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Predicting the long-term creep behaviour of glued laminated elements

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ABSTRACT: The long-term creep behaviour of timber structures is an ever-increasing research focus given the rise of mass timber buildings across the world. Experimentally examining such properties is a time-consuming and costly process and reducing the time required for such tests may prove very beneficial for the industry. This study examines experimentally determined long-term creep deflection data from unreinforced and reinforced glued laminated elements collected over 5 years and evaluates the data in periods of ½, 1, 2, 3, 4 and 5-year intervals. The creep data is presented for unreinforced beams and beams reinforced with two basalt fibre reinforced polymer rods. The rods are adhesively bonded and housed within grooved routed in the tensile face of the beams. Furthermore, two environmental conditions are examined. A proportion of beams are subjected to creep testing at a constant climate of 65 ± 5% relative humidity and temperature of 20 ± 2 °C and another proportion of the beams were subjected to creep loading in a variable climate which was cycled between 65 ± 5% and 90 ± 5% relative humidity. The midspan creep deflection of each beam was monitored over a 5-year period and curve fitting of a polynomial function utilising a least squares approach is implemented for the different time intervals. The model was then used to predict the relative creep behaviour after 50 years.

1. INTRODUCTION

Timber is a structural material that is being increasingly used in construction due to its environmental credentials but it is not without its challenges due to its natural variability in properties, anisotropic behaviour and long-term or creep performance. Predicting or modelling the behaviour of structural timber elements is an ever-increasing research focus and recent efforts to develop validated models have significantly increased the reliability and safety of structural timber design. Another motivation of predictive models is to reduce or negate the time require for experimental testing whereby the creep performance can be assessed. Experimental monitoring of the long-term behaviour of structural timber products or engineered wood products is a time-consuming and costly process and the benefits of validated models will provide a powerful tool to aid the further development of such engineered wood products in the future. The influence of the surrounding environment on timber elements is also very important in understanding the behaviour of this engineering material. For this reason, special attention is given to studies modelling viscoelastic creep behaviour in a constant climate and studies modelling mechano-sorptive creep behaviour in a variable climate (Bengtsson, 2001; O'Ceallaigh, 2016; Ranta-Maunus and Kortesmaa, 2000).

While in recent years there have been significant advances in finite element modelling of structural timber elements under long-term loading which consider different environmental conditions (Dubois et al., 2012; Fortino et al., 2013, 2009; Mackenzie-Helnwein and

Hanhijärvi, 2003; O'Ceallaigh et al., 2020; O'Ceallaigh and Harte, 2019), this paper focuses on the use of simple polynomial models to predict the long-term behaviour of structural timber elements. This study examines experimentally determined long-term creep deflection data from unreinforced and reinforced glued laminated elements collected over 5 years and evaluates the data in periods of ½, 1, 2, 3, 4 and 5-year intervals. The data are evaluated in these time intervals and the fitted models are used to predict future creep behaviour. The models will be used to predict creep deflection after 5 years (compared to experimental results) and 50 years of creep behaviour. It is clear that with greater data, the results converge towards a common result but the difference is not significant, and a conservative estimate can be determined after a shorter experimental programme. The evaluation of different time intervals will be examined in this analysis which may allow for reduced experimental times to be considered leading to increased productivity and a reduction in the cost of experimental activities.

2. LITERATURE REVIEW

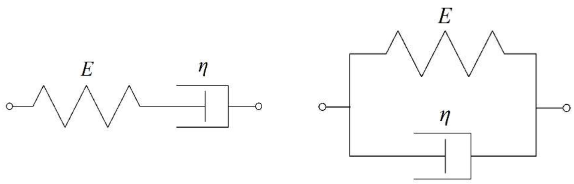
Rheology is the study of the flow of matter and rheological models can be used to describe time-dependent viscoelastic behaviour in timber elements. The basic elements of these models are known as spring and dashpot elements. When combining springs and dashpots in series and/or parallel, rheological or viscoelastic models can be created (Simo and Hughes, 1998). The spring behaviour as described in Equation (1) is a perfectly linear elastic representation of Hooke's law and models the elastic component of a viscoelastic material.

