International Academy of Wood Science

ACADEMY LECTURE

WOOD AS NATURAL SMART MATERIAL

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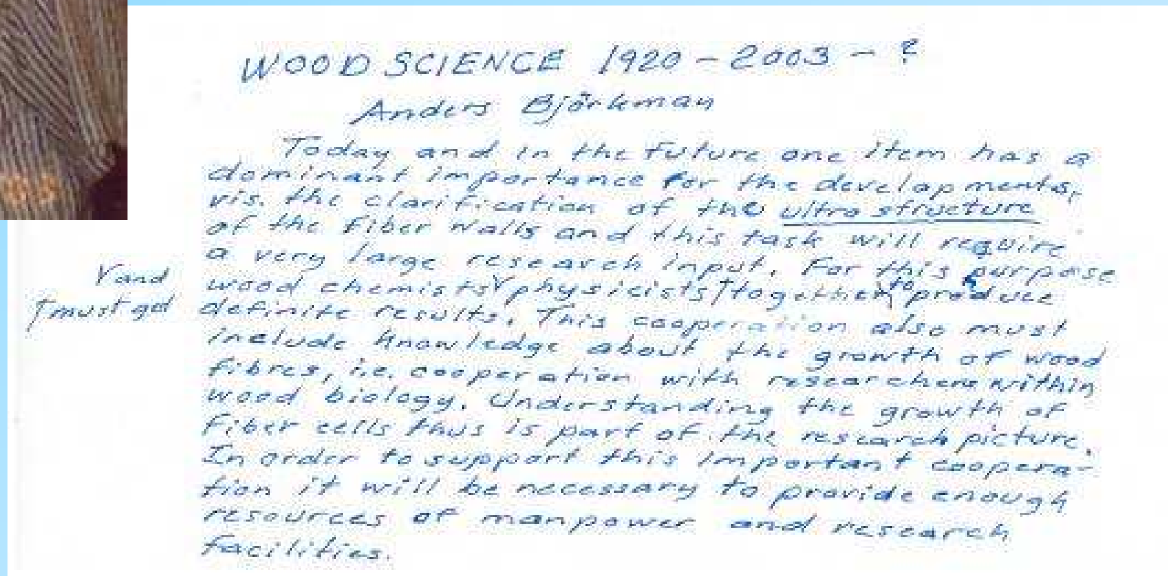
«It will not be too pessimistic to state that we shall not learn to know the wood ultrastructure truths before 2050 or perhaps 3000. Anyhow it is most fascinating science to deal with .»

A. Bjorkman “Wood Science1920-2003-?”



WOOD SCIENCE 1920 – 2003 – ?

Anders Björkman

Today and in the future one item has a dominant importance for the developments, vis. the clarification of the ultra structure of the fiber walls and this task will require a very large research input. For this purpose wood chemists and physicists must get together to produce definite results. This cooperation also must include knowledge about the growth of wood fibres, i.e. cooperation with researchers within wood biology. Understanding the growth of fiber cells thus is part of the research picture. In order to support this important coopera-tion it will be necessary to provide enough resources of manpower and research facilities.

- Nature that created wood as ultramicroscopic miracle, prompted to mankind to produce diverse modern artificial materials ranging from reinforced concrete to nanocomposites. Further studies of wood nanostructure discover new possibilities of biomimetic approach to creation of effective materials.

- Material scientists predict a prominent role of artificial smart materials in future. This term designates material which usefully reacts to the changes in environmental parameters.

- One of the main features of smart materials is «shape-memory effect». It means that these materials after forced change of the form are able to restore their initial form when original physical condition is recovered.

- Metallic shape memory alloys were synthesized the first. Later were created ceramics and polymers with the same property.

- We find a very broad spectrum of smart materials applications from deployable space structures to self-repairing auto bodies, switches, sensors, kitchen utensils, tools up to minimally invasive surgery and implants in biomedicine.

Examples of Topical Problems for Artificial Smart Materials

(Примеры актуальных проблем для искусственных умных материалов)

- fiber-reinforced elastic memory composites (Abrahamson et al. 2002)

- problems of behaviour of the shape memory polymers (Lendlein and Kelch 2002)

- **internal stress induced by constrained expansion of memory polymer nanocomposites (Gall et al. 2004)**

- model development for shape memory polymers **(**Siskind et al. 2008)

Examples of Wood Useful Properties under External Influence

(Примеры полезных свойств древесины, проявляющихся при внешних воздействиях)

- Hygroscopicity of wood gives possibility to use it as a sensor of surrounding air humidity.

- Wood constructions of buildings regulate, in some degree, the air humidity in living premises, by drying or humidifying of the air at changing weather.

- Swelling of wood tightens joints in articles and structures.

- Pit props of pine and spruce wood emit crackling which warns of coming mine destruction.

- Acoustic emission is used for monitoring of lumber stress state at drying.

- Sonorous ability of wood reveals itself in musical instruments.

- Piezoelectric properties of wood permit to create nondestructive methods of strength testing.

- Et cetera.

Wood Possesses «Memory Effect» – The Dominant Feature of Smart Materials

(Древесина обладает доминантным признаком умных материалов – «эффектом памяти»)

The notion «memory of wood» was introduced by us at the beginning of the 1980s. Previously some researchers (T. Takemura (1973) et al.) had used the analogous term for indication of purely temporal phenomena. In our case this is a metaphor which reflects the ability of wood to react to the restoration of initial physical state determined by its moisture content and temperature.

«Wood memory effect» is based on quazi-residual «frozen» strains (FS)

They were experimentally discovered by us at constrained shrinkage of wood in the early 1960s.

Integral Law of Wood Straining at Drying and Wetting

(Общий закон деформирования древесины при сушке и увлажнении)

$$\varepsilon = -\beta W + \alpha W + H_1 \int_0^{\tau} \frac{\dot{\sigma}}{E(W,T)} d\tau + H_2 \frac{\sigma}{E(W,T)}$$

Here: ε – strain

β – coefficient of shrinkage

$W=\Delta w$ – moisture content decrease from limit saturation of cell wall (FSP)

