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PARAMETER DETERMINATION AND PERFORMANCE COMPARISON OF THE RHEOLOGICAL MODELS FOR CREEP IN PARTICLEBOARD

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ABSTRACT

A rheological model presents the stress-strain relationship in a material throughout the entire exploitation period. The change of the properties of a stressed and strained material in the time domain could be assessed on the basis of the rheological model. This paper focused on the determination of model parameters and the comparison of several rheological models for particleboard coated with melamine foil. The model parameters were defined for four models: the purely mathematical power-law model (two-parameter) and two viscoelastic models, i.e., the Zener (three-parameter) and Burger (four-parameter) models, as well as a semi-empirical modified Burger (five-parameter) model. The performance of models was compared in two ways: (i) according to the fit to the experimental data and (ii) according to the better total strain prediction. The power-law and modified Burger models stood out as the best. The modified Burger model achieved better fitting to the experimental data, and the power-law model was slightly better at making predictions.

Keywords: rheological model, viscous creep, particleboard

1. INTRODUCTION

Mechanical properties of wood and wood-based materials vary over time because they depend on the conditions of exploitation (temperature, humidity, etc.), but they are also highly dependent on the duration and rate of loading. That is why many studies have dealt with the influence of time-dependent effects on the mechanical properties of wood and wood-based materials during the second half of the 20th century and up until today (e.g., Clouser, 1959; McNatt, 1975; Gerhards, 1977; Laufenberg, 1987; Laufenberg, 1988; Holzer, Loferski, and Dillard, 1989; Gerhards, 1991; Hunt, 1999; Laufenberg, Palka, and McNatt, 1999; Nielsen, 2006; Mirić-Milosavljević, 2012; Mirić-Milosavljević, 2015; Mirić-Milosavljević et al., 2019; Mihailović et al., 2022).

The duration-of-load effect refers to changes in stress and strain that occur over time under the impact of external load. These changes are very important for all engineering materials, including wood and wood-based materials that are installed into building structures, furniture, or interiors. Changes in stress and strain that occur over time can be represented by constitutive equations that are used for a particular rheological model and type of material and have their own specific parameters. In engineering practice, we commonly use constitutive equations that do not include all types of strain (elastic, viscous, viscoelastic, or plastic), but only the strains that prevail. In particleboards, the strain develops from an instantaneous elastic strain into a time-dependent viscous and viscoelastic strain and all the way to a plastic strain. During the period of particleboard exploitation, it is desirable that its properties remain in the domain of viscoelasticity, because this means that there will neither be material fractures nor excessive strains that endanger the stability of the structure.

Two types of changes that occur over time are typical for viscoelastic materials, and those are a change in strain at constant stress, i.e., viscous creep, and a change in stress at constant strain, i.e., the relaxation of stress. The simplest uniaxial tension or compression tests are commonly used methods for creep testing. However, three-point and four-point bending creep testing is often used because in this type of test the deformation is larger and therefore easier to measure than in the case of uniaxial stress. Creep testing can be performed in two ways: data in the given time range is recorded and then extrapolated outside that range, or special methods are used to speed up or slow down the viscoelastic process (by changing the stress level, temperature, or humidity), and then the time scale is empirically modified for a longer period of time. Both approaches are semi-empirical, and the obtained data may be more or less accurate.

Numerous rheological models have been used to model the particleboard creep phenomenon, ranging from the linear, power, exponential, and polynomial models to the viscoelastic model. Pierce and Dinwoodie (1977) and Pierce, Dinwoodie, and Paxton (1979) used the viscoelastic three- and four-parameter models to describe properties in different chipboards. They came to the conclusion that one of the parameters of the Burger model is not constant but can vary over time. That study lasted for 26.5 months. Further, based on tests that lasted for 44 months, Pierce, Dinwoodie, and Paxton (1985) came to the conclusion that the four-parameter Burger model is a good predictor of viscoelastic properties for the 30% stress level (relative to the maximum stress that leads to fracture) and for a period of 6 months, while it showed much higher strains than the actual ones after that time. Deviations were smaller for the 60% stress level. In order to reduce deviations from the actual strains that occur after a long period of time, these authors proposed to modify the Burgers model so that the viscous component is nonlinear with respect to time in order to gradually reduce the strain rate, and thus a new semi-empirical five-parameter model was obtained. The modified Burger model gives a more accurate overall strain than the Burger model but does not reveal a clear (elastic, viscous, or viscoelastic) strain structure. Dinwoodie et al. (1990) compared the prediction of deflection after 7 to 10 years according to the Burger model and modified Burger model on the basis of an experiment with particleboard specimens that lasted for 24 weeks. The modified Burger model's errors, when compared to the actual deflection, were within an acceptable range of +23% to -26%. However, in the case of the Burger model, the errors were in the range from +170% to +430%. These authors also found that an extension of the experiment duration to 39 weeks would reduce the error by half. Mundy et al. (1998) suggested using a 6-month-long experiment to determine the model parameters. They found that the model parameters obtained from such an experiment can be used to predict strain with great certainty even after 12 years. Following research by Pierce, Dinwoodie, and Paxton (1985), Dinwoodie et al. (1990), and Mundy et al. (1998), BS DD ENV 1156 was issued in 1999 as a standard that refers to the determination of duration of load and creep factors for wood-based panels. According to that standard, a minimum of 26 and a maximum of 52 weeks were proposed for the duration of the experiment. The recommended experiment duration according to BS DD ENV 1156 (1999) is demanding to perform in practice, while it also increases the price of the experiment. For this reason, some authors have tried to reduce the duration of measurements, e.g., Chen and Lin, 1997 (experiment duration 30 days); Fan et al., 2006 (experiment duration 14 days); Palija et al., 2006 (experiment duration 7 days); Houanou, Tchéhouali, and Foudjet, 2014 (experiment duration 15 hours and creep prediction in 60 hours).

