Preferred citation: C. Fellers, T. Haraldsson and P. Kolseth. The edgewise compression creep of paperboard: new principles of evaluation. In **Products of Papermaking**, *Trans. of the Xth Fund. Res. Symp. Oxford, 1993*, (C.F. Baker, ed.), pp 601–637, FRC, Manchester, 2018. DOI: 10.15376/frc.1993.1.601.

THE EDGEWISE COMPRESSION CREEP OF PAPERBOARD

NEW PRINCIPLES OF EVALUATION

Tony Haraldsson, Christer Fellers and Petter Kolseth.
STFI, Box 5604, 114 86 STOCKHOLM, Sweden

ABSTRACT

A suggested method to describe the creep behaviour of paperboard in edgewise compression works for paperboard in the same way as for other polymers. The relation between stress, strain and time may be determined by a simple equation involving two factors, a power function of time and a factor describing the non-linear behaviour of the stress-strain curve.

For engineering purposes, it is an advantage to be able to design a given product in terms of stress and strain in **isochronous curves.** In some applications the critical design criteria may be governed by a critical strain. For such applications **isometric curves**, i.e. stress versus time at different strains, are used.

The strain at break in compression of the investigated paperboards was found to be independent of time. The strain to break in creep was equal to the strain at break for stress-strain testing under straincontrol. By inserting the strain at break in creep in the creep equation, the **isometric curve** at break could be derived which by definition gives the relation between stress and lifetime.
The data in this investigation indicate that a rather small number of specimens and a reasonably short creep time are sufficient to provide a

good prediction of the long-term creep behaviour. In other words, the creep of paper follows the fundamental behaviour of the material already established at short times, and described by the creep equation.

INTRODUCTION

Containers made of corrugated board are often stacked on pallets. If the contents are heavy, the container at the bottom of the stack has to withstand and support considerable loads. Like all engineering materials, paper is viscoelastic and shows characteristic creep behaviour when subjected to a load. It is also well known that a container will break after a certain time when subjected to a given load and that the lifetime is drastically diminished as the load or the relative humidity of the ambient climate is increased. For engineering purposes, it is thus important to find ways to determine the maximum load that can be applied to a given container without causing damage or collapse to the container within a given time.

Lifetime determinations are timeconsuming both because of the nature of the problem and because the paper and the container construction have a certain variability which make the lifetime vary considerably at a given load. For this reason, a large number of samples must usually be tested to obtain an average lifetime value with sufficient precision for use in engineering calculations and in product development work.

Another complication with lifetime determinations in warehouses is that the ambient climate always varies during the loading period, so that the average creep rate is increased and the lifetime is diminished. A review of the effect of cyclic ambient climates on the creep behaviour of paper and other materials is given by Söremark and Fellers (1).

Fundamentally, the creep of a container or of a small corrugated board sample is related to the creep behaviour of the single plies. The purpose of this paper is to describe the creep behaviour of representative liner boards and corrugating media in a constant standard ambient climate of 50 % relative humidity as a first step towards understanding and describing the creep due to more complicated load or humidity histories. Single-ply creep measurements in a constant ambient climate have previously been reported for compression loading (2, 3) and for tensile loading (4-6).

Lifetime determinations in a constant ambient climate have also been performed on small corrugated board samples such as those used for the determination of edgewise compression tests on corrugated board (7-10) and on corrugated board containers (9-15).

Because of the problems mentioned, it is desirable to find ways to predict long-term behaviour from short-term tests. The lifetime of a container or a corrugated board specimen, i.e. the final failure point, is the aspect of creep which has been investigated most.

One simplified way of establishing the lifetime of a container is first to determine the mean compression resistance according to a standardised Box Compression Test, BCT and then to multiply this value by a safety factor determined by experience (15).
The linear relation between the log of time to failure and the log of creep rate in the secondary region of the deformation vs. time curve may also be utilised (3, 10, 13, 14, 16).

Another approach is to estimate the lifetime as a function of load by measuring the failure load as a function of deformation rate for corrugated board specimens (8). Caulfield (17) derived an expression to predict the lifetime from the loading rate for viscoelastic materials and used literature data for wood to verify his expressions.

In this paper, a new instrument has been used to study the creep of paperboard in edgewise compression (18). For the description of the creep behaviour, a method used for engineering design purposes was evaluated. The method which has previously been used to describe the non-linear creep behaviour of polymers (19-23) is described as follows:

Isochronous curves, i.e. curves relating stress versus strain at different constant times, are obtained from cross-sections through the creep curves at different times. Each isochronous curve may be described by a hyperbolic tangent function. From the time dependence of these functions, it is possible to make the data fit a creep equation which describes the relation between stress, strain and time.

In some applications, the critical design criterion may be governed by a critical strain. For such applications, an **isometric curve**, i.e. a curve of stress versus time at a given strain, may be derived by inserting the desired strain into the creep equation.

The strain at break in compression of the investigated paper boards was found to be independent of time. By inserting the strain at break into the creep equation, the isometric curve for the strain at break could be derived, which by definition gives the relation between stress and lifetime.

The data was subjected to statistical treatment. The necessary creep time and number of samples to be tested to obtain a given precision in the long time creep naturally depend on the variability of the material. The data in this investigation indicate that a fairly small number of specimens and a reasonably short creep time are sufficient to give a good prediction of the long-term creep behaviour. In other words, the creep follows the fundamental behaviour of the material already established at short times and described by the creep equation.

The conclusion drawn from this investigation is that the suggested method to describe the creep behaviour of paperboard in edgewise compression works for paperboard in the same way as for other polymers and that the relation between stress, strain and time may be described by a simple equation. This knowledge makes it possible to predict the strain and lifetime as a function of stress and to design paperboard products from engineering principles with more confidence than was previously possible.

MATERIALS AND METHODS

Paper board samples

Four different commercial papers were used in the investigation, covering the grammage region of 127-200 g/m^2, viz.:

Material K	Kraftliner, 185 g/m^2.
Material T	Testliner, 200 g/m^2.
Material N	NSSC corrugating medium, 127 g/m^2.
Material R	Corrugating medium based on recycled fibres, 150 g/m^2.

Testing climate

The SCAN-test standard climate of 23°C and 50 % RH was used (24).

The compression creep apparatus

Figure 1 shows a schematic representation of the new apparatus for the measurement of stress-strain and creep properties of paper board in compression.

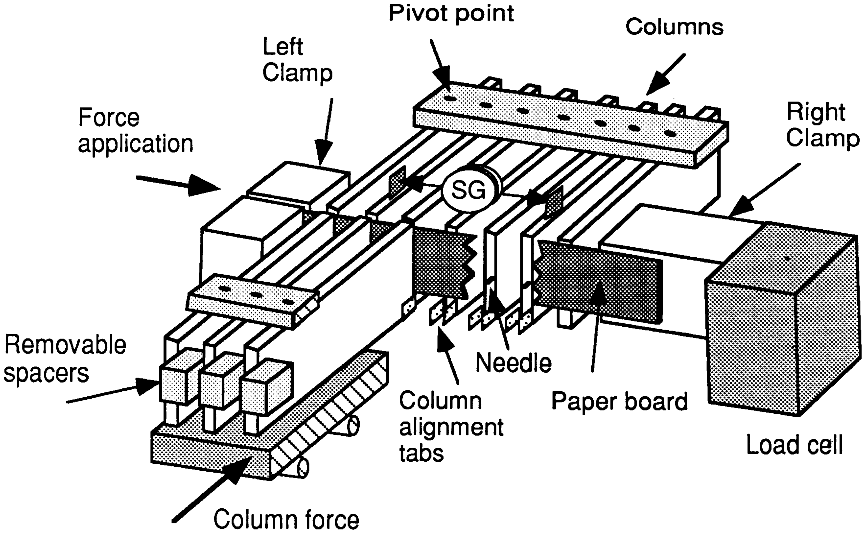

Figure 1. Principle of the apparatus for the evaluation of the stress-strain- and creep properties of paperboard in compression.