α– coefficient of swelling

σ – stress

E – stiffness modulus

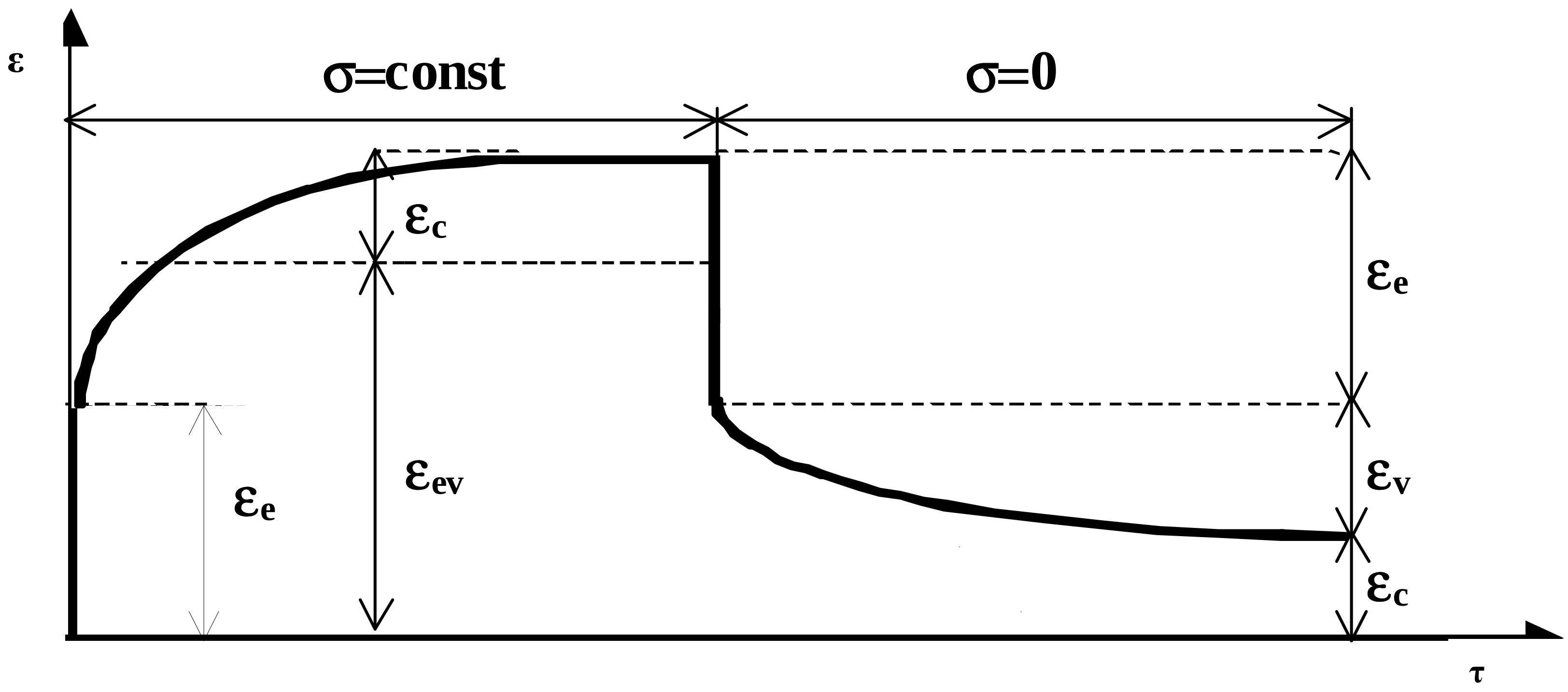
T – temperature decrease from 100˚C

$W(\tau)$,$T(\tau)$ and $\dot{\sigma}(\tau)$ are functions of time τ

H_1 and H_2 are Havisade`s functions accordingly for drying and wetting

Strain (ε) – Time (τ) Relation of Wood at Constant Moisture Content

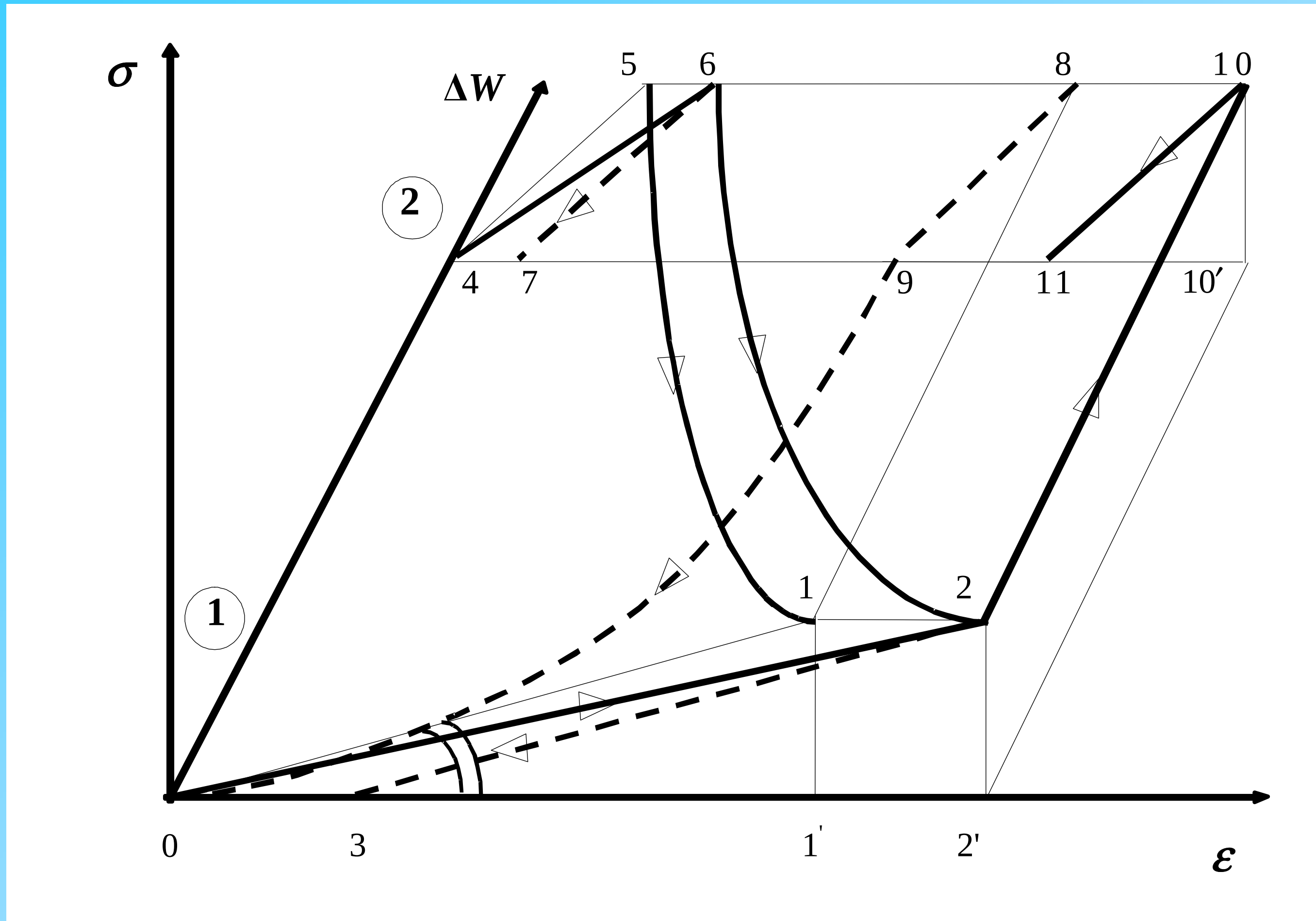
(Зависимость деформаций(ε) древесины от времени (τ) при постоянной влажности)



Here: ε_e – elastic strain; ε_v – viscous strain; ε_{ev} – elastic- viscous strain; ε_c – creep; σ – stress

Changes of Wood Hygromechanical Strains

(Изменения гигромеханических деформаций древесины)



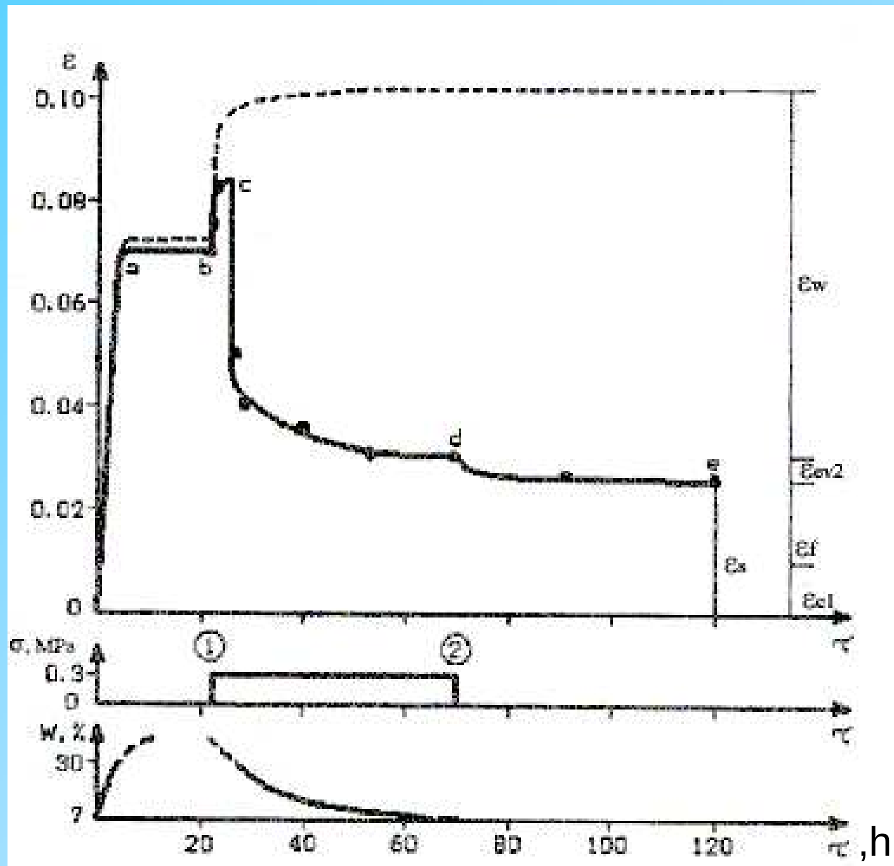
Here: σ – stress; ε – strain; Δw – drop of moisture content.

1– wet wood (w > 30%)

2 – dry wood

Changes of Strains ε, Stresses σ and Moisture Content w in Time τ of Experiment

(Изменения деформаций ε, напряжений σ и влажности w во времени τ)

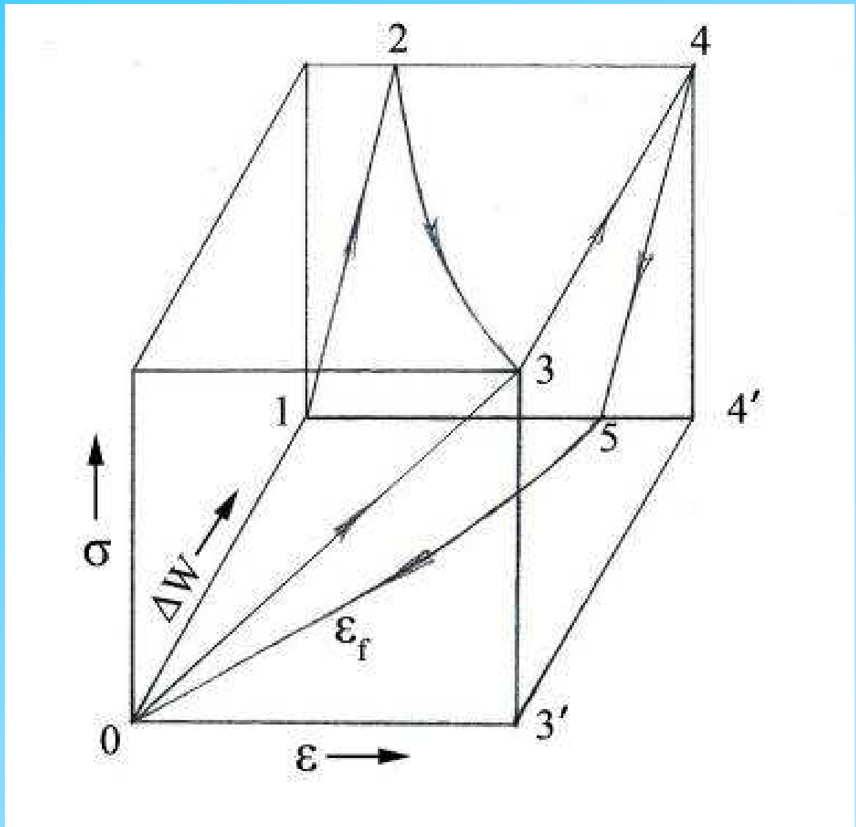


1 – wet wood

2 – dry wood

Scheme of Forming of Frozen Elastic-Viscous Strain at Wood Drying

(Схема образования замороженных упруго-эластических деформаций древесины при сушке)