According to Albin et al. (1991), after seven days, approximately 80% of the final particleboard deflection can be regarded as having already been achieved in practical use. It is further stated that because of that, according to DIN 68874 (1985), which refers to shelves and shelf supports of cabinet furniture, the prescribed load in standardised shelf creep testing is a uniformly distributed load lasting 28 days. It should be noted that, in most of the aforementioned studies, the bending creep test setup was a simply supported beam, symmetrically loaded with one or two concentrated loads, and that the actual load, especially for cabinet furniture elements (e.g., shelves), is very often in the form of a uniformly distributed load (DIN 68874, 1985; Tankut, Tankut, and Karaman, 2012).

The main idea in this research was to examine the possibilities of bending creep modelling of particleboard under conditions that are similar to the real conditions of use of cabinet furniture shelves. The dimensions of the specimens, as well as the type and level of load, were selected according to this principle. The bending creep was modelled using four rheological models: a two-parameter (power-law) model, a three-parameter (Zener or standard linear solid) model, a four-parameter (Burger) model, and a five-parameter (modified Burger) model. After the estimation of the parameters, the models were compared in 2 ways: (i) based on the fit to the experimental data and (ii) according to the better total strain prediction after 28 days. For the purpose of assessing the predictive capability of the model, the assumption was adopted (Albin et al., 1991) that the measured deflection after 7 days was 80% of the total deflection reached on day 28.

2. MATERIALS AND METHODS

2.1 Material

For the purpose of the experiment, a three-layer particleboard was used, coated with melamine foil, with a nominal thickness of 18 mm, exposed to uncontrolled atmospheric influences of the temperature and humidity at the warehouse. A total of 30 specimens were cut for different purposes (Table 1). The bending strength and modulus of elasticity were tested in both the parallel (designation ‖) and perpendicular (designation ⊥) directions of the board.

Table 1: *Number and dimensions of specimens, standard/type of test, and physical property to be determined*

Number of specimens	Dimensions (mm)	Standard or test type	Physical property to be determined
6	50 x 50 x 18	EN 323 (1993)	Density
4	50 x 50 x 18	EN 322 (1993)	Moisture
6 ‖	350 x 50 x 18	EN 310 (1994)	Bending strength and modulus of elasticity
6 ⊥	350 x 50 x 18	EN 310 (1994)	Bending strength and modulus of elasticity
8 ⊥	850 x 350 x 18	Creep testing	Deflection, bending strength and modulus of elasticity

The dimensions of the creep testing specimens were selected to match the dimensions of cabinet furniture shelves. The specimens for creep testing were cut in the direction perpendicular to the fibres, as this is a direction with poorer characteristics. After cutting, all the specimens were conditioned by being kept in chambers with low temperature and humidity variations for 10 days. The air temperature in the room, where the experiment was subsequently conducted, reached within 27 ± 5 °C, whereas the humidity was in the 71 ± 4% range.

For creep testing, the specimens were placed on horizontal supports so that the overhangs were symmetrical. Comparators for deflection measurement were placed in the midspan of the specimens. The supports span was 0.8 m, and the specimens were loaded with a uniformly distributed load in the form of sand-filled bags from which air was removed (Figure 1).

