# SHEAR CREEP OF POLYSTYRENE CORES IN WOOD-BASED PANELS

**André Jorissen[1], Johnny van Rie[2], Jeff Modderman[3], Hèrm Hofmeyer[4]**

**ABSTRACT:** This paper reports on an experimental study of shear creep in load bearing sandwich panels with a polystyrene core and wood-based faces. This is ongoing research at Eindhoven University of Technology (TU/e), in cooperation with industry, to provide scientific and experimental backgrounds to roof panels used for residential housing. For these panels, loaded perpendicular to plane, faces are loaded in tension or compression, whereas the core is mainly loaded in shear. Both the polystyrene core and the wood-based faces show time dependent behaviour (creep) of which only the time dependent behaviour of the core is dealt with in this paper. This by including experiments on panels of which the wood-based faces are replaced by steel, thus isolating the creep of the core. Furthermore, conform other studies on this subject, e.g. Taylor et al. [1], and Kilpeläinen et al. [2], the study presented in this paper indicates that the creep depends on the load ratio, i.e. the quasi-permanent shear relative to the shear stress at failure (strength). Therefore, load ratios were systematically varied. Results indicate that when the shear stress exceeds more than 50% of the shear strength, the tertiary creep phase is reached, and collapse will occur within 4 -5 years. When the shear stress is lower than 40% of the shear strength, the deformation is likely to stabilise in the secondary creep phase.

**KEYWORDS:** Sandwich panels, Shear creep, Polystyrene (EPS), Wood-based faces

## 1 BACKGROUND RESEARCH

When using sandwich panels with rigid foam cores for roofs, the panels are predominantly loaded perpendicular to plane. The deflection is usually decisive for the maximum allowed span. Suggested by current European regulations [3], the shear deformation is often the largest part of total deformation, regardless the type of rigid foam applied for the core. For the rigid foam the creep factor $k_{def}$ , defined as $k_{def} = \frac{u_{fin} - u_{inst}}{u_{inst}}$ with $u_{fin}$ = final and $u_{inst}$ = instantaneous deflection, is set to $k_{def}$=7.0 [3], which causes high predicted deformations. For steel sandwiches, which are usually loaded with low permanent loads at large spans this is not a problem, but for residential building roofs covered with tiles, i.e. large permanent loads at short spans, shear deformation is a considerable part of the total deformation and therefore has a serious impact.
Since there is obviously a difference in behaviour of thermosetting and thermoplastic materials, as shown by Gibson et al. [4], it was seen as an opportunity to allow for higher performance of wood-based sandwich panels by demonstrating that the value for $k_{def}$ for polystyrene loaded in shear is much lower than specified above. Knowing that the core is mainly loaded in shear, as shown in figure 1, and that the shear zones mainly occur in the vicinity of the supports, the research focuses on the shear creep. Furthermore, shear stresses in the core are relative low compared to the shear capacity: In a practical example, e.g. a sandwich panel with a thickness of 200 mm and a span of 4 m, with a dead load (self-weight and roof tiles combined) of 0.65 kN/m², a maximum shear

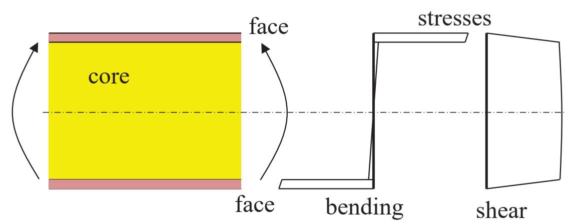


***Figure 1:*** *Stresses in a sandwich panel with thin faces: by approximation, uniform axial stresses in the faces and uniform shear stresses in the core exist* [5]

stress of 6.5 kPA results, whereas the characteristic shear strength of a polystyrene core is approximately 80 kPA. Consequently, the deflection is governing the design and therefore, as figure 2 illustrates, an accurate value for $k_{def}$ is necessary.

