THE CREEP FATIGUE INTERACTION IN SOLID PAPER

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Abstract

Paper is a commonly used material for short term loading applications. One of the problems with paper is the degradation of strength and energy absorption capability that occurs as a result of fatigue and creep loading. Tensile tests at different strain rates, low cycle fatigue test with variable hold time and room temperature creep tests have been conducted using dumbbell type specimens of solid paper. Fatigue result in a considerable reduction in the failure energy. The results suggest that the damage induced by fatigue loading is more effective than the damage induced by creep loading.

Introduction

Paper and cardboard are for their price comparatively strong materials and have the image of environmentally favorable materials. The primary usage is for packaging due to the excellent relation of stiffness to price and weight. For several reasons the possibility of using cardboard as a structural material has been suggested. This however requires research into several aspects of structural safety and long term stability. This paper deals with some of the aspects of fatigue and creep of solid paper made from recycled paper which although it has a lower quality compared to paper made from fresh fibers, it is widely available and in that sense more suitable for structural use.

Experimental method

Tests have been conducted on dumbbell specimens with a thickness of 1.5 mm, a parallel length of 38 mm and a width of 6 mm. The specimens were stamped out of solid paper. The paper used is has an inner layer made of recycled paper of a quality 775g/m^2 with outer layers of virgin paper of quality 125 g/m^2. De layers are glued together using polyvinyl alcohol adhesive. Resulting in a product of quality 1050 g /m^2. All specimens used for this publication were made with the machine direction (fibre direction) in the length axis of the specimen. This because the properties in this direction are the best and the paper should used with the loading in the machine direction. All specimens were taken from a single large sheet of paper from the middle of a production batch to limit the spread in properties as much as possible.

The tensile, fatigue and creep tests were conducted on a Zwick Z10 universal testing machine using test expert version 8.1 software. Specimens subjected to fatigue were loaded from zero stress to a specified maximum tensile stress, σ_{max}, then held at this stress for a fixed hold time, t_{hold}, then completely unloaded to the initial displacement and kept here for the same hold time as used before. Thus a form of block loading was used rather than the normal sinusoidal loading. In some tests different combinations of hold time at maximum or minimum stress were used. The standard displacement rate was 100 mm/minute. All data was recorded at every 1 μm of displacement. Thus complete stress/strain data are available. Creep tests were conducted the same way, but the maximum load was maintained until failure. All tests were conducted in laboratory air at a temperature of 20°C.

Tensile test results

Tensile tests were conducted on the solid paper to determine the basic elastic/non elastic properties. Results for testing the same paper in other directions were published earlier by Veer et al. (1). The tensile behaviour in the machine direction is mostly linear until failure. This is not typical for MD tests, as typified by the results published by van den Akker (2), which show much more non–linearity. The initial part of the tensile curve it incorrect because of the specimens slipping in the grips. The behaviour is strongly dependent on the strain rate as is shown in figures 1 and 2. It should be noted that even at the lowest strain rate used, non-linear tensile behaviour was only found at stress exceeding 22 MPa. Using this as an upper value fatigue maximum stresses of 12,14,16 and 18 MPa were used to ensure that loads in the range of 40 to 70% of the failure stress were used.

Table 1: Effect of strainrate on failure stress

Strain rate %/min	Failure stress (MPa)
0.2	26.6
2	29.4
20	29.9
200	35.2

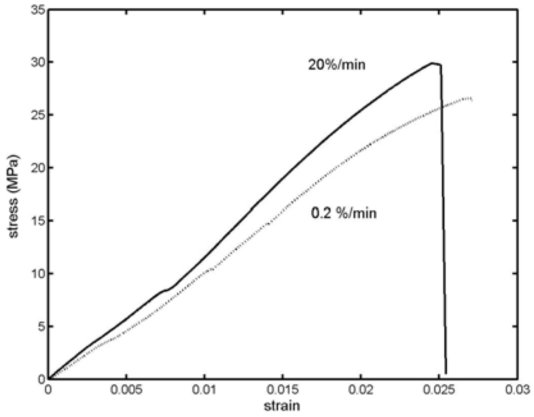

Figure 1: Effect of strain rate on tensile behaviour for solid paper tested in machine direction