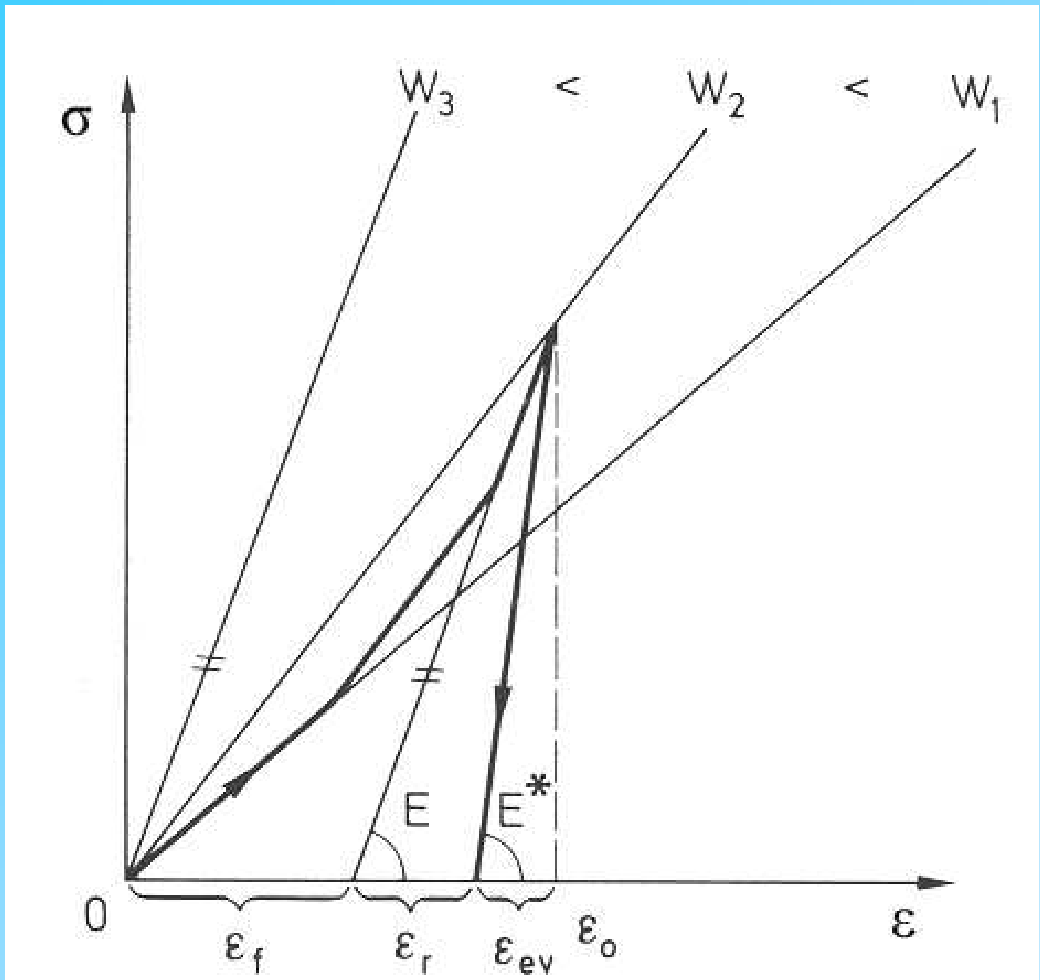


$$\varepsilon_f = \varepsilon_{ev1} - \varepsilon_{ev2}$$

Frozen strains are the result of temporary reconstruction of wood nanostructure under the control load influence at increasing wood stiffness processes of drying or cooling

Contribution of Frozen Strains to Stress-Strain State of Wood at Drying

(Вклад замороженных деформаций в напряженно-деформированное состояние древесины при сушке)



The FS as a part of set-strain are the main reason for the forming of dried lumber casehardening

$$\varepsilon_s = \varepsilon_f + \varepsilon_r$$

Frozen Strains Were Taken into Account at the Drying Stress Calculation

(Замороженые деформации были учтены при разработке метода расчета сушильных напряжений)

Step-by-step method for multy-sliced model of drying lumber

$$\sigma_i^j = \sigma_i^{j-1} + \beta \overline{E}_i^j \left[\Delta w_i^j - \sum_{i=1}^{n} \overline{E}_i^j \Delta w_i^j \Big/ \left(\sum_{i=1}^{n} \overline{E}_i^j \right) \right]$$

Here: σ – stress

β – coefficient of shrinkage

E – stiffness modulus

$\overline{E} = 0{,}5\left(E^j + E^{j-1}\right)$ – average stiffness modulus

Δw – moisture contents drop from limit of cell wall saturation (FSP)

j – step number

i – slice number

n – quantity of slices

Lumber Drying Schedules and Product Quality

(Режимы сушки пиломатериалов и качество продукции)

Lumber drying schedules parameters

- temperature
- humidity
- time

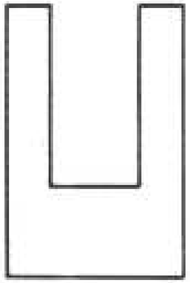
Product quality parameters

- moisture content
- moisture content gradient
- stress

Detection of Lumber Drying Stresses

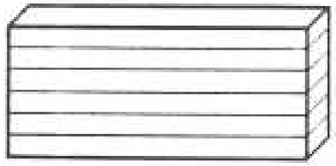
(Определение сушильных напряжений в пиломатериалах)

Qualitative evaluation of drying stresses



H.Tiemann (1917)

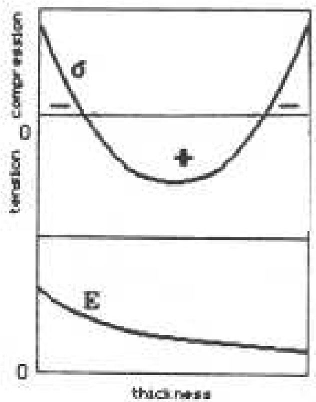
Slicing technique for deformation measuring



E.Peck (1929,1940)

I.Mc. Millen (1955)

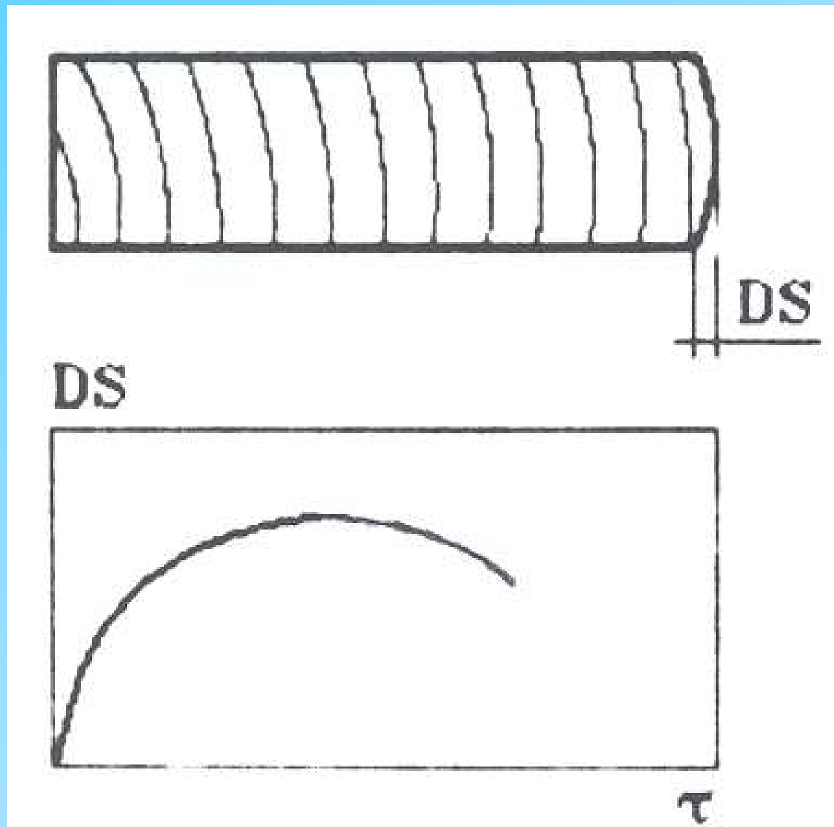
Method of stress measuring



B.N.Ugolev (1952)

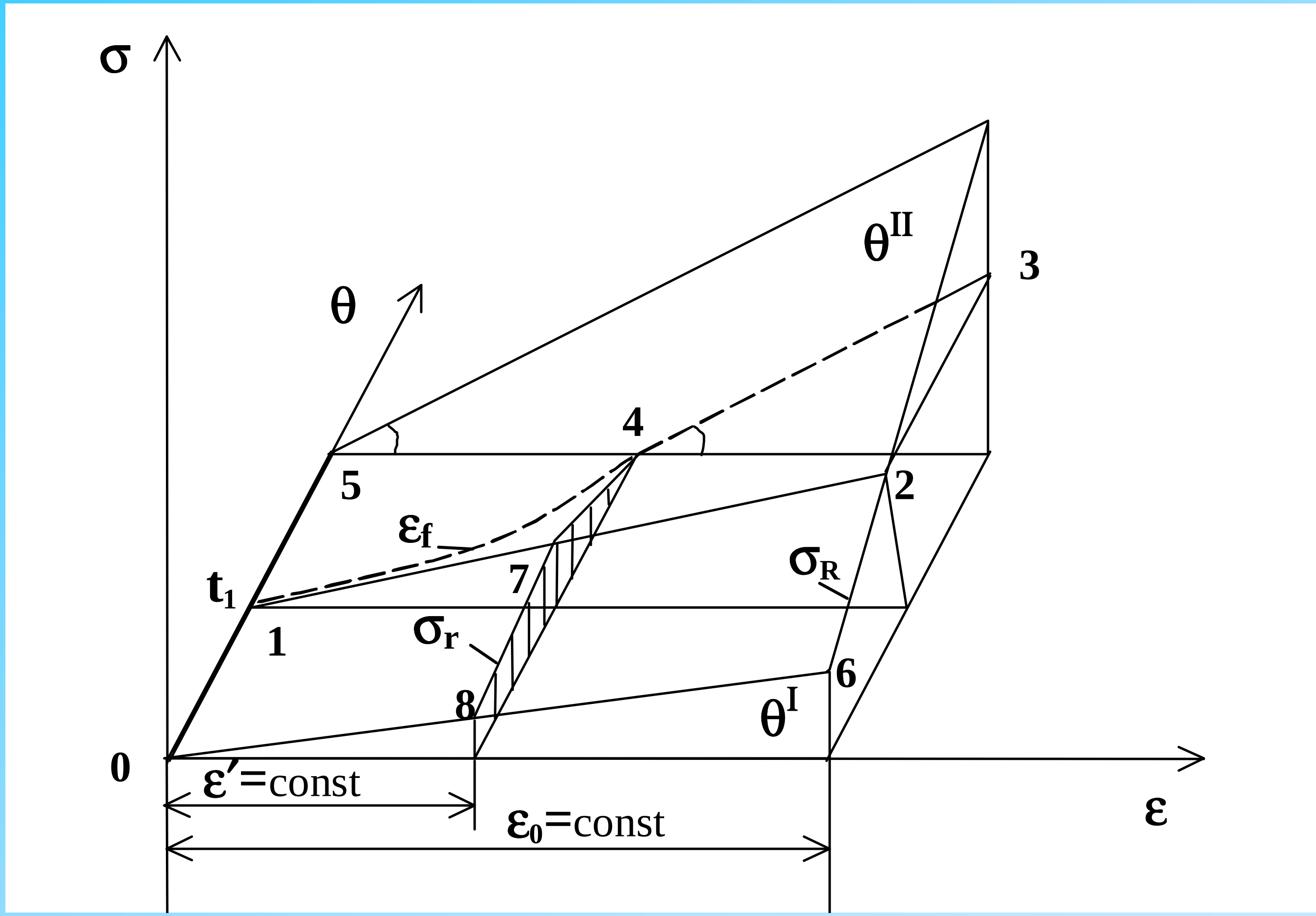
Method of Lumber Drying Stresses Monitoring by Differential Shrinkage (DS)

(Метод контроля сушильных напряжений в пиломатериалах по дифференциальной усадке)



