

CREEP BEHAVIOUR OF WOOD AND WOOD-BASED MATERIALS: RECENT ADVANCES IN THE STATE-OF-THE-ART AND OPEN QUESTIONS

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Abstract:

The rheological properties of wood and wood-based materials are becoming increasingly important both in timber construction, and in furniture and interior design. The topic has already been intensively researched in the 1970s and 1980s. In the context of work on modelling stresses and deformations, and the development of new engineered wood products (EWPs), investigations in this topic have been intensified in recent years. Several projects are ongoing, mostly concerning basic research on the rheological properties on solid wood. The objective of this study was to give an update on the state-of-the-art on creep behaviour of wood and wood-based materials, and to present some research questions relevant for the further development of the field. Characteristic values for K_{def} , i.e. correction factors to be taken into account due to creep of the material according to Eurocode 5, are usually used as a characteristic value in the timber construction. Because of the following reasons, basic studies on rheological properties of wood and wood-based materials are still largely lacking:

- *the development of new EWPs, especially from hardwoods,*
- *the use of new adhesive systems and the related change in adhesive properties,*
- *the reduction of formaldehyde content in adhesives for particleboard and medium-density fibreboard (MDF), and*
- *the increased use of waste wood and recycled wood in particleboard production (up to 100% particles may be based on waste wood or recycled wood).*

Key words: adhesives; influencing factors; recycled wood; rheological properties; wood-material parameters.

INTRODUCTION

Solid wood and wood-based materials are viscoelastic materials, i.e. all material properties such as modulus of elasticity (E), shear modulus (G), and Poisson's ratio (ν) are time dependent. Early studies in creep behaviour and on fatigue strength started in the 1970s focusing on particleboard, medium-density fibreboard (MDF) and solid wood (Gressel 1971, 1983, Niemz 1982, Dinwoodie *et al.* 1990a,b, Popper *et al.* 1999, Dinwoodie 2000, Fan *et al.* 2006). Since the re-introduction of multi-storey timber construction in the 1990s, the number of studies related to creep behaviour of wood-based materials and connections used in timber construction has increased, especially during the last ten years. For multi-storey timber buildings, consideration of creep deformation due to compressive stresses caused by a dead weight is mandatory. The creep strength of timber and the creep behaviour of different types of connections such as the TS3 connection, a new type of adhesively edge-joined connection system (<https://www.ts3.biz/en/technologien/>) or screw connections are also gaining importance. Extensive studies are currently being carried out on timber connections at for example the MPA Stuttgart (Stuttgart University, Germany). More information about wood connections and dynamic loading can be found in Ehlbeck *et al.* (1989).

Gong (2022) presents an overview of the consideration of the necessary deformations due to shrinkage and creep in timber construction. Eurocode 5 (CEN 2012) contains characteristic values for correction factor (K_{def}) to be taken into account due to creep of the material (Blass *et al.* 1995, Hoffmeyer 1995) as well as for the creep strength (K_{mod}). Reduction factors for the fatigue strength (K_{fat}) are also specified in Eurocode 5 (Niemz and Sonderegger 2021). A good compilation of the state of the art of

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characteristic values for the calculation of timber constructions in mechanical engineering was recently published by Wagenführ (2022).

In the 1970s, correction factors for the consideration of creep in the dimensioning of furniture made of wood-based materials (mainly particleboard and MDF) were used in the former German Democratic Republic (GDR). In the standards of that time (Technische Normen, Gütevorschriften und Lieferbedingungen (TGL) standards), the correction factors for creep were determined based on the type of material, the surface layering on the base material such as high-pressure laminate or veneer, and the load level (TGL 1972).

Whereas in the 1970s creep factors of 0.60-0.62 were used for particleboard, updated measurements of creep show a need of creep factors in the range of 3-4. Studies of wood-based materials in buildings also showed a need of higher creep-factor values than specified in the standards, e.g. Eurocode 5 (Grönquist 2023).

In early studies on creep, a measurement period of 12 weeks was usually used to estimate the creep factor, today it is often 40 weeks. Selected measurements over very long periods (e.g. several years) showed the necessity of corrections of the creep factors used and the use of reliable methods for estimating the long-term behaviour from the experimental data obtained. A comparatively complete compilation of work on creep behaviour was undertaken by Gressel (1983). Since then, further developments of the of wood-based materials itself have been made by the industry.