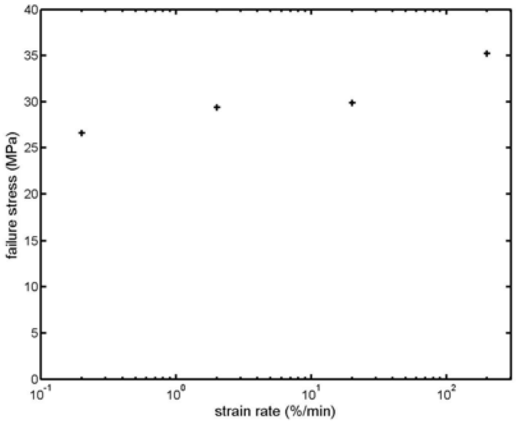

Figure 2: Effect of strain rate on failure stress

Fatigue tests with regular holdtimes

The development of the strain with increasing number of cycles is shown in figure 3. Initially a rapid increase in strain can be seen due to the fibre uncurling, as described by Rance (2). Essentially the strain increases continually on a cycle by cycle approach until failure. A short acceleration can be seen just before failure. Looking at the data cycle by cycle, as is shown in figure 4, it can be seen that at the start of the loading cycle the rate of increase in the strain is higher and that this later reduces to a much slower rate. Subsequent cycles result in a strain higher than in the previous cycle. It is not clear if the material shows some relaxation during the unloading part of the cycle. Table 2 summarizes the test results. There is clearly scatter in the results due to the inhomogeneous structure of paper.

Table 2: number of cycles to failure for tests with regular holdtimes

σ_{max} (MPa)	n_f 0.001 s	n_f 5 seconds	n_f 20 seconds	n_f 50 seconds
12	32130	7996	4195	4488
14	11876	3036	825	1544
16	2770	1076	392	292
18	1696	135	62	40

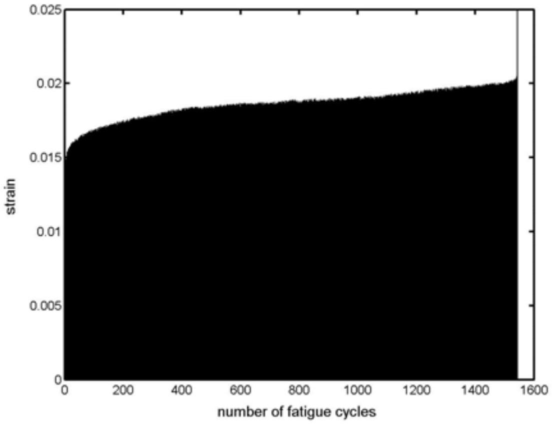

Figure 3: development of strain with increasing Number of fatigue cycles

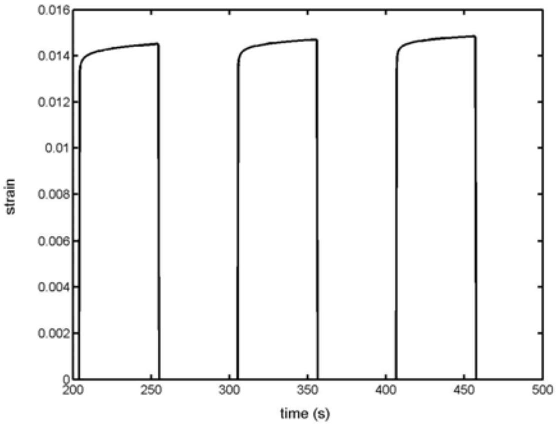

Figure 4: Changes in strain during subsequent loading cycles

Fatigue tests with irregular holdtimes

A number of tests with irregular holdtimes have been conducted to look at the combination of long periods at maximum load combined with short periods at zero load and the reverse. Figure 5 shows the strain against time for a test with a holdtime at maximum of 20 seconds followed by a holdtime at zero load for 1 second. The subsequent cycles match closely suggesting the absence of any relaxation. The fatigue life time results in table 3 however suggest that the increase in holdtime at zero load has only a negative effect. The results of a combination of a holdtime of 1 second at maximum load followed by a holdtime of 20 seconds at zero load are shown in figure 6. A clear increase in the displacement can be seen during the short loading compared to figure 5. This suggests that some relaxation takes place during the holdtime at zero load. Table 3 summarizes the results.