Scheme of Wood Deformative Conversions at Heating

(Схема деформационных превращений древесины при нагревании)



Here: $\Theta = 100° - t$ – drop of temperature

$\sigma_R = Et(\varepsilon_0 - \varepsilon_f)$ at ε_0 = const (**case a**)

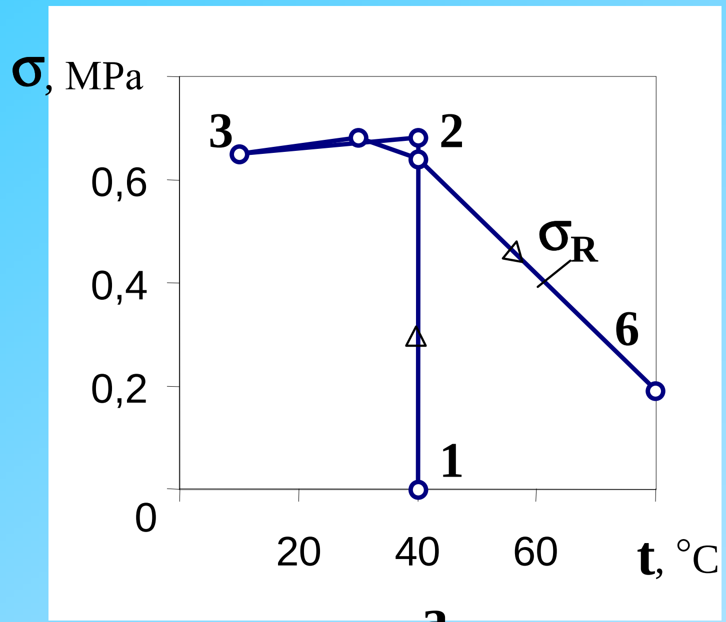
$\sigma_r = Et(\varepsilon' - \varepsilon_f)$ at ε' = const (**case b**)

E_t – modulus of elasticity

Wood «Stress Memory Effect» at Heating

(«Эффект силовой памяти» древесины при нагревании)

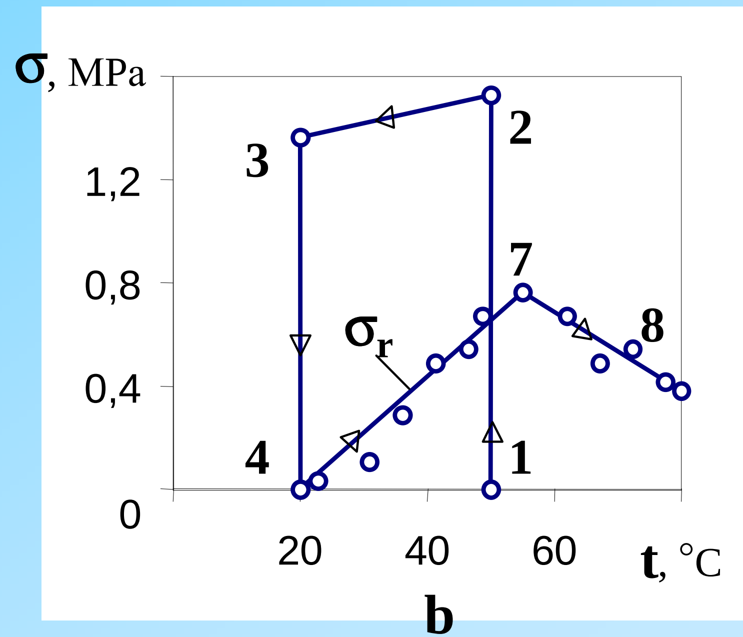
loaded wood and constant total strain



a

Pinus sibirica Du Tour, compression, tangential direction across the grain, ε_0=0,009

unloaded wood and constant frozen strain



b

Quercus robur L., tension , radial direction across the grain, ε'=0,007

Change of the Form of Ash Veneer and «Strain Memory Effect»

(Изменение формы ясеневого шпона и «эффект деформационной памяти древесины)

a) original state (heated wood)

b) under load

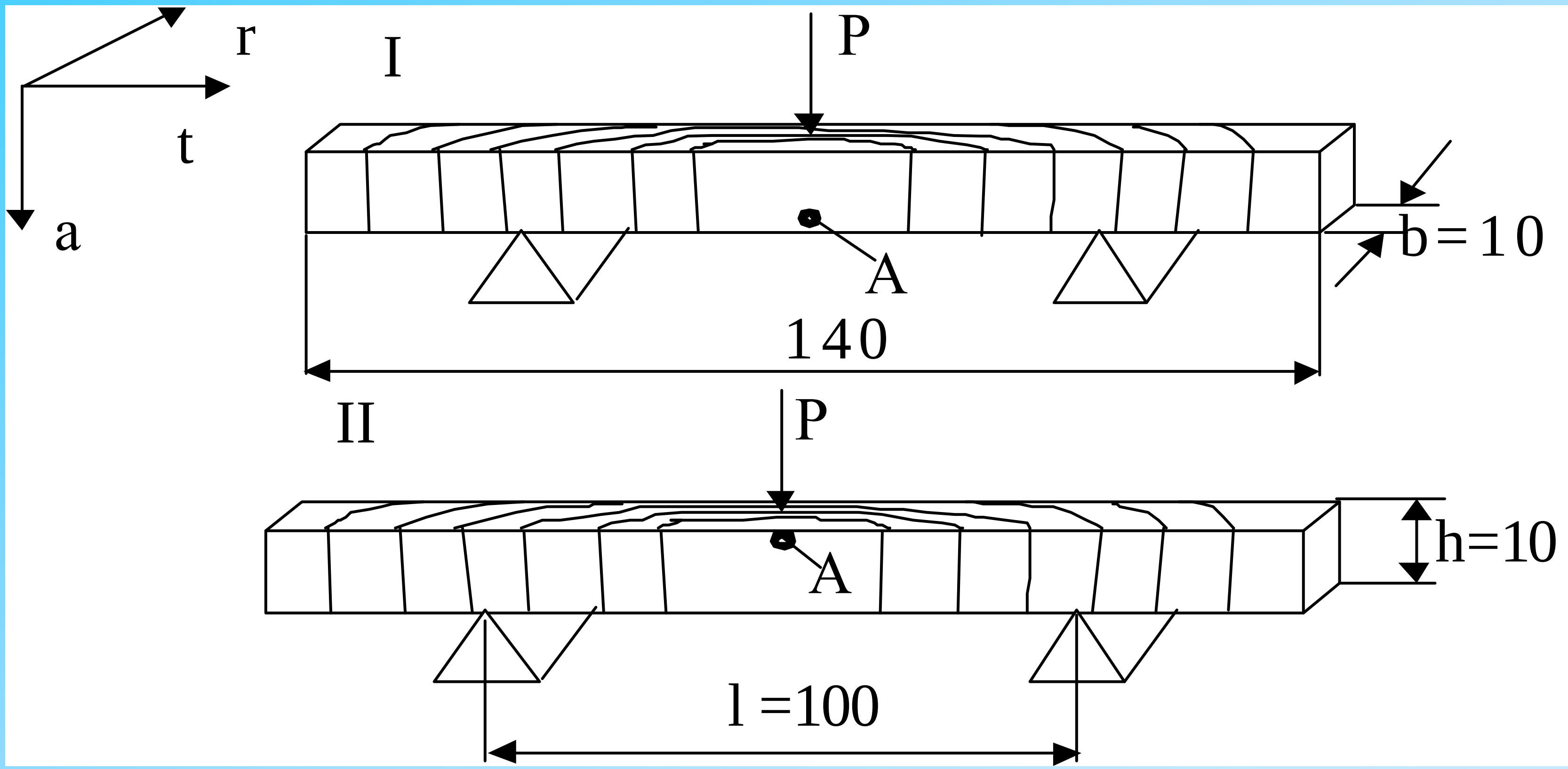
c) after cooling

d) after unloading («frozen strains»)

e) after heating

The Scheme of the Wood Specimen Loading

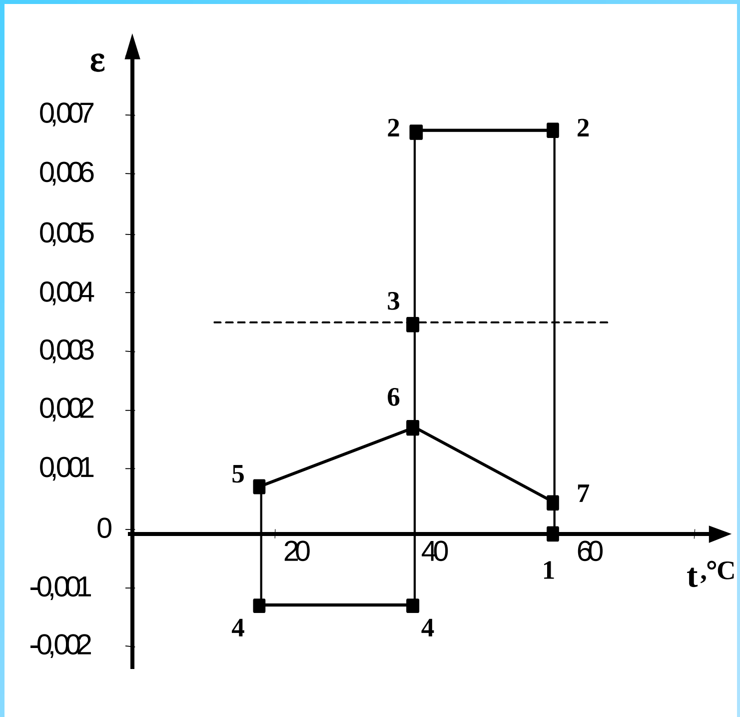
(Схема нагружения образца древесины)



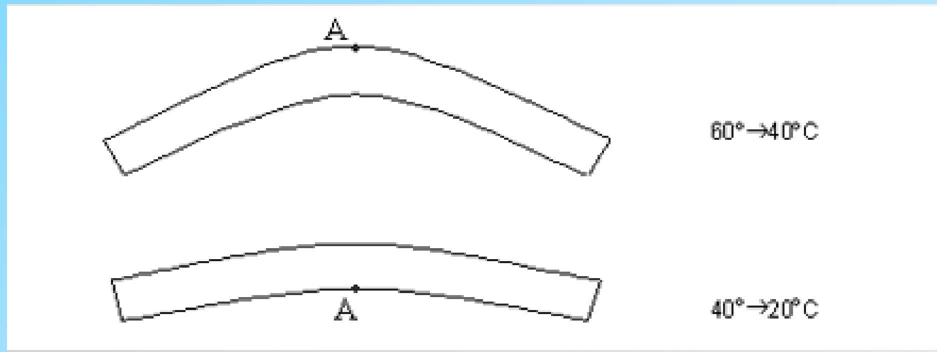
«Strain Memory Effect» at Heating of Previously Loaded (Tension – Compression) and then Unloaded Wood

