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## Fatigue in wood-based panels. Part 2: property changes during fatigue cycling of OSB, chipboard and MDF

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**Abstract** Wood-based panels are viscoelastic so when a load (stress) is applied to them there is a time lag before a deflection (strain) is produced, which results in hysteresis (a loss of energy). The capture of stress versus strain hysteresis loops is a non-interruptive method of monitoring the damage produced during fatigue testing. Hysteresis loops were captured throughout the flexural fatigue testing of OSB, chipboard and MDF in four-point bending allowing the development of fatigue damage to be followed. The MDF tested had a greater mean bending strength than the OSB and chipboard. When stresses were applied to the materials as a percentage of their bending strengths, the stresses applied to the MDF samples were larger than those applied to the OSB and chipboard samples. As a result the microstrains were greater for MDF than for the chipboard and OSB. The OSB was stiffer than the chipboard and MDF, which were both of similar stiffness. The information gained from the hysteresis loops indicates that the OSB, chipboard and MDF all had fatigue limits just below 20% of their bending strengths. The fatigue limit for the MDF is likely to be slightly lower than for the chipboard and the OSB.

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### Introduction

This paper examines the stress versus strain hysteresis loops captured during the fatigue tests described by Thompson et al. (2002). Hysteresis loop capture is a non-interruptive method of monitoring property changes and damage accu-

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mulation during fatigue tests. Hysteresis loops were captured for all three materials and were analysed in order to follow the changes in the following parameters:

1. The loop area, which represents the energy dissipated per cycle
2. The dynamic modulus, which follows changes in the stiffness as damage accrues
3. The fatigue modulus, which is a combination of fatigue damage and underlying creep
4. The microstrains (deflections) of the samples

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## Literature

At the University of Bath, stress versus strain hysteresis loop capture was first used to follow fatigue damage accumulation in wood laminates used for wind turbine blades. Initial testing used four-point bending (Tsai and Ansell 1990) but recent work has used axial loading of wood and laminated wood (Bond 1994; Hacker 1995). Collaborative research between the University of Bath and the Building Research Establishment (BRE) into the fatigue performance of chipboard began in 1990 and an overview of this work was provided by Thompson et al. (1996b). In the earliest stage of this collaborative work (Bonfield et al. 1994), hysteresis loops were captured for chipboard fatigue loaded at  $R=0.01$ , where:

$$R = \frac{\text{Minimum stress}}{\text{Maximum stress}}$$

It was concluded that the mechanism of fatigue damage accumulation was different from the mechanism of creep deformation. Dinwoodie et al. (1995) also found that the principle of superposition did not apply to chipboard under intermittent and constant loading. This implied that recovery occurs whilst the samples are unloaded and that the deformation mechanisms are different. However, Grossman and Nakai (1987) found the principle of superposition to apply to clear wood in bending. This indicates that wood-based panels behave differently than solid wood.

Thompson et al. (1994) found that decreasing the  $R$  ratio from 0.75 to 0.01 reduced the fatigue life, increased the rate of fatigue microstrain development, increased the hysteresis loop area and reduced the dynamic modulus. Thompson et al. (1996a) used hysteresis loop capture to predict a fatigue limit for chipboard at just below 20% of the bending strength. The magnitudes of the microstrains and the appearance of the loops were almost identical for the three frequencies tested but changed with the stress level applied. Pritchard et al. (1996) found that the hysteresis loop area increased more gradually for MDF than for OSB or chipboard as a function of the applied stresses imposed. This indicated that damage accumulation was more gradual for the MDF than for the OSB or the chipboard when based upon the stresses applied.

Tsai and Ansell (1990) showed that the compressive strength of wood was only about one third of the tensile strength, indicating that failure in bending is likely to be controlled by the zone loaded in compression. In contrast, Thompson (1996) found that fatigue failure of chipboard loaded in bending was

likely to initiate on the face loaded in tension. The fatigue performance of wood and wood composites relative to their static strengths is superior to that of crystalline materials (Kyanka 1980; Dinwoodie 1989). Unlike metals, static and fatigue failures in wood can be indistinguishable (Kyanka 1980).

Sekino and Okuma (1985) found the fatigue strength of chipboard after  $10^7$  cycles to be 38–44% of the static strength; however, the chipboards tested appear to be of a lower grade than the chipboards tested in this study. The fatigue tests reported by Sekino and Okuma (1985) were performed at frequencies of 1.0–2.0 Hz, at between 60% and 90% of the static bending strength. They found no significant difference between the results for the different resin types. The maximum deflections increased gradually until a critical deflection was reached followed by rapid failure. The critical deflection for the same type of board was constant for different stress levels. Only small reductions in the MOR and MOE of a few percent were observed prior to failure. Tanaka and Suzuki (1984) observed that the fatigue life increased as the resin content was increased in four different flakeboards. The fatigue performance improved with increasing adhesive bond strength, an observation also made for particleboard by Clad and Schmidt (1981).

