Creep of timber joints

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A creep analysis has been performed on nailed, toothed-plate and split-ring joints in a varying uncontrolled climate. The load levels varied between 30% and 50% of the average ultimate short term strength of these joints, tested in accordance with ISO 6891. The climate in which the tests were performed varied between about 40% and 90% relative humidity, which coincides with Service classes 1 and 2 of Eurocode 5 for timber structures. A large scatter in creep factors was found with the highest average creep values for the 30% load levels. In order to analyse the influence of moisture variations, a creep model was developed containing the effects of mechanical creep, the influence of yearly shrinking and swelling as well as mechano-sorptive creep. Furthermore, a method has been presented in order to be able to derive creep factors to be applied in design calculations, based on the creep factors determined in laboratory creep tests, taking into account the design stiffness values for these joint types.

Key words: Nails, toothed-plates, split-rings, joints, mechano-sorptive effects, creep factors

1 Introduction

In this paper test results of creep tests with nailed, toothed-plate and split-ring joints are presented. These varying climate tests were initiated by Kuipers in 1983. The specimen codes mentioned in this paper relate to the specimen number and location according to Kuipers and Kurstjens [1986]. Specimen sizes and geometries are shown in annex A.
The results from the uncontrolled environment are used to determine the creep rate and how and to what extent the climate variations lead to additional creep, the so called mechano-sorptive creep. Mechano-sorptive creep is defined as the additional deformations induced during the combined action of environmental (mainly moisture) actions and mechanical loads.
A theoretical model is presented to describe creep in an uncontrolled environment and to determine creep factors for the three types of joint. The model is based on the measured creep factors in the uncontrolled environment and incorporates a moisture dependent

function to describe mechano-sorptive deformations. Finally, a derivation method is given to relate the creep factors measured in the tests to creep factors which can be used in design codes such as Eurocode 5.

The creep factor k_{def} is defined as

$$k_{def} = \frac{\varepsilon - \varepsilon_0}{\varepsilon_0} . \tag{1}$$

Where ε_0 is the initial strain to be defined after some loading period for which, in this paper, 10 minutes has been chosen. Consequently, the total deformation or slip can be calculated as

$$\varepsilon = \varepsilon_0 (1 + k_{def}) . \tag{2}$$

2 Creep tests in an uncontrolled environment

2.1 Nailed joints

The basic analysis and parameter estimation is performed with the results of the tests which were started in 1984 [Kuipers and Kurstjens, 1986]. The creep results that are reported here are creep tests running for almost 5000 days by 1997 at constant load levels of 30%, 40% and 50% of the average short term strength. The creep factor for nailed joints after 4800 days varies for the 30% between 2.6 and 3.8, for the 40% joints between 3.3 and 4.4, and between 3.4 and 4.6 for the 50% loaded joints. It can be concluded that there is no conclusive evidence that the creep can be considered non-linear as a result of the mechanical load. The small non-linearity could easily have been caused by the variations in relative humidity, causing a shift of the creep function to the left. Since there is a difference of about a month between the start of each string, it is likely that the time difference between the start and the first moisture change has resulted in a small shift. It is however known that at higher load levels (above 60%) the non-linearity becomes no longer negligible, since a fracture process in the form of split formation along nail rows, leads to accelerated creep on logarithmic time scale [Van de Kuilen, 1992]. The creep curve is then no longer straight, eventually leading to failure. Figures 1 and 2 show the average creep curves of nailed joints loaded at 30%, 40% and 50% of the average short term strength for a period of up to 3000 days. On logarithmic time scale, it can be seen that the creep curve develops slowly from a line with a small slope into a line with a steep constant slope. Neglecting mechano-sorptive effects offers the possibility of describing the creep with only two parameters, which have to be determined from experiments. The displacements of the joints after 10 minutes of creep on which the creep factor is based are summarized in Table 1.

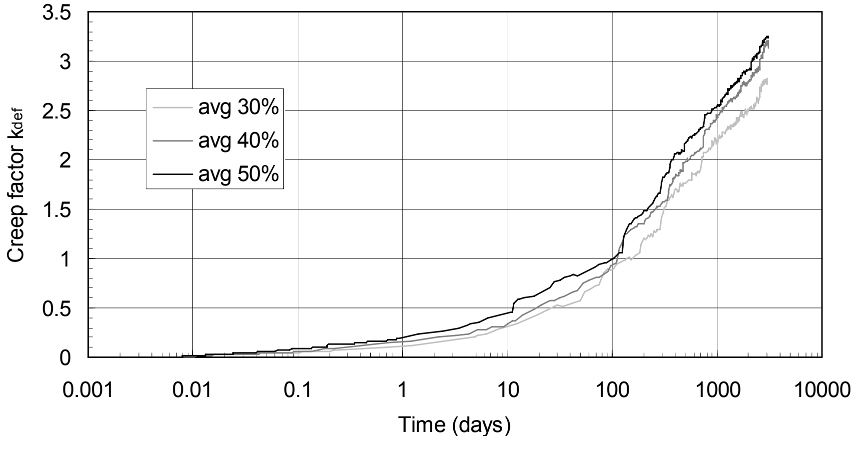

Figure 1: Average creep curves of nailed joints at 30%, 40% and 50% load level on a logarithmic time scale

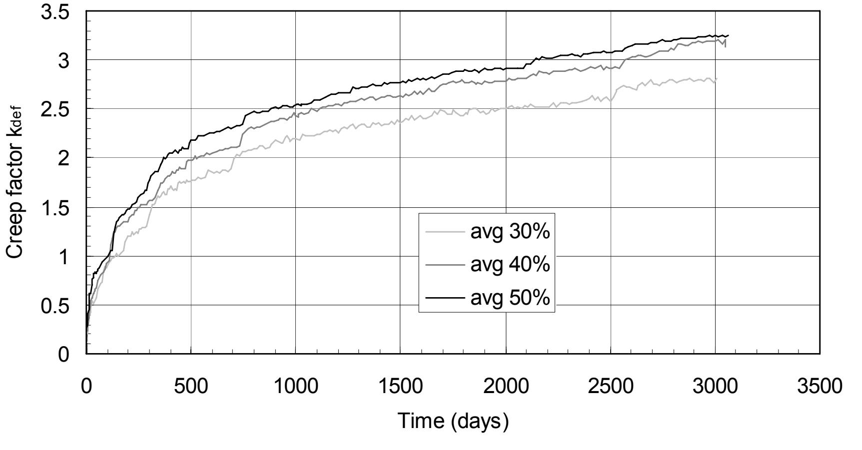

Figure 2: Average creep curves of nailed joints at 30%, 40% and 50% load level on a linear time scale