(«Эффект деформационной памяти при нагревании предварительно нагруженной (растяжение – сжатие) и затем разгруженной древесины)

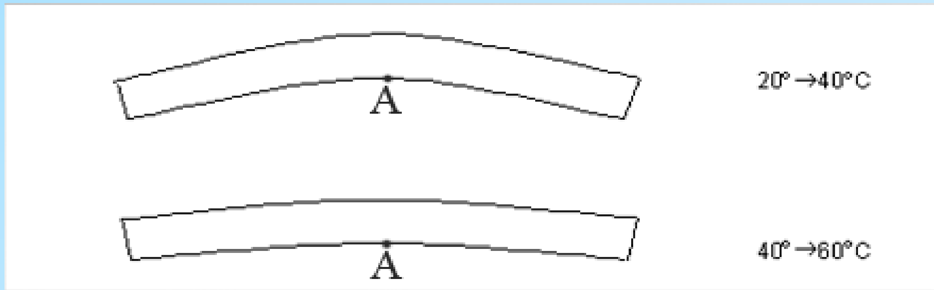
a)



b) After loading – cooling – unloading



After heating



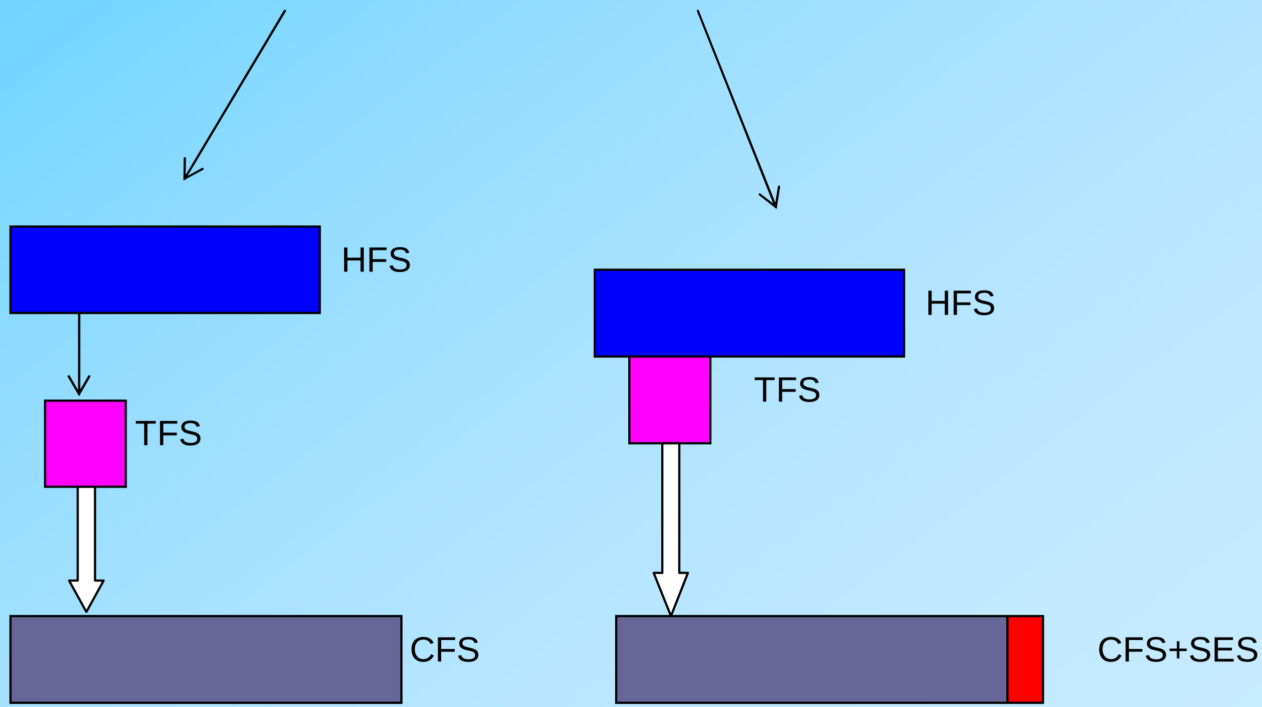
Contribution of Hygrofrozen Strains (HFS) and Thermofrozen Strains (TFS) in Complex Rrozen Strains (CFS)

(Вклад гигрозамороженных деформаций (HFS) и термозамороженных деформаций (TFS) в комплексные замороженные деформации (CFS))

Complex frozen strain (CFS)

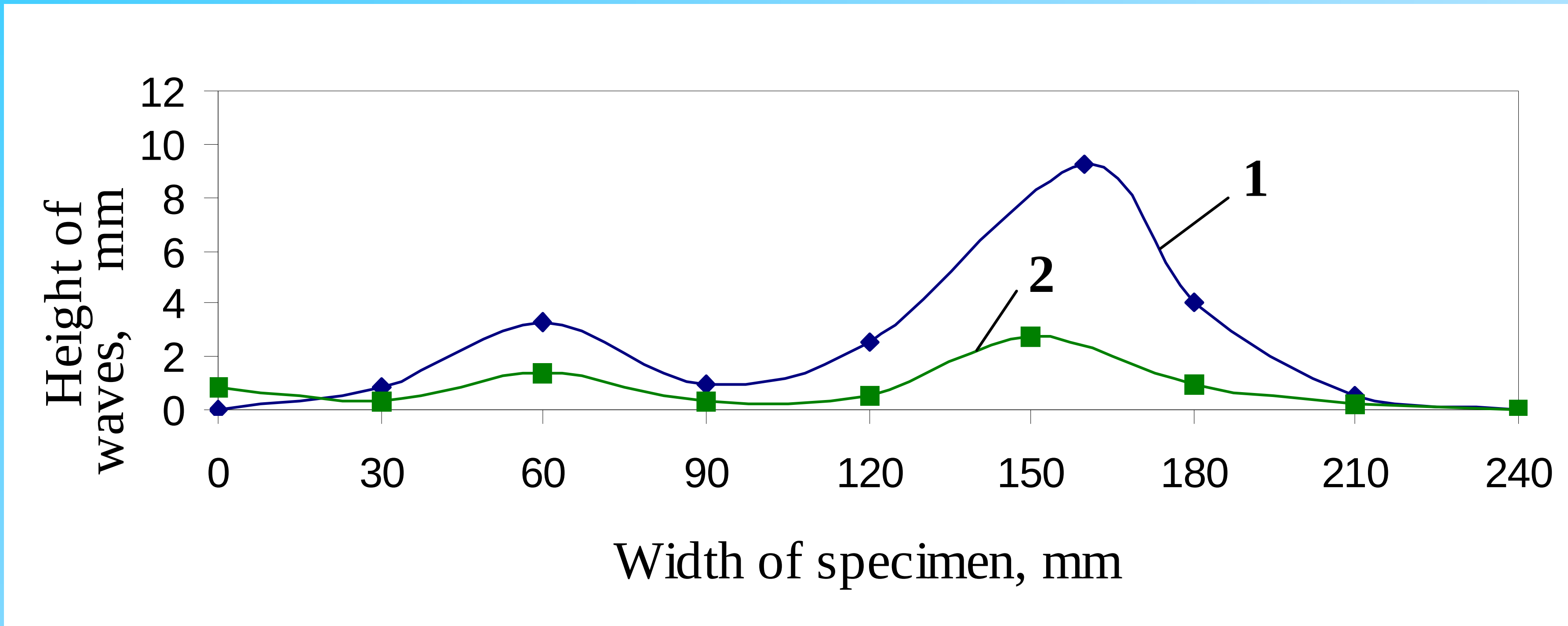
Wood drying and cooling under load

consecutive simultaneous



Using Hygro-Thermofrozen Strains to Remove Veneer Waviness

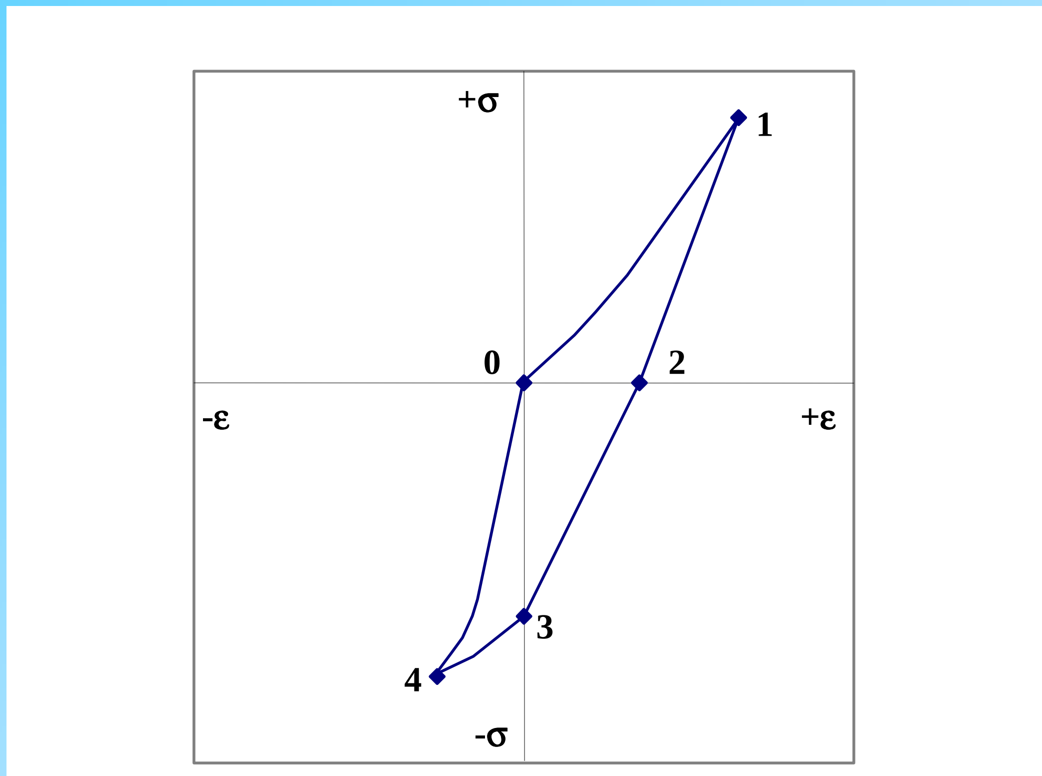
(Использование гигро-термозамороженных деформаций для устранения волнистости шпона)



1 – original state, 2 – after cooling and drying of loaded specimen.