Cyclic creep can be defined as the maximum deflection during cyclic loading and is the development of deformation in the material under cyclic loading. Tanaka and Suzuki (1984) found the cyclic creep rate to increase gradually at first and then increase rapidly before failure. Failure eventually occurred when the maximum deflection equalled the critical deflection for the particleboard.

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## Experimental procedure

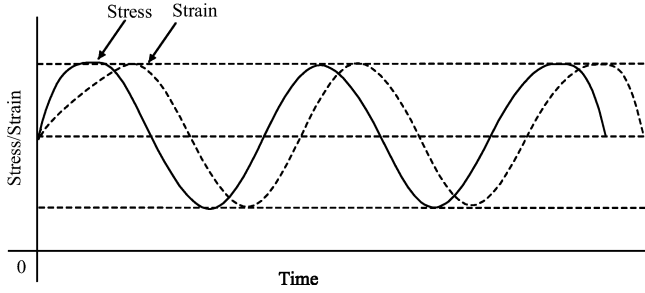
The detail of the three wood-based panels, the test equipment, and the conditions were provided in part 1 of this paper (Thompson et al. 2002). The load applied to the sample was accurately controlled throughout testing. During all the fatigue tests the true centre point deflections were measured using linear variable differential transformer (LVDT) displacement transducers. Creep tests were run in parallel to the fatigue tests as a control and the centre point deflections were also measured for these samples. The applied load and the centre point deflection from the fatigue and creep samples were monitored using a custom built fatigue data acquisition system (FDAS) and were entered into standard beam formulae. This enabled stress versus strain hysteresis loops to be captured at pre-determined time intervals for all of the fatigue tests. The measured deflections and applied loads were also measured for the creep samples and were reported by Thompson (1996).

Six samples of each of the materials (OSB, chipboard and MDF) were tested at the 80, 70, 60 and 50% stress levels, at  $R=0.1$ . Only limited samples were tested at stress levels below 40% because at low stress levels the samples were runouts (did not fail), so further tests would have required excessive machine time.

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## Hysteresis loop capture

Wood-based materials are viscoelastic, so when the load is applied to a sample the strain lags behind the applied stress (Fig. 1), and energy is dissipated due to



**Fig. 1** The lag between the applied stress and the resulting strain

internal friction and damage. The energy dissipated is the area under the stress versus strain curve. When a full loading and unloading cycle has occurred a loop is produced and this can be plotted on stress versus strain axes. The FDAS captured the creep microstrain, maximum and minimum fatigue microstrain, and the hysteresis loop area and the dynamic modulus (average stiffness during the loop capture) were determined. This information was stored by the computer ready for analysis. Hysteresis loops were captured at pre-determined time intervals throughout every fatigue test. Loops were captured every two minutes at the start of tests, then every hour and eventually once every twenty four hours as the tests continued.

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## Experimental results

### First and last captured hysteresis loops

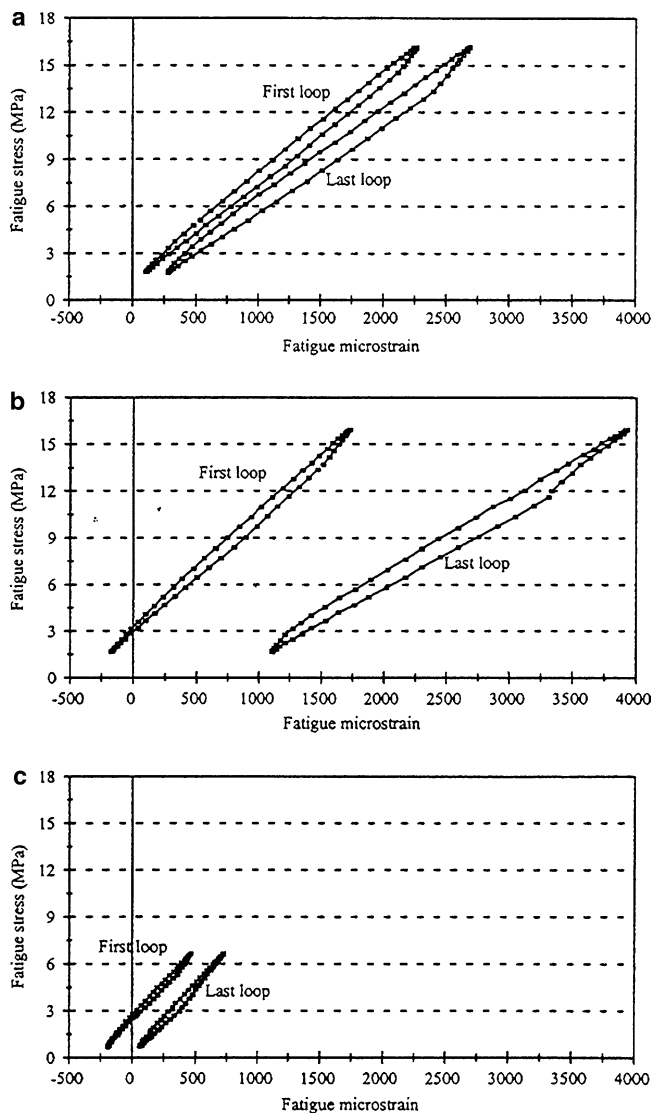
Figure 2a–c shows the first and last hysteresis loops captured for OSB samples tested at each of the stress levels 70%, 50% and 30%, respectively. Figure 3a–c shows the same information plotted for samples of chipboard tested at stress levels 70%, 50% and 30%, respectively. Figure 4a–c shows the same information plotted for samples of MDF tested at stress levels 70%, 50% and 20%, respectively. The figures provide a pictorial view of the changes in the hysteresis loop parameters as a result of fatigue loading.