The reasons for the changes in properties of wood-based materials over the past decades are complex, but three circumstances are important to mention:

- Changed material structure, especially for particleboard for which the density has, in general, been considerably reduced from 750-800kg/m³ in the 1970s (Kehr and Jensen 1975) to 600-650kg/m³ today (also considerably lower densities occur in e.g. furniture construction). For particleboard, the source of raw material has also changed, particularly in terms of the particle geometry. Sawdust from sawmills, waste from production, and virgin low-quality round timber was earlier the main source for particleboard manufacture. Today, up to 100% can be recycled wood from furniture, packaging, timber buildings, etc.

- Conventional adhesives with reduced formaldehyde content have in the last decades been introduced on the market and are now used for the manufacture of various EWPs. New bio-based adhesives have also been developed and are now showing increasing use in the particleboard production. These adhesives have in most cases completely different creep properties compared to older types of adhesives.

- The development of new EWPs such as laminated veneer lumber (LVL) from European beech and Norway spruce, cross-laminated timber (CLT), cross-laminated strand timber (CLST), compact density fibreboard (CDF), a MDF with a high adhesive content and a density above 1000kg/m³ produced by Swiss Krono.

Despite the new manufacture conditions that apply to many wood-based materials and EWPs, few studies on long-term behaviour have been carried out. One obvious reason is that the experiments are time consuming and costly. Existing modelling approaches, e.g. by Gressel (1986) and those found in Eurocode 5 are, however, still valid and can be used for a first updating material creep properties.

In addition to creep behaviour, relaxation (e.g. in EWPs with large cross-sections, CLT, prestressed structures etc.) as well as fatigue strength under static and dynamic loading (e.g. in timber highway bridges) are becoming more and more important in construction.

SYSTEMATIC OF RHEOLOGICAL PROPERTIES AND INFLUENCING FACTORS

Rheological properties include (Fig. 1):

- **Creep** - time dependent deformation of wooden beams, plates (flooring), and columns.
- **Stress relaxation** - relaxation of pre-stress, relaxation of stresses due to moisture variation or between bonded lamellae, relaxation of drying stresses (Popper *et al.* 1999; Niemz and Sonderegger 2021).
- **Creep rupture strength** – stress and strain values at failure after a period of creep deformation of a wooden element, but also in the broader sense (Hoffmeyer 1995, Smith *et al.* 2003).
- **Fatigue** - a dynamic property related to cyclic loading like vibration or swelling/shrinking over a very long period (see e.g. Roth 1935, Bodig and Jayne 1982, Mohr 2001, Smith *et al.* 2003, Clerc 2020, Ross 2021).

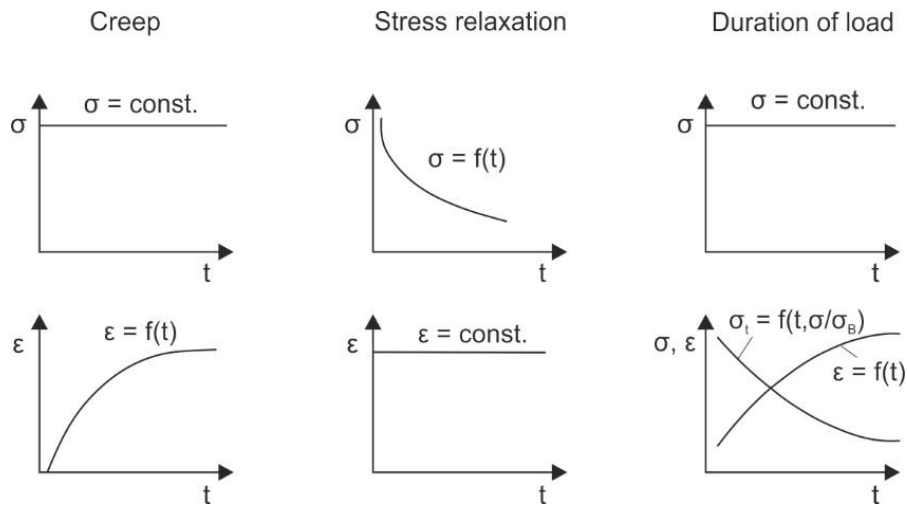


Fig. 1.