$$\sigma = E\varepsilon \tag{1}$$

Where σ = stress, E = modulus of elasticity and ε = strain. The dashpot behaviour as described in Equation (2) is a viscous element that extends at a strain rate proportional to the applied stress:

$$\sigma = \eta\dot{\varepsilon} \tag{2}$$

Where η = viscosity coefficient and $\dot{\varepsilon}$ = strain rate. The two most common models are known as Maxwell and Kelvin models which comprise Maxwell and Kelvin elements, respectively (Hanhijärvi, 1995; Marques and Creus, 2012; Simo and Hughes, 1998). The Maxwell element combines a spring and a dashpot in series as seen in Figure 1a. The Kelvin element combines a spring and dashpot in parallel as seen in Figure 1 b.



a) b)

Figure 1: Rheological models: a) Maxwell element, b) Kelvin element.

In practical applications, generalised models are required to accurately model viscoelastic material behaviour. Generalised models combine a number Maxwell or Kelvin elements, which increases the number of parameters and gives a better representation of the behaviour of the material being studied. In relation to timber elements, the viscoelastic component of creep is sometimes neglected in numerical models due to its relatively low contribution to the total creep deformation, which occurs under changing moisture content conditions (mechano-sorptive creep), however, rheological models have been extensively used to model the viscoelastic behaviour of timber. In 1971, Senft & Suddarth (1971) utilised a Burger model which consists of Maxwell and Kelvin elements. They examined small specimens of Sitka spruce at stress levels of 10, 20, 40 and 60% of ultimate strength for load durations up to twenty days. The three and four-parameter models adequately simulated the time-dependent viscoelastic creep behaviour of timber, however, they suggest a four-parameter model for durations longer than 24 hours or at high-stress levels. This model was limited to a uniaxial direction and could only model viscoelastic creep as changes in relative humidity were omitted.

In another study by Gressel (1984), the creep behaviour was predicted and compared to experimental tests with a duration of ten years where a 5-parameter model was developed and found to perform well. This was also observed by Dinwoodie et al., (1990, 1984) in a series of studies over a 15-year period quantifying and predicting the creep behaviour in particle board. The most suitable model for the long-term prediction of creep was a five-parameter model (Four element model with non-linear viscous dashpot).

2.1. Reinforcement

A relatively low number of studies have attempted to predict the long-term performance of reinforced beams under constant or variable climate conditions and these have been limited to the uniaxial case. In a study by Plevris & Triantafillou (1995), an analytical model is employed to predict the creep behaviour of CFRP reinforced timber beams. The model was developed to account for moisture effects; however, the final analytical results were compared to a small sample of CFRP reinforced timber beams tested in a constant climate condition. Different percentage area reinforcement ratios were used when reinforcing each beam. The experimental and analytical data showed good agreement in a constant climate and the percentage area reinforcement ratio was deemed to provide a significant contribution to the deformation behaviour of reinforced beams. In Davids et al. (2000) a uniaxial model was developed to model the creep behaviour of GFRP reinforced timber beams in a variable climate. The model, combining viscoelastic and mechano-sorptive creep strain parameters, was fitted using the unreinforced specimen test results and then shown to accurately predict the relative creep (RC) deflection of the GFRP reinforced beams in a variable climate.

2.2. Objectives

In this study a polynomial model is used, which is adapted from that developed by Gressel (1984) and is a variation of the Burger model, incorporating a number of model parameter constants. The model is a 5-parameter model incorporating a spring for the initial instantaneous deflection, followed by a time-dependent deflection component, controlled by both the Kelvin model and a non-linear viscous dashpot. The model is shown in Figure 2.

In this rheological model, when a beam experiences a load, the initial instantaneous deflection is governed by the spring element shown on the left-hand side of Figure 2. This is then followed by a time-dependent deflection, controlled by both the Kelvin element shown in the centre of the schematic and the non-linear dashpot located on the right-hand side.

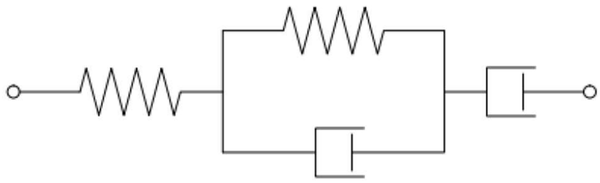


Figure 2: Model: Five Parameter.