### Fatigue microstrains

The maximum fatigue microstrain is produced at the surface of the sample when the hydraulic ram is at the top of its stroke with the maximum load applied to the sample. Figure 5a and b shows the median initial and median final maximum fatigue microstrains for the OSB, chipboard and MDF samples, plotted as a function of stress level, reducing from 80% to 20%.

### Dynamic moduli

The dynamic modulus is the average stiffness of the sample during the fatigue test. It is the gradient of the individual hysteresis loop at a specific time in the test and is measured from the two extreme points of each loop, as shown in

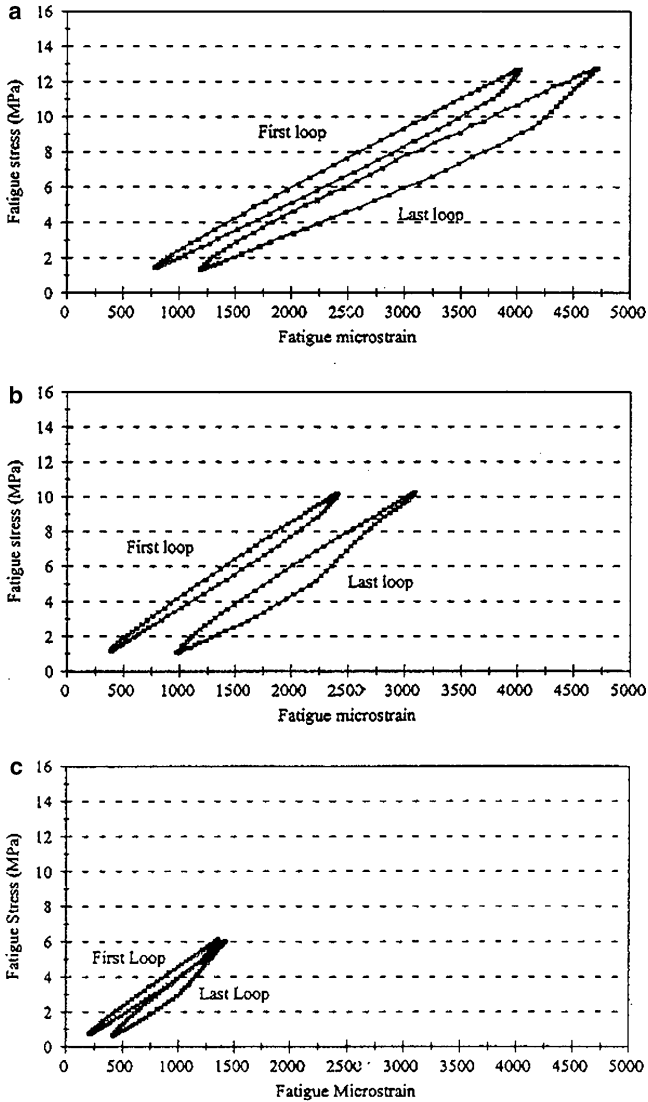


**Fig. 2** First and last captured hysteresis loops for OSB cycled at  $R=0.1$  at **a** 70% stress. **b** 50% stress. **c** 30% stress

Fig. 6. This value makes it possible to examine how the stiffness of the sample changes as a result of the cyclic loading. If the stiffness of a sample decreases, then it is being damaged. Figure 7a and b shows the median initial and median final dynamic moduli with respect to reducing stress level for the OSB, chip-board and MDF.