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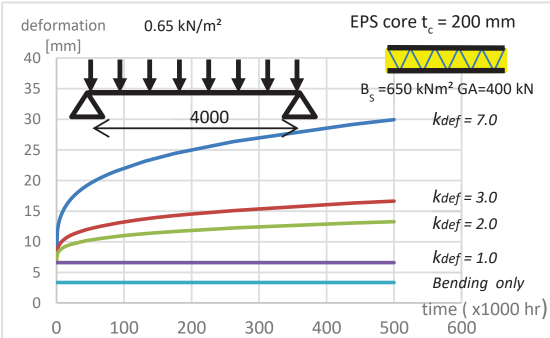


***Figure 2:*** *Effect of different values of* $k_{def}$ *on time dependent deformation of a given single span sandwich beam.*

# 2 OBJECTIVE

The objective of this study is to describe the shear creep as a function of the shear load relative to the shear strength of a polystyrene core as applied in wood-based sandwich panels. Therefore, two types of tests are carried out. Pure compact shear tests, according to EN 12090 [6], and tests on beams with Uniform Distributed Loads (UDL), for which the shear stresses and deformations are analysed. The objective of these tests is to show that the different set-ups, for which the bending test is the more realistic one, result in comparable finding for time dependent behaviour. Comparable time dependent behaviour allows small and simple tests on creep in the future, while making sure the creep results do agree with the end use situation. Furthermore, after unloading, being loaded for a long period, the specimen are loaded up to failure and the characteristic residual strength is determined to provide an indication on the strength degradation in time. Results are compared with the results found in previous studies [1,2].

## 2.1 TIME DEPENDENT DEFORMATION BEHAVIOUR

In engineering practice, time dependent deformations (creep) are calculated according to Equation (1) showing a proportional relationship between the instantaneous deformation $u_{inst}$ and the creep deformation $u_{creep}$ ($= u_{fin} - u_{inst}$).

$$u_{creep} = k_{def} u_{inst} \tag{1}$$

Due to creep, part of the stress strain behaviour is non-linear. Furthermore, part of the creep deformation obtained during loading will not recover; part of the deformation remains at time $t$. Figure 3 shows the qualitative deformation behaviour of a polymer affected by creep (or a structure consisting of this material), including unloading after time $t$.

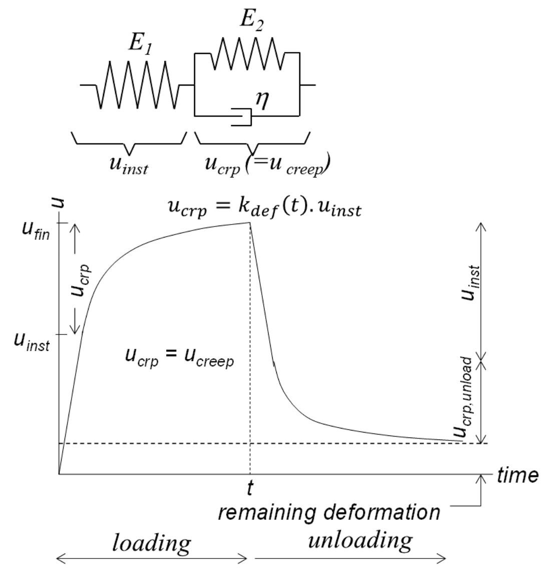


***Figure 3****: Top: Shear creep model, Bottom: Deformation behaviour of a polymer affected by creep* [7]

Consequently, both the instantaneous deformation $u_{inst}$ and the creep deformation = $k_{def}$ * $u_{inst}$ are governing the final deformation $u_{fin}$. The creep factor $k_{def}$ is generally assumed to be only time dependent and is defined as a fixed value for the ratio $u_{creep}/u_{inst}$ after 50 years of permanent loading. Furthermore, at least for wood and wood-based products, the creep factor is influenced by the material moisture content and its fluctuations. In engineering practice, the creep factor is generally assumed not to be affected by the load. For polymers however, the creep factor does not only depend on time but also on the load (stress) level, and significantly so, as shown in Figure 4. The dotted line indicates the stress level which is not to be exceeded. If stress levels are high, progressively higher strains will occur, the so-called tertiary phase is reached, and collapse is due to happen.