Systematics of the rheological behaviour of wood and wood-based materials under static load (Niemz and Sonderegger 2021). σ - stress, t - time, and ε - strain.

Important factors influencing the rheological behaviour are:

- The structure and properties of the wood material itself (species, fibre length, density, sorption behaviour, etc.) and type of wood-based material (Table 1).
- The duration of load (Fig. 1), the type and level of load (Figs. 2 and 3), and the evaluation method for estimating the long-term behaviour (Fig. 4 and Table 1).
- The type of adhesive used in the wood-based materials and EWPs (Figs. 5 and 6).
- The climate, i.e. temperature and relative humidity (RH), and mechano-sorptive effects related to RH changes (Fig. 7 and Table 2).

Characteristic values and important influencing factors are compiled in Tables 1-4 and Figs. 1-7. For more information to Eurocode 5 and K_{def} see also Blass *et al.* (1995).

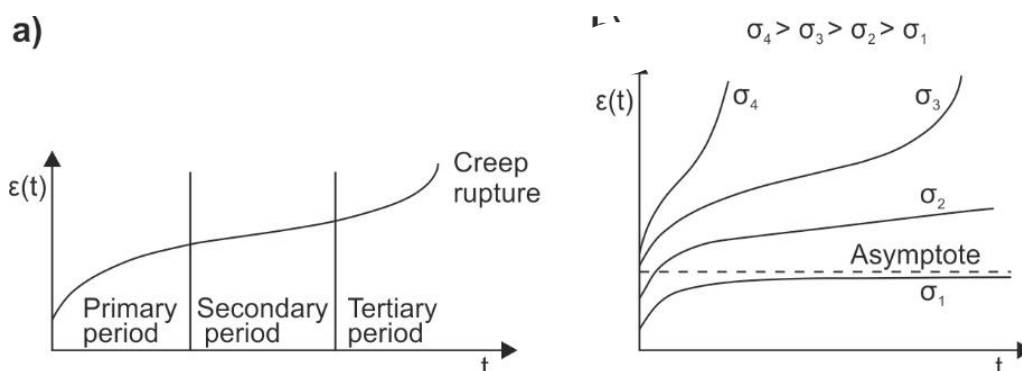


Fig. 2.

Deformation of wood under load as a function of time and load level (Odquist in Niemz 1982).

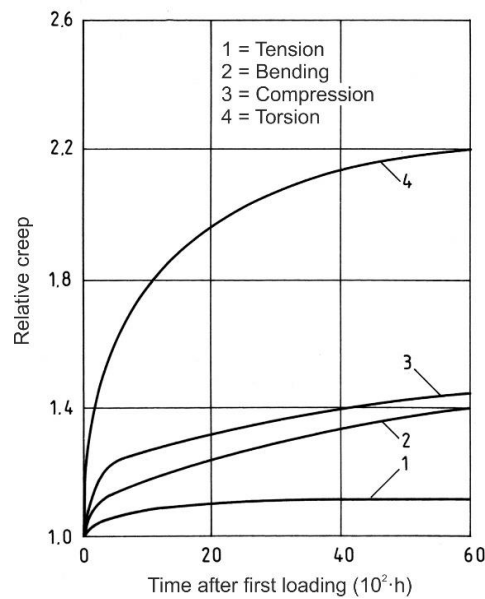


Fig. 3.

Influence of the type of load on the creep of Norway spruce (Gressel 1984).

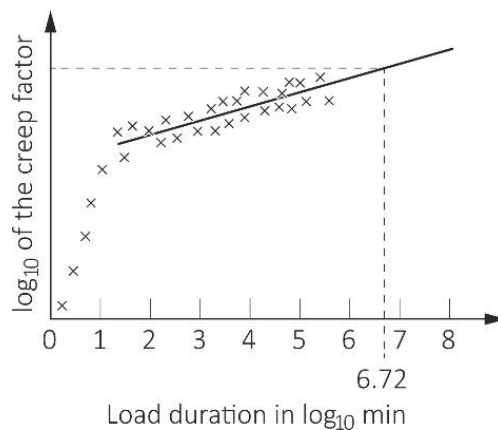


Fig. 4.