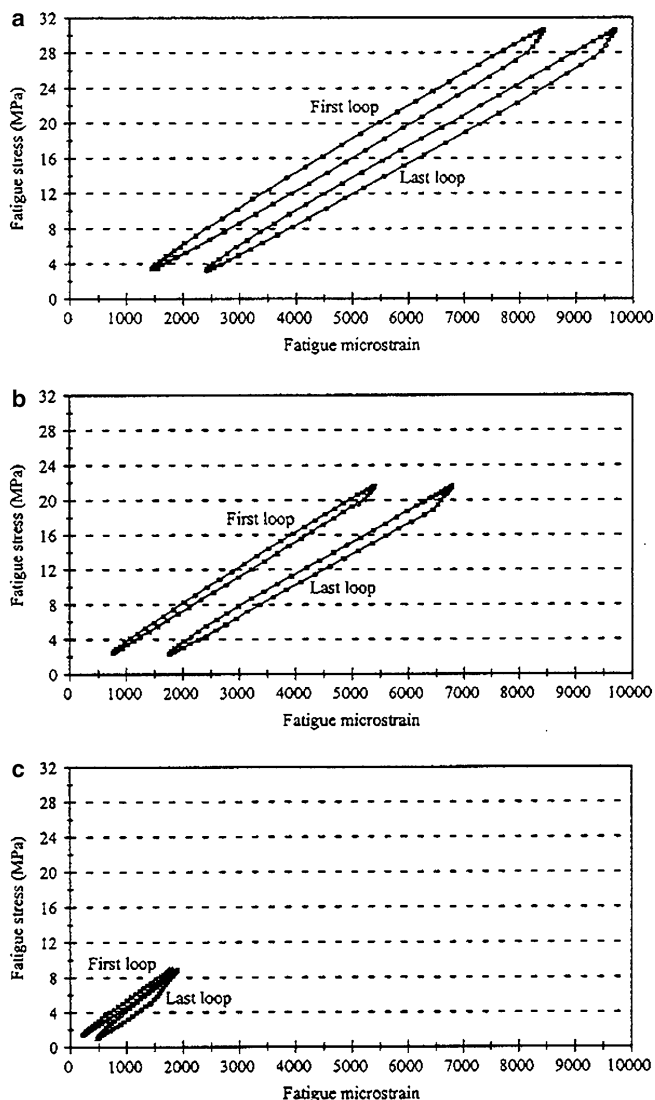
### Fatigue moduli

The fatigue modulus is the gradient of the line from the starting point of loading at the beginning of a test (the origin), to the stress versus strain maximum for



**Fig. 3** First and last captured hysteresis loops for chipboard cycled at  $R=0.1$  at **a** 70% stress. **b** 50% stress. **c** 30% stress

each hysteresis loop. Unlike the dynamic modulus, the fatigue modulus takes account of the creep occurring in the sample, as well as any fatigue damage causing a decrease in the average stiffness. The fatigue modulus is demonstrated in Fig. 8. The fatigue modulus was used to predict the fatigue life for polymer composites by Yang et al. (1992) and for wood laminates by Hacker (1995). The fatigue modulus is based on the stress range divided by the strain range, where the strain is increasing throughout a fatigue test. It incorporates the effects of both fatigue damage and creep, which occur simultaneously. Figure 9a and b shows the effect of changing stress level upon the median initial and median final fatigue moduli, respectively, for the OSB, chipboard and MDF. It must be

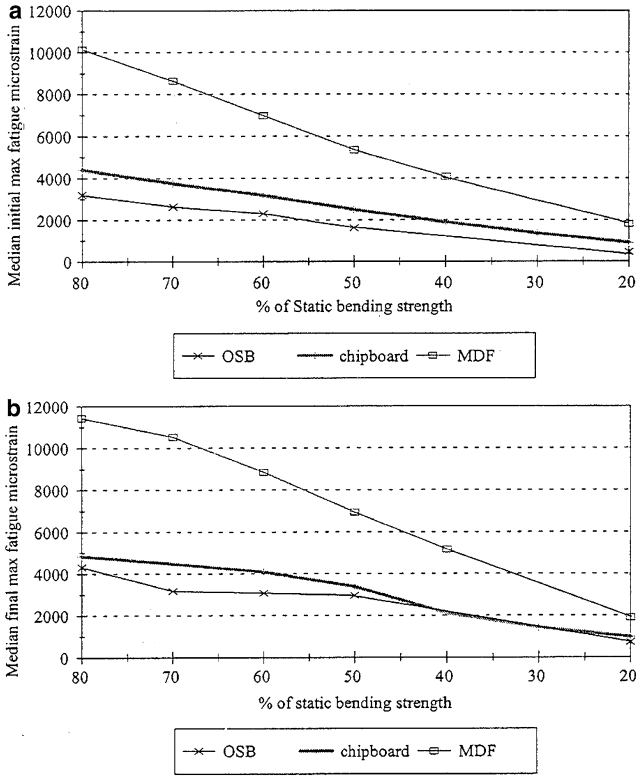


**Fig. 4** First and last captured hysteresis loops for MDF cycled at  $R=0.1$  at **a** 70% stress. **b** 50% stress. **c** 20% stress

noted that the initial fatigue moduli are identical to the initial dynamic moduli because at this stage there has not been any creep deformation. As a consequence, Fig. 9a is identical to Fig. 7a.