Table 1: Displacements in mm after 10 minutes for nailed joints loaded to 30%, 40% and 50%

30%	DNb 01	DNb 02	DNb 03	DNb 04	DNb 05
	0.255	0.283	0.299	0.280	0.371
40%	SND 31	SND 32	SND 33	SND 34	SND 35
	0.445	0.547	0.456	0.387	0.544
50%	SND 36	SND 37	SND 38	SND 39	SND 40
	0.834	0.781	0.728	0.837	0.836

These displacements show that there is a small non-linearity in the relationship between load level and 10 minutes displacement. The average values for the three load levels are 0.298, 0.476 and 0.803 mm respectively. Test series of nailed joints that were initiated in 1962 at load levels of 60% and up, has 8 nailed joints that still had not failed in 2005 [Van de Kuilen, 1999]. The load levels of these joints were 60% and 65% each with 4 specimens. The average 10 minutes displacement was determined at 1.65 and 2.22 mm for the 60% and 65% load level respectively. With creep factors of 3.4 and 4.2 the average displacement after 34 years of creep are 7.1 and 11.5 mm. After 13 years the creep factors were about 2.5 and 3.1 which is slightly less than observed in the newer tests. This is most probably caused by the fact that these tests were started in September at high moisture season, while the newer tests were started in the dry season with changes in relative humidity quite soon after the start of the test.

*2.2 **Toothed-plate joints***

The average creep curve of three series of 5 toothed-plate joints is shown in Figure 3 on a logarithmic time scale for 30%, 40% and 50% load level. The creep curve is steeper for 30% than for 40% and 50%. Partial failures have occurred at load levels of 40% and 50% and these have been excluded from the average creep curves after the failure had initiated. Generally, a shear plug failure under the bolt initiates an increase in creep rate. Sometimes, a single split in the centre of the middle member can be observed.

Two main increases in creep factor can be determined due to the mechano-sorptive effect, with some smaller changes affecting the creep factor in later stages of the tests. An important conclusion is that the higher the load level, the lower the increase in creep factor. The main increases in creep factor occur during severe decreases in relative humidity in the laboratory. The average values have been determined without the contribution of partially failed joints. The creep rate seems to be dependent on the load level, which

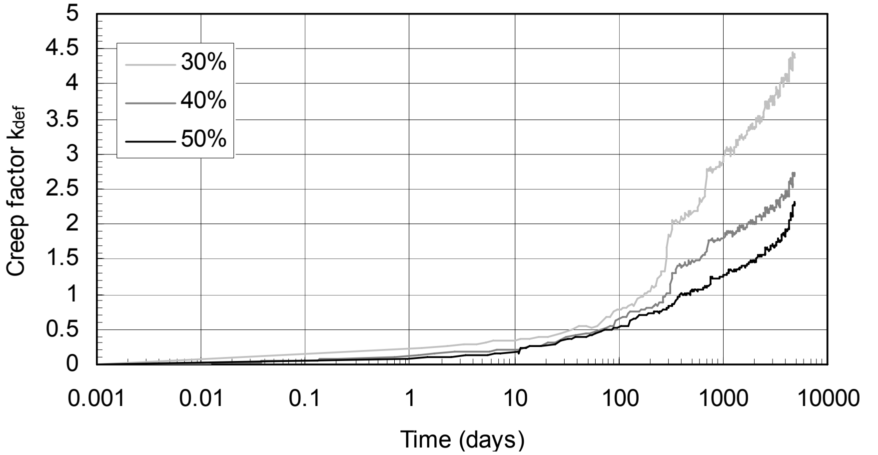

Figure 3: Average creep curves of toothed-plate joints at 30%, 40% and 50% load level on logarithmic time scale

disagrees with the findings of the nailed joints, where the creep rate seems to be the same for the load levels presented. This may have to do with a stronger influence of moisture variations around the connector, whereas in nailed joints direct moisture uptake is very limited. Also, the fact that the creep factor for 30% load level is higher than for 40% and 50%, may have to do with the moisture effect and plastic deformations during the loading stage. A higher load level leads to higher plastic deformations during loading. Consequently, this strain capacity is no longer available for any possible mechano-sorptive strain. The displacements of the joints on which the creep factor is based are summarized in Table 2. The average values for the different load levels are 0.445, 0.755 and 1.176 mm respectively. The displacements reached by the 30% loaded joints vary between 2.0 and 2.4 mm. The largest displacement of a 40% joint without split formation is 3.4 mm displacement (DKa 37). The displacement of joint DKa 36 at the start of tertiary (creep leading to failure) creep was approximately 4.4 mm after a loading period of 2500 days. Specimen DKa 40, with a single split in the middle member has a displacement of about 2.3 mm after 4800 days. The displacement, at which tertiary creep at 50% load was initiated, was about 3 mm for SKD 21 and 4.5 mm for SKD 23. The fact that the initiation of visible cracks starts from a displacement of about 2.3 mm until about 4.5 mm indicates that in the future even joints at 30% load level could show partial failures and possibly even total failures.

Table 2: Displacements in mm after 10 min. for toothed-plate joints loaded to 30%, 40% and 50%

30%	SKD 36	SKD 37	SKD 38	SKD 39	SKD 40
	0.327	0.392	0.268	0.639	0.599
40%	DKa 36	DKa 37	DKa 38	DKa 39	DKa 40
	0.607	0.977	0.981	0.704	0.505
50%	SKD 21	SKD 22	SKD 23	SKD 24	SKD 25
	1.213	1.216	1.206	0.954	1.293

2.3 ***Split-ring joints***

The creep curves of the split-ring joints are presented in Figure 4. Besides the large increases in short time spans due to variations in relative humidity, a yearly influence is also present in the form of a shrinkage and swelling effect. Apparently the influence of the moisture variation is such that the diameter of the split-ring varies over the year. The amount of the yearly variation in diameter is discussed in Section 4. A further similarity to the toothed-plate joints is found in the fact that the 30% joints show the highest creep values. At 50% load level two joints have failed so far, but none at lower load levels. The remaining three joints at 50% load level have a creep factor between 3.6 and 5.4, where the creep of one of these has been influenced by the repair activities of the test set-up after failure of a joint. The displacements of the joints on which the creep factor is based are summarised in Table 3.