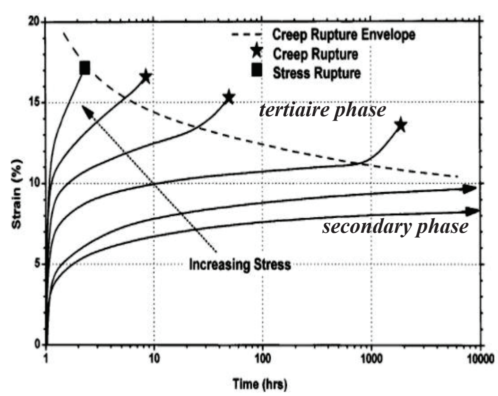


***Figure 4:*** *Strain over time for different stress levels* [8]

At lower stress levels the creep rate decreases and creep stabilises, reaching the secondary phase, as such avoiding failure.

# 3 MODELLING SHEAR CREEP

## 3.1 SHEAR CREEP AS NONLINEAR MATERIAL BEHAVIOUR

Previous studies have shown that polystyrene foam reacts differently to various load types. When compressed, the foam behaves as a cellular material, i.e. it has an elastic, by approximation quadratic stress-strain relationship, whereas most solids are about linear [1]; under stresses due to bending it will react purely elastic until failure (brittle) [1]. As discussed in relation to figure 1, in a sandwich panel the core is predominantly loaded in shear and consequently this research focuses solely on shear and the determination of the shear creep. Models describing shear creep both as linear and nonlinear have been developed by Taylor et al. [1], Kilpeläinen et al. [2], and Findley et al. [7], and will be introduced by first presenting the so-called Burgers Model for which the arrangement of the spring and dashpot elements are shown in figure 5.

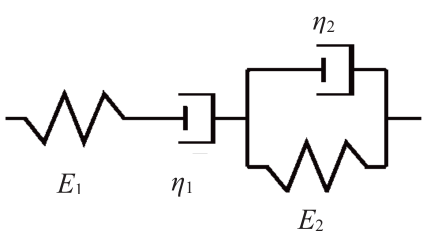


***Figure 5****: Creep according Burgers model*

Representing for the spring elements $\sigma = E\varepsilon$ and for the dashpots $\sigma = \eta\frac{d\varepsilon}{dt}$, the Burgers model results in:

$$\varepsilon(t) = \sigma\left[\frac{1}{E_1} + \frac{t^p}{\eta_1} + \frac{1}{E_2}\left(1 - e^{-\frac{E_2}{\eta_2}t}\right)\right] \qquad (2)$$

in which $t$ equals the time, and $p$ is a factor to be determined. If $p$=1, the behaviour of the first part of the model, represented by the spring ($E_1$) and dashpot ($\eta_1$) is completely linear in time. With $p < 1$, the tertiary phase can be postponed or avoided. With $p > 1$, creep will grow progressively, entering the tertiary phase, which must be avoided.

Findley et. al [7] used the above model, and demonstrated it functioned correctly for viscoelastic materials, such as polymers, with their typical time dependent behaviour: They start with instantaneous elasticity, followed by delayed elasticity and visco-elastic flow.

Taylor et al. [1] tried several different creep deflection models, to fit the data measured over 3 months and to predict the creep after 6 months, and concluded that the so-called power model and the 5-element model are suitable to predict relative deflection on beams with EPS or PUR cores. To derive the 5-element model, they

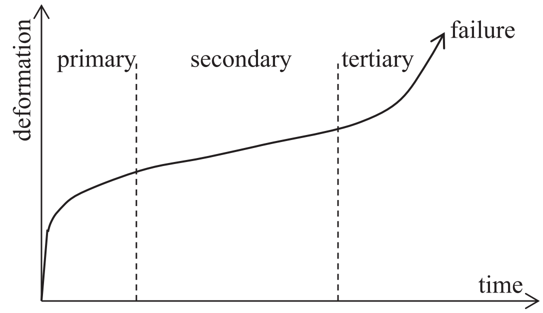


***Figure 6:*** *Creep phases*

rephrased the Burgers model and changed $\eta_1$ into $\eta_1(t)$, resulting in Equation (3).

$$\Delta(t) = \Delta_0 + B_1(1 - e^{-B_2 t}) + B_3 t^{B_4} \qquad (3)$$

In which $\Delta(t)$ is the deformation, $\Delta_0$, $B_1$, $B_2$, $B_3$ and $B_4$ are parameters, and $k_{def}$ can be found by equation (1).