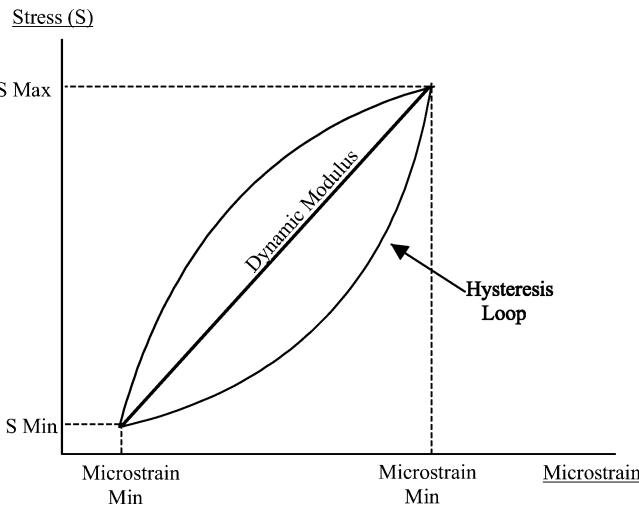
#### Hysteresis loop areas

The area of a stress versus strain hysteresis loop represents the total energy dissipated in the sample during an individual loading and unloading cycle and is an indication of the damage produced in that sample. Figure 10a shows the effect of reducing the stress level from 80% to 20% on the median initial and median final hysteresis loop areas for the chipboard and the OSB. Due to the



**Fig. 5** Median maximum fatigue microstrains for OSB, chipboard and MDF cycled at  $R=0.1$  at medium frequencies and at a range of stress levels. **a** Initial. **b** Final

magnitude of the hysteresis loop areas for MDF the equivalent data for MDF has been plotted separately in Fig. 10b.



**Fig. 6** Dynamic modulus



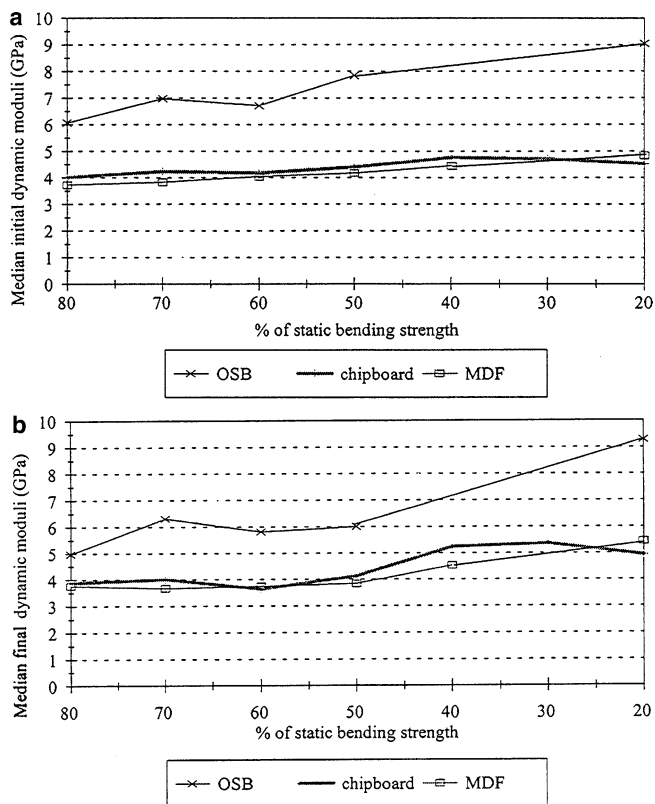


Fig. 7 Median dynamic moduli for OSB, chipboard and MDF cycled at  $R=0.1$  at medium frequencies and at a range of stress levels. **a** Initial. **b** Final

## Discussion

Before examining the captured loops and the parameters derived from them it must be noted that the first hysteresis loop and hence the value for each