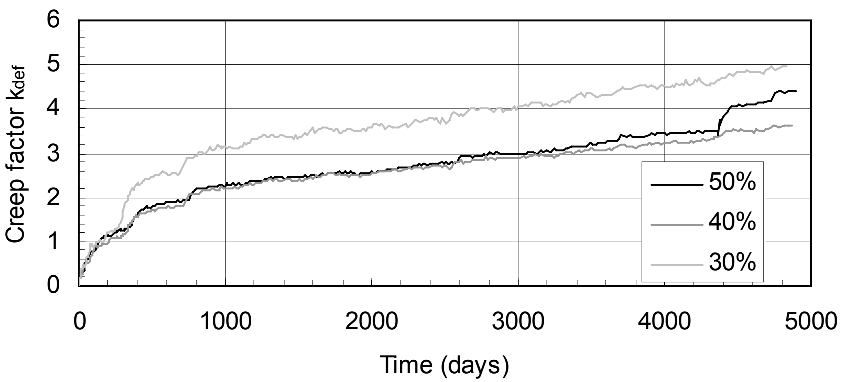

Figure 4: Average creep curves of split-ring joints at 30%, 40% and 50% load level at a linear time scale

Table 3: Displacements in mm after 10 minutes for Split-ring joints loaded to 30%, 40% and 50%

30%	DRa 39	DRb 08	DRb 09	DRb 10	DRb 11
	0.117	0.291	0.304	0.383	0.122
40%	DRb 16	DRb 17	DRb 18	DRb 19	DRb 20
	0.667	0.422	0.268	0.369	0.198
50%	SRD 31	SRD 32	SRD 33	SRD 34	SRD 35
	0.343	0.311	0.389	0.430	0.317

3 Moisture content variations

In order to be able to study the influence of the varying moisture content in more detail both the relative humidity was measured as well as the mass of a control specimen. The mass of this control specimen was measured on the same regular basis as the temperature and the relative humidity. The variation in relative humidity and mass could be described by a sine function. The measurements of the first 3000 days are shown in Figure 4.
The density at 12% moisture content was determined at 455 kg/m^3 which is 3% more than the average density of 440 kg/m^3 of the timber used. Because of this small difference it is assumed that the moisture content function is in close agreement with the actual moisture content of the creep specimens.
In order to show the influence of moisture variations on the creep factor, the creep curves of the nailed, toothed-plate and split-ring joints at 30% load level are shown for each individual specimen. It was found that the lower the load level, the higher the influence of a moisture variation on the creep factor.

4 Creep modelling

4.1 Mechanical creep

Mechanical creep can be described using the following creep equations. Backgrounds of this equation can be found in Krausz and Eyring [1975], Van der Put [1989].

$$\varepsilon = \varepsilon_0 + C_1' \ln(1 + C_2'(t - t')) \quad (3)$$

A numerical sensitivity analysis for the delay time t' has been performed in Van de Kuilen [1992]. It was found that the values of C_1 and C_2 were hardly influenced when the creep time is long enough. This is always the case for the tests described here and the equation can be further reduced by neglecting t', which can be interpreted as a shift of the time axis. Writing the equation as a deformation factor in accordance with Eurocode 5 it follows that the creep factor C_f can be written as

$$C_f = k_{def,creep} = \frac{\varepsilon - \varepsilon_0}{\varepsilon_0} = C_1 \ln(1 + C_2 t), \quad (4)$$

in which C_1 and C_2 are parameters to be determined. C_2 influences the bending point in the creep curve and is equal to the inverse of the relaxation time. Since C_2 depends on the applied stress, the creep curve shifts along the logarithmic time axis. As indicated earlier, the value of C_2 is influenced by moisture variations. The parameters C_1 and C_2 have been determined for a creep time of 13 years.

*4.2 **Mechano-sorptive creep***

Mechano-sorptive creep is modelled as a function of the rate of variation of the relative humidity or timber moisture content. After the first couple of major changes it is found that a moisture content increase results in a decrease of the creep factor and vice versa. This is found in all joint types. Additionally however, in the split-ring joints a shrinkage and swelling process of the timber can be noticed which has to be taken into account. The first changes generally give increases in creep factor independently of the sign of the moisture change, which is similar to test results found in timber. Due to the "uncontrolled" environment it is assumed that during the first changes, consecutive changes in the same direction are considered as single changes. As such it is possible that the first couple of positive changes as well as the first couple of negative changes are modelled as the "first" positive change and the "first" negative change. Furthermore, a moisture content change rate to a level that has not been reached earlier during the test seems to lead to an increased mechano-sorptive effect. So besides the effect of $\Delta\omega/\Delta t$ the history of the maximum values of $\Delta\omega/\Delta t$ must also be remembered, and values of $\Delta\omega/\Delta t$ that have not been encountered earlier must be incorporated into a creep model. These values will be denoted $\Delta\Omega/\Delta t$.

The load level effect is present in the measurement due to the initial displacement, since the displacement after 10 minutes is used as the reference creep value. Therefore, mechano-sorptive changes may seem small for the higher load levels, it is to be remembered that they are influenced by the definition of the creep factor. Variations in temperature have a much smaller influence than the variations in moisture content. Based on these considerations and measurements the following model is defined to account for mechano-sorptive effects in nailed and split-ring joints

$$k_{def,ms} = a\frac{\Delta\omega}{\Delta t} + b\frac{\Delta\Omega}{\Delta t} , \tag{5}$$

in which

$\Delta\omega/\Delta t$	is the rate of change in moisture content [1/time];
$\Delta\Omega/\Delta t$	is the rate of change in moisture content with a level that has not taken place in the joints history [1/time];
a, b	are constants to be determined from tests [time];

The first term is a combination of shrinkage and swelling and mechano-sorptive recovery. It depends on the type of fastener used whether this gives an increase in k_{def} at increasing moisture content or a decrease. A positive value of a indicates that the swelling during a positive value of $\Delta\omega/\Delta t$ is larger than the mechano-sorptive recovery. A negative value indicates that the recovery is larger than the swelling.
The calculation of ω is based on the multi-linear approximation of the hysteresis curve describing the relation between relative humidity of air and the timber equilibrium moisture content.

