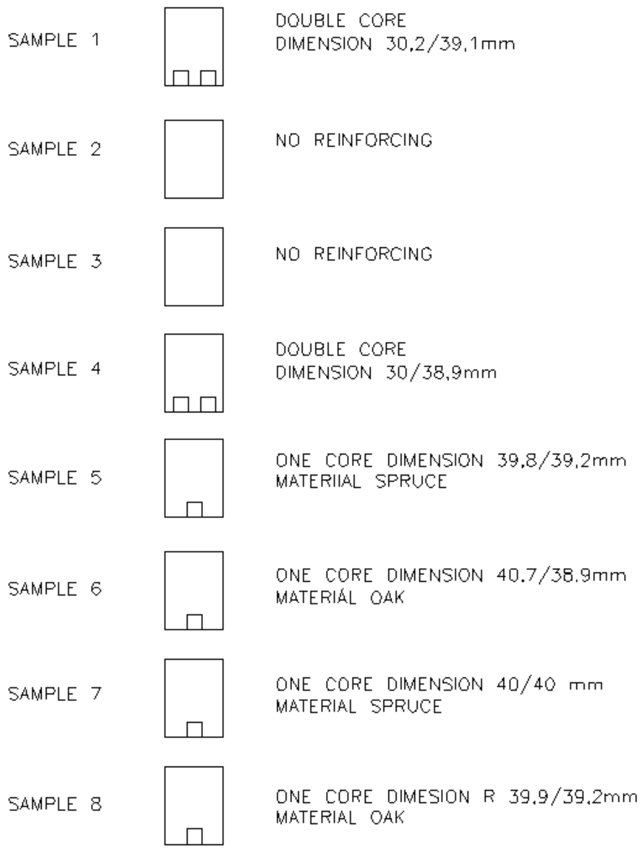


Fig. 2: Cross sections of laboratory samples

Laboratory tests were performed on presser line 600 *kN* (Fig.3). Samples were set on hinge supports and loaded in thirds of span with point force (Fig.5) using similar work progress as described in paper (Lokaj et al., 2011) published in Transactions of VŠB-Technical University of Ostrava . For comparison with analytic and numerical model (FEM) there was chosen sample nr. 8 the member with one inserted oak core (40x40 mm) at the bottom of the cross section.

Fig. 3: Test of load bearing capacity in TZÚS Ostrava

Beams with dimension 30x50x1000 *mm* were cut off the end parts of the samples after the four point bending test. Estimation of stage of degradation by ligniperdous insect was done on these beams

(Tab.3).These beams were also used for load bearing capacity bending test and the test to find out modulus of elasticity on the EU 40 press in the FAST laboratory (Tab.2).