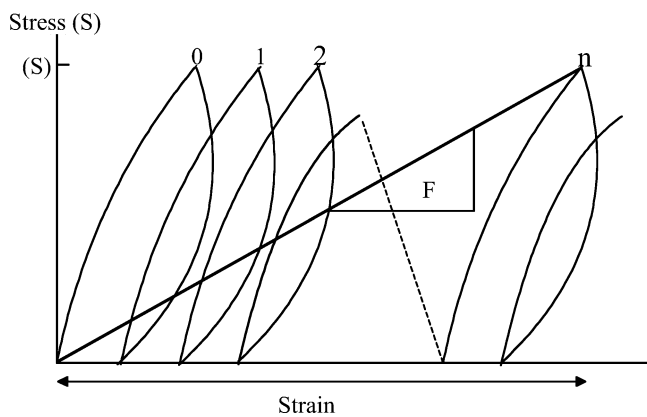
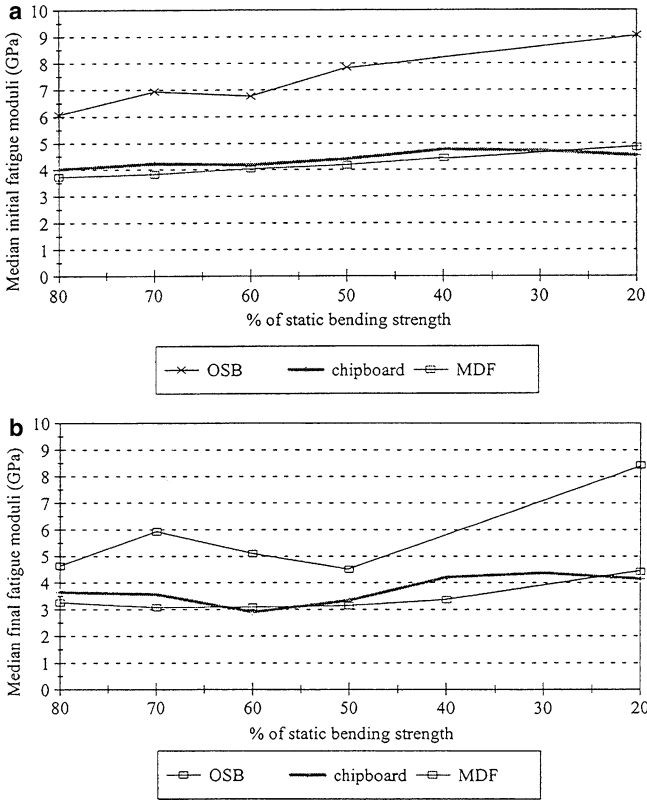


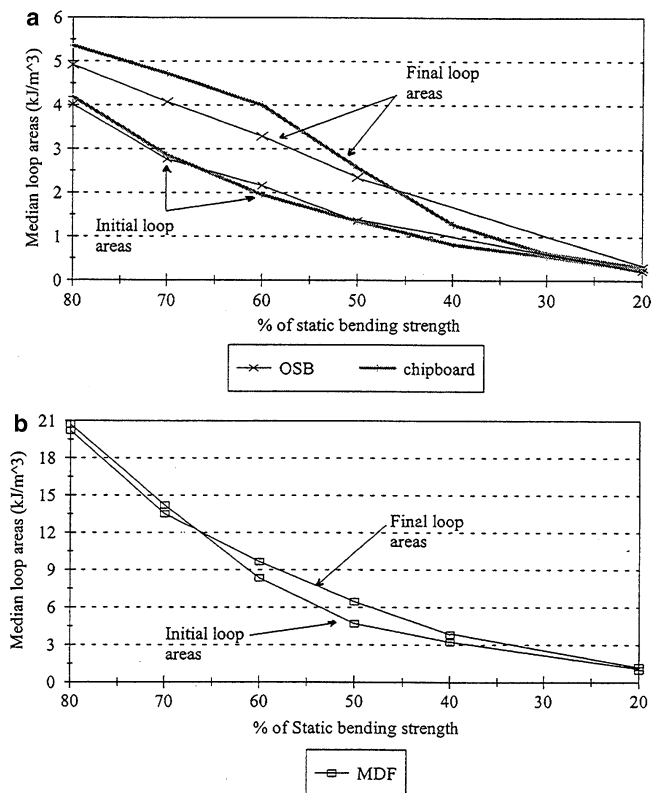
Fig. 8 Fatigue modulus



**Fig. 9** Median fatigue moduli for OSB, chipboard and MDF cycled at  $R=0.1$  at medium frequencies and at a range of stress levels. **a** Initial. **b** Final

parameter is for the first loop captured by the FDAS, rather than the first loading cycle. This capture occurred after approximately 30–60 loading cycles. Also, the last hysteresis loop captured and hence the last value for each parameter may be for the last loading cycle, or they may have been captured up to 24 h before this for the longer, lower stress level tests. Once the final stage of fatigue deformation is reached, in which the strain rate increases rapidly leading to failure, it is unlikely that the last strain value will be captured by the FDAS. However, the last loop capture and hence the last value for each parameter will be the smallest number of cycles away from the end of the test at the highest stress levels. This is because in the shortest tests the loop captures are still in close succession (every 2 min).

The hysteresis loops, Figs. 2a–4c, reduced in size with decreasing stress level for all three materials because smaller stresses produced smaller strains. In all tests the last loop increased in area and moved along the strain axis to a more positive range of microstrains compared to the first loop. This indicates that damage has been produced in the sample and therefore the energy dissipated per cycle of loading has increased and deformation has occurred. The magnitudes of the loops for the OSB and the chipboard were similar. The stress range for the OSB was slightly greater than that for the chipboard due to the higher strength of the OSB. The strength of the MDF was considerably greater than



**Fig. 10** Median hysteresis loop areas for at  $R=0.1$  at medium frequencies and at a range of stress levels. **a** OSB and chipboard. **b** MDF

that for the OSB and the chipboard, so the stress range in the plots for the MDF, Figs. 4a–c, was considerably greater resulting in larger hysteresis loops.