Two clamps for holding the test piece at its ends are firmly mounted on low-friction roller slides. Because of the rather large clamping area, 25 mm times 30 mm, no failure occurred close to the clamped area. The lateral pressure in the clamps is achieved by turning the screws by hand with a torque wrench.

In order to be able test the compressive properties of paper it is necessary to keep the test piece perfectly straight during the loading. This is accomplished by providing lateral support for the test piece by means of 17 pairs of 3 mm thick, 25 mm wide columns separated by gaps of 0,6 mm. The total length of the supported part of the test piece is 60 mm. The columns are able to pivot slightly around pins. The length of the columns is 150 mm with the pins mounted 100 mm from the end making contact with the paper. The 17 pairs were ground together after assembly to ensure parallel support for the paper. The spacing between the columns is 0,1 mm less than that recommended (25, 26) for use in the short-span compression test (27).

The columns are pressed against the paper with a force of 60 N applied by a hanging load. To ensure good support of the test piece during the loading it is necessary that opposite columns follow the paper movement without misalignment. Opposite columns are therefore connected by alignment tabs and made to follow the movement of the paper by means of short needles protruding from each of the column pairs. The loading on the left-hand clamp is provided by a hanging load for the creep experiments and by an electromagnetic actuator for the stress-strain experiments. The actuator also serves the purpose of holding the left-hand clamp in position during clamping and of releasing the left-hand clamp in the creep experiments. The force is measured by a 500 N load cell, connected to the right-hand clamp. The strain in the test piece is recorded from the movement of two of the columns separated by a distance of 45 mm. The movement is detected by a strain gauge arrangement mounted on top of the columns and covering a total strain range of 2 %.

The load and strain gauge signals are fed to a PC through an A/D-converter. Appropriate computer programs were used for carrying through the creep experiments and the subsequent evaluation of the data.

Stress-strain testing

The stress in the stress-strain experiments is applied by an electromagnetic actuator connected to the left-hand clamp. With the apparatus it is possible to achieve linear strain or stress ramps vs. time and to record the corresponding stress-strain curves of paperboard under either stress-control or strain-control at different rates.
To determine the mean stress-strain properties, 10 samples were tested for each data point.

Creep testing

In creep testing, the stress is kept constant and the strain is recorded as a function of time. The stress in the creep experiments is applied by a hanging load which is connected to the left clamp by a string. Before starting the creep test, the string is stretched by the hanging load while the actuator holds the left clamp in position. The test piece is then mounted. By a computer command, an actuator then releases the left clamp and the creep testing starts.

The shortest reliable time in a creep strain test depends on several factors. The time constant of the amplifiers must be considered and only small oscillations of the stress can be allowed at each load level. Furthermore, in order to diminish the effect of the loading procedure, it is necessary to wait a certain time after the ramp time up to the desired load until the first reliable strain results can be obtained. Since the loading time for the tests never exceeds 0,1 seconds, which is also within the range of the time constant of the strain amplifier, it is safe to start using the collected data at 1,0 second, i.e. more than one decade later than the time to reach the desired load level, as common practice (28). Ten data points are collected over each decade of time or at least one point per 0,01 % strain.

About 80 samples in MD and CD respectively of each paperboard were tested and used to determine the creep properties. In the trial where isochronous curves in compression and tension were compared, 20 samples were used in the same apparatus.

Equations for the description of creep

If creep causes failure, three distinct stages in the time-dependence of the deformation can be identified, viz.: primary, secondary and tertiary. The region for which creep deformation is approximately linear with time is designated secondary creep.

A number of investigators have described creep strain as a function of stress and time in terms of linear springs and linear viscous elements. These models are used in linear viscoelasticity. Few engineering materials can however be described by linear viscoelasticity. A large number of descriptive equations have therefore been used to model the creep of materials but none has universal applicability. Reviews of creep equations are given in several papers (28-32).

The task is to find an equation which gives the relation between strain, stress and time.
We propose that there is a class of materials for which the strain ε is a non-linear function of the two independent variables time t and stress σ^W as in equation (1).

$$\varepsilon = f(t) \cdot g(\sigma^W) \qquad (1)$$

Two such hypothetical materials, described by equations (2) and (3) are used to describe uniaxial creep of paper.

$$\sigma^{w} = (t/t_o)^n \cdot \alpha_1 \cdot \tanh(\varepsilon \cdot \alpha_2/\alpha_1) \tag{2}$$

$$\sigma^{w} = (1 - m \cdot \log t/t_o) \cdot \beta_1 \cdot \tanh(\varepsilon \cdot \beta_2/\beta_1) \tag{3}$$

where σ^w= stress= force/(width · grammage), Nm · kg^{-1}

For paper we choose to use the term "stress" as a shorter term for "specific stress" i.e. stress divided by density or force per width per unit grammage.

$m, n, \alpha_1, \alpha_2, \beta_1, \beta_2$ = material constants, t_o= constant= 1 s.

At small strains the hyperbolic tangent function becomes linear and both equation (2) and (3) describes the behaviour of a linear viscoelastic material namely that isochronous curves are linear, i.e. that the relation between stress and strain is linear at equal time.

We define a useful engineering parameter, a "creep stiffness index" by means of equation (4) and (5) respectively as the initial slope of the isochronous stress-strain curve. The creep stiffness is by definition the same in compression and in tension.

$$E^{w,cr}(t) = (t/t_o)^n \cdot \alpha_2 \tag{4}$$

$$E^{w,cr}(t) = (1 - m \cdot \log t/t_o) \cdot \beta_2 \tag{5}$$

where $E^{w,cr}(t)$= creep stiffness index, Nm/kg

A logarithmic time dependence is used in most of the creep investigations on the small corrugated board samples and corrugated containers. The advantage is a straight line representation of stress vs. log time, the disadvantage that a finite lifetime is reached at zero stress, which was shown not to be true for materials in general (33).

A power function to describe the time dependence is suggested among others by Findley (29) and Turner (20) to describe creep and by Andersson (34) and Gunderson et al. (35) to describe the dependence of failure stress of paper on the rate of straining.
The hyperbolic tangent description of the non-linear stress-strain behaviour was originally suggested to describe the tensile properties of paper (36) and was used to describe the stress-strain curve of paperboard in compression (35, 37-39).

To test whether either of equations (1-5) were suitable for describing uniaxial creep of paper in compression and in tension, the four different paperboard samples were tested in MD and CD. The equations were fitted to the recorded data by means of the Gauss-Newton method.

Definition of the strain at break in the creep trial.

In stress-strain experiments it is easy to define the strain at break as the strain at the maximum force. In creep experiments this method is not readily available since the force is constant and the strain rapidly rises at the break point. The following principle was used to define and to find the strain at break on the creep curve, shown in figure 2.