Tab. 2: Modulus of elasticity

Sample	b(mm)	h(mm)	l(mm)	W(%)	ρ(kg/m^3)	Length 10 L (mm)	pilodyn průměr	F40	W40	**E (MPa)**	**E_{avg}(MPa)**
1a	30,20	51,60	98,40	10,00	4336,81	31,50	17,67	0,62	2,91	**14746,63**	
1b	30,07	50,80	98,30	10,00	4641,75	50,05	18,00	0,44	4,01	**7929,07**	
1c	29,50	49,08	99,60	10,00	4597,56	32,94	13,00	1,32	6,52	**16478,50**	**15260,0**
1d	30,50	49,90	99,70	10,00	4527,53	47,20	14,67	0,63	3,25	**14544,45**	
1e	30,12	48,30	99,60	10,00	4713,67	27,70	17,33	1,06	4,86	**18215,05**	
1f	30,60	47,70	99,60	10,00	4663,70	32,30	14,33	1,18	5,12	**19646,45**	
4a	28,68	48,98	1001,00	10,00	434,52	42,30	15,67	0,99	6,35	**13130,06**	
4b	28,33	47,24	1003,00	10,00	396,33	68,00	14,33	0,40	3,42	**11076,95**	
4c	30,00	49,51	1004,00	10,00	425,82	38,63	13,33	0,42	3,31	**9901,97**	**10161,3**
4d	30,55	48,88	998,00	10,00	447,56	27,18	15,67	0,78	6,30	**9846,99**	
4e	31,14	49,16	998,00	10,00	391,42	47,24	15,67	0,32	3,54	**6850,56**	
5a	30,05	49,50	995,00	10,00	348,64	28,57	18,33	0,80	7,50	**8356,54**	**8356,5**
6a	28,84	48,95	992,00	10,00	461,29	19,22	12,00	1,70	7,10	**20088,71**	**26610,0**
6b	30,33	48,27	992,00	10,00	449,63	16,90	13,67	1,35	8,60	**13042,55**	
8a	28,23	50,28	99,80	10,10	4616,80	27,06	15,33	0,92	4,26	**17200,54**	
8b	29,66	49,37	100,30	10,70	4507,37	26,08	12,33	2,33	7,25	**25576,20**	
8c	29,33	48,41	99,60	10,80	4787,21	27,76	10,67	1,35	6,27	**18344,25**	
8d	29,88	48,59	99,40	13,50	4677,24	25,50	11,33	1,50	5,79	**21433,67**	**20601,7**
8e	30,21	49,37	99,60	10,10	4335,24	37,67	13,00	1,26	4,95	**19888,58**	
8f	30,27	49,60	99,90	10,00	4333,65	29,56	15,00	1,56	5,67	**21167,19**	
J smrk	39,00	39,80	99,40	10,00	5424,90	25,81	11,00	2,15	10,62	**22982,51**	**22982,5**
J(1) dub	31,08	38,20	97,50	11,70	5831,16	24,50	9,20	1,18	7,79	**24341,70**	**24341,7**

Stage of damage by ligniperdous insect was calculated as a ratio of volume weight of part of healthy timber against the volume weight in the part with major number of insect fly out holes.

Tab. 3: Comparison of volume weight of damaged part of sample and healthy part

	Damaged timber					Healthy timber				
Sample	lenght (mm)	width (mm)	height (mm)	weight (kg)	volume weight (kg/m^3)	lenght (mm)	width (mm)	height (mm)	weight (kg)	volume weight (kg/m^3)
1a	306,31	29,82	49,70	199,40	**439,24**	32,53	29,03	48,34	21,10	**462,22**
1b	141,40	29,05	49,03	114,20	**567,03**	35,72	28,67	48,37	29,50	**595,53**
1c	200,02	30,27	50,07	135,20	**445,98**	28,30	29,30	49,40	16,80	**410,14**
1d	165,90	29,31	48,10	107,50	**459,62**	77,87	28,90	47,34	50,20	**471,20**
1e	104,00	30,07	50,04	73,00	**466,49**	73,04	29,56	48,80	45,20	**429,00**
1f	225,95	30,06	50,36	142,10	**415,44**	97,75	30,32	48,41	61,80	**430,73**
4a	65,15	29,08	48,59	38,00	**412,79**	64,85	28,73	49,44	38,60	**419,05**
4b	234,18	28,04	48,04	114,90	**364,24**	62,20	30,25	49,73	31,40	**335,58**
4c	162,64	29,78	49,02	102,10	**430,03**	46,92	22,40	46,20	23,30	**479,85**
4d	204,00	27,18	46,10	117,80	**460,86**	117,53	29,15	49,14	80,30	**476,97**
4e	174,16	30,30	50,44	96,30	**361,79**	44,08	30,40	49,30	35,00	**529,79**
5a	32,48	29,52	46,40	15,50	**348,40**	134,40	30,33	49,50	65,70	**325,60**
6a	73,06	27,70	49,11	44,30	**445,73**	138,17	30,32	50,02	94,20	**449,54**
6b	308,15	30,12	49,09	221,10	**485,26**	114,57	30,28	49,85	79,00	**456,81**
8a	182,67	29,61	50,20	121,00	**445,63**	66,53	30,11	50,27	42,10	**418,07**
8b	120,09	16,51	29,37	20,60	**353,76**	131,30	29,40	40,40	69,10	**443,08**
8c	204,14	29,56	48,57	135,70	**463,00**	27,85	30,48	48,69	19,20	**464,54**
8d	127,34	30,34	49,79	83,50	**434,07**	164,10	29,82	48,96	109,20	**455,79**
8e	75,90	30,03	48,12	48,40	**441,29**	128,50	29,41	47,80	79,50	**440,09**
8f	123,40	30,47	49,54	84,30	**452,57**	128,10	29,71	49,30	83,30	**443,96**