This model is represented in Equation (3).

$$RC = \beta_1 + \beta_2\left(1 - e^{-\beta_3 t}\right) + \beta_4 t^{\beta_5} \tag{3}$$

Where RC is the relative creep at time t, t is the time in weeks and β_1, β_2, β_3, β_4 and β_5 are model parameter constants.

Relative creep is defined as the deflection at time, t, over the initial elastic deflection where the initial deflection is defined as the deflection 60 seconds after the load has been applied (Equation (4)).

$$RC = Relative\ Creep\ = \frac{w\ (t)}{w_0} \tag{4}$$

Where $w(t)$ = deflection at time, t, and w_0 = initial deflection at time zero at t_0 = time zero which is 60 seconds after loading.

3. EXPERIMENTAL TEST

This study utilises experimental data gathered at the Timber Engineering Laboratory at the University of Galway where long-term experimental creep tests on unreinforced and reinforced glulam beams are being carried out in constant and variable climates. While the mechanical response comprises several components, namely, elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components, this study will utilise a rheological model to predict the performance of these beams. This section provides an overview of the structural beams, climate conditions, and experimental creep test set-up at the University of Galway.

3.1. Structural Beams

The structural beams subjected to creep testing are glued laminated beams manufactured using C16-grade structural timber. The beams comprise four laminations with each beam measuring approximately 98 mm x 125 mm x 2300 mm. They were laminated by applying a phenol resorcinol formaldehyde adhesive and clamping to a pressure of 0.6 N/mm^2 in accordance with EN 14080 (CEN, 2013). A proportion of the beams are reinforced with two Basalt Fibre Reinforced Polymer (BFRP) rods measuring approximately 12 mm in diameter, to reinforce the tensile face of the timber beams. The cross-section of the reinforced beams can be seen in Figure 3.

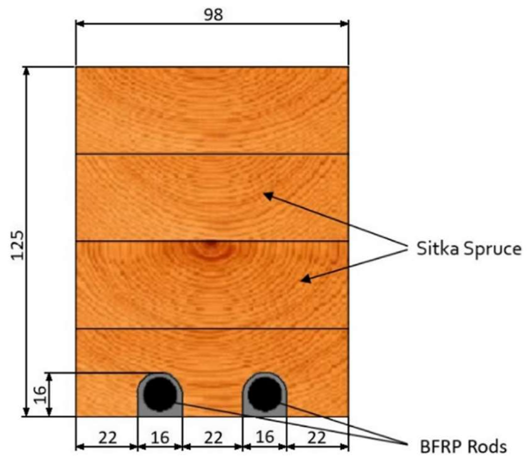


Figure 3: Cross-section of the manufactured beam reinforced with two BFRP rods in the tensile lamination (O'Ceallaigh, 2016; O'Ceallaigh et al., 2018).

3.2. Climate Conditions

The long-term tests are performed in conditioning chambers under two climate conditions. One of these chambers had a constant relative humidity of 65% ± 5% and a temperature of 20°C ± 2°C throughout. In the second variable climate chamber, the relative humidity cycle length was set to 8 weeks (4 weeks at 90% RH and 4 weeks at 65% RH) until week 152 whereby the cycle length was increased to 16 weeks (8 weeks at 90% RH and 8 weeks at 65% RH).

3.3. Matched Groups

In order to analyse the long-term effect of reinforcement and constant and variable climate conditions on glued laminated beams, it was desirable to create matched groups to examine the long-term performance of such beams. Four of these matched groups consisting of nine beams each were created for the long-term test programme. The group naming convention is as follows.

- Group UC = Un-Reinforced Constant Climate Group
- Group UV = Un-Reinforced Variable Climate Group
- Group RC = Reinforced Constant Climate Group
- Group RV = Reinforced Variable Climate Group

To confirm that the groups were equally matched, statistical Student's t-tests were carried out to compare the means (local elastic modulus and local bending stiffness) of each matched group to one another to a significance level of 0.95 (α = 0.5). To perform a Student's t-test, each group being compared should follow a normal distribution. Shapiro-Wilk tests were performed on each group to assess normality. Once normality or a normally distributed sample cannot be rejected, Levene's test was performed to examine the homogeneity of the group or sample variances. When comparing groups using Levene's test, a proportion of the groups had equal variances and a proportion had unequal variances. For equal variances, Student's t-test was implemented as it assumes equal variances. In the case of unequal variances, an adapted version of the Student's t-test known as Welch's t-test or unequal variances t-test was used to compare the means of both groups. The results have shown no statistical evidence to suggest that the mean of any group is not equal to any other group in their unreinforced state. This is valid when examining both, mean local elastic modulus and mean local bending stiffness.