Methodology for estimating the creep factor after 10 years according to the EN 1156 standard (CEN 2013). The first 5 minutes are not considered.

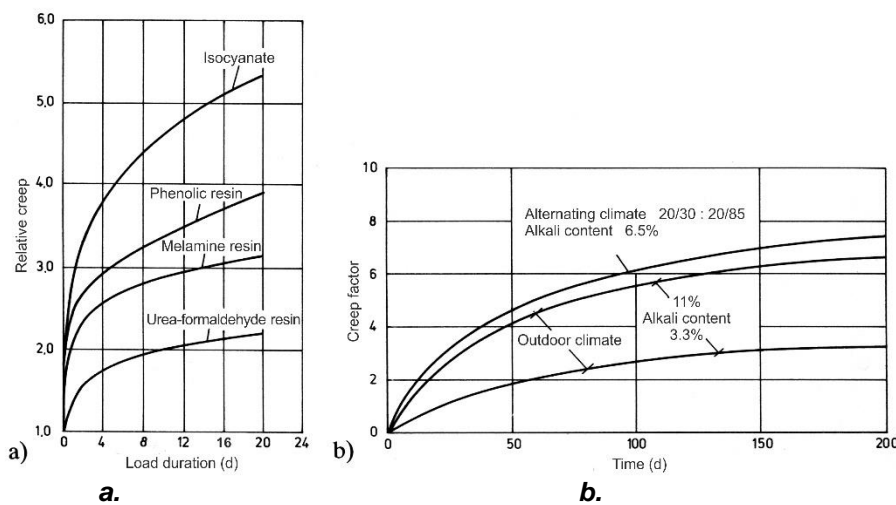
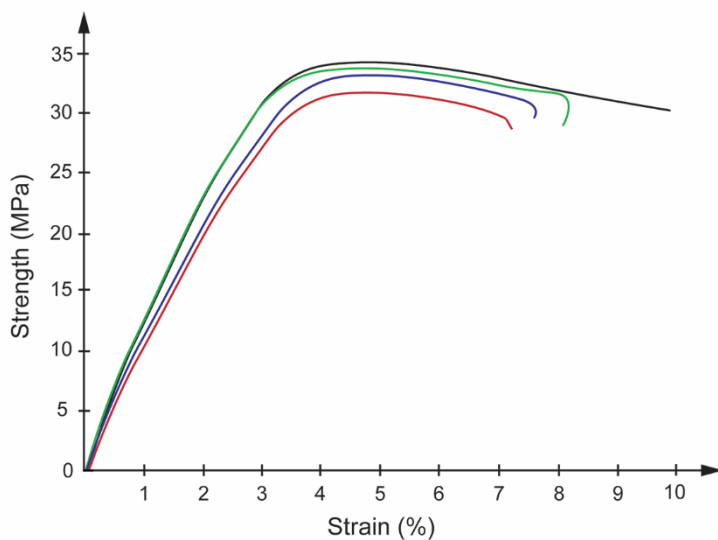


Fig. 5.

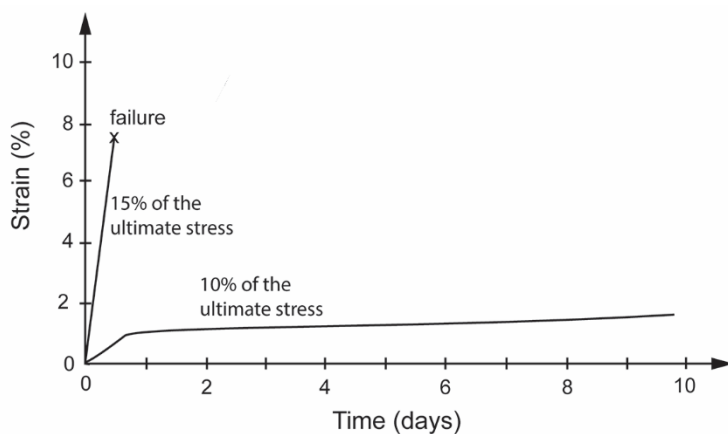
Creep in particleboard: a - influence of the type of adhesive, and b – influence of the alkali content of the adhesive on creep properties (Gressel 1984).



a.



b.



c.