The influence of shrinkage and swelling of the fastener holes is discussed in Section 4.4. The value of b is generally a negative value. As a result, a negative change in moisture content leads to an increase in $k_{def,ms}$. Since the first couple of positive and negative changes always lead to increases in k_{def} an absolute value of $b\Delta\Omega/\Delta t$ is taken for those changes. Generally after two seasons the number of positive and negative changes is such that increases in moisture content lead to decreases in deformation and vice versa. The influence of this second parameter fades away in the course of the test since the chances of a moisture content change with a rate that has not taken place earlier reduce with time.

A complication arises when the test data of the first months after the start of the test is analysed. During these first months the deformation is measured every day, a change in relative humidity leads to a very high value of $\Delta\omega/\Delta t$. The first 70 days of the creep tests are therefore excluded from the model since this would lead to unrealistic results.

4.3 *Modelling of moisture dependent joint stiffness*

The stiffness of joints is generally denoted K_{ser} . This value is dependent on the moisture content, but the extent of the dependence, however, is not known. Hoffmeyer [1995] gives for the dependency of the modulus of elasticity on the moisture content a value of 1.5% per 1% moisture content change. If it is assumed that this dependency also applies to the joint stiffness in a creep test, it can be expressed approximately according to

$$K_{ser,w} = K_{ser,12}(1-0.015(\omega(t)-\omega_{12})) , \qquad (6)$$

where

$K_{ser,12}$ is the reference stiffness at 12% moisture content [N/mm];

$\omega(t)$ is the moisture content as a function of time (%).

In this equation, the moisture content may vary between about 8% to 20%, which is in line with moisture contents in indoor and covered outdoor timber applications.
The variation in deformation caused by the moisture dependency is calculated as $u = F / K_{ser,\omega}$. Since this is a linear relationship an increase in moisture content leads to a decrease in stiffness and consequently an increase in deformation. Therefore this behaviour counteracts the mechano-sorptive effect. Inclusion of this moisture dependent joint stiffness leads to a more complete description of the creep of joints. Since the parameters a and b of the mechano-sorptive model have to be determined from tests, they assume a different value than if this moisture dependent stiffness was not included. However, since in both cases the change in deformation is linearly related to the change in moisture content, it can be seen to be included in the term $a\Delta\omega/\Delta t$ from the previous section.

4.4 *Modelling of the influence of shrinkage and swelling on the fastener holes*

Depending on the type of fastener, the variation of moisture content of the timber leads to a change in the size of the hole in which the fastener is placed. In the case of a nailed joint where the nails have a diameter of 2.8 mm the variation in hole size will hardly, if at all, be noticeable. The larger the size of the hole, the more pronounced the effect will be in absolute terms. In the toothed-plate and split-ring joints there is a combination of fasteners: a 12 mm bolt and a 73 mm toothed-plate or a 75 mm split-ring. Since the teeth of the toothed-plate are pressed into the wood fibres and the connector itself is a stiff plate there will hardly be an effect of a variation in diameter due to changing moisture content. The only effect can be on the bolt hole diameter. The split-ring connector is more flexible and is pressed into a routed circle. A change in circle diameter can easily be followed by the split-ring leading to a change in the measured deformation.

In dry periods the joint will shrink and in wet periods the joint will expand. This leads to changes in deformation and thus a change in the measured creep factor. The variation in diameter is directly related to the variation in moisture content. The average swelling coefficient for spruce in the longitudinal direction is estimated at 0.01 i.e. a change in diameter of 0.01 x $\delta\omega$ x D. Since the average moisture content changes according to the linearized moisture content curve model are about 6 % between the wet and the dry season, the length of the split-ring can vary between 73 +/- 0.023 mm. At first glance this value seems to be negligible. By way of definition of the creep factor however, an influence of this variation is noticeable since the creep factor is derived relative to the initial displacement. This value was 0.24 mm for the five split-ring joints at 30% load and about 0.35 for the 40% and 50% load level. Hence, the value of k_{def} will vary by about 0.023/0.24 or 0.09 around the average value over the year. The difference between the dry and the wet season is 0.18. An effect of this size should clearly be noticeable in the test results, shown in Section 2. The effect is certainly present, but to a far lesser extent than predicted on the basis of the moisture content models. It is concluded that the moisture content variations are better described by the dummy specimen than by the theoretical models. The effect is only modelled for the split-ring joints, since the effect on a 12 mm bolt of a toothed-plate joint is negligible for the following reasons:

- the diameter is six times smaller and thus the shrinkage and swelling are six times smaller;
- the bolt transfers only a part of the load (approximately 40%), while the toothed-plate is not affected by the moisture variation;
- the initial displacement is larger for toothed-plate joints, reducing the variation of k_{def} .

Furthermore, it is worth mentioning that by way of definition of the creep factor, this effect is more pronounced with lowly loaded joints than with highly loaded joints. Since the instantaneous deflection is large at high loads, the influence of shrinkage and swelling of holes on the creep factor gradually decreases.

4.5 *Application of the model*

The model with a logarithmic creep equation and function for the mechano-sorptive effects is applied on the joints. Basically the input of the model consists of the two factors for the creep, that have been determined from the tests, and the variation in relative humidity as measured in the laboratory. The creep factors have been adjusted to a lower value, especially the delay time of the governing second process. This is in agreement with the measurements in the constant climate, where the creep lines are shifted to the right on the time axis. The steepness of the creep lines is hardly affected by the mechano-sorptive effects except for very short periods with high creep rates.
In the following the results of the application of the model on the average creep curves of the three load levels of the three joint types is shown. The values of *a* and *b* have been determined based on a least square minimization routine. The whole model describing the creep factor reads

$$k_{def,tot} = k_{def,creep} + k_{def,sh/sw} + k_{def,ms}, \tag{7}$$

where

$k_{def,tot}$	the total creep factor;
$k_{def,creep}$	the creep factor due to mechanically induced creep, see Equation 4
$k_{def,sh/sw}$	the creep factor due to shrinkage and swelling, see Equation 6
$k_{def,ms}$	the creep factor due to the mechano-sorptive effect, see Equation 5

Due to the fact that the shrinkage and swelling effect is described with a similar function to that of the moisture variations in the mechano-sorptive function, the two last parts are treated as one.