Figure 1: *The testing method for bending creep behavior*

Three load levels were selected to correspond to the load range prescribed for classes L25 and L50 according to the standard for testing shelves in cabinet furniture, DIN 68874 (1985). The magnitudes of uniformly distributed load and load durations by specimens are shown in Table 2. The deflection was measured after 1, 5, 10, 50, 100, 500, and 1440 min from the load applying and then once daily. For the specimens loaded with 14 kg, the load duration was 14 days, and for the ones loaded with 19.6 kg and 25 kg, it was 7 days. Already after 100 minutes, a large deflection, which was beyond the range of the measuring instrument, was measured on specimen 5, and inconsistent results were recorded on specimen 6, which was the reason to exclude those two specimens from further consideration.

Table 2: *The duration and load levels on the creep testing specimens*

Specimen no.	Sand mass	Total load (sand and self-weight)	Total load per unit area	Total load per unit length	Stress in the midspan $max\,\sigma_z = \sigma_0$	Duration of load
	(kg)	(N)	(N/m2)	(N/m)	(MPa)	(days)
1	14	171.63	613	214.53	0.908	14
2	14	171.68	613	214.59	0.908	14
3	25	279.19	997	348.99	1.477	7
4	25	279.24	997	349.05	1.477	7
5*	14	171.14	611	213.92	0.905	14
6*	19.6	226.07	807	282.59	1.196	7
7	19.6	225.92	807	282.41	1.195	7
8	14	171.09	611	213.86	0.905	14

* Specimens excluded from further consideration.

2.2 Methodology

Four rheological models were used to show the relationship between stress and strain, and those were the power-law (two-parameter) model, the Zener (three-parameter) model, the Burger (four-parameter) model, and the modified Burger (five-parameter) model. Equations (1-4) show the mathematical formulations of strain development over time for all four models.

The power-law model:

$$\varepsilon(t) = \varepsilon_0 + a t^b. \tag{1}$$

The Zener model:

$$\varepsilon(t) = \frac{\sigma_0}{E_H} + \frac{\sigma_0}{E_K}\left(1 - e^{-\frac{E_K}{\eta_K}t}\right) = \beta_1 + \beta_2\left(1 - e^{-\beta_3 t}\right). \tag{2}$$

The Burger model:

$$\varepsilon(t) = \frac{\sigma_0}{E_H} + \frac{\sigma_0}{E_K}\left(1 - e^{-\frac{E_K}{\eta_K}t}\right) + \frac{\sigma_0}{\eta_N}t = \beta_1 + \beta_2\left(1 - e^{-\beta_3 t}\right) + \beta_4 t, \tag{3}$$

The modified Burger model:

$$\varepsilon(t) = \frac{\sigma_0}{E_H} + \frac{\sigma_0}{E_K}\left(1 - e^{-\frac{E_K}{\eta_K}t}\right) + \frac{\sigma_0}{\eta_N}t^{\beta_5} = \beta_1 + \beta_2\left(1 - e^{-\beta_3 t}\right) + \beta_4 t^{\beta_5}. \tag{4}$$

In the above equations, ε_0 represents instantaneous deformation (the first recorded data), $\varepsilon(t)$ deformation at an arbitrary moment of time t, and σ_0 is a constant applied stress (Table 2). Coefficients a, b, β_1, β_2,..., β_5 are parameters of the model. The power-law model is purely mathematical, and coefficients a and b in Equation (1) have no physical meaning. Parameters β_1 and β_2, as can be seen from Equations (2)–(4), have physical meaning and represent a deformation: the elastic deformation (β_1) and the viscoelastic deformation (β_2). Parameters β_3 and β_4 also have physical meaning: the reciprocal value of parameter β_3 represents retardation time, while the reciprocal value of parameter β_4 is the time it takes for viscous deformation to develop. Parameter β_5 has values $0 \leq \beta_5 \leq 1$, and no physical meaning. Thus, models (2) – (4) allow the estimation of the following material parameters from the experiment: the initial modulus of elasticityE_H, the viscoelastic modulus E_K, the dynamic viscosity of the viscoelastic part of the model η_K, and the dynamic viscosity of the viscous part of the model η_N, as well as the aforementioned characteristic times.

Retardation time τ_r is an important parameter that has a physical meaning and represents the critical time required for changes in the molecular structure of the material to occur under the action of external load and for a new equilibrium state to be established at the molecular level, i.e., for a second-order phase transition (non-adiabatic) to occur. Different names can be found in the literature for parameter τ_r, such as retardation time (Ferry, 1980; Shaw and MacKnight, 2005), creep time (Lakes, 2009), or viscous creep time (Mirić-Milosavljević, 2012). The term retardation time will be used here. After reaching the retardation time, further changes, such as a small subsequent increase in strain under the action of external load over time, are not critical, as they do not lead to a change in molecular structure. Retardation time is also the time that can help estimate the minimum required duration of the experiment.