Kilpeläinen et al. [2] applied the power model, and used Equation (4) as a method to fit the data:

$$k_{def}(t) = A_1\, t^{A_2} \qquad (4)$$

Based on this latter model, the $k_{def}$ is low for steel sandwich panels since these panels are used for long spans and relatively low loaded.

## 3.2 PANEL STRENGTH

Given the presented studies, it is obvious that to find the proper value for $k_{def}$ of a sandwich panel with steel faces, the focus must be on the shear creep in the polystyrene core. Additionally, it should be realised that polystyrene foam transfers shear via and along the walls of each cell, thus the proper fusion, the so-called sealing of the cells, is important. Therefore, in the experiments below not only identical grades of EPS foam are used, but also exactly identical procedures for the production of the core are applied, and fusion strength is tested too. This is not only carried out on "fresh" elements, before applying loads, but also after the experiments, to demonstrate that the residual strength is hardly degraded in time, thus showing that the polystyrene is still in the secondary phase, where the load level is below a certain upper limit.

# 4 EXPERIMENTS

Two different types of experiments have been carried out: (a) polystyrene specimens loaded in shear (compact shear test according to EN 12090) and (b) panels loaded in bending. Both test setups are shown in Figure 6a and 6b respectively. The bending tests are positioned and monitored in a climate-controlled environment.


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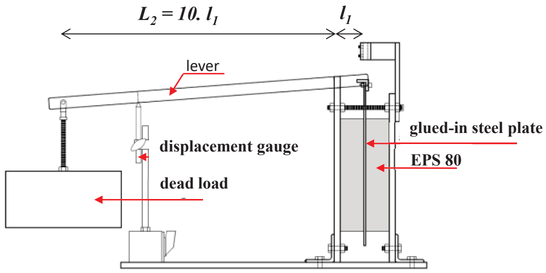
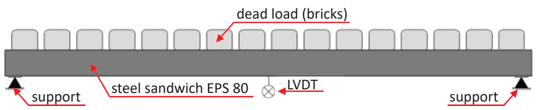



**(a)**




**(b)**

**Figure 6**: (a) *Shear test EN 12090 as modified for long term loading. $l_1$ =40 mm; $l_2$ = 400 mm;* (b) *Bending test setup for long term loading. Core thickness = 100 mm. Steel plate thickness = 0.4mm. Panel width =200 mm. Panel length =2100 mm.*

The compact shear tests (See Figure 6a and 7) comprise of 3 series of 6 samples each, loaded relative to the average shear strength by 27%, 41% and 54% respectively (no round percentages due to recalibration and resulting shear strength adjustments). These shear tests ran from June 2011 to April 2020, in a dry and heated, but not climate-controlled environment. After the tests ended, a shear test up to failure was carried out to check the residual strength.

***Figure 7:*** *Overview of compact shear tests*

Measurements were carried out at "regular" time intervals: a small time period (30s) in the beginning (June 2011) going up to once a month at the end (April 2020). This since at the end hardly any changes were visible, using a displacement resolution of 0.05 mm.

The second type of experiments consists of series of simply supported panels carrying bricks as a Uniform Dead Load (UDL), see Figure 6b, 8 and 9. These tests were done in a climate-controlled room at Eindhoven University of Technology.

***Figure 8*** *side view of all UDL samples, showing data loggers and LVDT's*


***Figure 9:*** *front view of the UDL samples, percentage per column, 6 samples per percentage*

For the specimens in bending, the focus is on the study of the polystyrene core, and the normally wood-based faces are replaced by steel faces.

Four different load levels are applied: 10%, 20%, 30%, and 40% relative to the characteristic shear strength of the

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polystyrene core (80 kPA). These percentages differ slightly from those used for the compact shear tests. The reason for that is that the percentages for the compact shear tests are determined after loading comparable specimen to failure.

The measurement of the total deflection is carried out at bottom side of the beam, in the middle, thus excluding measuring compression at the supports. Also these experiments were part of a long running experimental program, which was halted after 5 years due to a failure in the climate room. Afterwards the residual shear capacity was tested. In order to test a part of the polystyrene core that was well loaded by shear, the test specimens were taken near the supports.