Nailed joints

The model parameters are presented in Table 4. Since from figure 2.1 it can concluded that the creep rate for all load levels is about equal, it was decided to keep the constants C_1 and C_2 equal for the three load levels. The parameter *a*, describing the mechano-sorptive effect is negative for the 30% load level and positive for the 40% and 50% load level. A positive value of *a* indicates that the combined effect of mechano-sorption and shrinkage and swelling deformation gives a restoration of the bond structure. Close examination of the creep curves shows that especially after more then 10 years, the mechano-sorptive process is more pronounced than in the first five years. This leads to the conclusion that the value of parameter *a* should be time-dependent, changing from a positive value in the beginning to a negative value after about ten years. The value given in Table 4 is an average value for the whole period, while a time dependent value may improve the quality of fit.

Table 4: The four parameters for nailed joints

Load level	C_1 [-]	C_2 [1/days]	a [1/days]	b [1/days]
30%	0.60	0.02	-7.0	-12.4
40%	0.60	0.02	6.4	-19.2
50%	0.60	0.02	8.9	-21.9

Close analysis of the creep and model curves leads to the conclusion that after the first few years (about 4, see also Figure 1) a positive relationship between the moisture content and creep factor changes into a negative relationship, indicating a slight recovery of creep during wetting periods and a slight increase of creep during drying periods. A more complex model may describe the creep curve better, but the scatter in test results is such that there is no need for this. Since creep has to be determined for long load durations a value of *a* of -8 is proposed. The value of *b*, giving the large increases in the first years of the creep tests seems to be slightly dependent on the load level but a constant value of -15 can be used.

Since in general the mechano-sorptive influences are small in the case of nailed joints, the most practical solution is to neglect them. Nailed joints can be modelled using a two parameter logarithmic time function.

Toothed-plate joints

In contrast to the nailed joints the factor C_1 depends on the load level and cannot be taken as a constant since the creep rate differs considerably among the tested load levels. From the figures it can be concluded that a good description of the creep curves is possible with the four parameters currently used in the model. The scatter in individual test results is comparable with that of the split-ring joints shown in Figure 5. The parameter C_2 is taken as constant at 0.015 for all three load levels. The value of C_1 was taken 0.8, 0.5 and 0.35 for the load levels of 30%, 40% and 50% respectively. On this basis and on the input of the relative humidity, the values for *a* and *b* have been determined. All values are summarized in Table 5.

Table 5: The four parameters for toothed-plate joints

Load level	C_1	C_2 [1/days]	a [1/days]	b [1/days]
30%	0.85	0.015	-28.5	-8.7
40%	0.50	0.015	-21.6	-17.0
50%	0.35	0.015	-22.4	-9.1

It can be seen that the values of a are negative and, considering the scatter, found to be independent of the load level. The value can be taken at -25. This means a strong mechano-sorptive effect counteracting the effects of stiffness decreases at moisture content increases. The value of b is most probably also load independent and a value of -11 is proposed, based on the average value. The creep curves and the model prediction are shown in Figure 7 for the 30% load level and Figure 8 for the 40% load level.

An attempt has been made to see whether the creep rate parameter C_1 is related to the moisture variation. The value of C_1 was determined by neglecting the first major increase of the creep factor but it is certainly influenced by the following moisture variations. Therefore a sensitivity analysis was performed on the influence of a constant value of C_1, independent of the load level, on the value of b. A value of 0.35 for C_1 was assumed for all load levels and the parameter b was determined. The value a was kept constant. It was found that for the 40% load level a similarly good description was obtained as before, if b was taken at -32.8. For the 30% load level a good fit was obtained for the first 1000 days

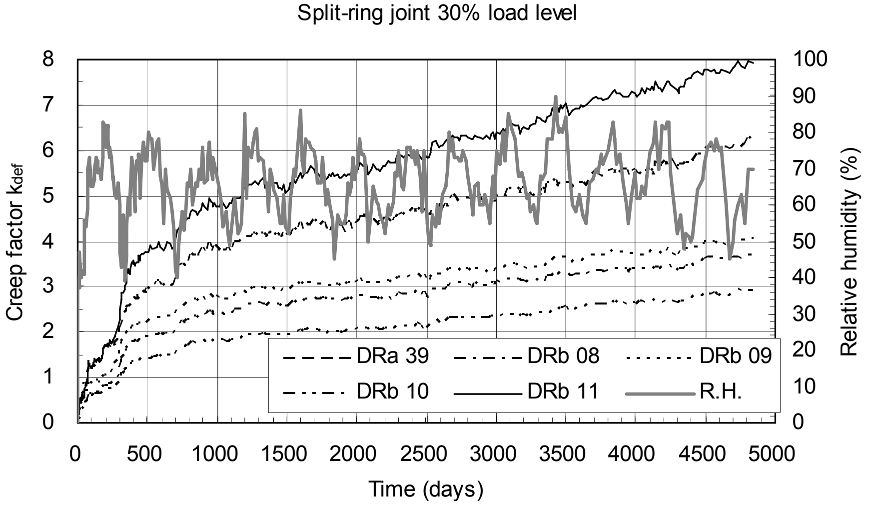

Figure 5: Creep of split-ring joints as influenced by relative humidity variations

with a value for *b* of -57.0 but the creep lines started to deviate due to the great difference in rate. These values differ greatly from the values given in Table 5 and consequently it can be concluded that the load dependency of the creep is not negligible. However, even in this case the difference between the predicted and the measured creep value after 5000 days is 3.94 for the creep model compared to 4.37 for the test result. The model value is 10% below the averaged measured value, which can be considered reasonable.