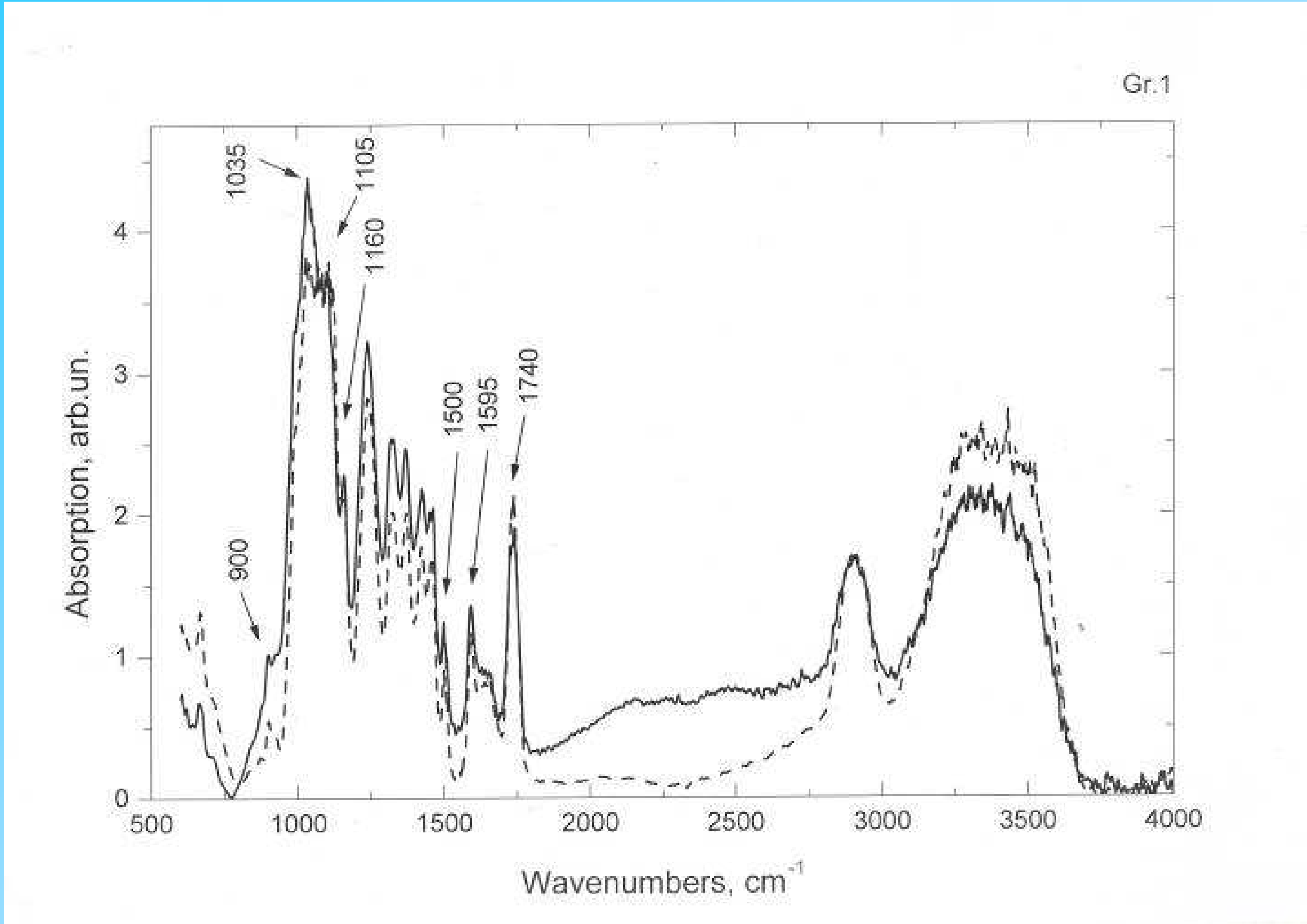
Wood Stress-Strain Behavior of the Surface Zone of a Board at Drying and Conditioning Moisture-Heat Treatment

(Напряженно-деформированное состояние поверхностной зоны доски при сушке и кондиционирующей влаго-теплообработке)



IR- Absorbtion Spectrum of Birch Wood

(ИК- спектры поглощения древесины березы)

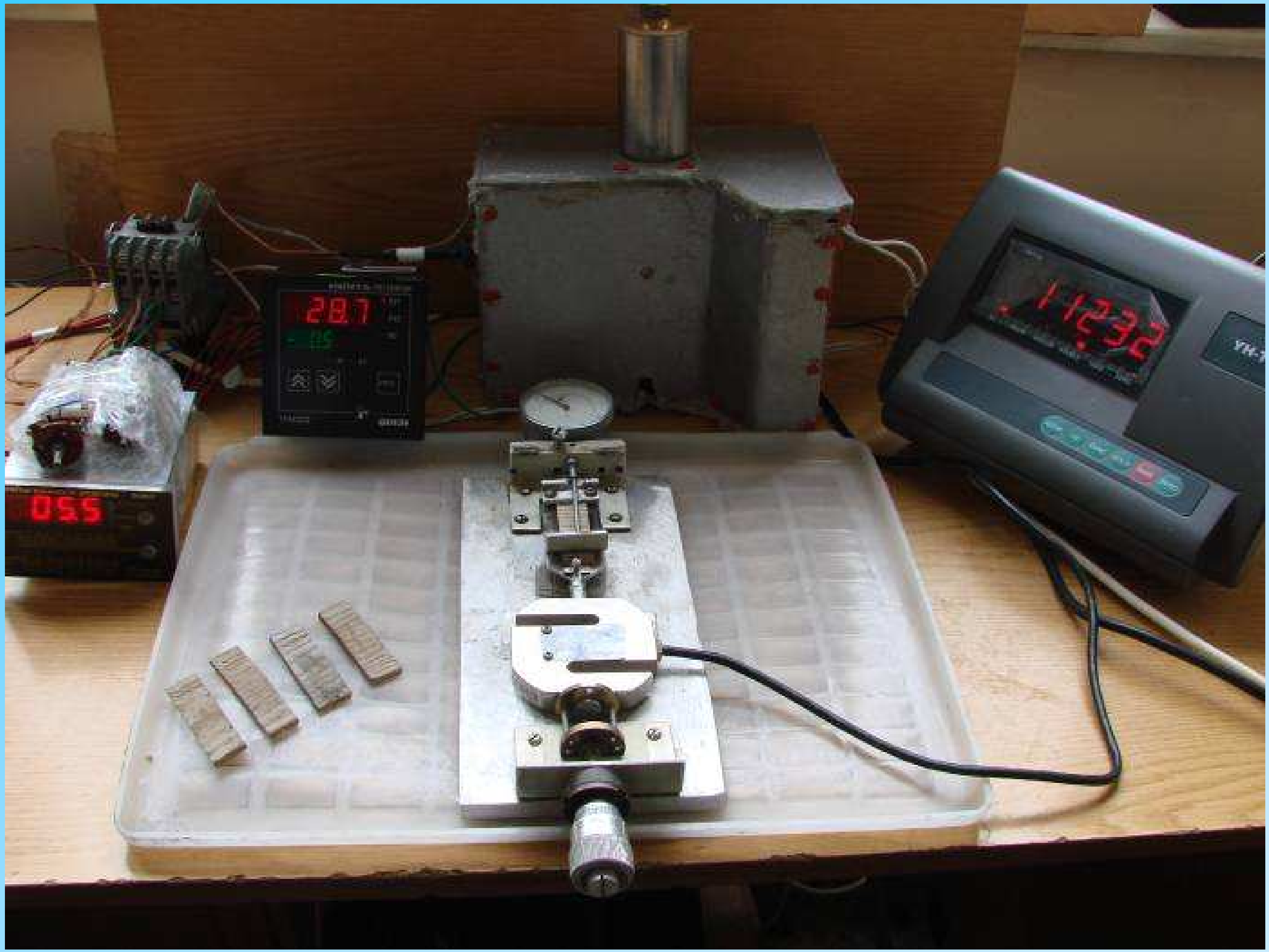


- - - - after free drying

—— after constraind shrinrage

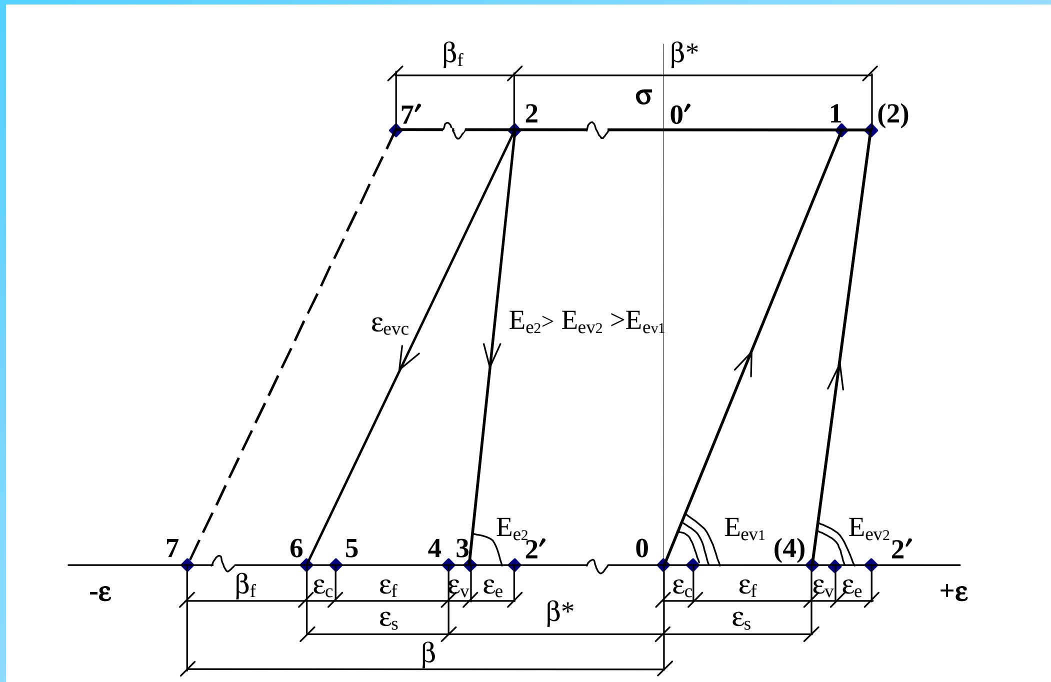
Experimental Device

(Экспериментальная установка)