For a simply supported beam (with a rectangular cross-section of height h and beam span ℓ), loaded with a uniformly distributed load, the measured deflection $f(t)$, was converted into a longitudinal deformation $\varepsilon(t)$ according to the equation:

$$\varepsilon(t) = (24h/5\ell^2)\cdot f(t). \tag{5}$$

Based on the experimental data, the parameters of the rheological models in Equations (1)–(4) were estimated using the GRG nonlinear solving method in Excel's Solver add-in. The performance of the established rheological models was compared in two ways: (i) according to the fit to the experimental data and (ii) according to the better prediction of creep deformation after 28 days.

After fitting data with four nonlinear theoretical models and visually examining the fitted curves, goodness-of-fit was assessed based on two quantitative measures: the Sum of Squared Residuals (SSR) and Residual Standard Error (RSE). The estimation of the non-linear regression model parameters in the solving method used is based on the method of least squares, i.e., minimising SSR. RSE was calculated through SSR and the number of experimental data, but the number of model parameters was also taken into account.

In the second phase, the prediction potential of each of the models was examined. Prediction means that the theoretical model, whose parameters are estimated by fitting to experimental data in a certain time range, is extrapolated into the future. The idea in this paper was to obtain performance assessment for each model, as well as to compare the models regarding prediction in the near future (2-4 times longer than the duration of the experiment). Due to the fact that there were no measurements longer than 14 days to compare the results of the model, following the statements from Albin et al. (1991), the assumption was adopted in this paper that the measured deflection after 7 days was 80% of the deflection that would be reached on day 28. Therefore, based on the measurements, the predicted deflection and the predicted deformation after 28 days were easily calculated as $f_{28} = f_7/0.8$, and $\varepsilon_{28} = \varepsilon_7/0.8$. Here, f_7 and ε_7 are the measured deflection and deformation after 7 days. The model performance was assessed based on the differences between the predicted deflection, i.e., longitudinal deformation, f_{28} and ε_{28}, and the estimated deflection and deformation after 28 days obtained by the four rheological models, $\hat{f}_{28}$ and $\hat{\varepsilon}_{28}$.

3. RESULTS AND DISCUSSION

The basic physical characteristics of particleboard were determined according to the standards specified in Table 1. The measured moisture content and density of the specimens were 8.51 ± 0.13% and 638 ± 8.28 kg/m^3, respectively. The mean bending strength was 12.66 ± 0.82 MPa, and the modulus of elasticity was 3139 ± 66.51 MPa. The average specimen density for the bending creep experiment was 635 ± 4.15 kg/m^3, and the average mass was 3.46 ± 0.025 kg.

3.1 Fitting rheological models to experimental data

Figure 2 shows the development of deformation over time on all specimens: the experimental data (open circles) calculated using Equation (5) and fitted theoretical curves for the four models used. For each specimen, the experimental data and corresponding theoretical curve are displayed in the same colour. When observing the experimental data, the differences in the size of the deformation depending on the load level can clearly be seen in the figure. Specimens 1, 2, and 8, which were loaded with 14 kg each, had the lowest deformation, both initially and at a later time of measurement; the initial part is less steep, and the increase in deformation over time is slower than in the two specimens loaded with 25 kg each (specimens 3 and 4). Based on the visual examination of theoretical curves fit to the experimental data in Figure 2, it seems that the best model was the modified Burger model, followed by the power-law and Burger models, while apparently the worst one was the Zener model.