Stage of damage mentioned above si probably inaccurate indicator of real state of timber because it depends on density which can be quite different in two parts of relatively small sample (different density of annual rings, presence of knags). This different density in one piece of timber can cause paradox of negative value of stage of damage.

Five percent quantile of modulus of elasticity $E_{0,05}$ = 6100 *MPa* was calculated from histogram on Fig.6. This value approximately matches modulus of elasticity of timber class C18. For analytic calculation and for numerical model were used values from the tests.

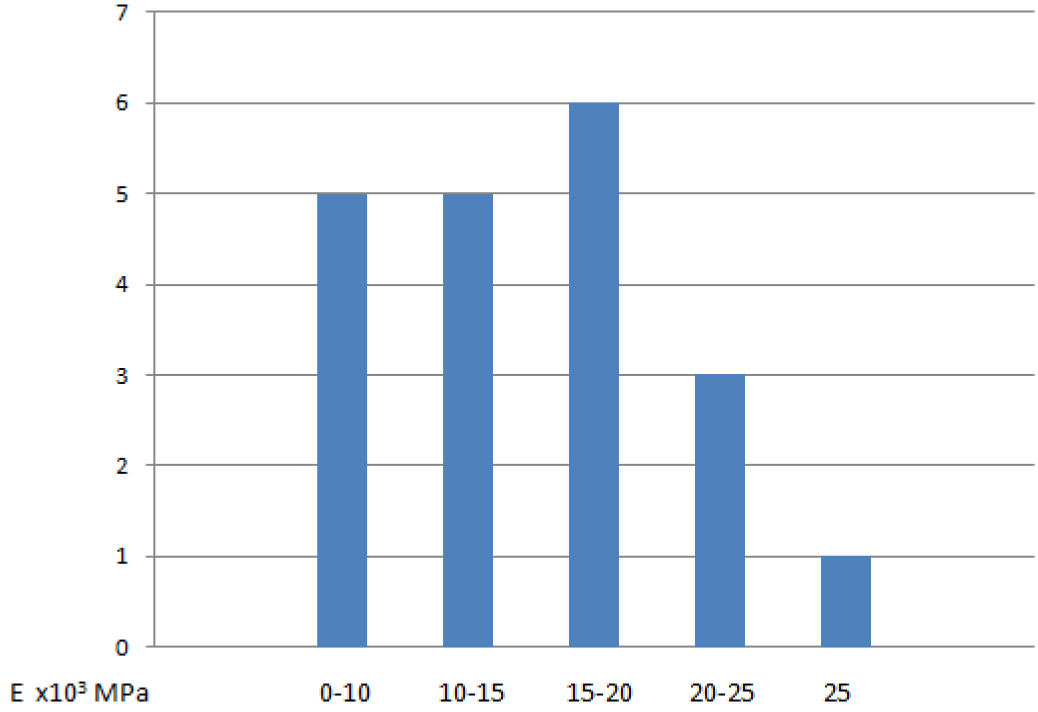


Fig. 4: Modulus of elasticity histogram for 20 pcs. of beams

5. Model of behavior of reinforced flexural members

Calculation of load bearing capacity and rigidity of reinforced member was done with the expectation that it will behave like member with composite cross section and different elasticity characteristics. Cross section for calculation and numerical model are at the Fig.5.