# 5 RESULTS

## 5.1 PANELS LOADED IN BENDING

The single span tests show, although there are quantitative differences between series, very similar qualitative behaviour. Since the frequency of sampling is rather high, it is possible to discern even climate effects and similar.

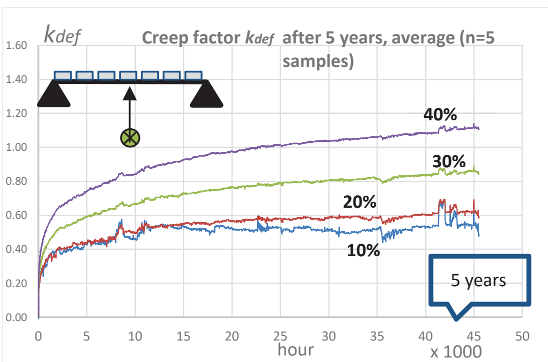


***Figure 10**: averages for series loaded from 10% to 40% of the characteristic strength; single span uniform distributed load experiment.*

Figure 10 shows there is a strong relation between the load and the relative displacement over time. Also, the smaller the load, the more vigorously the beam responds to other events, mostly climate effects. Also, the lower load levels show a lower increase of creep, and thus a lower strain rate. At 42000 hours a serious disturbance occurred, visible for all series. The reason for the disturbance is unknown.

## 5.2 COMPACT SHEAR TESTS

As mentioned earlier, the compact shear tests consist of three series, namely using load ratios equal to 27%, 41%, and 54%. Also here, a strong dependency on the relative shear stress was visible, as shown in figure 11. The most interesting result was that all samples of the 54% series failed after 4 years, indicated by the cross.

Exact failure times cannot be determined, for data logging was carried out at quite large intervals (700h). It is obvious that since the load was active for a very long period, the degradation of the core was due to progressive creep, and it may be concluded that a shear stress of 54% is well within the tertiary phase. The series of 27% and 41% were monitored for 9 years. After that period, these samples had still not failed.

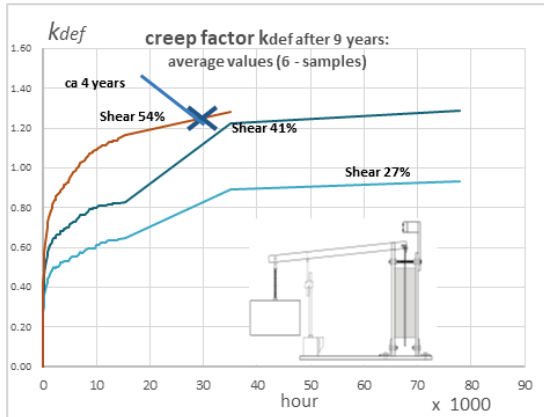


***Figure 11:** average per series of shear tests*

Final measurements were carried out after 12 years, but since the tests were not monitored properly in between 9 and 12 years, the deformations after 9 years were excluded from the study. However, since the samples did not fail, the residual strength could still be determined. At least it is known that 41% still holds after 12 years, so it is likely that when the shear stress is lower than 40% of the shear strength, the deformation stabilises in the secondary creep phase.

## 5.3 COMPARISON COMPACT SHEAR TEST WITH PANELS LOADED IN BENDING

All experimental results, but as average values of the 6 samples per series, are shown in figure 12.

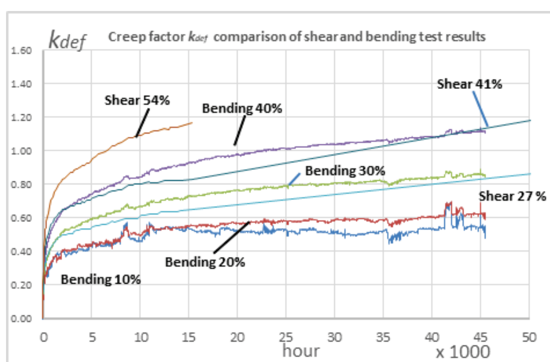


***Figure 12:** Comparison averages of all experiments*

The compact shear experiments show resemblance with the panels loaded in bending, particularly for load ratios up to 30%. It seems that the $k_{def}$'s found in shear tests are slightly higher than those found in the bending tests.