The median initial fatigue microstrains, Fig. 5a, decreased with decreasing stress level from 80% to 20% for all three materials. Decreasing the applied load reduced the resulting deflection. The magnitude of the deflections for the MDF was considerably greater than for the OSB and the chipboard. The MDF was considerably stronger than the OSB and chipboard, so the equivalent percentage stress levels for the MDF were at considerably higher stresses resulting in larger deflections. In addition, the constituent particles in the MDF are fibres, which are smaller than the particles in OSB and chipboard. It is generally accepted that the smaller the constituent particles, the more susceptible the wood-based panel is to static creep (Dinwoodie and Bonfield 1995). It is consistent that the magnitude of the fatigue deflections is dependent upon particle size as well as the stress levels because the values for OSB are generally slightly lower than those for chipboard; thus, there may be an increased propensity for cyclic creep as the particle size is reduced.

The final maximum fatigue microstrains also decrease with decreasing stress level for all three materials (Fig. 5b). This is because the samples have not failed at stress levels below 40%. For stress levels between 80% and 50% the median values were calculated from failed samples. However, the final stage of deflec-

tion is not captured so it is not possible to determine the magnitude of the ultimate microstrains to failure. The changes in the maximum fatigue microstrains between the two plots are very small at the lowest stress levels. This implies that at design stress levels of around 20% stress there is virtually no difference between the three materials as was shown in the S-N results in part 1 of this paper (Thompson et al. 2002).

The surfaces of OSB are not smooth or uniform due to the large particles, unlike the uniform surfaces of chipboard and MDF. This introduces possible errors when measuring the centre point deflections. There was a possibility that the OSB wood chip which the transducer probe was contacting could bow out from the surface producing an unrealistic increase in the measured microstrain. The uneven surface of the OSB samples produced the negative values for the initial fatigue microstrains shown in Fig. 2b and c. The OSB samples did not lie completely flat on the lower rollers until the load was applied and some of the microstrain values should be up to 1,000 greater. The OSB strength data was varied, as described in part 1 of this paper (Thompson et al. 2002) so it is not known with a high degree of confidence whether or not samples were loaded at the appropriate stress level. However, the use of median values in the figures has eliminated the effects of extreme values from inappropriate stress levels.

The problems encountered with OSB show that the measurement of true centre point deflection may not be the best method of measuring the strains for OSB, at least not for samples of the dimensions tested in this research. However, if strain gauges were used as an alternative method of strain measurement these would also be subject to similar errors.

The median values for the initial dynamic moduli were very similar for chipboard and MDF but were significantly higher for OSB (Fig. 7a). The dynamic moduli were slightly higher at lower stress levels for all three materials and increased to a greater extent for OSB. The increases occur because as the stress level is reduced, less damage is produced by the initial fatigue cycles. The samples remain stiffer and smaller deflections are produced.

The median final dynamic moduli were fairly constant between the 80% and 50% stress levels for all three materials (Fig. 7b). The values for MDF and chipboard were again very similar and those for OSB were considerably higher. Below the 50% stress level the median final dynamic moduli increased with reducing stress level. However, none of these samples had failed so the moduli would probably have decreased prior to the failure of these samples. Both the initial and the final values for the dynamic moduli were higher for all three materials than the representative static moduli values provided in the literature (WPPF 1994).

The OSB tested was significantly stiffer than the chipboard and MDF. However, in any evaluation of wood-based panels it is important to remember that the panels tested are representative of an individual manufacturer's product. There will always be a considerable variation in the properties of wood-based panels manufactured from different wood species, produced by different manufacturers and using different resins.

The stiffness of the MDF might have been expected to be considerably lower than that for chipboard due to the very large deflections produced in the MDF samples. However, the deflections in the MDF samples were produced by applying considerably larger stresses than those applied to the chipboard and OSB. This means that MDF has a very similar stiffness to chipboard but can

sustain larger strains before failure occurs. The finer structure (fibrous particles) of MDF possesses a larger internal surface area and contains many smaller less critical flaws than chipboard allowing it to strain to a greater extent (Pritchard et al. 1997).

As was explained earlier, the median initial fatigue moduli for OSB, chipboard and MDF in Fig. 9a are identical to the median initial dynamic moduli of Fig. 7a because the initial loop captures are not affected by the strain in the samples.