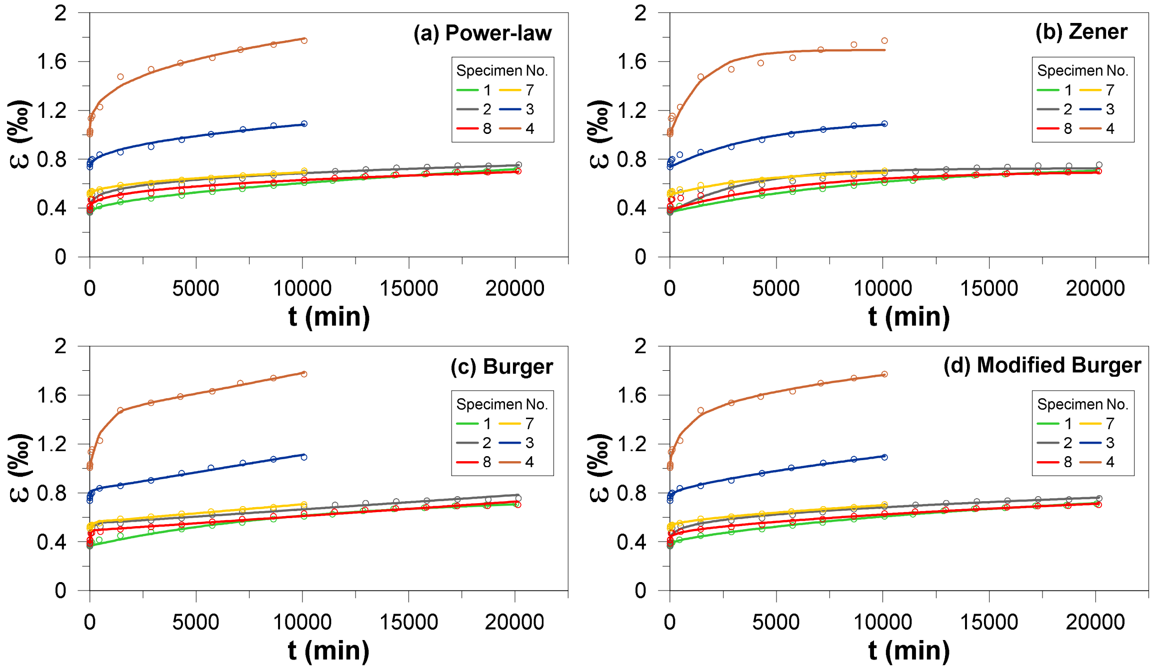

***Figure 2**: Experimental data (open circles) for all six specimens and corresponding fitted theoretical models (lines): (a) the power-law model; (b) the Zener model; (c) the Burger model; (d) the Modified Burger's model*

The results of parameter estimates, as well as goodness-of-fit (GoF) measures, sum of squared residuals (SSR), and residual standard error (RSE), for the power-law, Zener, Burger, and modified Burger models are shown in Table 3 for each specimen. Table 3 also shows the material parameters calculated through model parameters for the Zener, Burger, and modified Burger models (Eqs. 2–4).

It can be seen from the table that retardation time for the Zener model for specimens 2, 3, 4, 7, and 8 ranged from 1 to 4.27 days, and for specimen 1 it amounted to as much as 6.94 days. For the Burger's model for specimens 2, 3, 4, 7, and 8, it was from 0.02 to 0.36 days, and for specimen 1 as much as 6.03 days, and for the modified Burger's model it ranged from 0.49 to 65.57 days.

Table 3: *Fitted model parameters, material parameters and estimated GoF measures SSR and RSE of the power- law, Zener's, Burger's and modified Burger's models*

Model	Model and material parameters and GoF's	Specimen No. 1	2	8	7	3	4
power-law	*a* (10^3/day)	0.08081	0.19375	0.12420	0.07693	0.14411	0.39378
	b (-)	0.55934	0.26222	0.34690	0.44930	0.45399	0.35278
	SSR (‰)^2	0.0010679	0.0078971	0.0064494	0.0005535	0.0038207	0.0123774
	RSE (‰)	0.0077025	0.0209458	0.0189288	0.0070937	0.0186369	0.0335443
Zener	$_1$ (10^3)	0.36585	0.36315	0.38610	0.50895	0.73575	1.00575
	$_2$ (10^3)	0.39269	0.36245	0.31609	0.19490	0.38943	0.68897
	$_3$ (1/day)	0.14406	0.41803	0.23368	0.36575	0.31719	0.99291
	$^2{}_r$ (day)	6.94	2.39	4.27	2.73	3.15	1.00
	E_H (MPa)	2482.09	2501.26	2344.52	2348.69	2007.76	1469.02
	E_k (MPa)	2312.42	2506.07	2863.79	6133.24	3793.22	2144.45
	η_K (MPa·s)	1.39E+09	5.18E+08	1.06E+09	1.45E+09	1.03E+09	1.87E+08
	SSR (‰)^2	0.0038777	0.0561229	0.0236422	0.0030229	0.0123017	0.0431492
	RSE (‰)	0.0151030	0.0574574	0.0372924	0.0173866	0.0350738	0.0656881
Burger	$_1$ (10^3)	0.36585	0.36315	0.38610	0.50895	0.73575	1.00575
	$_2$ (10^3)	0.32960	0.18394	0.10594	0.05069	0.08796	0.43637
	$_3$ (1/day)	0.16569	25.13668	41.26481	14.77633	27.33819	2.77308
	(1/day)	0.00305	0.01690	0.016970	0.02108	0.04143	0.04868
	$^2{}_r$ (day)	6.03	0.04	0.02	0.07	0.03	0.36
	E_H (MPa)	2482.09	2501.26	2344.52	2348.69	2007.76	1469.02
	E_k (MPa)	2755.08	4938.31	8544.65	23580.35	16793.91	3385.81
	η_K (MPa·s)	1.44E+09	1.70E+07	1.79E+07	1.38E+08	5.31E+07	1.05E+08
	η_N (MPa·s)	2.57E+07	4.64E+06	4.61E+06	4.90E+06	3.08E+06	2.62E+06
	SSR (‰)^2	0.0037745	0.0040376	0.0032179	0.0006674	0.0020618	0.0153943
	RSE (‰)	0.0153592	0.0158854	0.0141816	0.0086114	0.0151356	0.0413580
Modified Burger	$_1$ (10^3)	0.36585	0.36315	0.38610	0.50895	0.73575	1.00575
	(10^3)	0.38535	0.31717	0.35609	0.49990	0.75808	0.17326
	$_3$ (1/day)	0.07711	0.01525	0.04305	0.02871	0.04761	2.0237
	(1/day)	0.04890	0.18191	0.10145	0.05828	0.09691	0.27827
	(1/day)	0.25693	0.23342	0.18228	0.27719	0.22201	0.38330
	$^2{}_r$ (day)	12.96	65.57	23.22	34.84	21.00	0.49
	E_H (MPa)	2482.09	2501.26	2344.52	2348.69	2007.76	1469.02
	E_k (MPa)	2356.49	2863.88	2542.12	2391.20	1948.61	8527.29
	η_K (MPa·s)	2.64E+09	1.62E+10	5.10E+09	7.20E+09	3.54E+09	3.64E+08
	η_N (MPa·s)	1.60E+06	4.31E+05	7.71E+05	1.77E+06	1.32E+06	4.59E+05
	SSR (‰)^2	0.0004276	0.0080683	0.0029651	0.0001746	0.0013333	0.0074514
	RSE (‰)	0.0053391	0.0231924	0.0140596	0.0046716	0.0129100	0.0305192