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### 5.4 COMPARISON PANELS IN BENDING WITH RESULTS OF KILPELÄINEN

Kilpeläinen et al. [2] performed bending tests and modelled the results according to the power model. Using equation (4) for fitting the data, Kilpeläinen found for $A_1$ = 0.195 and for $A_2$ = 0.177.

Figure 13 shows the Kilpeläinen et al. predictions for our bending experiments (dotted lines), equation (4) with the above values by the "Design envelope", and our panels in bending.

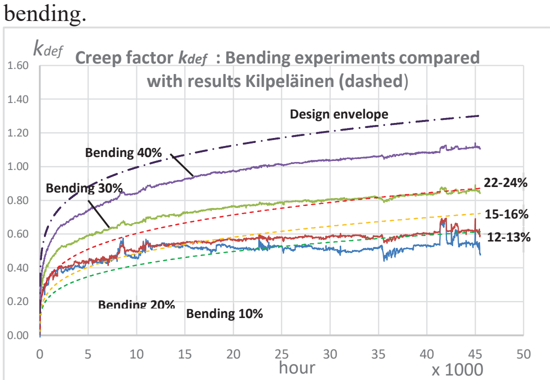


***Figure 13:*** *Comparison averages of beam experiments with* [2]

Overall, predictions agree reasonably well. The power model used by Kilpeläinen et al. seems to underestimate at the start, but agrees after 5 years. Also the proposed upper limit ("Design envelope") is well above the 40% level; This design curve indicates a value for $k_{def}$ = 1.95. For Finnish conditions (following Kilpeläinen et al.), including high quasi-permanent snow loads this is understandable, but for more average conditions, a 40% shear stress level will not be reached.

### 5.5 DESIGN LIMITS AND EXPERIMENTS

Three design limits are compared with both type of experiments. The design limits are the equation (3) as found by Kilpeläinen et al. [2]; the envelope equation by Kilpeläinen et al. [2], which leads to a $k_{def}$ = 1.49 based on the power model (Equation 5); and the limit using the five points model of Taylor et al., leading to $k_{def}$ = 1.60, Equation 6. This last equation (6) shows only four parameters, however, for determining $k_{def}$ the parameter $\Delta_0$ (Equation 2) vanishes.

$$k_{def}(t) = 0.053\, t^{0.275} \tag{5}$$

$$k_{def}(t) = 0.171(1 - e^{0.0065\, t}) + 0.143\, t^{0.174} \tag{6}$$

Kilpeläinen et al. [2] equation (3) is the dashed line almost at top. Clearly the 54% compact shear test was above this line and would have been rejected by all design limits. The second limit, the envelope equation by Kilpeläinen et al. [2] is just above the 30% and well above the 20% bending results. Finally, the Taylor et al. approach (Equation 6) is fitted on the data of this experiment and extrapolated to $k_{def}$ ($t$=50 years) = 1.60. It is almost coincident with the 30% bending tests.