Figure 9b shows that the median final fatigue moduli were roughly constant with decreasing stress level from 80% to 50% stress and then increased as the stress level was reduced further for all three materials. The reason the median final fatigue moduli remain roughly constant between the 80% and 50% stress levels is because the values represent failed samples and the approximate critical strains remained roughly constant for each of the three materials. When the stress level is reduced to below 50% the samples may be a considerable time away from failure or even an infinite time away, so the fatigue modulus is unlikely to have reduced to any great extent. As was the case for the dynamic moduli the values for chipboard and MDF were very similar and those for OSB were significantly higher. The changes in the fatigue moduli were greater for OSB than for chipboard and MDF. The fatigue moduli decreased throughout testing for all the samples tested for all the stress levels.

The decreases observed for the fatigue moduli are greater than those for the dynamic moduli because of the creep component. As occurred with the dynamic moduli the decreases in the fatigue moduli for MDF could be expected to be greater than for the other two materials. However, again applying larger stresses produced the large deflections.

The magnitude of the initial and final loop areas decreases with decreasing stress level for the OSB and chipboard (Fig. 10a). Considering that the OSB is stiffer than chipboard and the stresses imposed on it are on average 35% higher than those applied to the chipboard, the loop areas are very close. This shows that cyclic loading produces a similar quantity of damage per loading cycle on both OSB and chipboard when loaded at the same percentage stress level. This reflects the similarity between the two materials observed from the normalised S-N plot in part 1 of this paper (Thompson et al. 2002).

The hysteresis loop areas for MDF were considerably larger than for the OSB and chipboard, up to five times greater for the equivalent stress levels (Fig. 10b). However, the difference between the values for the MDF and the other two materials reduced as the stress level was reduced. The median initial and median final hysteresis loop areas for the MDF show similar trends to those for OSB and chipboard, decreasing with decreasing stress level. One reason why the magnitudes of the loop areas for MDF are so much greater than for the other two materials is again because the stresses applied to the MDF samples were greater. The static strength of the MDF was greater than for the other two materials and it was the static strength that determined the stress levels for the fatigue tests. However, the strength of the MDF samples was only twice as high. This could mean that the MDF samples are damaged more rapidly than the OSB and chipboard. This notion is also supported by the normalised S-N plot in part 1, where the MDF samples have an inferior fatigue performance to the other two materials loaded at the equivalent percentage stress levels. The increased loop areas may also be caused by MDF having a

much larger internal surface area due to the considerably smaller constituent particle size. This may increase the material's capacity to absorb energy. The magnitude of the loop areas for MDF is, however, exaggerated because when higher stresses are applied the increase in loop area is not directly proportional to the increased stress due to the shape of the loops captured.

The loop areas for MDF at the 80% and 70% stress levels must be treated with caution. The deflections were large and will have caused a beam formula error in the applied stresses due to the angle of the sample's neutral axis to the inner support, but this does not appear to have affected the moduli.

The most important feature seen in Fig. 10a and b is that for all three materials the difference between the median initial and the median final loop areas decreases with decreasing stress level. This difference tends towards zero just below the 20% stress level. This was also observed previously for chipboard exposed to high and low frequency fatigue loading (Thompson et al. 1996a). If there is no change in the hysteresis loop area from the start to the finish of testing then no damage is being produced in the sample and it will never fail. This suggests that there is a fatigue limit for both the OSB and chipboard at a stress level slightly below 20%. Considering the S-N results from part 1 of this paper (Thompson et al. 2002), and the loop areas, it is likely that the fatigue limit for the MDF is also below 20% stress but slightly lower than for the OSB and chipboard.

Tsai and Ansell (1990) indicated that the fatigue limit for wood would be at a stress level of less than 25%. Kollmann and Krech (1961) and Gillwald (1966) both showed wood-based composites to have inferior fatigue performances compared to solid wood.

## Conclusions

1. The median initial and final fatigue microstrains for the OSB, chipboard and MDF decreased with reducing stress level.
2. The fatigue microstrains were considerably higher for the MDF than for OSB and chipboard but due to its strength the stresses applied to the MDF were considerably higher.
3. The median initial dynamic moduli were very similar for the chipboard and MDF despite the large deflections for the MDF. Both were lower than for the OSB. The dynamic moduli reduced with reducing stress level for all three materials.
4. The median final fatigue moduli and dynamic moduli decreased with decreasing stress level for failed samples for all three materials.
5. The fatigue moduli for chipboard and MDF were very similar but those for OSB were considerably greater.
6. The magnitude of the decreases in the dynamic moduli were always less than for the fatigue moduli.
7. The hysteresis loop areas were very similar for OSB and chipboard, showing that the damage produced per loading cycle was similar. The loop areas for MDF were far greater but this might be over emphasised due to the larger stress range for the MDF.
8. The hysteresis loop areas reduced with decreasing stress level for all three materials. The change in loop area tended towards zero for all three materials at a stress level just below 20%. No increase in the hysteresis loop areas

indicates that no damage has occurred. This indicated that all three materials have fatigue limits at just below 20% stress with the fatigue limit for MDF slightly lower than those for OSB and chipboard.

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