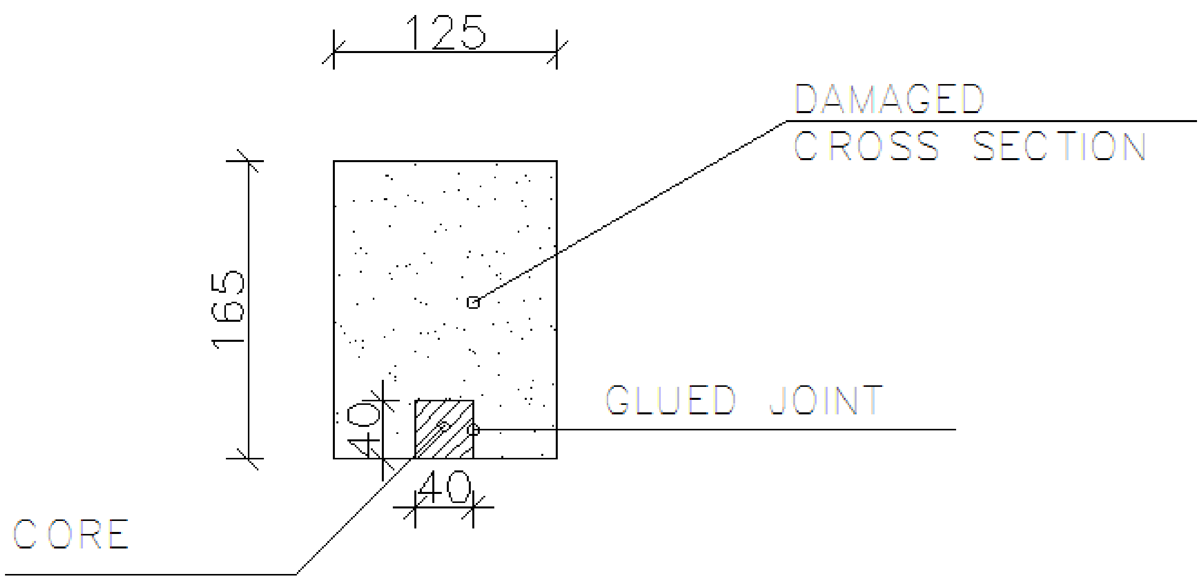


Fig. 5: Cross section used for numerical model a analytic calculation

Analytic calculation below is based on method of effective rigidity of composite cross section mentioned for example in standards (Eurocode 5, 2006 and ČSN EN 408, 2004). Static scheme for the model and calculation is shown on the Fig.6.

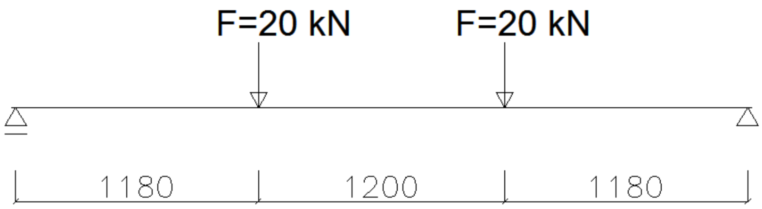


Fig. 6: Static scheme used in analytic calculation and numerical model

Ratio between modulus of elasticity of both materials (5% quantile):

$$n = \frac{E_1}{E_2} \tag{1}$$

Changed width of:

$$b_{3n} = n.b_{3s} \tag{2}$$

Centre-of-gravity position:

$$z_T = H - \left[\frac{A_1.h_{A1}}{2} + 2.A_2\left(h_{A1} + \frac{h_{A2}}{2} \right) + n.A_3\left(h_{A1} + \frac{h_{A2}}{2} \right) \right] / (A_1 + 2A_2 + nA_3) \tag{3}$$