Fig. 6.

Creep tests of adhesive films under tension and selected results (Bachtiar 2017, Bachtiar et al. 2022, unpublished works at ETH former chair of Wood Physics). a - test setup (adhesive films under test: strain and creep measurements with digital image correlation); b - stress-strain diagram from 1C-PUR (4 replicates); c - creep from bone-based adhesive under different load level, i.e. 10% and 15% of the ultimate tensile strength.

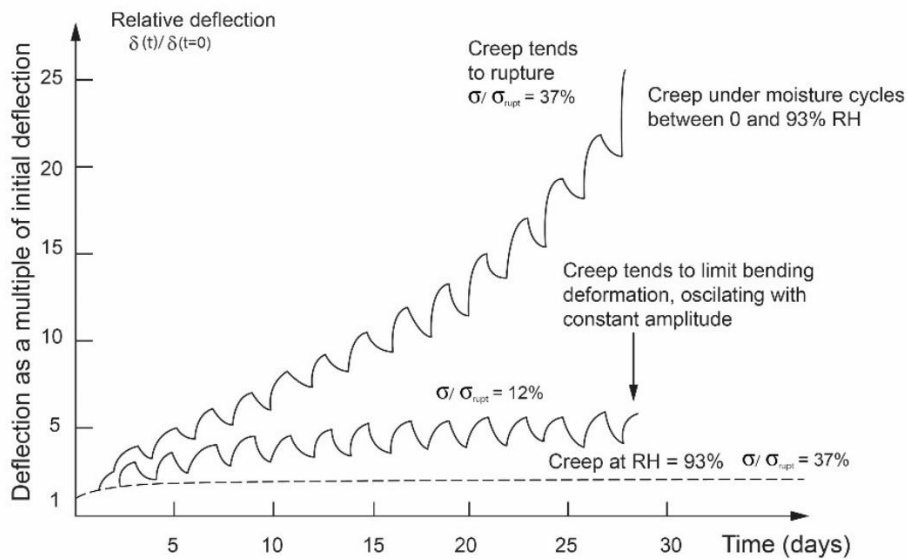


Fig. 7.

Creep of solid wood under constant and cycling (wet and dry) climate at different load levels (after Hearmon and Paton 1964 in Sandberg et al. 2021).

Table 1

Creep deformation¹⁾ in relation to the final deformation state of solid wood (Norway spruce, Scots pine) and wood-based materials under constant bending stress (20% of ultimate bending strength) at different duration of loading (Gressel 1984)

Material	Climate	Duration of loading				
		6 weeks	1.1 year	2.2 year	3.3 years	11 years
Solid wood	20°C/65%	40%	67%	73%	79%	100%
	Outdoor under roof	49%	70%	74%	79%	100%
Plywood	20°C/65%	22%	47%	59%	68%	100%
	Outdoor under roof	21%	47%	58%	68%	100%
Particleboard	20°C/65%	35%	61%	71%	79%	100%
	Outdoor under roof	20%	43%	54%	64%	100%

Creep deformation corresponds to creep factor φ

Table 2 shows the deformation factor (k_{def}) for deflection correction for the Services Classes defined in Eurocode 5 (CEN 2012). The Service Classes define strength values and can be used to calculate deformations of structural timber members under defined environmental conditions, and are defined as:

- Service Class 1 is characterised by a moisture content in the materials corresponding to a temperature of 20°C and the RH of the surrounding air only exceeding 65% for a few weeks per year. In Service Class 1 the average moisture content in most softwoods will not exceed 12%.
- Service Class 2 is characterised by a moisture content in the materials corresponding to a temperature of 20°C and the RH of the surrounding air only exceeding 85% for a few weeks per year. In Service Class 2 the average moisture content in most softwoods will not exceed 20%.
- Service Class 3 is characterised by climatic conditions leading to higher moisture contents than in Service Class 2.