Table 3: number of cycles to failure for tests with irregular holdtimes

Holdtime at 18 MPa (s)	Holdtime at 0 zero load (s)	n_f (seconds)
20	1	153
20	5	75
20	20	62
1	1	611
1	5	752
1	20	877

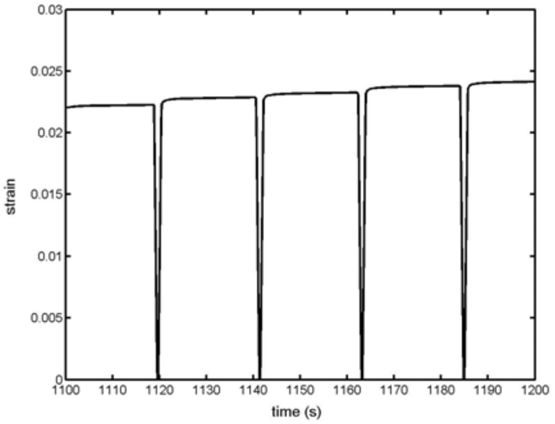

Figure 5: strain development in the time for test with holdtime of 20 seconds at maximum load and 1 second at zero load

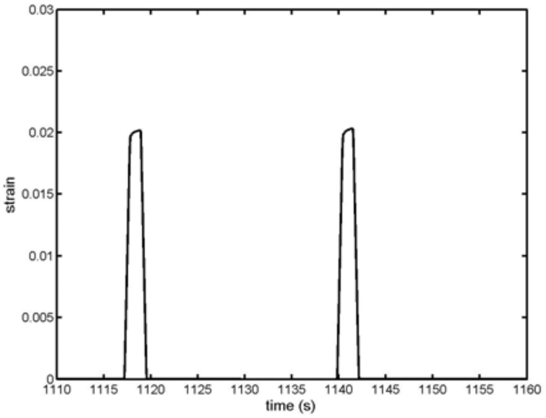

Figure 6: strain development in the time for test with holdtime of 1 second at maximum load and 20 seconds at zero load

Comparison of creep and fatigue tests

A number of creep tests have been conducted at the same stress levels as used for the fatigue tests. The results of a comparison is given in table 4. Figure 7 compares a detail of a creep test with a fatigue test at the same stress level. The results seem to match but a comparison of the whole test, as given in figure 8 shows that fatigue loading leads to failure more quickly than pure creep loading. This can also be seen by comparing fatigue tests with short periods at maximum load where the total time at maximum stress is less than 10% of that in a creep test. Thus although some deformation takes place during a fatigue cycle, the cyclic nature of the fatigue loading causes more damage than the static loading during creep.

Table 4: Comparison of fatigue and creep tests

Type of test	Time to failure (s)	n_f	Time at maximum stress (s)
Creep σ_{max}=18 MPa	9310	1	9310
Fatigue σ_{max}=18 MPa, holdtime maximum=20s Holdtime zero load =1 second	2796	127	2540
Fatigue σ_{max}=18 MPa, holdtime maximum=1s Holdtime zero load =20 second	19902	877	877

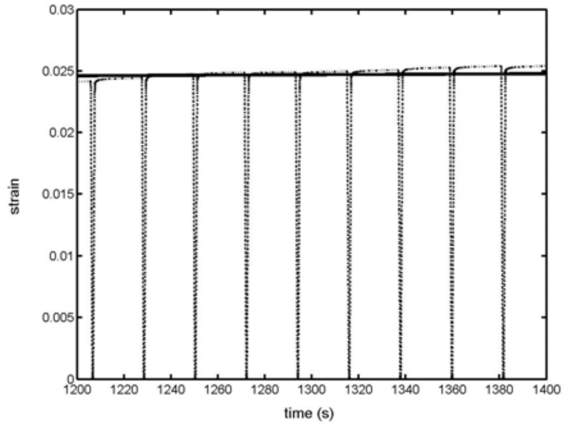

Figure 7: detail of creep test and fatigue test
With holdtime of 20s at maximum load and
1 second at zero load