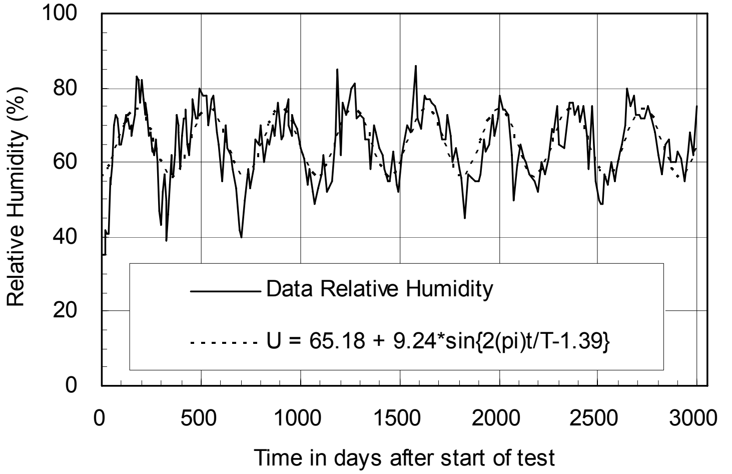

Figure 6: Variation of relative humidity

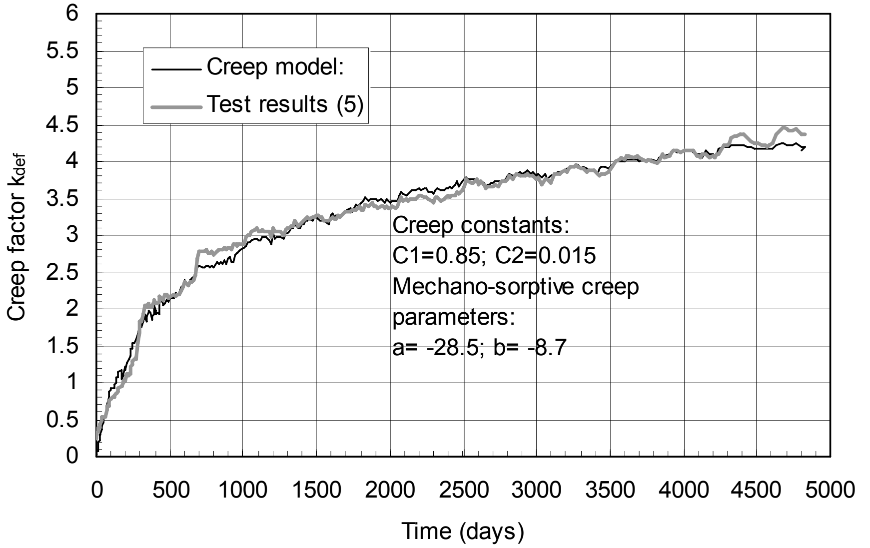

Figure 7: Creep model applied to toothed-plate joints at 30% load level

Split-ring joints

The split-ring joints were treated similarly to the nailed joints. The value of C_1 was taken as a constant for all series, even though the creep tests indicated a steeper creep curve for the 30% load joints. The value of C_1 was 1.0 compared to 0.8 for the 40% and 50% joints. For the model a value of 0.7 was used for all load levels. The factor C_2 was taken as 0.01, being a lower bound value of the mechanical creep parameter estimation. The results of the model are shown in Figures 9 and 10 for the 30% and 40% load level respectively.

The model gives a slight underprediction of the creep factor in the last stages of the test, but describes the curves well for a period of up to twelve years. After that, small splits developed in some joints which were visible on the end of the middle member. Consequently, a higher creep rate resulted.

In the last part of the curve the deviations are considerable. This is caused by the fact that failure started to occur on one of the specimens, leading to a high creep. Since the creep curve after 3500 days is based on only four joints, it is obvious that if one fails, the creep factor is significantly affected. The results of the parameter estimation are given in Table 6. The 40% and the 50% parameters are almost equal indicating that these joints are comparable, something which was also found for the 10 minutes displacement of the joints. The 30% load level shows high values for both *a* and *b*. A high positive value of *a* indicates a strong effect of the shrinkage and swelling of the split-ring. Furthermore, the

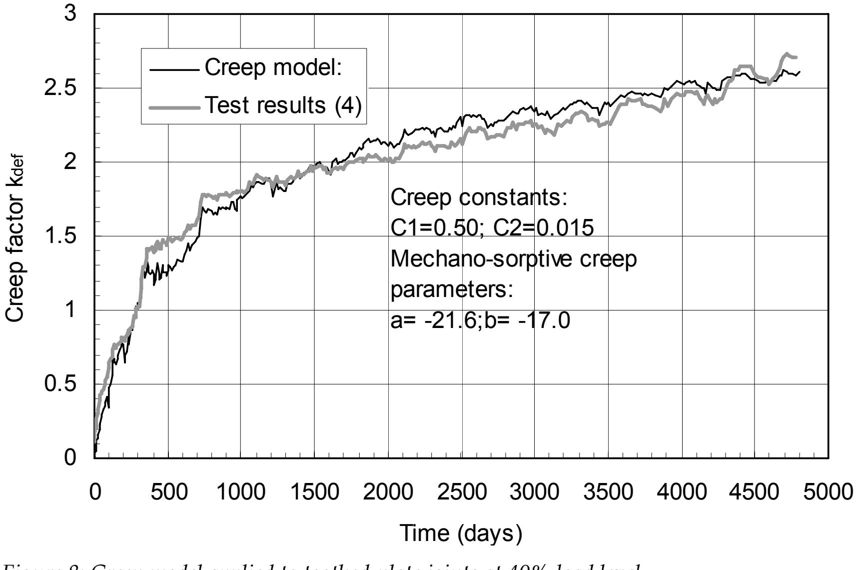

Figure 8: Creep model applied to toothed-plate joints at 40% load level

mechano-sorptive effect leads to higher creep factors at lower loads, quite similar to the toothed-plate joints although the rate differences are smaller in this case. For parameter *a*, a value of 20 is proposed and for parameter *b*, a value of -20 is appropriate.