3.2 Comparison of models according to the goodness-of-fit measures

It is difficult to compare the results of GoF measures for all specimens and models, which are shown in Table 3. Therefore, those results were summarised in Table 4 in a way that shows only the ranks of individual models according to SSR and RSE (rank "1" indicates the best model, i.e., the one with the lowest SSR, i.e., RSE error, and so on). These results confirmed the initial conclusions drawn on the basis of the visual inspection of diagrams in Figure 2. The modified Burger's model was the best in all specimens, except specimen 2. The power-law model was the second best, whereas the Zener's model was the worst.

Table 4: *Ranking of the rheological models for all specimens according to the goodness-of-fit measures SSR and RSE*

Spec. No.	SSR				RSE			
	Power-law	Zener	Burger	Modif. Burger	Power-law	Zener	Burger	Modif. Burger
1	2	4	3	1	2	3	4	1
2	2	4	1	3	2	4	1	3
8	3	4	2	1	3	4	2	1
7	2	4	3	1	2	4	3	1
3	3	4	2	1	3	4	2	1
4	2	4	3	1	2	4	3	1

3.3 Comparison of models according to the creep prediction

The accuracy of a 28-day prediction of bending creep of the theoretical models was estimated here in relation to the target points-predicted deflection and deformation after 28 days, f_{28} and ε_{28}. The calculation procedure for f_{28} and ε_{28} was explained in the Methodology chapter. Figure 3 shows the experimental data (open circles) and target points ε_{28} (red crosses) for each specimen. The theoretical bending creep curves for 28 days (coloured lines) are shown next to them. These theoretical curves represent the prediction of 28-day bending creep based on 14-day creep data (specimens 1, 2, and 8) or 7-day creep data (specimens 7, 3, and 4).

Figure 3 shows the development of deformation over time, and for practical application it is also important to have data on the predicted deflection. The predicted deflection according to each theoretical model was calculated from the deformation using Eq. (5). Table 5 shows the predicted deflection after 28 days (f_{28}) for each specimen (target points), and the deflections calculated according to four theoretical models $\widehat{f}_{28}$. Relative errors of the model prediction in relation to f_{28} are also shown in parentheses. For each of the specimens, the results of the best model are bolded.

In general, Table 5 and Figure 3 show that the theoretical curves for the power-law and modified Burger's models are always between the curves for the Zener's and Burger's models. It is obvious that the predictions of deflection according to these two models are much closer to the target points than the predictions obtained using the Zener's and Burger's models. Only the results for specimen no. 1 deviated from this general conclusion. For other specimens, the Burger's model significantly overestimates the target points (between 19% and 45%), and the Zener's model significantly underestimates the target points (15% to 24%). The power-law model had the smallest error in three specimens, so it could be said that according to the prediction criterion, it was the best overall of all the investigated models. Admittedly, this model overestimated the target point by almost 17% in specimen 1, but for other specimens, the absolute value of the error did not exceed 4%. The Modified Burger model was the best in two cases, and its error was always lower than 10% in absolute value. This model generally slightly overestimated the target points.