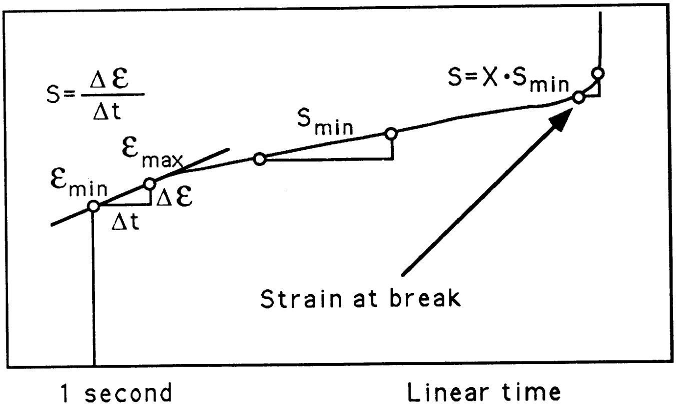

Figure 2. Principle for the determination of strain at break during creep testing.

At the starting time of one second, a variable strain, ε_{min} is recorded. An increment of Δ ε is added to this strain and we obtain ε_{max} and the corresponding time increment Δ t. The strain increment included approximately four data points.
The slope of the curve $S= \Delta \varepsilon / \Delta t$, at a given strain, ε_{min} is determined by making a linear regression to all the data points in the increment.

The slope of the curve is scanned in steps of 0,01 % strain units. First the minimum slope S_{min} is determined. Secondly the strain on the curve is determined where the slope is larger than X times S_{min} This strain defines the strain at break during creep. The numerical values of Δ ε and X are discussed in the results.

Construction of isochronous curves and isometric curves from creep curves.

Isochronous curves, i.e. stress versus strain at different times are constructed by making cross-sections in the creep curves at different times, figure 3. Isometric curves, i.e. stress versus time at equal strain, are constructed by making cross-sections in the creep curves at different strains, figure 4.

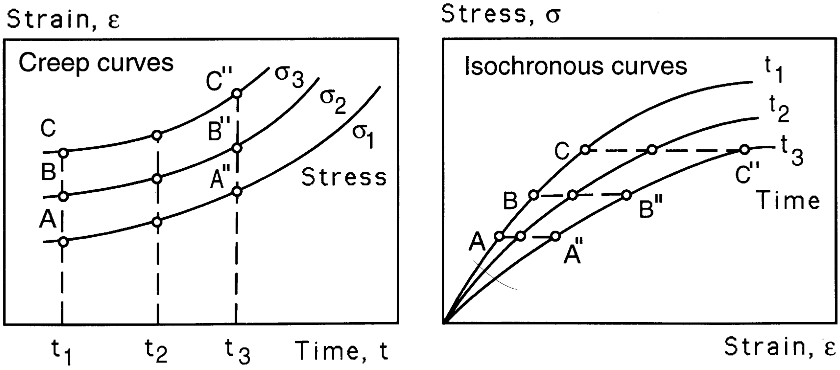

Figure 3. Construction of isochronous curves from creep curves.

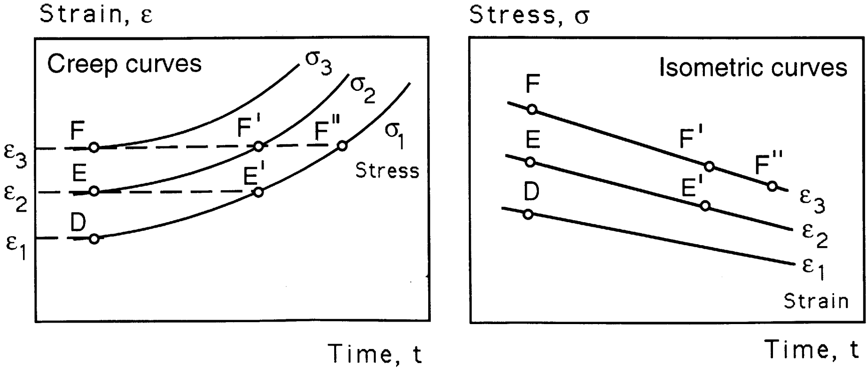

Figure 4. Construction of isometric curves from creep curves.

RESULTS

The purpose of this paper is to describe the creep behaviour in compression of representative linerboards and corrugating mediums using a new instrument. The measurements were performed in a constant standard ambient climate of 50 % relative humidity as a first step towards understanding and describing the effect on creep of more complicated load or humidity histories. Comparisons are also made with tensile creep properties.

Four different paper boards used for the manufacture of corrugated board were tested in MD and CD.

We have chosen to use data for one of the investigated papers, paper K, in most of the figures to illustrate a particular aspect of creep behaviour. We have carefully checked that the results in those cases were representative for all the investigated papers. In some investigations it was however necessary to use the data for all four materials to establish the universal applicability of the results. We are not at this point however aiming to make a numerical comparison of the creep behaviour of the four papers.

Creep curves

Creep curves in CD for paper K at different stress levels are shown in figure 5. Only a few of about 80 recorded curves are shown. The curves are plotted in figure 5a) against linear time up to 200 seconds and in figure 5b) against log time up to 10^6 seconds. The time 200 seconds is indicated by a dotted line. The star-point on each curve show the strain at break in creep defined by using $\Delta\varepsilon$=0,04 % and X=4 in figure (2). Note the variation in strain at break.

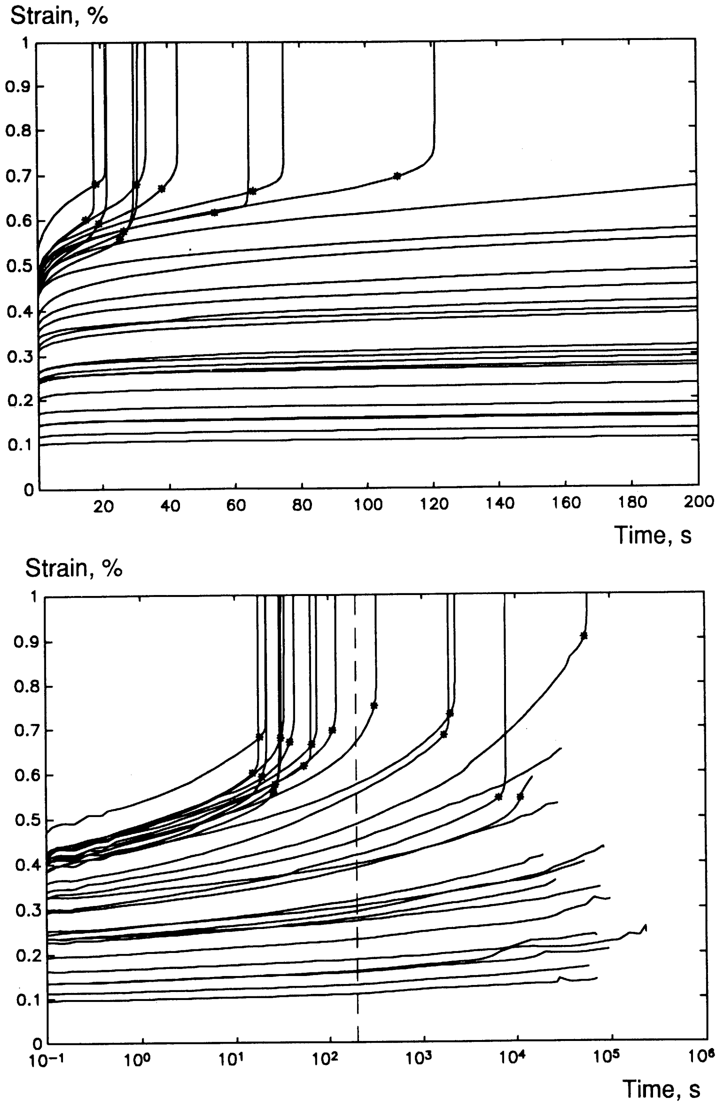

Figure 5. Creep curves in CD for paper K at different stress levels, plotted in a) linear time and b) log time.