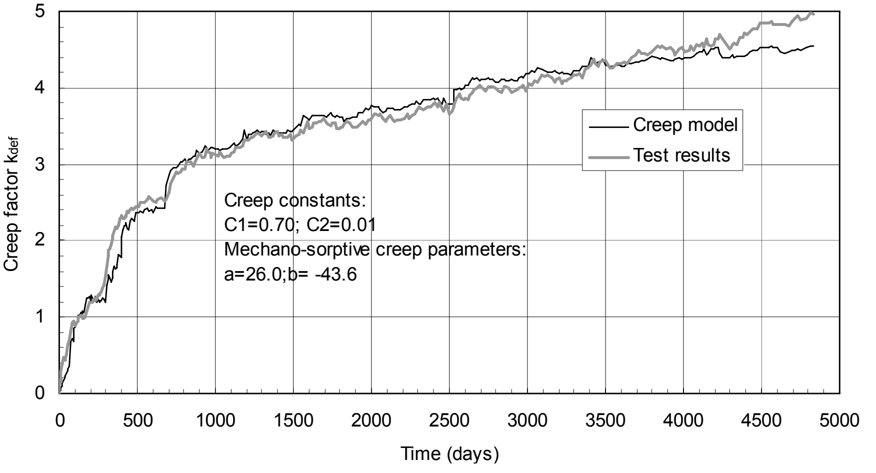

Figure 9: Creep model applied to split-ring joints at 30% load level

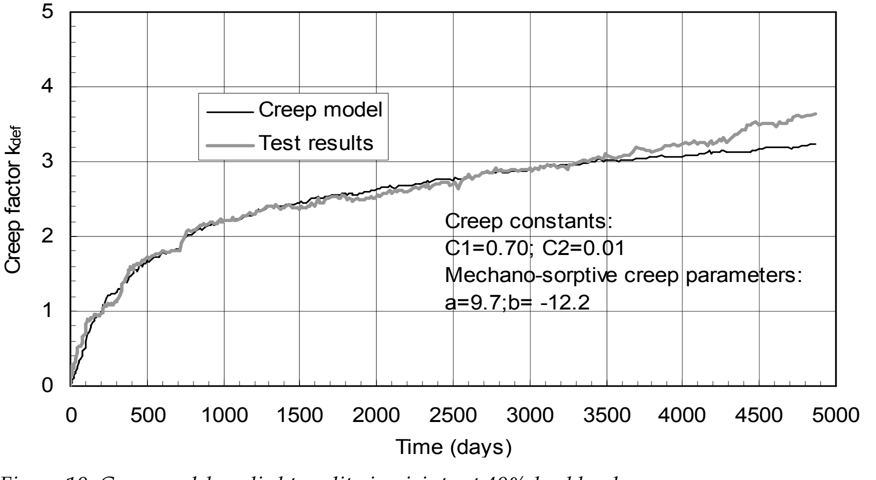

Figure 10: Creep model applied to split-ring joints at 40% load level

Table 6. The four parameters of split-ring joints

Load level	C_1	C_2 [1/days]	*a* [1/days]	*b* [1/days]
30%	0.70	0.01	26.0	-43.6
40%	0.70	0.01	9.7	-12.2
50%	0.70	0.01	13.5	-13.1

5 Creep factors for joints

The creep values obtained for joints seem high compared to those for timber, see for instance [Leicester, 1983, 1992], [Morlier, 1992]. However, the creep values measured on joints are not directly applicable as design values. This is because of a major difference in creep research between timber and joints. From each individual piece of timber the modulus of elasticity can be determined prior to the creep test or in the uploading stage of the test. Furthermore, this modulus of elasticity is the same as used in the design stage of a construction. A creep factor determined on timber can thus be used directly in the design process. This procedure cannot be applied in the case of joints. A prior loading of a joint means that initial slip has been removed from the actual creep test. This slip will not or only partly be recovered after unloading and a difference will be found if the same joint is used in the creep test. Additionally, the design value of the joint stiffness K_s should be determined in accordance with EN 26891 (ISO 6891). This stiffness value K_s is used to determine the "instantaneous slip" u_{inst} and is quite different from the stiffness measured by simply dividing the applied load by the measured initial slip.
The initial slip in a creep test is generally taken as the slip after 1 minute, 10 minutes, 1 hour or even 12 hours. Often, the 10 minutes value is taken, but no effect on the definition of "initial stiffness" has previously been reported.
As a consequence, the reported creep factors in the previous section of up to 5 and of up to 20 by Leicester, [1992] cannot be used without modification. A method for modification is presented here in order to create a table with design creep factors for the three joint types.

This derivation was done assuming that the final deformation calculated with the joint stiffness from a design code and a load duration class had to be same as the final deformation measured in the creep test. Additionally, the comparison was performed using the average values of the measurements, which is the same procedure as for timber beams. The following requirement must be fulfilled

$$u_{\infty,calc} = u_{\infty,meas} \text{ ,} \tag{8}$$

in which

$$u_{\infty,calc} = u_{inst}(1 + k_{def,EC5}) \text{ ,} \tag{9}$$

where

$$u_{inst} = \frac{F_d}{K_s} \; , \tag{10}$$

according to the method in EC5.

The measured final displacement using the theory applied here results in

$$u_{\infty,meas} = u_{10\min}(1 + k_{def,meas}) = \frac{F_d}{K_{10\min}}(1 + k_{def,meas}) \, , \tag{11}$$

with the initial displacement u_{inst} determined after 10 minutes of testing which is equal to the load $F_d \,/\, K_{10\min}$. For the value of $k_{def,meas}$ the creep model was taken, including the mechano-sorptive parameters. The value of $K_{10\min}$ is determined on the basis of the tests with 30% load level. The values found were 45 kN/mm, 21 kN/mm and 35 kN/mm for the nailed, toothed-plate and split-ring respectively.
Substituting Equations 9, 10 and 11 in 8 and solving for the creep factor $k_{def,EC5}$ for timber joints is found as

$$k_{def,EC5} = \frac{K_s}{K_{10\min}}(1 + k_{def,meas}) - 1 \, . \tag{12}$$

In Table 7 a proposal has been made for k_{def} factors for nailed, toothed-plate and split-ring joints, to be incorporated into Eurocode 5. Calculations are made for the maximum time in a load-duration class i.e. for permanent loads a value of 50 years is used for $k_{def,meas}$. The C_1 values according to Section 4.5 are used, i.e. 0.6, 0.5 and 0.7 for the nailed, toothed-plate and split-ring joints respectively. For C_2 a value of 0.011 is taken, or 90 days time for the creep curve bend. This will be the average period before seasons change from dry to wet or from wet to dry. For the mechano-sorptive creep the difference is taken between the model prediction with and without the mechano-sorptive effect after 4800 days. It is assumed that after these 13 years most of the mechano-sorptive creep has taken place and very rapid and large moisture variations have a small chance of occurring.
K_s values are derived as 51 kN/mm, 20 kN/mm and 39 kN/mm for the respective joint types. These values are derived in accordance with Eurocode 5 and the equations given in Blass [1995]. The values correspond reasonably with those determined in the short term

tests program, except for the toothed-plate joints. The theoretical stiffness of the toothed-plate joints is double that reported in Kurstjens [1989], which were based on the results of 34 short term tests per joint type.

The contribution of the mechano-sorptive effect to the creep factor after 10 and 50 years is estimated at 0.5 for nailed joints and 2 for toothed-plate and split-ring joints. For the medium term load duration class the mechano-sorptive contribution is estimated at 0.2 for the nailed and 0.5 for toothed-plate and split-ring joints.