In specimens loaded with a higher load, and the measurements that lasted for 7 days (specimens 3, 4, and 7), the power-law and modified Burger's models were much better than the Zener's and Burger's models. An explanation for the poor predictions of the Zener's and Burger's models can be found in the relatively short duration of the experiment, combined with the mathematical formulations of these models. Namely, coefficient β_2 in Eq. (2) of the Zener model is a key factor for the magnitude of the predicted deformation, since the sum $\beta_1 + \beta_2$ (β_1 is the initial deformation) represents the asymptote to which the creep curve (2) tends to approach, whose reliability is compromised when the duration of the experiment is short. In the Burger model, the last term in Eq. (3) gave a constant strain rate, and therefore this model overestimated the target points.

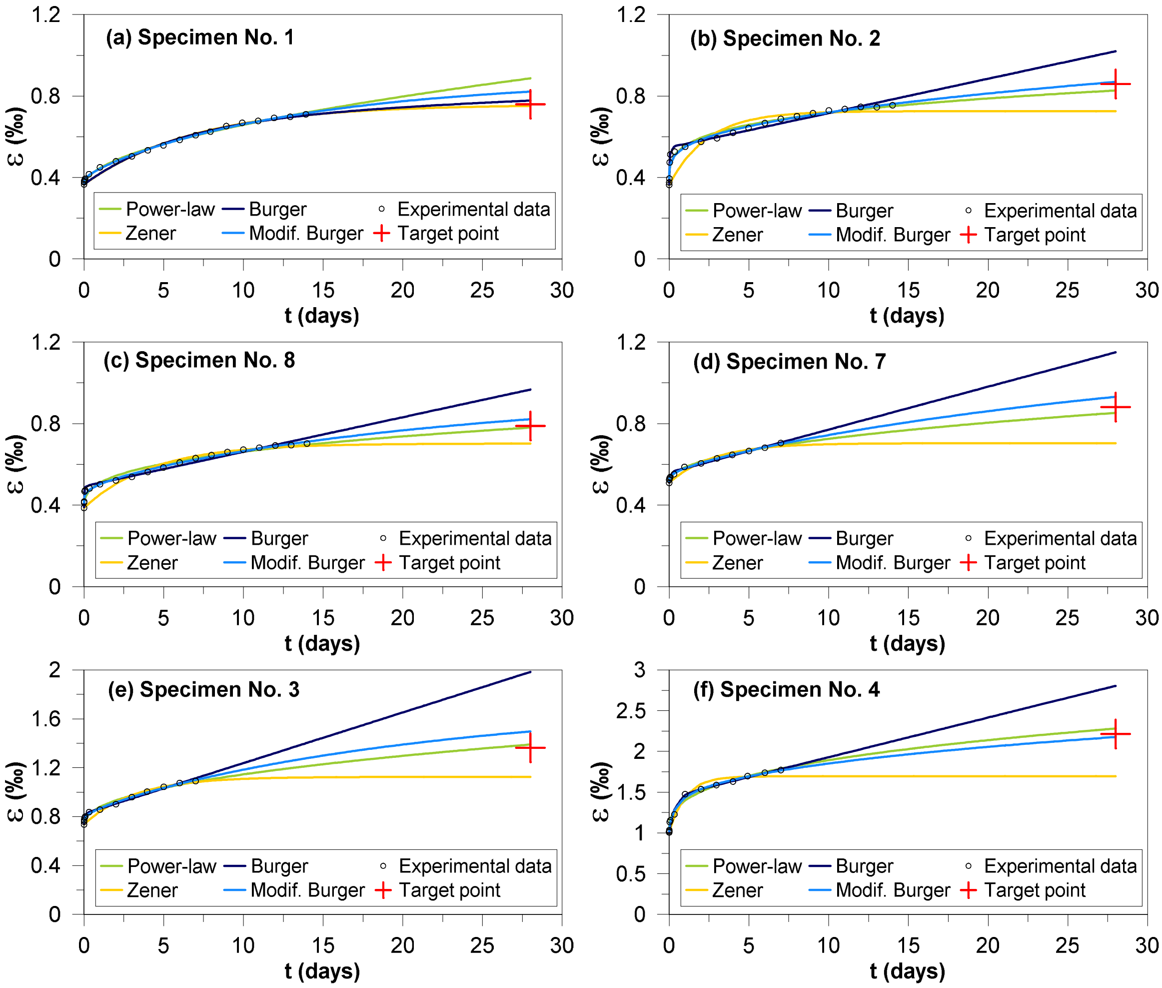

Figure 3: *Prediction of 28-day of bending creep based on 14-day creep data, (specimens 1, 2 and 8), or 7-day creep data (specimens 3, 4 and 7). For each specimen circles represent experimental data, the red cross represents the target point, and the coloured lines theoretical creep curves.*