All the recorded data for each paper in either MD or CD were used to find the material constants in equation (2). The ability of equation (2) to fit the data is demonstrated in figure 6 at a few stress levels for paper K in CD. The solid lines are the measured curves at a given stress level and the dotted lines are the strains fitted to equation (2). Note that some predicted curves lie above and some below the measured curves.

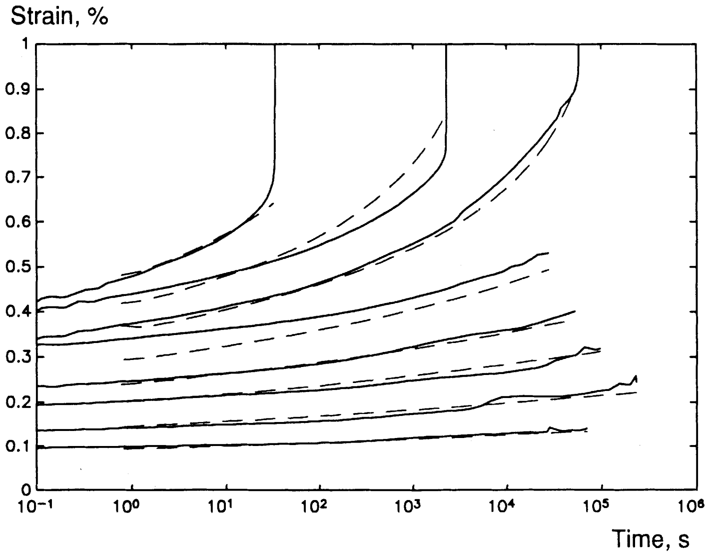

Figure 6. Creep curves and fitted curves at a few stress levels for material K in CD. The solid lines are the measured curves at a given stress level and the dotted lines are the strains fitted to equation (2).

Figure 7 shows the relation between strains fitted to equation (2) and measured strains for all data points for paper K in CD. The deviation from a straight line is primarily due to the non-uniformity of the paper but may also be influenced by the variation in the testing conditions. The data points are reasonably well symmetrically distributed around the 1:1 line which establishes that the chosen equation (2) fits the data well.

The relation between strains fitted to equation (3) and measured strains had a pattern similar to that in figure 7.

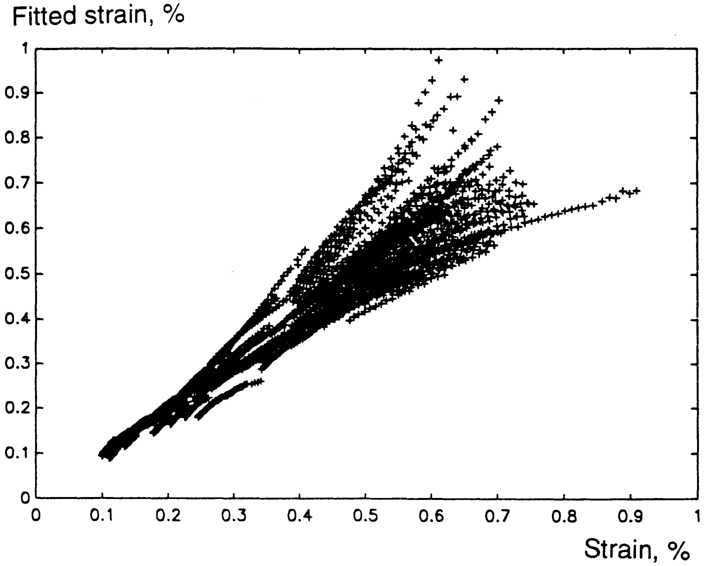

Figure 7. The relation between strains fitted to equation (2) and measured strains for all data points for paper K in CD.

Isochronous curves and creep equations

From the creep curves, isochronous curves were constructed. A short-time and a long-time isochronous curve are shown in figure 8 in both MD and CD for paper K. Note that the long-time isochronous curve contains fewer measurement points. Each isochronous curve in figure 8 is described by the previously described hyperbolic tangent function in equation (2), by considering all the data-points. The fit is excellent and also representative for all the investigated papers.

Within the investigated time span there is no significant difference between the power function of time in equation (2) and the logarithmic time function in equation (3) in any of the investigated papers. The differences appear at longer times, as will be shown later.

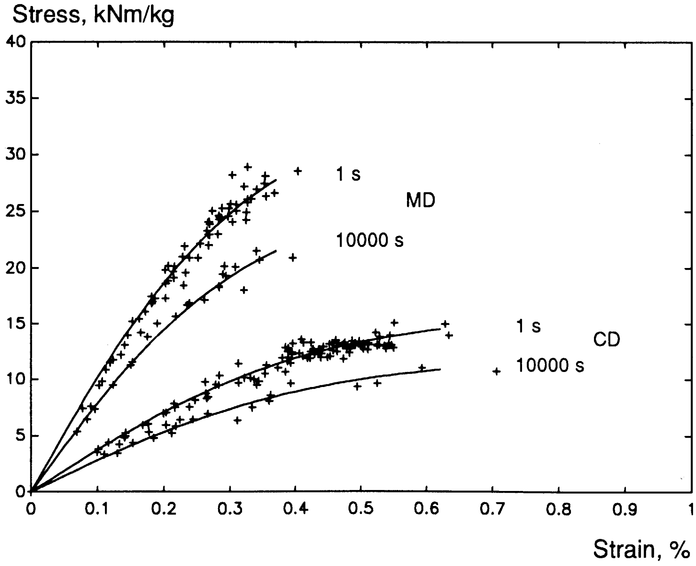

Figure 8. Isochronous curves for paper K in MD and CD, each at a short time, 1 second and a long time, 10.000 seconds The solid lines are the fit according to equation (2) using all the recorded data for this paper. The points in the figure are the actual data points at each particular time.

Isochronous curves in tension and compression

From creep trials in tension and compression in MD and CD on paper K, isochronous curves were constructed, figure 9. Only the initial part of the tensile isochronous curves are shown. The initial slope of the curves, the creep modulus according to equation (4), was the same in tension and compression for this paper as expected from linear viscoelastic theory. At higher strains, the curves deviate from linearity, a non-linear viscoelastic behaviour. Furthermore the compression curve lies below the tensile curve, a fact that was earlier found also when the stress-strain curves in compression and tension were compared (18, 26, 40).