Effective modulus of elasticity:

$$\begin{aligned} I_{eff} &= (nI_3 + nA_3.(0{,}1074 - 0{,}04)^2) + I_1 + \\ &+ A_1.(0{,}140 - 0{,}1074)^2 + 2.\left(I_2 + A_2.(0{,}1074 - 0{,}0{,}04)^2\right) \end{aligned} \tag{4}$$

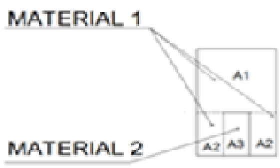
Stress at the bottom of the cross section:

$$\sigma_{m,Ed} = \frac{M_{Ed}.z_t}{I_{eff}\, n} \tag{5}$$

Analytic calculation was performed for comparison with numerical model and real test results. Calculation was done in MS Excel table (Tab.4)

Tab. 4: Calculation of stress at the bottom of the cross section

Material nr. 1	$E_{1;0,05}$	6,1	GPa					
Material nr. 2	$E_{2;0,005}$	16,7	GPa					
Material ratio	n	0,365	-					
Real width of core	b_{s3}	0,04	m					
Cross sectio characteristics of part 1	h_1(m)	0,125	b_1(m)	0,125	A_1(m^2)	0,016	I_1(m^4)	2,03E-05
Cross sectio characteristics of part 2	h_2(m)	0,04	b_2(m)	0,043	A_2(m^2)	0,002	I_2(m^2)	2,27E-07
Cross sectio characteristics of part 3	h_3(m)	0,04	b_{n3}(m)	0,015	A_3(m^2)	0,001	I_3(m^2)	7,79E-08
Centre-of-gravity	z_T(m)	0,087	m					
Effective modulus of elasticity	I_{eff}	4,08E-05	m4					
Design force	F	20000	N					
Bending moment	M	23600	Nm					
Stress at the bottom of cross section	**$\sigma_{m,d}$**	**18,38**	**MPa**					



Before performing real tests in TZÚS Ostrava numerical (FEM) model was made in ANSYS software. Static scheme is the same as at the Fig.6. Results of the numerical model were quite well matched with output of the analytic calculation.

Model results leads to conclusion that reinforcing core overdraw bigger part of tension (Fig.6, Fig.7).

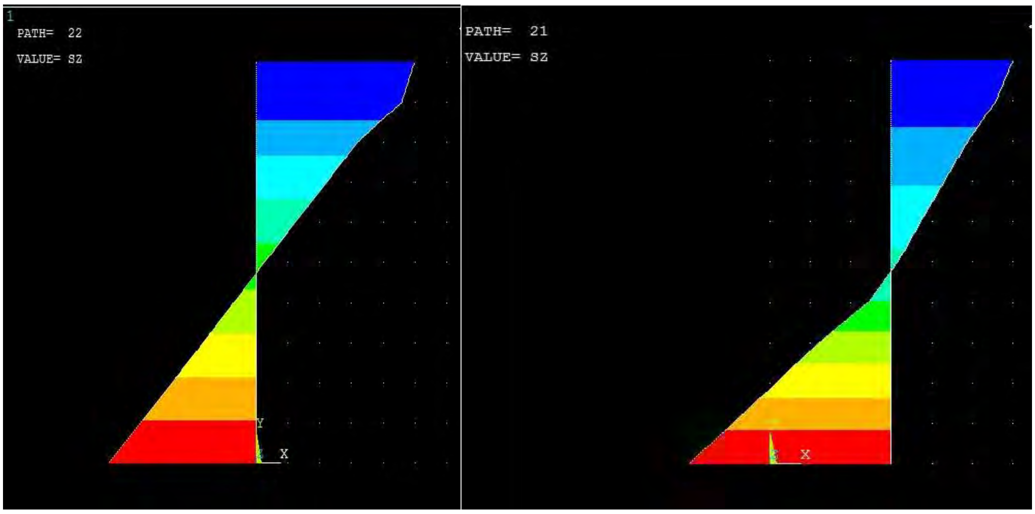


Fig. 7and 8: Normal stress plotted trough the height of cross section (left-not reinforced member, right-reinforced member)