Scheme of Wood Deforming at Constant Load, Drying and Unloading

(Схема деформирования древесины при постоянной нагрузке, сушке и разгрузке)



Here: 0-1– tension of wet wood

1-2– drying of loaded wood

2-3-4–unloading and time exposure of dry wood

sections:0-4 – «reduced shrinkage» β*

4-5 – frozen elastic-viscous strain εf

5-6 – creep εs

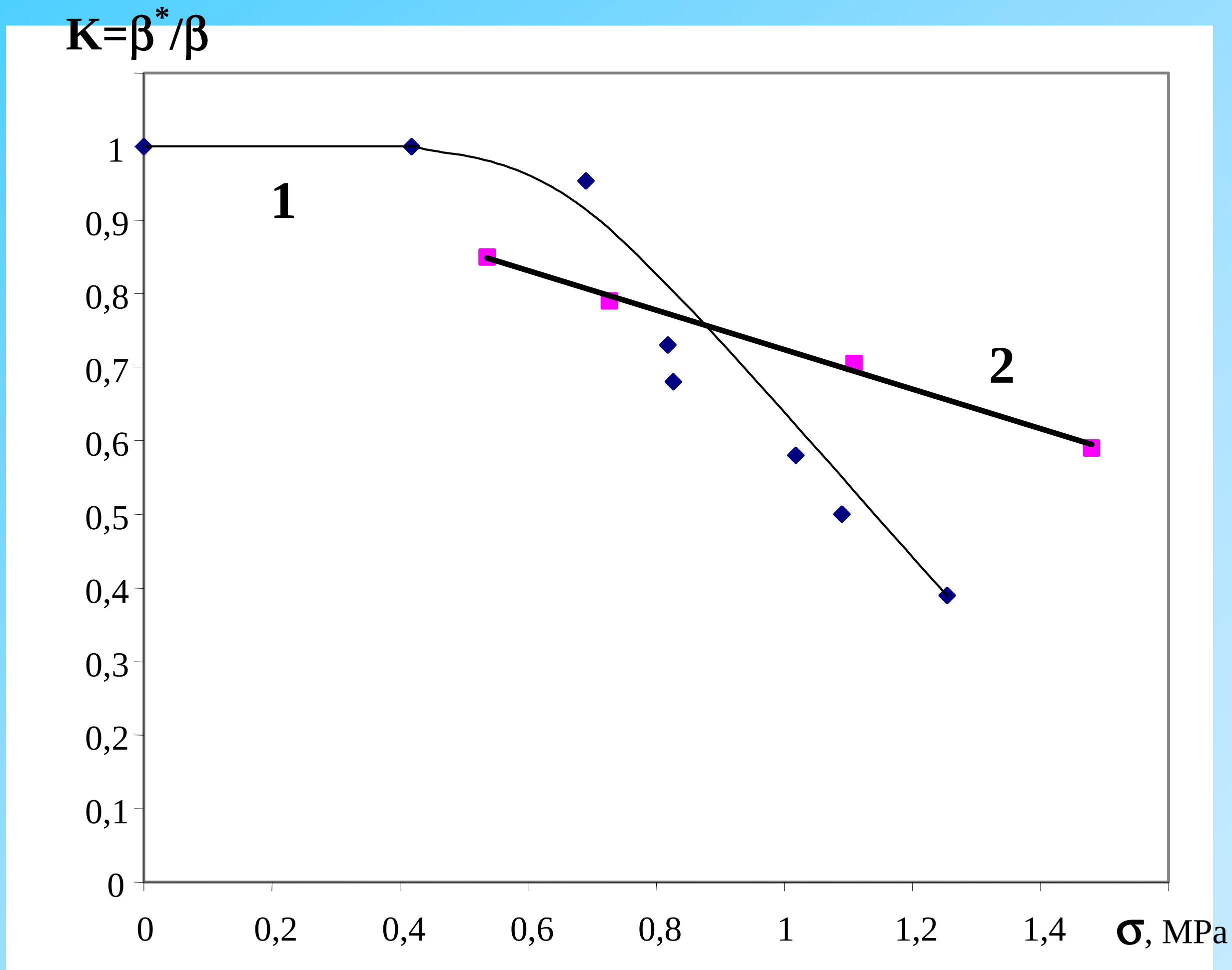
4-6 – quasi-residual set-strain εs

6-7 – « frozen shrinkage» βf

0-7 – free shrinkage β

Effect of Tension Load on Reducing Shrinkage Degree

(Влияние растягивающей нагрузки на степень уменьшения усушки)

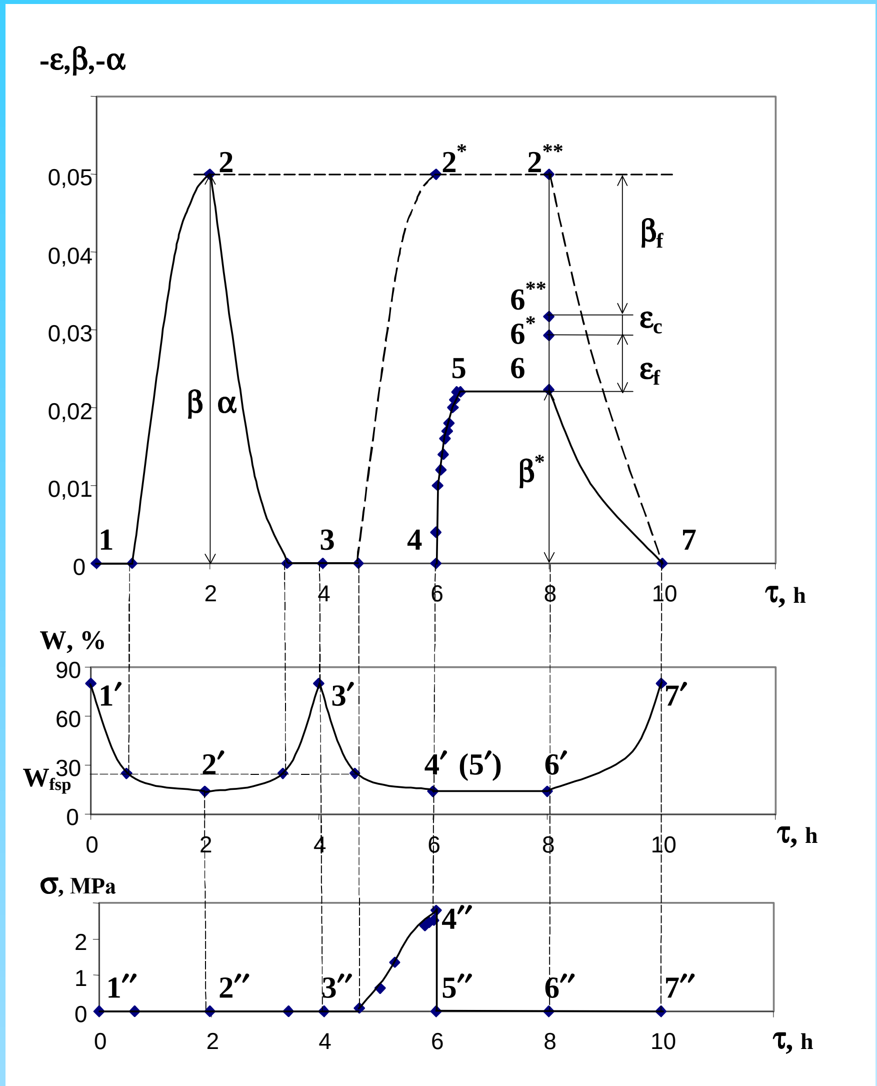


1– *Fraxinus excelsior* L., t = 80 °C (our date)

2– *Fagus orientalis*, t = 20°C (by N.Chulitsky)

Detection of «Frozen Strain» and «Frozen Shrinkage» at Drying Fastened Specimen

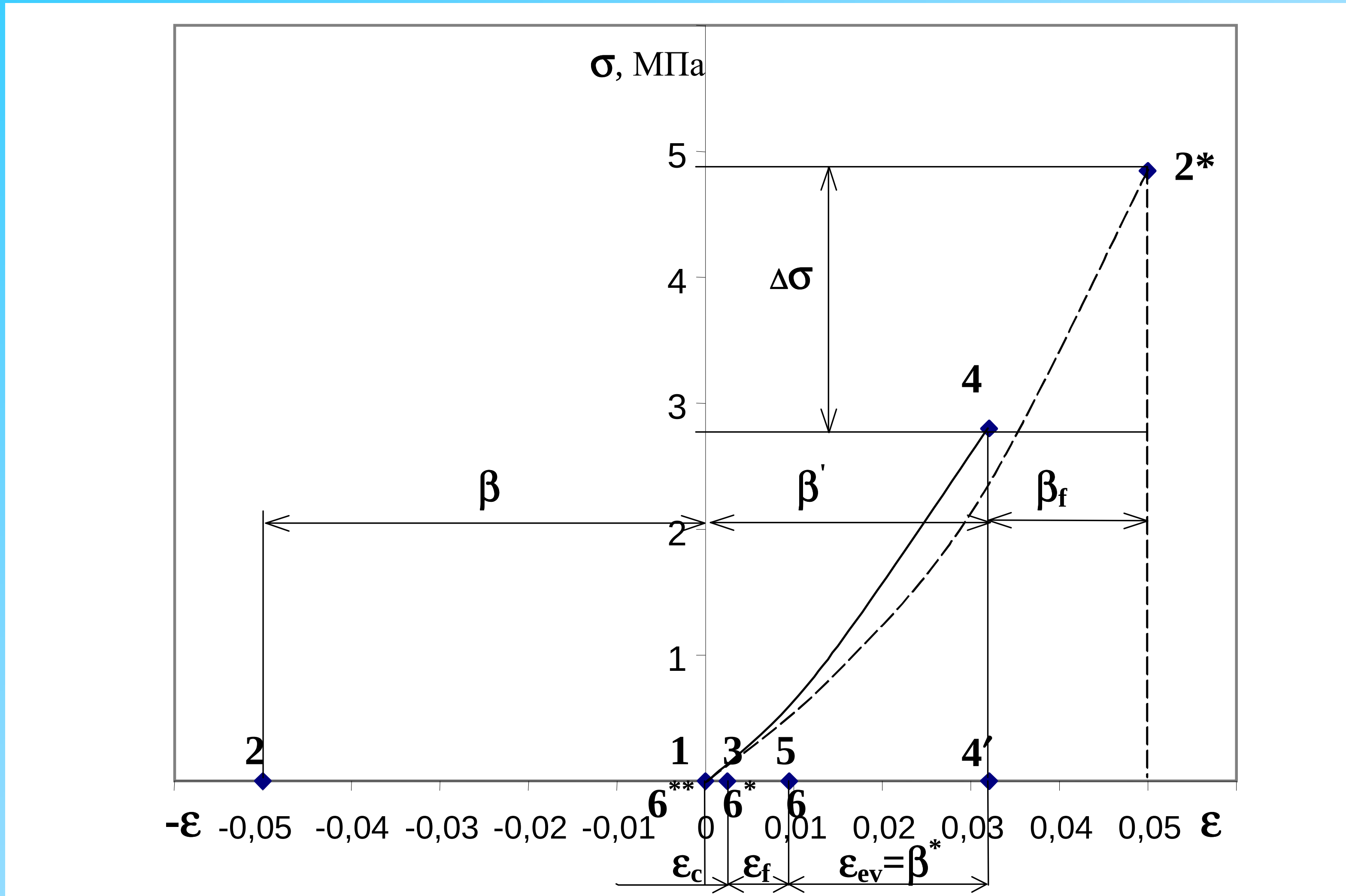
(Определение «замороженной деформации» и «замороженной усушки» при сушке закрепленного образца)