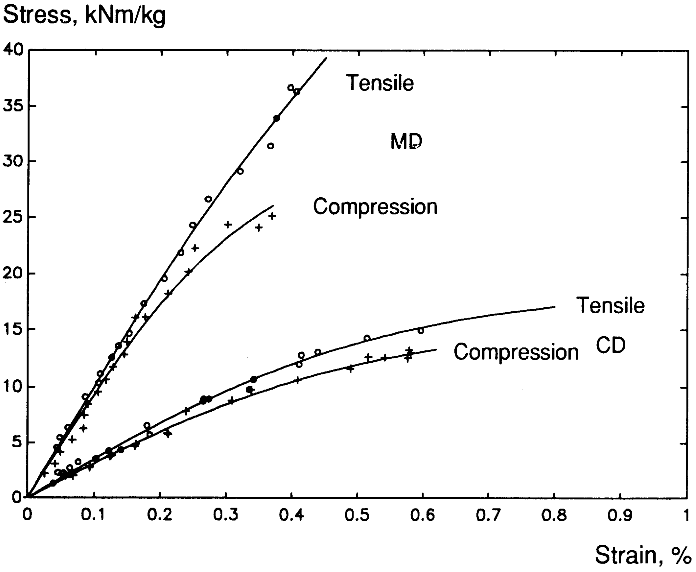

Figure 9. Compression and tensile isochronous curves for paper K in MD and CD (10 seconds).

Strain at break

In order to investigate whether the strain at break is a time-independent material constant, it was determined by three different tests:

1) by creep tests
2) by stress-controlled stress-strain tests and
3) by strain-controlled stress-strain tests.

Typical results are shown in figure 10 for paper K in MD and CD.

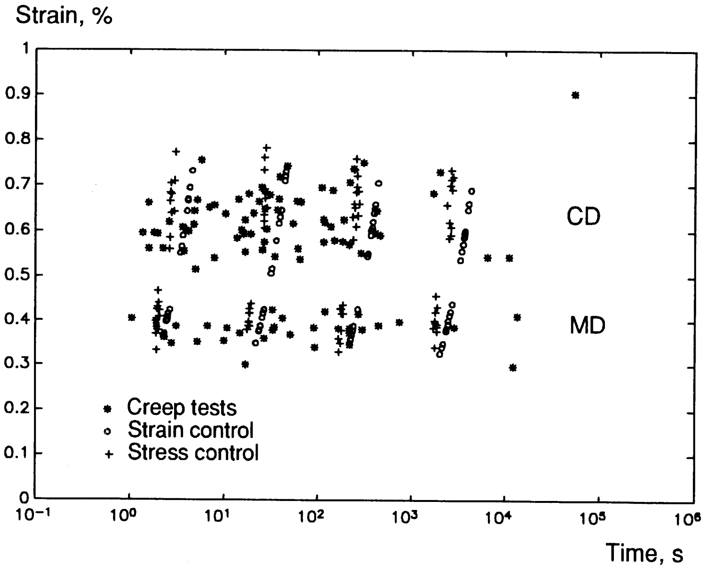

Figure 10. Strain at break determined for paper K in MD and CD.
1) by creep tests 2) by stress-controlled stress-strain tests and
3) by strain-controlled stress-strain tests.
($\Delta\varepsilon$=0,04 % and X=4 according to figure 2)

The variation in strain at break was considerable for all the papers in all these tests. A statistical analysis of the data showed that the strain at break in each type of test, for a given paper, was time-independent on the 95 % confidence level. A difference however existed between the strain at break determined by the three tests. The mean values for each one of the three tests, using all the data points at all the times, are shown and compared in table 1 for the four papers tested.

The strain at break determined by creep tests is on average equal to the strain at break determined by the strain-controlled stress-strain test but 9 % lower than the strain at break obtained by the stress-controlled stress-strain test. The reason for the higher values in the stress-controlled test is difficult to explain considering the time-independence of the strain at break. The acceleration of the strain at the end of the test, when the actuator maintains a constant stress-rate, may be one explanation (18). Different combinations of $\Delta\varepsilon$ and X, figure (2), were tried for the determination of strain to break in creep. The results were however insensitive to minor changes in the chosen values given in figure 10.

Based on these results, we decided to use the constants given in figure 10 in the forthcoming determination of the strain at break in creep tests. As will be shown later, the chosen procedure for measuring the strain at break in creep also makes sense in the determination of the lifetimes by means of isometric curves.

Table 1. Strain at break by three different tests: 1) by creep tests 2) by stress-controlled stress-strain tests and 3) by strain-controlled stress-strain tests. The results are shown for all four papers in MD and CD.

	Strain at break, %*)			**Difference, %**	
Paper	Creep tests (1)	Stress control (2)	Strain control (3)	$\frac{(1-3)}{3}$	$\frac{(2-3)}{3}$
K MD	0,38±0,01	0,40±0,01	0,39±0,01	− 2,3	+ 3,9
CD	0,63±0,02	0,68±0,03	0,63±0,02	+ 0,6	+ 8,7
T MD	0,41±0,01	0,47±0,01	0,42±0,01	− 1,9	+10,9
CD	0,70±0,02	0,76±0,03	0,70±0,02	− 0,1	+ 7,2
N MD	0,42±0,01	0,46±0,01	0,42±0,01	− 0,5	+ 9,5
CD	0,88±0,04	0,82±0,03	0,79±0,03	+11,9	+ 4,3
R MD	0,55±0,02	0,62±0,02	0,54±0,02	+ 2,8	+15,1
CD	0,96±0,03	1,00±0,03	0,88±0,04	+ 9,0	+13,3
			Average	+ 2,4	+ 9,1

*) Mean value and 95% confidence limits for approximately 40 samples. $\Delta\varepsilon$=0,04 % and X=4 according to figure 2.

Construction of isometric curves by means of the creep equations.

In some applications, the critical design criteria of paperboard products may be governed by a critical strain. For those applications, isometric curves i.e. stress versus time at different strains, may be derived by inserting desired strains in the creep equations (2) or (3). To illustrate the difference between the power function in equation (2) and the logarithmic function in (3), we have in figure 11 plotted isometric curves in MD and CD for paper K up to the point on a logarithmic time scale where the equation (3) intersects with the time-axis. The points in the figures are the recorded values at a particular strain. (1.000 years is about $3 \cdot 10^{10}$ s).