3.4. Experimental Tests

The beams were then loaded in the creep frame at the University of Galway (See O'Ceallaigh et al., (2019, 2018)). Each beam is loaded in four-point bending so that the bending stress on the compression face is 8 MPa. The instantaneous elastic deformation was recorded for each beam and the creep deflection has been recorded at regular intervals with time.

3.5. Experimental Results

The mean deflection results for each group are presented in Figure 4. It can be seen that each group is subjected to an initial elastic deflection when the beams are loaded. In subsequent weeks, it can be seen that the groups experience increased deflection with time. Group UC and Group RC experience viscoelastic creep as they are loaded in a constant climate. Group UV and Group RV experience significantly greater deflection and this is due to the viscoelastic creep coupled with mechano-soprtive creep and swelling/shrinkage effects. The results are presented as total deflection (mm) and but additionally, in order to focus on the long-term effects, the results are presented using the normalised measure of relative creep (RC – see Equation (4)). RC is closely related to the k_{def} factors as shown in Equation (5) which are utilised in Eurocode 5 (CEN, 2005) design guidelines to account for long-term creep deformations in structural timber elements.

$$k_{def}\ (t-t_0) = \frac{w(t)-w(t_0)}{w(t_0)} = RC - 1 \tag{5}$$

4. RESULTS

For the purpose of this analysis, the relative creep behaviour of each group is assessed by curve fitting of a polynomial function (Equation (3)) utilising a least squares approach for the different data/time intervals. An example of the process is presented in Figure 5 whereby the time interval after 3 years is presented.

The resultant fit of each group is also shown and extrapolated to predict the relative creep behaviour after 5 years (260 Weeks). The k_{def} factors, determined using Equation (5), are presented in Table 1 for all time intervals. The k_{def} factors after 5 years are presented and are compared to the experimental test results after 5 years (5 year (Exp)). The results are also presented graphically in Figure 6. It can be seen from both Table 1 and Figure 6 that the prediction of k_{def} is improved with increasing data as expected. The 5-year time interval best predicts the experimentally determined creep after 5 years, however, it is also noted that the results for shorter periods of data also produce relatively accurate

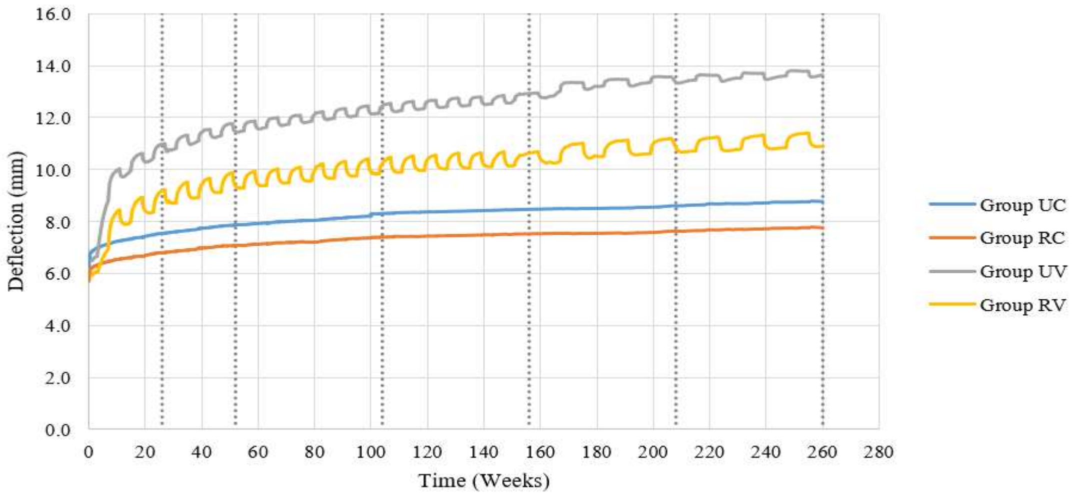


Figure 4: Long term creep behaviour of Group UC and Group RC in a constant climate and Group UV and Group RV in a Variable climate over a 5 year period.

and often conservative predictions. For example, when examining Group UC after 2 years of data, the predicted k_{def} factor is 0.424 compared to the experimental result of 0.401. This is a percentage difference of 5.5% or, when converted back to creep deflection, represents a difference of only 0.16 mm. it is important to note that this was the case for the constant climate conditions and the creep behaviour for the variable climatic conditions is more pronounced.