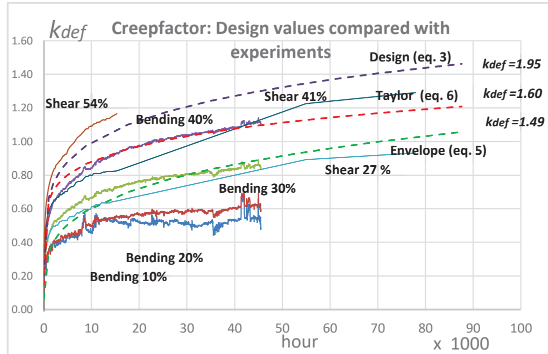


***Figure 14: Compact*** *shear and bending experiments compared with 3 proposed design limits*

This latter design limit shows a better similarity up to 10.000 hr compared to the power model, which obviously is due to the higher number of parameters fitted. Also, when the permanent relative shear stress is lower than 25%, using $k_{def}$ = 1.60 is an upper limit for the expected relative deformation after 50 years. This is a sound limit, since in the Ultimate Limit State (ULS) state (following EAD 140022 [3]) the EPS for the load duration class "permanent" is limited to 25%. Besides, applying $k_{mod}$ and $\gamma_m$ also will reduce the actual occurring stress in the Service Limit State (SLS). The limit by the envelope equation of Kilpeläinen et al., green dotted in figure 14, represents the 25% relative shear stress and is derived from results in [2], so it is similar to the design limit but considerably lower. If this later limit (envelope equation) is applied for permanent load duration in SLS states then the conclusion would be that indeed the bending experiments at 10% and 20% are acceptable, and that the compact shear tests at 54% and 41% are rejected. The 27% compact shear test is close to the Envelope (Eq.5), just slightly above, but is rather uncertain in development in time, so no conclusion can be drawn here. At least there is no safety margin. The 30% bending test seems to get under the 25%, but to be sure, this measurement is simply too short.

### 5.6 RESIDUAL STRENGTH AFTER CREEP TESTS

To determine the residual strength of the bending tests afterwards, several parts of their cores were tested for shear. These parts were taken near the support of the beams, and results are shown in Table 1. The results agree with the shear capacity at the start of the experiment, which was characteristically 80 kPA: the strength of most of the specimen was above 80 kPA, and the characteristic value was about 80 kPA, so it seems that the capacity was not affected. Possibly because stresses were too low, or that there was some ‘restoring’ effect: For the series up to 20% strains are most likely to be recoverably. For the 27% and 41% series, this is more uncertain.

***Table 1****: Residual shear strength of samples bending tests*

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| No. | S10% [kPa] | S20% [kPa] | S30% [kPa] | S40% [kPa] |
|---|---|---|---|---|
| 1 | 92.84 | 86.17 | 97.44 | 88.03 |
| 2 | 85.30 | 86.89 | 96.03 | 92.59 |
| 3 | 92.22 | 83.84 | 93.29 | 89.52 |
| 4 | 90.72 | 82.40 | 90.82 | 92.59 |
| 5 | 95.23 | 83.95 | 92.76 | 86.35 |
| 6 | 94.79 | 81.09 | 95.37 | 89.69 |
| 7 | 95.04 | 81.39 | 96.34 | 89.05 |
| Char. 5% | **84.94** | **78.97** | **89.66** | **84.91** |

Also, the compact shear test samples were tested for strength, by placing the entire setup in a pressure bench. Results on average were slightly lower than the original 80 kPA, see Table 2.

***Table 2****: Residual shear strength of shear samples*

| No. | S27% [kPa] | S41% [kPa] | S54% |
|---|---|---|---|
| 1 | 91.59 | 77.05 | x |
| 2 | 91.34 | 79.04 | x |
| 3 | 82.95 | 86.91 | x |
| 4 | 79.23 | 91.18 | x |
| 5 | 76.86 | 86.46 | x |
| 6 | 94.33 | x* | x |
| Char. 5% | | **72.88** | |
| *Sample used for calibration | | | |

This may be the effect of the series 41%, since these are a bit lower, but not dramatically. Sample 6 was lost while measuring; the value was 72 kPa, but Young's Modulus was suspiciously low, and so results were not trusted.

## 6 CONCLUSIONS

The study in this paper shows for EPS a strong relationship between creep (deformation) and load levels. Also, it is demonstrated that different experimental set-ups (bending and compact shear) agree well with respect to determination of shear creep, with the notion that compact shear tests seem to lead to slightly higher creep values. Furthermore, it shows that, the bandwidth in between tertiary creep (5 years at 54%) and the upper limit of secondary creep (9 years at 40%) is rather small.

Those samples that 'survived' the bending experiments still have the original shear load capacity, which supports the small bandwidth hypotheses. In general, when a shear stress at 25% of the shear strength is applied in serviceability limit state conditions, the creep factor $k_{def}$ will never be larger than 1.6 after 50 years. This is the case for a power model similar to Kilpeläinen et al. [2] as well as for a model according to Taylor et al. [1].

The residual strength of the samples after the test is reassuring. It proves that a long-sustained load on polystyrene can be accepted. Additional details related to this paper can be found in Modderman [9].

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