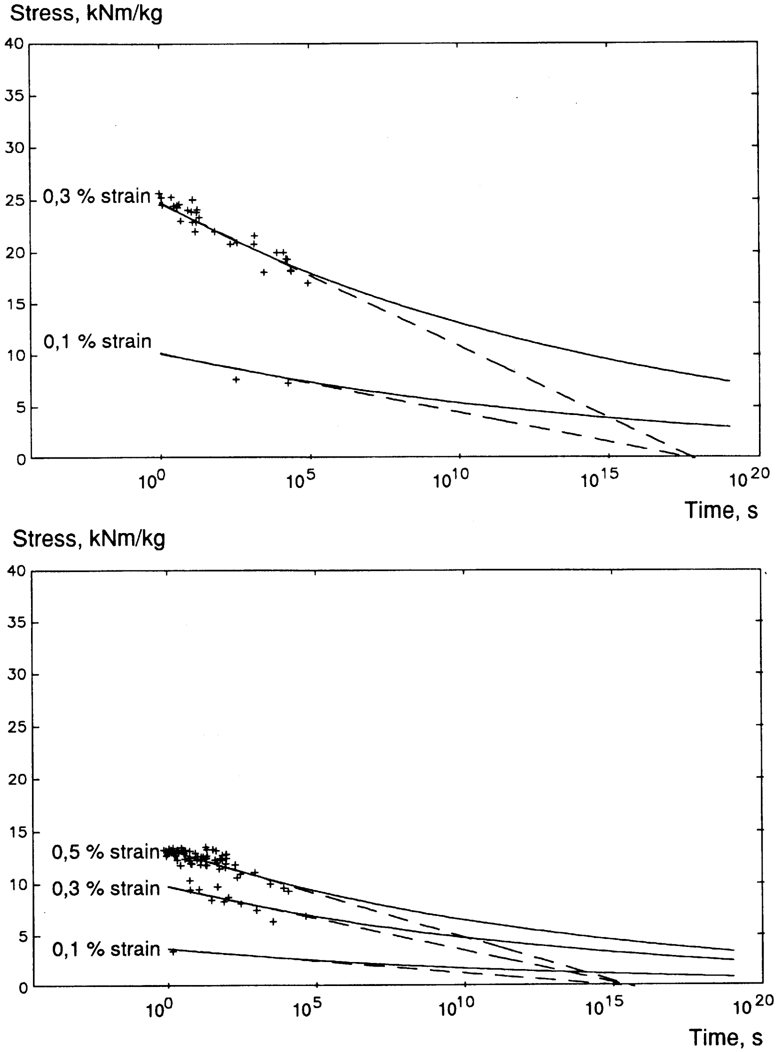

Figure 11. Isometric curves a) in MD and b) in CD for paper K. The points in the figures are the recorded values at a particular strain. The strain levels are given in the figure. Equation (2), solid lines, equation (3), dotted lines.

There is no significant difference between the two equations up to about one week of creep ($6{,}05 \cdot 10^5$ s) and a statistical treatment of the data could not show which of equations (2) or (3) was the better within the time scale used. Both equations initially give linear curves in the lin-log diagram. At longer times, the logarithmic representation remains linear while the power-curve shows a less steep slope.

We decided to use the power function in equation (2) in the remainder of this paper for two reasons:

1) Equation (2) has the appealing property that a given percentage decrease of stress, starting from any stress level, results in a constant increase in log creep time to a given strain.

2) Zhurkov (33) found that the lifetime of some materials, particularly at high temperatures at low stresses, did not show a linear dependence of stress in a lin-log diagram as expected according to the Eyring theory of reaction rates. The reason for the deviation was not however elucidated. This aspect may be of great importance when papers are tested at higher relative humidities.

Lifetime determinations by the isometric curves for the strain at break.

As stated earlier, the strain at break in compression of the investigated paper boards was found to be independent of time. By inserting the strain at break during creep in the creep equation (2), the isometric curve at break could be derived, which by definition gives the relation between stress and lifetime, i.e. the time to reach the strain at break, figure 12. Note that more points appear below the curve at longer times. The reason is that only the weakest samples reach the failure-point at a given stress in the investigated time interval. The strong samples which would have been placed above the curve never reached the failurepoint.

The excellent fit of equation (2) to the actual lifetime points further verifies that the chosen procedure for the determination of strain at break in creep was satisfactory as was also the choice of the constants $\Delta\varepsilon$ and X in table 1.

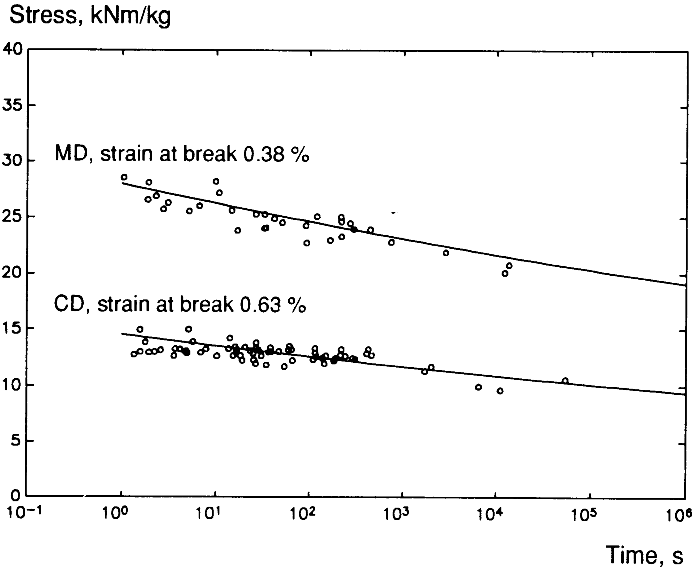

Figure 12. Lifetimes in MD and CD for paper K. The strains at break during creep in MD and CD are given in the figure.

A statistical analysis of the creep data

The problem of estimating the precision of a given isometric curve for a given paper is not trivial and is difficult to solve analytically. We have chosen to illustrate one aspect of the problem, namely to estimate the importance of creep time and number of creeptests to predict the isometric curve at the strain at break at one week of creep. The following procedure was performed in MD and CD for all papers:

In trial one, a total of about 80 tests were initially performed, figure 12, and this was considered to give a "true" prediction of the creep behaviour. The stress at 10^6 seconds of creep was determined (about 1,5 weeks).

In trial two, the same curves were used, but the creep time was now truncated at given times, between 50 and 40.000 seconds. For each truncated time, equation (2) was solved. The stress at 10^6 seconds was then compared to the stress in trial one. Figure 13 gives the estimation of the error in stress at 10^6 seconds.

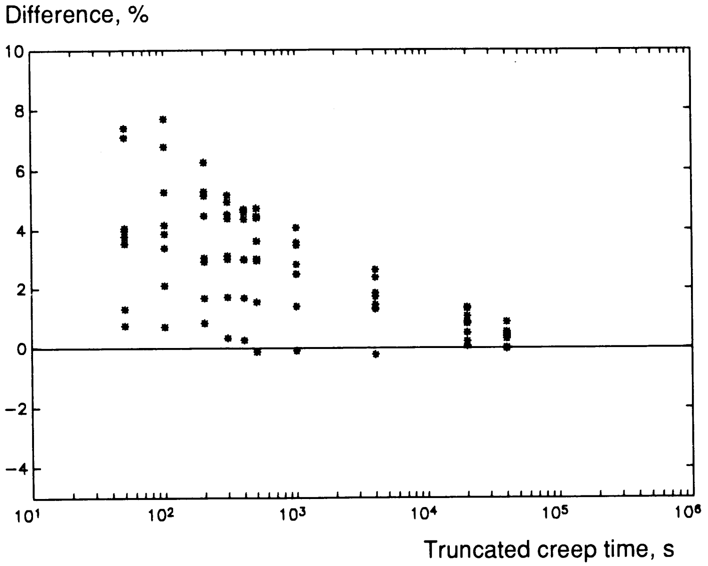

Figure 13. Estimated error in stress after one week of creep as a function of the truncated creep-time. Data for four papers in MD and CD for 80 creep tests.

As expected, the percentage stress-difference tend to increase as the creeptime was diminished. The difference was at most 8 % when using creep-times of 100 seconds. The difference was diminished to half that value if the creep-time was increased one decade to 1.000 seconds.

The appearance of the corresponding isometric curve for paper K is shown in figure 14. The predicted stress-differences at one week of creep are given in the figure.