Table 1: The predicted k_{def} factors for 5 years.

Time Interval	Group			
	UC	RC	UV	RV
½ year	0.437	0.431	1.269	1.052
1 year	0.432	0.414	1.259	1.019
2 year	0.424	0.410	1.258	1.007
3 year	0.426	0.392	1.262	1.018
4 year	0.413	0.379	1.278	1.030
5 year	0.409	0.375	1.288	1.036
5 year (Exp)	0.401	0.366	1.296	1.010

If we examine the case of the variable climates, we can see that for Group UV a k_{def} factor of 1.258 is predicted after 2 years of data. This is a percentage difference of 2.9% when compared to the 5 year experimental result of 1.296. When converted back to creep deflection, this represents a difference of only 0.24 mm although it should be noted that this is an under-prediction in the case of Group UV. Interestingly, in the case of the reinforced beams, the reduced creep that was observed experimentally when compared to the unreinforced groups was also well predicted with conservative over predictions.

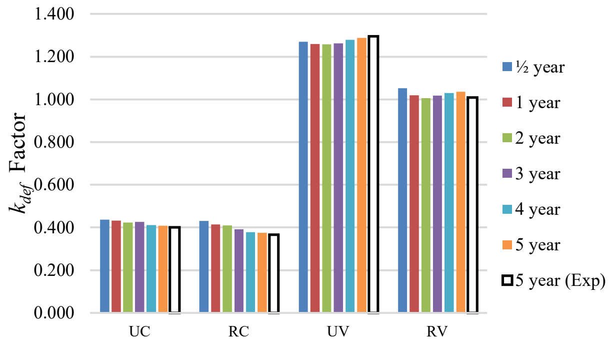


Figure 6: The k_{def} factor after 5 years based on different time intervals compared to the experimentally determined k_{def} factor after 5 years.

The goal of this study was to focus on predicting the creep deflection behaviour after 50 years and examining the results for different time intervals to further examine the influence of test duration and the prediction of creep for engineered wood products.

In Table 2 and Figure 7, the predicted k_{def} factors after 50 years are presented. It should be noted that current structural design guidelines for glued laminated elements in Eurocode 5 provide

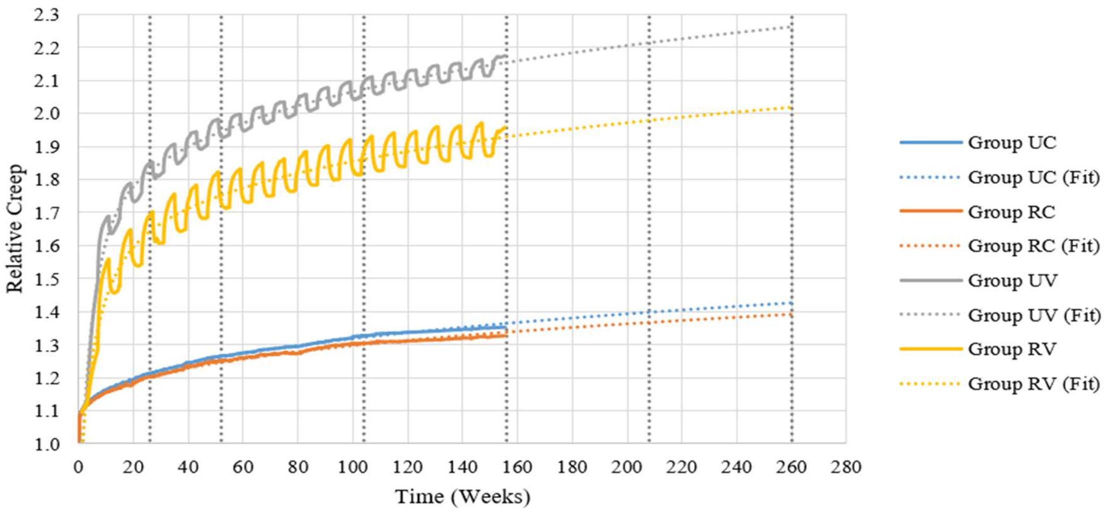


Figure 5: Relative creep (RC) behaviour of each group over a 3 year period and fitted curves.