For practical application, it is important to compare the predicted and measured deflection with the permissible deflection (DIN 68874, 1985), which is $\ell/100 = 8\,mm$ (where ℓ is the shelf span). Table 5 shows that for specimens 3 and 4, the predicted deflection f_{28} and predictions of the theoretical models $\hat{f}_{28}$ exceed the permissible deflection. Those specimens were loaded with 997 N/m^2, which corresponds to class L50 according to standard DIN 68874 (1985). In fact, the deflection measured after 7 days on specimen 3 slightly exceeded the permissible limit (8.08 mm), but for specimen 4 it amounted to as much as 13 mm. This was expected because at higher load levels, the viscoelasticity range is exited. For specimens loaded with lower levels of stress, neither $\hat{f}_{28}$ nor f_{28} exceeded the permissible deflection, except for the Burger model prediction for specimen 7.

All the results indicated that the power-law and modified Burger's models were the best. The modified Burger's model achieved a better fit to the experimental data, and the power-law model was slightly better at predicting. If those two models are compared, their characteristics should be taken into account, as well as the usability of the data that can be obtained after determining model parameters. The power-law model has only two parameters to be estimated, and it has not proved to be worse than the modified Burger model, which has as many as five. Therefore, the power-law model should be given priority if it is necessary to quickly and easily estimate the parameters of the model after a not-so-long measurement. This would be "a parsimonious modeling." On the other hand, the power-law model is purely mathematical and not related to the properties of the material. The modified Burger model is not purely physical, but properties of a material can be determined based on it (Eq. 4 and Table 3). This model is certainly not parsimonious, as it has as many as five parameters, but nowadays there are a number of software tools that can easily solve the problem of non-linear regression in complicated models.

Table 5: *Deflections after 28 days for all specimens: the predicted deflection f_{28}, and theoretical deflections estimated on the basis of the four models $\hat{f}_{28}$. The relative error of each model in respect to f_{28} is shown in brackets*

Spec. no.	Load (sand) mass (kg)	Duration of the experiment (days)	Predicted deflection f_{28} (mm)	Theoretical deflection, $\hat{f}_{28}$ (mm)			
				Power-law	**Zener**	**Burger**	**Modif. Burger**
1	14	14	5.63	6.57 (16.8%)	**5.57 (-1.03%)**	5.76 (2.44%)	6.09 (8.23%)
2	14	14	6.36	6.13 (-3.68%)	5.37 (-15.52%)	7.56 (18.78%)	**6.44 (1.21%)**
8	14	14	5.84	**5.78 (-0.94%)**	5.20 (-10.95%)	7.16 (22.73%)	6.09 (4.28%)
7	19.6	7	6.53	**6.32 (-3.19%)**	5.21 (-20.10%)	8.52 (30.55%)	6.90 (5.79%)
3	25	7	10.10	**10.30 (1.94%)**	8.33 (-17.48%)	14.69 (45.49%)	11.09 (9.80%)
4	25	7	16.40	16.90 (3.05%)	12.55 (-23.45%)	20.78 (26.71%)	**16.13 (-1.67%)**

* The results of the model with the lowest error compared to f_{28} are bolded.

4. CONCLUSIONS

This study deals with the modelling of the bending creep of particleboard based on the results of an experiment conducted on specimens loaded with a uniformly distributed load. The parameters of the model were estimated for four models, i.e., the power-law, Zener, Burger, and modified Burger models. After the comparison of the performance of these models according to the goodness-of-fit to the experimental data and according to the better prediction of the creep deflection, the following conclusions can be summarised:

1. On specimens exposed to uniformly distributed load, corresponding to the class L50 (DIN 68874, 1985), the deflections exceeding the allowable ones have already been recorded after 7 days.
2. The power-law and modified Burger models stood out as the best. The modified Burger model achieved better fitting to the experimental data, and the power-law model was slightly better at making predictions. The Zener model significantly underestimated, and the Burger model overestimated the target points.
3. The power-law, as a parsimonious model, could be recommended when there is a need to quickly and easily estimate the parameters of the model after a not-so-long measurement. On the other hand, this model is purely mathematical and is not related to the properties of the material.
4. If it is important to estimate the parameters of the material and even to estimate future deformations, our results indicated that the modified Burger model should be recommended.

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