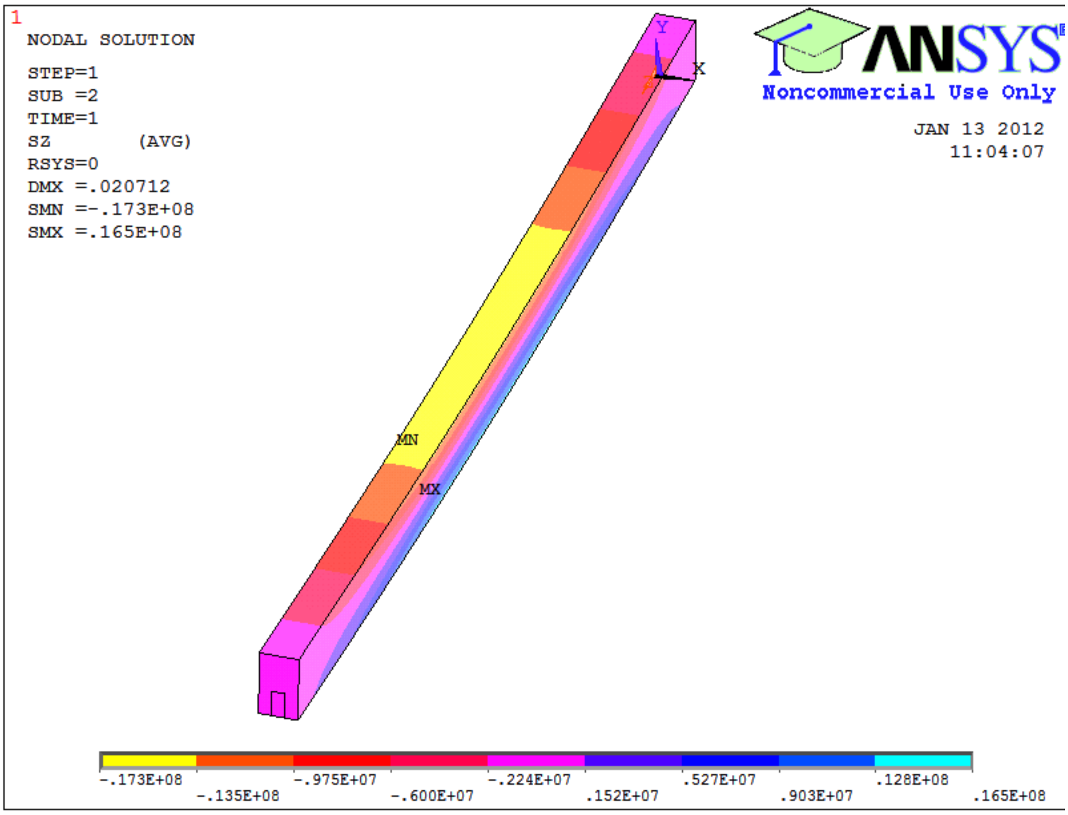
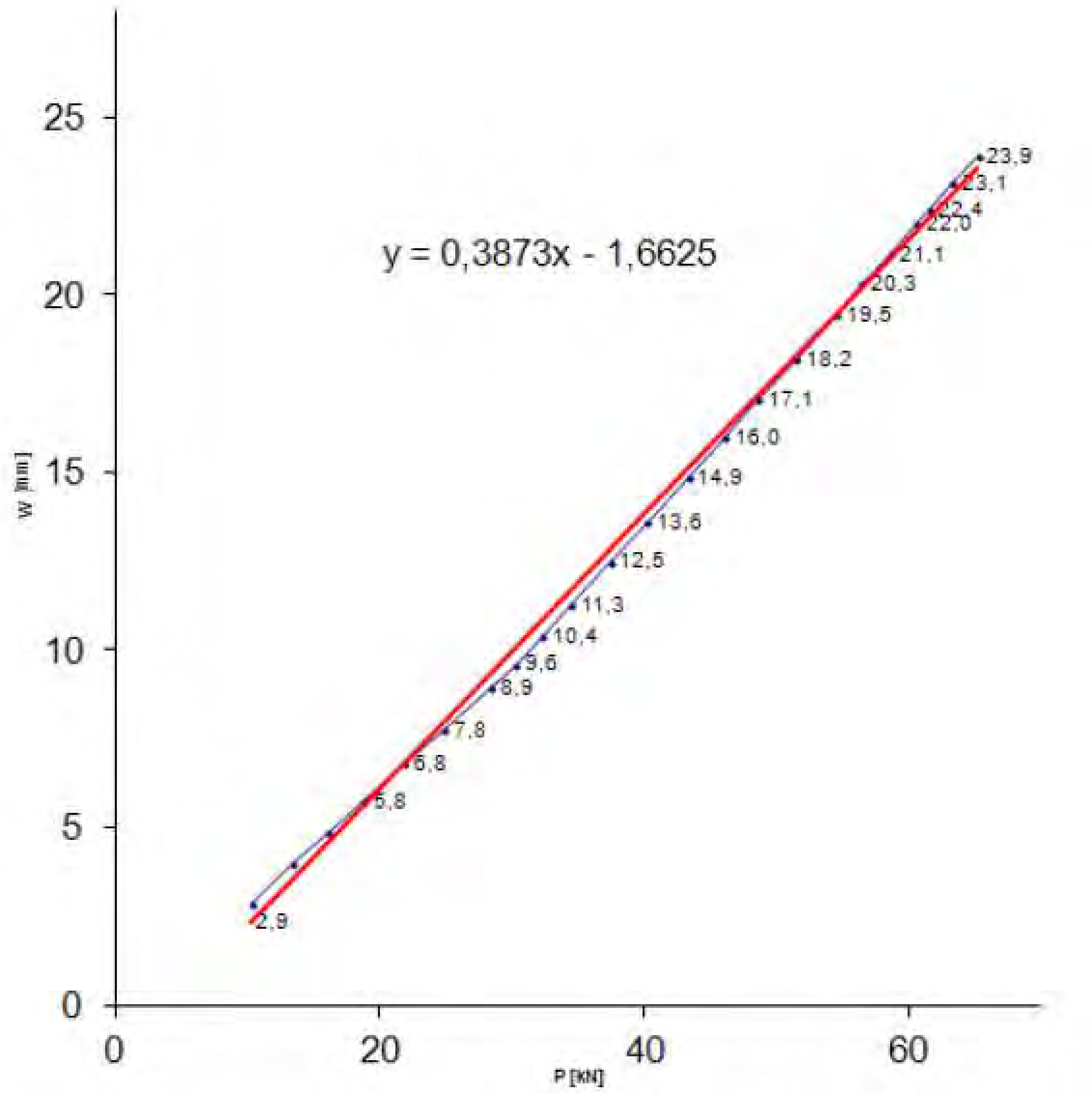


Fig. 9: Normal stress on the beam

Difference between results (tension at the bottom of the cross section) from the analytic calculation and numerical model is around 10 %. These results can be compared to result of the test on the Fig.10.

Fig. 10: Test results for the sample nr. 8



6. Conclusion

From the results of model, testing and theoretical data follow that the reinforcing of the timber member with the wooden core is suitable for constructions which have to preserve its original look.

Beams tests proves that the timber almost 400 years old still have similar mechanical properties as the new timber.

Measured values of mechanical properties (stiffness and strength) reinforced timber beams has quite high variability. For reliable and safe design reinforced timber members it seems to be suitable to use new design procedures based on probabilistic methods inspired by papers (Janas et al.,2009) or (Lokaj et al., 2009) published in the proceedings of International Conference on Civil Structural and Environmental Engineering Computing or paper from Applied Mechanics and Materials (Lokaj et al., 2011)

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