k_{def} factors of 0.6 for Service Class 1, 0.8 for Service Class 2 and 2.0 for Service Class 3. To draw comparisons to the climate conditions used in this study, Group UC and RC would be representative of Service Class 1 conditions and the climate subjected to Group UV and RV is representative of Service Class 3 conditions.

Table 2: The predicted k_{def} factors for 50 years.

Time Interval	Group			
	UC	RC	UV	RV
½ year	0.92	1.07	1.88	1.58
1 year	0.92	1.00	1.87	1.52
2 year	0.92	0.89	1.84	1.46
3 year	0.89	0.78	1.85	1.49
4 year	0.80	0.70	1.91	1.53
5 year	0.77	0.68	1.94	1.55
EC 5	0.60	-	2.00	-

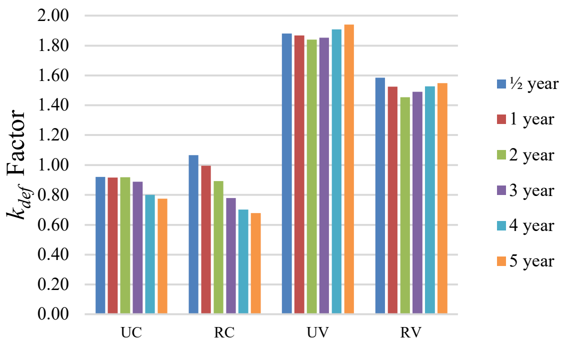


Figure 7: The predicted k_{def} factor after 50 years based on different time intervals.

It can be seen that in all cases, the k_{def} factor tends towards the recommended values for the relevant Service Classes. Group UC and RC provide conservative over-predictions and are decreasing with increasing time intervals. In the absence of experimental data on specimens subjected to creep testing for 50 years, it is best to compare to the recommended values in current design standards (Eurocode 5 in this case). If we look at Table 2, it is clear that all values are above the Eurocode 5 recommended values for all time intervals with reduced creep behaviour predicted for reinforced beams. When examining Group UV and RV, it can be seen that the k_{def} factors are typically increasing with increasing time intervals but are currently not providing conservative predictions (compared to recommended Eurocode 5 values). It is also seen that the reduced creep behaviour of reinforced beams (Group RV), which was observed experimentally after 5 years has also been predicted after 50 years using the rheological model presented in this study. Overall, this study has examined the possibility of utilising reduced time frames of test data to evaluate long-term creep behaviour. The results show that it is difficult to extrapolate to 50 years in both constant and variable climates without some degree of error and caution and engineering judgement is recommended when seeking to predict such behaviour. It is noted that the mechano-sorptive creep component is not discretely modelled in this study and significant improvements can be made to this simplistic rheological model.

5. CONCLUSIONS

The creep behaviour of unreinforced and reinforced glued laminated elements has been predicted utilising a simplistic 5-parameter rheological model. The model has been fit to creep curves (of different time intervals) using a least squares approach to examine the influence of test duration on the predicted long-term creep behaviour. The findings show that reduced creep behaviour is predicted for the reinforced beams and although the difference is not significant in the constant climate, there is a larger reduction in the creep behaviour of reinforced beams in a variable climate when compared to the unreinforced beams. The findings also show that creep deflection after 5 years can be well predicted from only 2 years of data but when extrapolated to 50 years, it is clear that with greater time intervals, the results tend toward the recommended values in Eurocode 5 and utilising data of shorter durations should be used with caution and consideration for potential errors in the prediction.

The predictions in the variable climate, particularly Group UV, tend towards the recommended value in Eurocode 5 however, the proposed future work will incorporate further elements to focus on the mechano-sorptive creep component solely in addition to the 5-parameter rheological model presented here to better predict the creep behaviour in the beams subjected to creep loading in a variable climate.

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