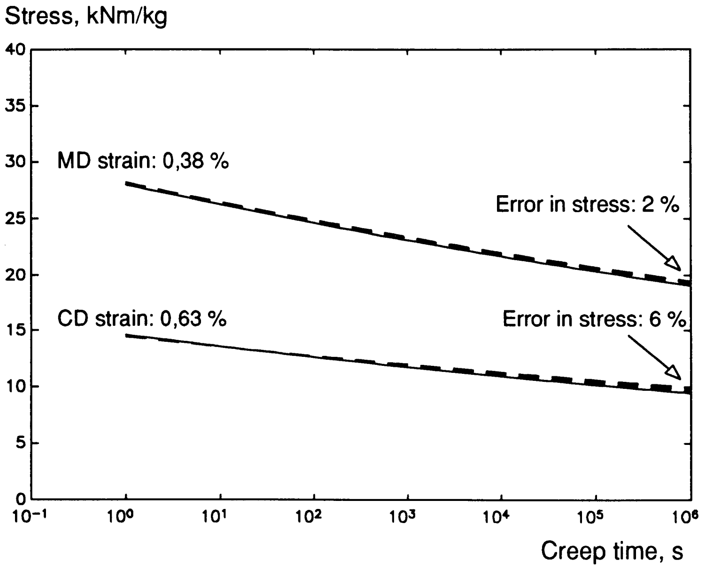

Figure 14. The appearance of the isometric curve for paper K in MD and CD for the different truncated creep-times given in figure 13. The predicted maximum errors in stress at one week of creep are given for 80 samples. Compare the curves in figure 12.

To illustrate the importance of the number of creeptests we performed trial two a second time but with half the number of samples selected randomly once among the 80 samples for each of the papers. The results are given in figure 15. The predicted error in stress at one week of creep was compared to the stress in trial one, as in figure 13. As expected, the estimated errror in stress was higher for 40 than for 80 tests. The error at shorter times was negligible.

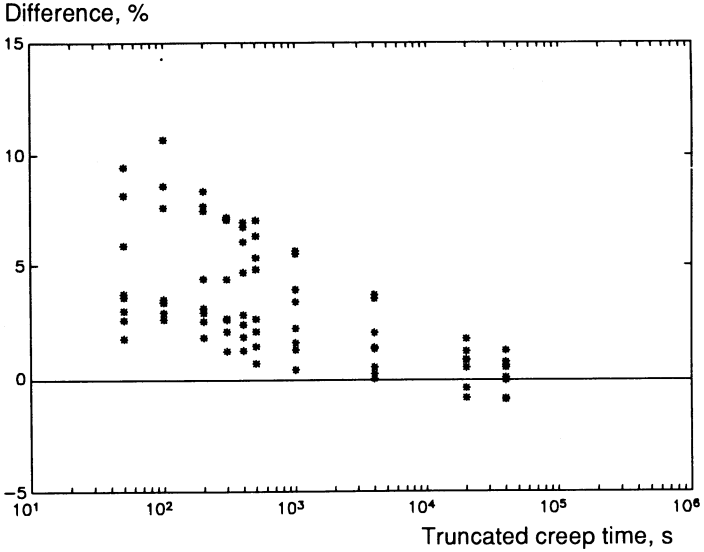

Figure 15. Estimated error in stress after one week of creep as a function of the true creeptime. Data for four papers in MD and CD for 40 creep tests.

DISCUSSION

The suggested method for the description of the creep behaviour of paperboard in edgewise compression works for paperboard in the same way as for other polymers. The relation between stress, strain and time may be determined by a simple equation consisting of two factors, a power function of time and a factor describing the non-linear behaviour of the stress-strain curve.

For engineering purposes, it is an advantage to be able to design a given product in terms of stress and strain, according to the isochronous curves.

In some applications, the critical design criteria may be governed by a critical strain. For these applications, isometric curves, i.e. stress versus time at different strains, are used.

The strain at break in compression of the investigated paperboards was found to be independent of time. The strain to break in creep was equal to the strain at break in stress-strain testing in strain-control. By inserting the strain at break in creep into the creep equation, the isometric curve at break could be derived. By definition, this gives the relation between stress and lifetime.

The necessary creep time and number of samples to be tested to obtain a given precision of long-term creep naturally depend on the variability of the material. The data in this investigation indicate that a fairly low number of specimens and a reasonably short creep time are sufficient to obtain a good prediction of long-term creep behaviour. In other words, the creep of paper follows a fundamental behaviour of the material already established at short times, described by the creep equation.

The number of tests and creeptimes naturally affects the precision of the measurement and must be chosen with regard to the purpose of each investigation. Further studies are needed to find statistical methods to optimise the necessary total testing time, i.e. number of specimens and creep time for each specimen, to predict the creep behaviour of paper with the desired precision.

The conclusion from this investigation is that it possible to predict long-term behaviour of paperboard products from engineering principles with more confidence than was previously possible.

ACKNOWLEDGEMENTS

We would like to express our gratitude to Cellulosaindustriens Stiftelse för Teknisk och Skoglig Forskning samt Utbildning, and to ASSI, MoDo, SCA, and STORA for their financial support. Thanks are also expressed to Mr Leif Falk for his skilful manufacture of the machine parts and to Mr Hilding Ekman and Mr Mats Sundqvist for electronic and computer design.

The authors also extend their thanks to Dr J. Anthony Bristow for linguistic revision.

REFERENCES

1. Söremark, C. and Fellers, C. (1993).
   Mechano-sorptive creep and hygroexpansion of corrugated board in bending. Journal of Pulp and Paper Science **19**(1): J19-J26.

2. Gunderson, D. E. (1981).
   A method for compressive creep testing of paperboard.
   Tappi Journal **64**(11): 67-71.

3. Byrd, V. L. (1984).
   Edgewise compression creep of fiberboard components in a cyclic-relative- humidity environment. Tappi Journal **67**(7): 86-90.

4. Brezinski, J. P. (1956).
   The creep properties of paper. Tappi Journal **39**(2): 116-128.

5. Schulz, J. H. (1961).
The effect of straining during drying on the mechanical and visco-elastic behavior of paper. Tappi Journal **44**(10): 736-744.

6. Sanborn, I. B. (1962).
A study of irreversible, stress-induced changes in the macrostructure of paper. Tappi Journal **45**(6): 465-474.

7. Greenway, G. W. (1971).
Compressive fatigue of short columns of kraft liner, semichemical corrugating medium and corrugated board.
Tappi Journal **54**(5): 758-761.

8. Thielert, R. (1986).
Edgewise compression resistance and static load- lifetime relationship of corrugated board samples. Tappi Journal **69**(1): 77-81.

9. Leake, C. H. (1988).
Measuring corrugated box performance.
Tappi Journal **71**(10): 71-75.

10. Leake, C. H. and Wojcik, R. (1989).
Influence of the combining adhesive on box performance.
Tappi Journal **72**(8): 61-65.

11. Kellicutt, K. Q. and Landt, E. F. (1951).
Safe stacking life of corrugated boxes. Fibre Containers **36**(9): 28-38.

12. Stott, R. A. (1959).
Compression and stacking strength of corrugated fibreboard containers. Appita **13**(2): 84-89.

13. Moody, R. C. and Skidmore, K. E. (1966).
How dead load, downward creep influence corrugated box design.
Package Engineering **11**(8): 75-81.

14. Koning Jr, J. W. and Stern, R. K. (1977).
Long- term creep in corrugated fiberboard containers.
Tappi Journal **60**(12): 128-131.

15. Thielert, R. (1984).
Determination of stacking load- stacking life relationship of corrugated cardboard containers. Tappi Journal **67**(11): 110-113.