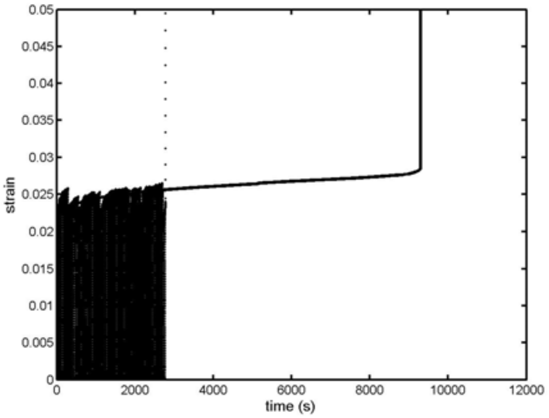

Figure 8: Comparison of strain development in
the time for creep test and fatigue test with
holdtime of 20 seconds at maximum load and
1 second at zero load

Discussion

The results show that for paper fatigue loading is more damaging than creep loading. There is a clear effect of holdtime at maximum load on the fatigue life. This can be seen in figure 9. The results however suggest that at stress levels of 12 and 14 MPa there is no effect of increased holdtime above 20 seconds. This saturation is however clearly dependent on the stress level as at 18 MPa the effect of increased holdtime is still visible.

A comparison of the tensile test, creep and fatigue stress/strain response is shown in figure 10. Although the creep test fails at a lower stress level than in the tensile test the failure strain is increased. The failure energy in creep seems to be comparable or exceed that in tension. Fatigue loading clearly reduces the failure energy and is much more damaging than creep. This effect is usually ignored in the literature. It would potentially invalidate some of the results of Batchelor and Wanigaratne, (4). Additionally models for the viscoelastic behaviour of paper, such as that published by Lif, Ostlund and Feller, (5), do not incorporate an fatigue based acceleration.

What happens in the specimens is however unclear. Failure seems in all cases to occur by failure in the inner layer followed by the outer layer as the inner layer fails. The failure in the inner layer seems to extend over a volume of several mm in length. All fracture surfaces show decohesion in the inner layer over a certain length. Considering the relatively increases in strain during a fatigue test, such as shown in figure 3 the following explanation is offered.

Loading results in a reordering of the paper fibres which results in a loss of Young’s modulus. At a certain point reordering becomes impossible and the weak inner layer of recycled fibres starts to develop cracks which lead to failure in several cycles with an increased development of strain at this point. The cyclic nature of the fatigue loading and unloading accelerates the reordering process compared to creep loading where the reordering seems to be much slower.

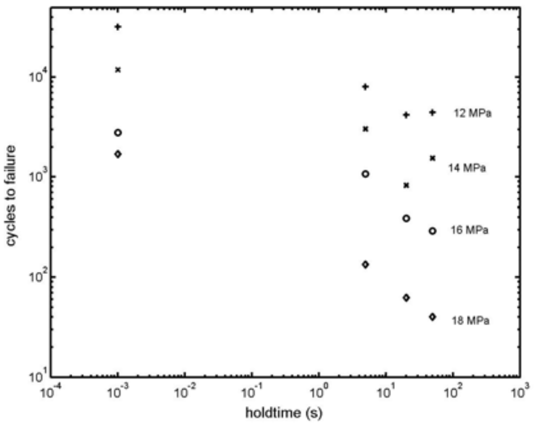

Figure 9: number of cycles to failure at different holdtimes and stress levels

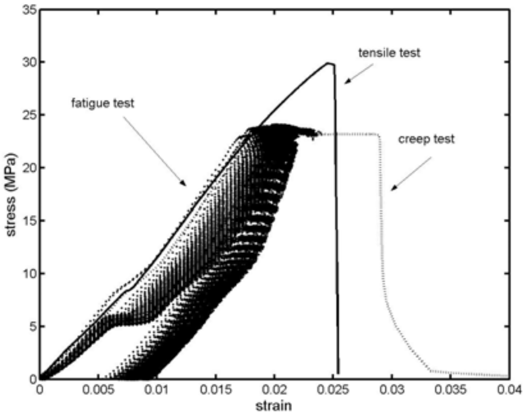

Figure 10: stress-strain plot for tensile test, creep test and fatigue test

Conclusions

From the results it is concluded that for solid paper tested in the machine direction:

- Fatigue loading causes more damage than creep loading
- Fatigue life is strongly dependent on frequency
- Creep loading does not decrease the failure energy significantly
- The damage that accumulates in a fatigue cycle stabilizes after a certain holdtime.
- The period after which this stabilisation occurs depends on the stress level

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