Table 7: Proposal for deformation factors k_{def} *for Eurocode 5*

Load duration class	Time	Nailed joints	Toothed-plate joints	Split-ring joints
Permanent	50 years	4.3	4.4	6.5
Long term	10 years	3.2	3.6	5.2
Medium term	6 months	1.1	1.0	1.5

The values in Table 7 are based on the average values as measured in the creep tests. However, the scatter in test results is very large as shown in Section 2. The scatter is such that for the load duration classes long term and permanent a variation in creep factor of ± 50% may be assumed.

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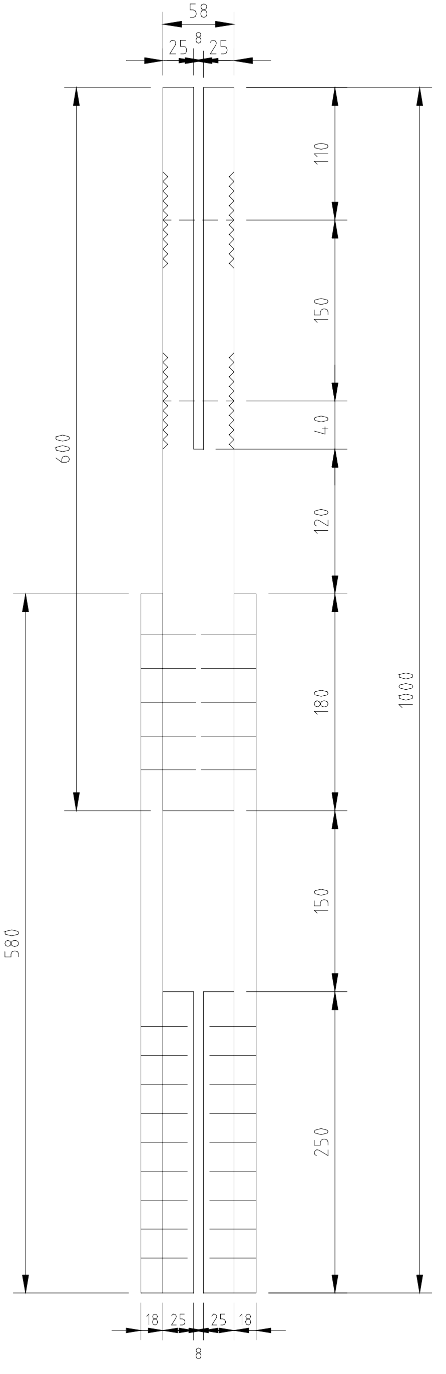
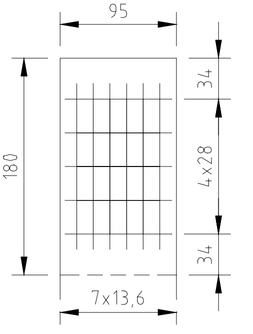
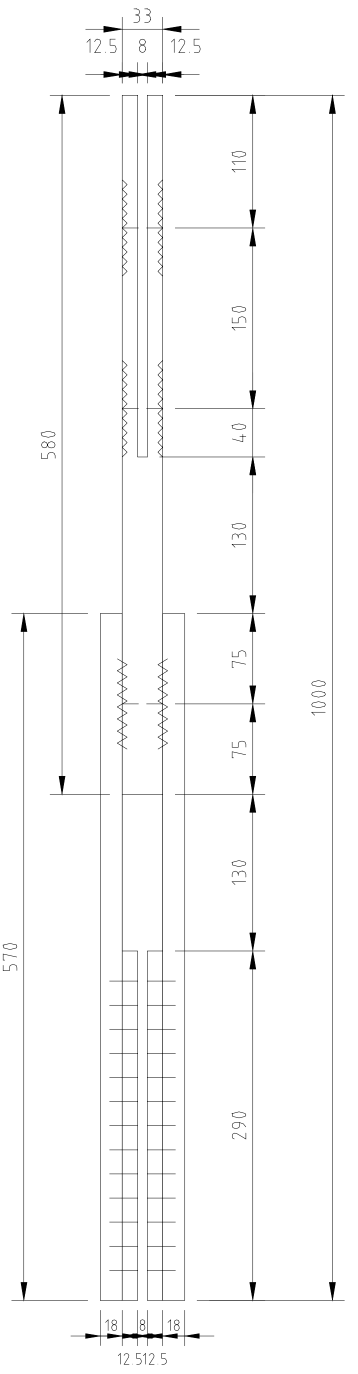
Annex A. Nailed, toothed-plate and split-ring joint



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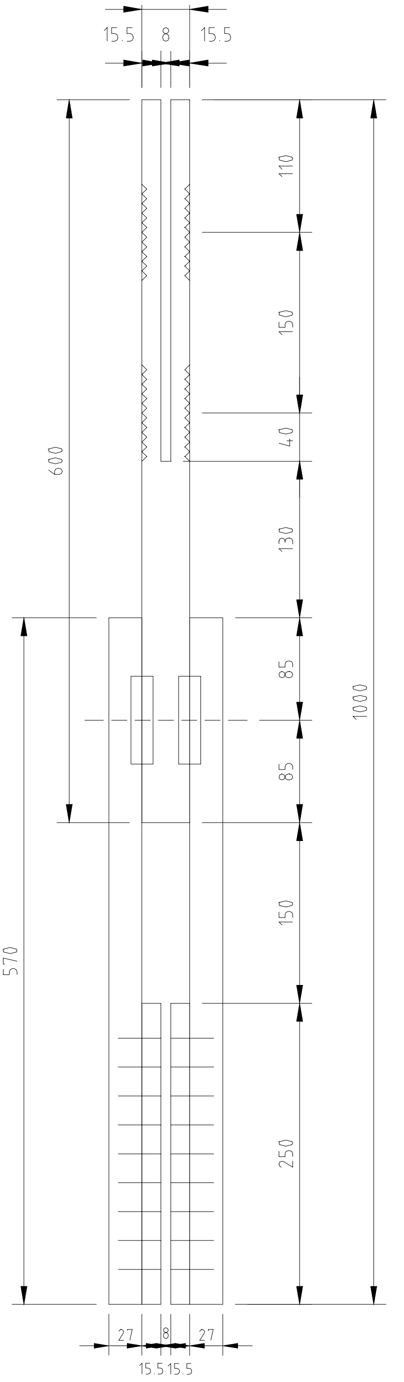
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