Fraxinus excelsior L., tangential direction across the grain, t = 80 °C

Free Shrinkage and Stress-Strain State at Wood Drying

(Свободная усушка и напряженно-деформированное состояние древесины при сушке)



Fraxinus excelsior L., tangential direction across the grain, t=80 °C

Drying Stress Calculation Equation with Reducing Shrinkage Coefficient

(Уравнение для расчета сушильных напряжений с уменьшающимся коэффициентом усушки)

$$\sigma = \sum_{i=1}^{n} K_{\beta}(\sigma) \cdot \Delta w_i E_i(w,t)$$

Here: K_{β} – coefficient of shrinkage

Δw – moisture content drop from limit saturation of cell wall (FSP)

σ – stress

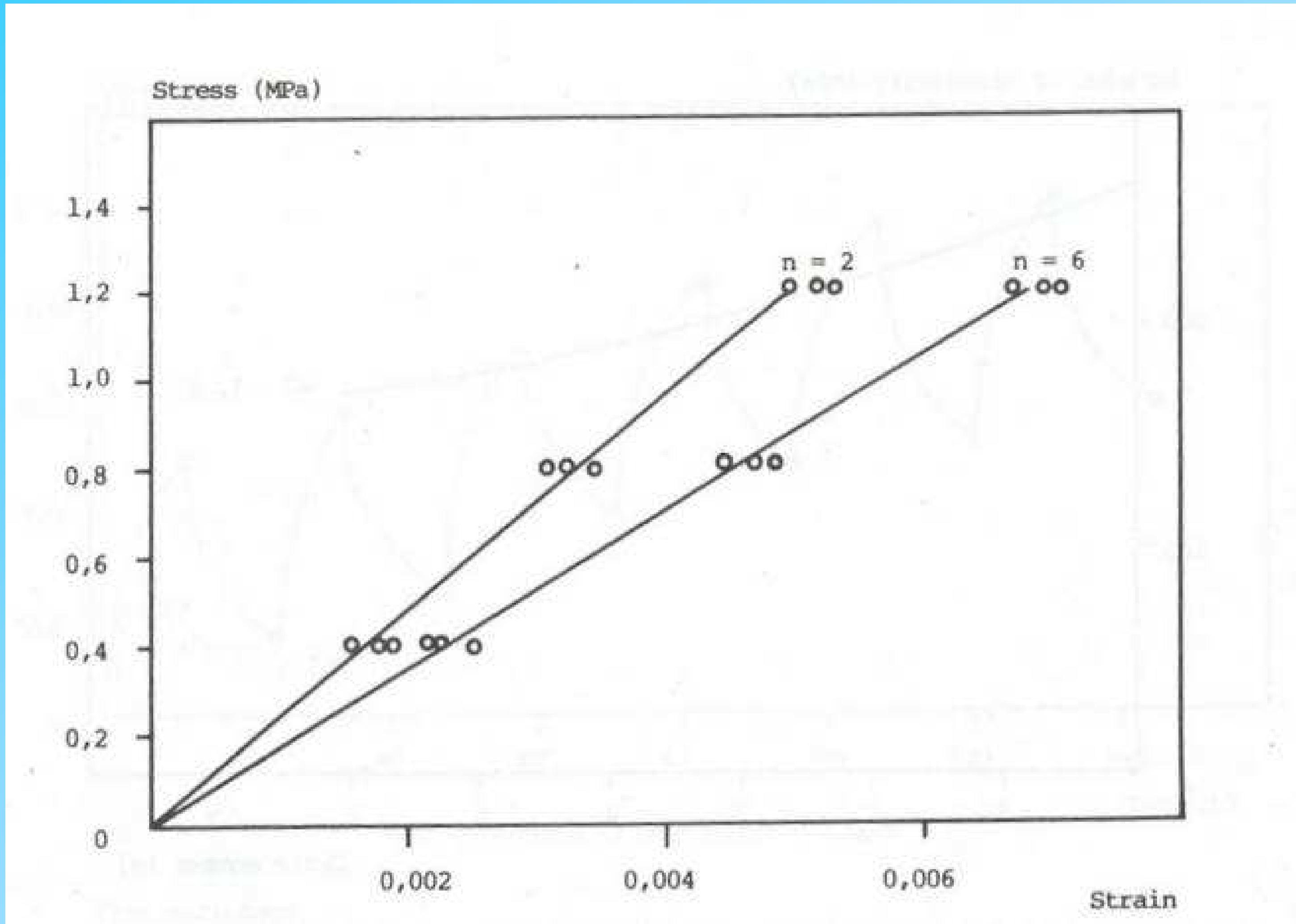
E – stiffness modulus

t – temperature decrease from 100 °C

w – moisture content

Decreasing of Wood Stiffness at Hygrofatigue

(Уменьшение жесткости древесины при гигроусталости)



n– number of sorption–desorption cycles: MC from 12 to 20 %
Picea abies; tangential direction across the grain

Wood Deformative Conversions at Change of Moisture and/or Content or Temperature

(Деформационные превращения древесины при изменении влажности и/или температуры)

Free hygro- (ε_w) and thermo- (ε_t) strains	Hygromechanical (ε_{hm}) and thermomechanical (ε_{tm}) strains				
Before loading	At loading				
(a) change moisture content (w) or temperature (t)	(b) constant w or t	(c) single change w or t	(d) single simultaneous change w and t	(e) cyclical change w or t	(f) cyclical simultaneous change w and t
hygroscopic: swelling shrinkage *temperature:* expansion contraction	elastic ε_e viscous ε_v creep ε_c	elastic ε_e viscous ε_v creep ε_c *drying* hygrofrozen ε_{hf} *cooling* thermofrozen ε_{tf} *wetting* wetloaded ε_{wl} *heating* thermoloaded ε_{tl}	elastic ε_e viscous ε_v creep ε_c *drying and cooling* hygro-thermofrozen ε_{htf} *wetting and heating* wet-thermoloaded ε_{wtl}	elastic ε_e viscous ε_v creep ε_c hygrofatigue ε_{hF} thermofatigue ε_{tF}	elastic ε_e viscous ε_v creep ε_c hygro-thermofatigue ε_{htF}
	At unloading				
	elastic ε_e viscous ε_v residual ε_r	elastic ε_e viscous ε_v set ε_s	elastic ε_e viscous ε_v set ε_s	elastic ε_{eF} viscous ε_{vF} set ε_{shF} , ε_{stF}	elastic ε_{eF} viscous ε_{vF} set ε_{shtF}

Wood Strains at Drying or Wetting

(Деформации древесины при сушке или увлажнении)

hygro	mechanical	hygromechanical	
Before loading	At loading		
free shrinkage $\beta = K_\beta (W_1 - W_2)$ $W_1 > W_2$ $W_i < W_{fsp}$ free swelling $\alpha = K_\alpha (W_1 - W_2)$	elastic ε_e viscous ε_v creep ε_c plastic ε_p	Drying Shrinkage of loaded wood (constrain shrinkage) $\beta' = K'_\beta (W_1 - W_2)$, где $K'_\beta = \hat{K}'_\beta$ - at tension $K'_\beta = \check{K}'_\beta$ – at compression $\hat{K}'_\beta < \check{K}'_\beta$	Wetting Swelling of loaded wood $\alpha' = K'_\alpha (W_1 - W_2)$, here $K'_\alpha = \hat{K}'_\alpha$ - at tension $K'_\alpha = \check{K}'_\alpha$ – at compression $\hat{K}'_\alpha > \check{K}'_\alpha$ ε_{wl} - wetloaded elastic-viscous strain ε_{wc} - wet-creep strain $\varepsilon_{c1} > \varepsilon_{c2}$ ε_{wp} - wet-plastic strain $\varepsilon_{p1} > \varepsilon_{p2}$
	At unloading		
	elastic ε_e viscous ε_v creep ε_c plastic ε_p residual $\varepsilon_r = \varepsilon_c + \varepsilon_p$	at tension reduced shrinkage (hypo-shrinkage) $\hat{\beta}^* < \beta$ at compression hyper-shrinkage $\check{\beta}^* > \beta$	at tension hyper-swelling $\hat{\alpha}^* > \alpha$ at compression hypo-swelling $\check{\alpha}^* > \alpha$
		frozen shrinkage $\beta_f = \beta - \beta^* - \varepsilon_s$ frozen elastic-viscous strain $\varepsilon_f = \varepsilon_{ev1} - \varepsilon_{ev2} = \varepsilon_{lw}$ set strain $\varepsilon_s = \varepsilon_f + \varepsilon_r = \varepsilon_f + \varepsilon_c$ total frozen strain $\varepsilon_F = \varepsilon_f + \varepsilon_c + \beta_f$	

Classification gives an opportunity to consider it as a peculiar Mendeleev's table and detect “blank spots”, lay out research programs. Further research of deformative conversions will permit to improve wood technology and create new smart wood composites.

Thank you for your attention