16. Byrd, V. L. and Koning Jr, J. W. (1978).
Corrugated fiberboards. Edgewise compression creep in cyclic relative humidity environments. Tappi Journal **61**(6): 35-37.

17. Caulfield, D. F. (1985).
A chemical kinetics approach to the duration-of-load problem in wood. Wood and Fiber Science **17**(4): 504-521.

18. Haraldsson, T., Fellers, C. and Kolseth, P.
A method for measuring the creep and stress-strain properties of paperboard in compression. To be published.

19. Ogorkiewicz, R. M. (1970).
Engineering properties of thermoplastics.
Wiley- Interscience. London, New York, Sydney, Toronto.

20. Turner, S. (1974).
Deformational behaviour.
In: Thermoplastics, properties and design. (Ed: R. M. Ogorkiewicz).
P. 30-50. John Wiley & sons. London, New York, Sydney, Toronto.

21. ASTM (1977).
ANSI/ASTM-D-2990-77.
Standard test methods for tensile, compressive and flexural creep and creep- rupture of plastics. 753-763.

22. DIN-53444 (1990).
Prüfung von Kunststoffen. Zeitstand-Zugversuch.

23. ISO-899 (1981).
Plastics-Determination of tensile creep.

24. SCAN-P2:75 (1975).
Paper and board- Conditioning of test samples.

25. Cavlin, S. and Fellers, C. (1975).
A new method for measuring the edgewise compression properties of paper. Svensk Papperstidning **78**(9): 329-332.

26. Fellers, C. (1983).
Edgewise compression strength of paper.
In: Handbook of Mechanical and Physical Testing of Paper and Paperboard. (Ed: R. E. Mark). P. 349-383.
Marcel Dekker. New York, Basel.

27. SCAN-P46-83 (1983).
Paper and board- Compression strength. Short span test.

28. Kolseth, P. and de Ruvo, A. (1983).
The measurement of viscolelastic behavior for the characterization of time-, temperature-, and humidity-dependent properties.
In: Handbook of physical and mechanical testing of paper and paperboard. (Ed: R. E. Mark). P. 255-322.
Marcel Dekker. New York, Basel.

29. Findley, W. N., Lai, J. S. and Onaran, K. (1976).
Creep and relaxation of nonlinear viscoelastic materials.
North- Holland Publishing company. Amsterdam, New York, Oxford.

30. Bodig, J. and Jayne, B. A. (1982).
Mechanics of wood and wood composites.
Van Nostrand Reinhold Company. New York, Cincinnati, Toronto, London, Melbourne.

31. Pecht, M. G., Johnson Jr, M. W. and Rowlands, R. E. (1984).
Constitutive equations for the creep of paper.
Tappi Journal **67**(5): 106-108.

32. Pecht, M. G. and Johnson Jr, M. W. (1985).
The strain response of paper under various constant regain states.
Tappi Journal **68**(1): 90-93.

33. Zhurkov, S. N. (1965).
Kinetic concept of the strength of solids.
International Journal of Fracture Mechanics **1**(4): 311-322.

34. Andersson, O. and Sjöberg, L. (1953).
Tensile studies of paper at different rates of elongation.
Svensk Papperstidning **56**(16): 615-624.

35. Gunderson, D. E., Considine, J. M. and Scott, C. T. (1988).
The compressive load-strain curve of paperboard: Rate of load and humidity effects. Journal of Pulp and Paper Science **14**(2): J37-J41.

36. Andersson, O. and Berkyto, E. (1951).
Some factors affecting the stress-strain characteristics of paper.
Svensk Papperstidning **54**(13): 437-444.

37. Urbanik, T. J. (1982).
Method analyzes analogue plots of paperboard stress-strain data.
Tappi Journal **65**(4): 104-108.

38. Gunderson, D. E. (1983).
Edgewise compression of paperboard: a new concept of lateral support. Appita **37**(2): 137-141.

39. Gunderson, D. E. (1984).
A comparison of three methods for determining the edgewise compressive properties of paperboard. Appita **37**(4): 307-313.

40. Fellers, C. (1986).
The significance of structure for the compression behavior of paperboard.
In: Paper Structure and Properties. (Ed: J. A. Bristow and P. Kolseth). P. 281-310. Marcel Dekker. New York, Basel.

Transcription of Discussion

EDGEWISE COMPRESSION CREEP IN PAPERBOARD - NEW PRINCIPLES OF EVALUATION

T Haraldsson, C Fellers & P Kolseth

V Padányi, Amcor Research & Technology Centre, Australia
Thanks for the presentation, it is very impressive work. I would like to comment in view of what I said in my presentation. If you take account of the age of the sample before you do all this experimental work, and you make sure that all your samples are at the same age, the scatter in your points would be enormously reduced.

C Fellers
I am quite sure that the papers used were all at the same age. They had been stored for a very long time before testing. They were old reels from commercial paper machines.

V Padányi
Long storage time does not guarantee the same thermal history.

C Fellers
I will keep that in mind and I think we all have to consider what you say in future testing.

Dr F El Hosseiny, Weyerhaeuser Paper Co, USA
You have assumed that the lifetime of a combined board is controlled only by the lifetime of the liner and medium but the combined board is made of starch also. Are we justified in ignoring the effect of starch?

C Fellers
The first examples in my presentation were just aimed to put our work in the right perspective. There are many lifetime studies being performed and I feel that the first step is to work with the material itself and to develop a method where we can start comparing and evaluating the different components of the corrugated board. I realise that once you put them together with starch and so on, it is a much more difficult situation. We know from a lot of work from Leake (Ref. 9, 10), for example and other people, the quality of the starch and its moisture sensitivity etc. takes a great role. The next step is how you transfer this type of methodology to boxes? It could be done but it is more complicated.

Prof M Kortschot, University of Toronto, Canada
The compressive strength is really a structural property rather than a material property. It depends on the gauge length of the specimen and in the diagram of your tester, the gauge length, if I read it correctly, is just 0.6mm....

C Fellers
It is like 70mm and we have put a strain gauge on the paper.

M Kortschot
You have a lot of side supports which prevent lateral motion and constrain the buckling of the sheet. I think it is probably true that the compressive failure strains that you observed are valid only for a very short gauge length materials. Would you use those strains to predict the failure of liner board in a box configuration?

C Fellers
You are touching on a very important subject. We are trying to measure the material properties as good as we can and this follows the tradition from Dennis Gunderson at FPL and STFI. We have tried to do everything to prevent the buckling. Once you put them into the corrugated board construction we know that there might be microbuckling phenomena between the flute tips etc. So I agree with you that is the next step to account for all those things too.

Dr D Gunderson, US Dept. of Agriculture (FPL), USA
I would like to compliment you on the very nice methodology. One of the questions that is asked is do we have to use compressive creep data - is there any promise that we will be able to use tensile testing data to work in compression or will we always have to work with a rather complicated compressive creep apparatus?

C Fellers
With reference to the slide I showed earlier (Fig. 9). What we have here is tensile curves, compression curves and creep modulus. As long as you are working at small strains the two curves have the same linear creep response, linear viscoelasticity, but as you go up close to failure which would be the true situation in a box, these two have a very significant difference. The difference is different for all these five papers we have been investigating. There is no universal scaling law between tension and compression. It depends on furnish and MD/CD etc. So basically you cannot replace tension for compression. You need to make compression measurements.