Table 2

Deformation factor (k_{def})¹⁾ for deflection correction according to Eurocode 5/EN 1995-1-1 (CEN 2012)

Material	Type of panel	Service Class		
		1	2	3
Solid wood, glulam, LVL	-	0.60	0.80	2.00
CLT	-	0.80	1.00	-
Plywood	EN 636-1	0.80	-	-
	EN 636-2	0.80	1.00	-
	EN 636-3	0.80	1.00	2.50
OSB	OSB/2	2.25	-	-
	OSB/3, OSB/4	1.50	2.25	-
Particleboard	P4	2.25	-	-
	P5	2.25	3.00	-
	P6	1.50	-	-
	P7	1.50	2.25	-
Fibreboard: HDF ²⁾	HB.LA	2.25	-	-
	HB.HLA1/2	2.25	3.00	-
Fibreboard: MDF	MBH.HLA1/2	3.00	-	-
	MBH.HLS 1/2	3.00	4.00	-
MDF	MDF.LA	2.25	-	-
	MDF.HLS	2.25	3.00	-

1) K_{def} corresponds to creep factor φ ; 2) HDF - high-density fibreboard

Table 3

Creep parameters for solid wood, particleboard and MDF (Niemz and Sonderegger 2021)

Material	Creep factor φ
Solid wood	
- in fibre direction	0.1 ... 0.3
- perpendicular to the fibres	0.8 ... 1.2 ... 1.6
Particleboard with particles from	
- disc flaker (flat chips)	0.4 ... 0.6
- hammer mill (waste chips)	0.1 ... 2.0 ... 2.5
MDF	0.4 ... 0.6
High-density fibreboard (HDF)	0.5 ... 0.7
Plywood	0.3 ... 0.45

Table 4

Creep factors from different particleboards (Niemz 1996-2000, unpublished)

Particleboard	Density (kg/m ³)	Bending strength (N/mm ²)	Modulus of elasticity (N/mm ²)	Creep factor (φ) after number of days of loading:	
				182	659
Melamine coated 16 mm	634	18.9	3299	0.8	-
Melamine coated 19 mm	575	17.3	2616	0.9	2.1
Uncoated 16 mm	611	19.5	2947	0.7	1.8
Uncoated 19 mm	609	18.3	3070	1.1	2.3
Uncoated 24 mm	484	7.9	1261	0.8	1.7

TRENDS IN WOOD RHEOLOGY RESEARCH

Measurements have shown that creep deformation, especially for particleboards, is significantly higher today than some decades ago. There has also been an increased use of CLT and glulam in indoor climates where there is occasionally low RH in heated premises during the cold (below 0°C) winter period when RH below 20% and a high RH in the summer (often 50-70%). These climatic fluctuations lead to mechano-sorptive creep and increased cracking, where the stresses due to considerable shrinkage of the wood material in winter can only be partially reduced by relaxation. Some notable causes for the higher creep deformation wood-based materials and EWPs includes:

- Particleboards and MDF have been significantly advanced due to reduced density and reduction of UF resins content.

- New types of particleboards for special purposes, e.g. very high density and adhesive content such as the compact density fibreboard (CDF) from Swiss Krono (SWISS KRONO Tec AG, Luzern, Switzerland).
- Increased use of recycled wood in particleboard and thus changes in geometry and structure of the particles. Particles from waste-wood are produced in hammer mills which give another geometry and size than particles directly from industrial production (Table 1).
- The use of new adhesives, e.g. polymeric diphenylmethane diisocyanate (PMDI) adhesive for particleboard and bio-based adhesives which have altered sorption behaviour and creep-deformation properties (Dunky and Mittal 2023). In the case of PF-bonded particleboards (not so commonly used today), the alkali component has a clear influence on equilibrium moisture content of both the PF the resins and the particleboard itself (Fig. 5b). Also, classic adhesives such as PUR, MF, UF absorb moisture, as have been shown by Kläusler (2014) and Bachtiar *et al.* (2022). Reduced formaldehyde content in urea-formaldehyde (UF) adhesives, and further development of traditional UF/MUF-based adhesives by reducing the formaldehyde content changes the cross-linking process and thereby the creep behaviour.
- Ageing of adhesives, an issue not well investigated (Clerc *et al.* 2017).
- Development of new EWPs such as CLT, LVL from Norway spruce and European beech, increased use of glulam with large cross-sections and the development of adhesives specially designed for timber construction such as one-component polyurethane (1C-PUR), melamine formaldehyde (MF), melamine-urea-formaldehyde (MUF), phenol-resorcinol-formaldehyde (PRF), and emulsion polymer isocyanate (EPI) adhesives (Niemz *et al.* 2015).
- Development of new material combinations such as hybrid wood-concrete flooring elements, see e.g. Eisenhut (2015) and Chapter 35 in Niemz *et al.* (2023).

SELECTED ONGOING WORKS ON RHEOLOGICAL PROPERTIES

Creep and wood physics in general are not in the focus of current wood research, and there are few or no funding opportunities. The focus in wood-science research today is rather on subjects related to functionalisation of wood, wood modification, and biological aspects. The research is often on a relatively basic level with quick results, which mainly is a result of the today predominant time limit for dissertations (3-4 years).

Long-term tests are time-consuming and cost-intensive for both labour and for equipment. In addition, the scientific output (H-factor, number of citations etc.) is not as high as in the basic research areas. Publications are also presented in journals outside of the classical journals in the wood science and technology field. Nevertheless, there is some excellent ongoing research activities in the areas of wood rheology, characteristic values for orthotropy, and sorption behaviour. Some examples are:

- Earlier research by the Chair of Wood Physics at the ETH Zurich (Ozyhar 2013, Ozyhar *et al.* 2013, Hassani *et al.* 2015, Huc and Svensson 2018).
- On-going studies at ETH Zurich (currently 3 PhD works under the direction of Dr. F. Wittel) on the influence of the structural level.
- Work at the Uppsala University, Sweden, directed by Dr. K. Gamstedt (PhD thesis by Rhodel Bengtsson in the end of 2023).
- Research at InnoRenew CoE in Slovenia and at Luleå University of Technology on creep in densified wood (Han and Sandberg 2019, Han *et al.* 2022a,b).
- Work in Sweden under the direction of Dr. S. Svensson (University College of Borås, Sweden) concerning orthotropy of viscoelastic properties.
- Studies at the University of Main, USA on creep in glulam.
- Industrial projects in the wood-based panel industry in Germany by IHD Dresden and WKI Braunschweig.
- Research at Rosenheim University of Applied Sciences on creep in particleboard, under the direction of Dr. T. Leps.
- In situ measurements at the ETH House of Natural Resources in Zurich of creep in LVL made of European beech under the direction of Dr. P. Grönquist.
- Studies of reinforcement of wood and wood-based panels with fibres and various types of adhesives. A cooperation between University Göttingen (Dr. C. Mai) and Technische Universität Dresden - TU Dresden (Dr. M. Zauer).

There are ongoing studies at the State Key Laboratory of Tree Genetics and Breeding, Research Institute of Wood Industry, Chinese Academy of Forestry in Beijing, P. R. China on the creep behaviour of wood using dynamic mechanical analysis (Jiang and Lu 2009, Chapters 8 and 9 in Niemz *et al.* 2023). There are also several important studies published over the last few decades by e.g. Gressel (1983, 1986),

Ehlbeck and Belchior-Gaspar (1989), Dube (1999), Hering (2011), Hering *et al.* 2012, Reichel (2015), Svensson (2018), Niemz (2021).

CONCLUSIONS

Expanding the knowledge and understanding of some “key areas” of wood rheology is critical to advance our knowledge of creep behaviour, providing valuable addition to the existing pre-knowledge. This will help our understanding of material behaviour in the long-term and contribute towards higher-performing wood and wood-based products. The following critical key areas regarding creep properties in wood, wood-based materials and EWPs are identified:

- Systematic determination of characteristic values for new and further developed wood-based materials and EWPs with focus on materials used in the timber construction such as. CLT, glulam, LVL, and wood-concrete elements.
- Systematic determination of characteristic values for creep and its influence of orthotropy, especially for mechano-sorption, for different species of solid wood.
- Systematic determination of characteristic values for creep of adhesives and glued timber elements, with focus on the new generations of adhesives, (modified UF, MUF resin, modified polyurethane and MF resins for structural applications, biobased adhesives).
- Time estimation of the creep factors and of the creep rupture strength, fatigue, and reliable short-term methods for extrapolation.
- Characteristic values for fatigue under dynamic loading.

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