# 9 Conclusions and Recommendations for Future Work

## 9.1 Conclusions

A new combined technique of resin embedding and confocal laser scanning microscopy has been developed for quantitative analysis of paper structure at the fibre level. Fibre dimensions, fibre orientation and fibre collapse have been measured simultaneously in paper by using the new technique and image analysis. Comparisons between the measured values of fibre wall areas by the new technique in paper with those measured by the routine confocal microscopy technique on free fibres show close agreement. The fibre orientation measured in the handsheets compares reasonably well with the theoretical value of fibre orientation of a random sheet. It is concluded that the measurements made by the new technique are valid. For the first time, a technique is available for quantitative analysis of paper structure at the fibre level.

This technique has been used to study the mechanisms of densification of the paper structure in wet pressing. A fibre shape factor and twist angle of fibre cross-section in paper have been defined for the purpose of quantifying the changes in the transverse dimensions of fibres in paper in wet pressing. It was found that fibre twist, fibre collapse and gap closure are the major types of movement of fibres in paper in wet pressing. In particular, fibre twist has been found and quantified for the first time. The results show that the number of fibres with twist angles greater than $10^{o}$ is reduced by wet pressing. The degree of collapse of fibres in the handsheets is symmetrically distributed at the low pressing pressure. The fibres in the handsheets cannot be totally collapsed by wet pressing even when the very high pressing pressure (4000kPa) is used. The experimental data also suggest that out of plane fibre deflection angle is independent of wet pressing pressure.

Fibre twist, fibre collapse and gap closure occur simultaneously at low pressing pressures, and the gap closure is the predominant mechanism in paper structure densification at low pressing pressures (less than 500kPa). Increasing pressing pressure only increases the apparent density slightly and the density increase is mainly contributed by the additional twist and collapse of the fibres at the high pressing pressure (greater than 500kPa).

Based on the above new technique, a new technique for measuring properties of fibre-fibre contacts has been developed. Properties of fibre-fibre contacts, including the free fibre segment length, number and nature of fibre-fibre contacts and out-of-plane angle of fibre segments have been measured in paper. It is the first technique that can determine all of the parameters associated with the fibre-fibre contacts simultaneously in paper. For the first time, data of fibre-fibre contacts in 'real' paper is available for testing models of fibre-fibre contacts. It has been found that fibre length seems to have no effect on the properties of fibre-fibre contacts. Fibre cross-sectional shape has no significant effect on the frequency of fibre bonding along a fibre and the distribution of the free fibre length. This study shows again that the out-of-plane deflection angles of the free fibre segments have no regular trend with the pressing intensity. However, the out-of-plane deflection distance has been reduced by wet pressing since the free fibre length has been reduced. The experimental data has shown that the distribution of free fibre length for a normal sheet is not negative exponential. It seems to fit a two-parameter Weibull probability density function, even if no theoretical basis is given for using the Weibull density function. It has been demonstrated that model structures of fibre-fibre contacts can be reconstructed using the data measured by the new technique. Such model structures are important for simulations of load distribution along the length of a fibre.

This thesis presents a new model that relates the fibre cross-sectional dimensions and the apparent density of paper to the number of fibre-fibre contacts per unit length of fibre. It is the first model that considers the effects of fibre cross-sections on the fibre-fibre contacts and it is also the first time such a model has been fully verified with experimental data. The model has also been converted into two expressions for $RBA$, which have been verified with measured results by two different methods. It has been shown that both of the two expressions can predict $RBA$ well. It has also been demonstrated that the $RBA$ can be measured by using the combined technique of nitrogen adsorption and spray dry fibres on a teflon surface.

This thesis also presents a new analytical model for tensile strength of paper based on the assumption that the macroscopic fracture of paper is trigger by the failure of fibres lying in the direction of the applied load. The new model relates the tensile strength to the zero-span strength of the component fibres through a factor $r$. The value of $r$ is the ratio of the peak load and the average load in the fibres. It is the first analytical model that attempts to predict the start point of paper failure under load. It has been shown that the shear lag analysis does not seem to apply to the fracture of paper.

Model structures of a fibre of interest connecting the fibre network matrix were constructed by using the experimental data and the Weibull density function. Simulations of load distribution on the fibre of interest have been done for situations of no bond breakage, as well as with bond breakage. The simulations suggest that the value of $r$ is a 'dynamic value', which is determined by the way that the fracture of paper is triggered. It has been shown that bond breakage occurs before the sheet fracture, and it significantly affects the value of $r$. The simulation model is still at very preliminary stage. It has not included the fracture of fibres, which is believed to be the trigger of the fracture of paper. Therefore, it is not surprising that the preliminary simulations can not predict the correct values of $r$. However, a very good correlation has been shown between the tensile index calculated by the peak average load from the bond breakage model and the measured tensile index, although the predicted value was still only 1/3 of the measured value. This indicates the promise of the bond breakage model. Further modifying the bond breakage model by including fibre fracture is expected to provide better prediction of the sheet fracture and therefore better calculation of $r$ value for testing the simple fibre fracture model. It is beyond the scope of this PhD to do this and will be done in the future work.

## 9.2 Recommendations for Future Work

### 9.2.1 Further study on the fibre-fibre contacts

In this thesis, although the nature of fibre-fibre contacts was classified into full and partial contacts, there is no theoretical basis for doing this. The type of the contacts was determined by the operator by examining the cross sections of fibre-fibre contacts. A contact that had about the same distance as the fibre width then this was defined as a full contact. A contact about half or less of the fibre width was defined as partial contact. How to define the partial and full contacts in a more scientific way is a question to be answered in future work. For doing this, a series cross-sectional images at different depth of a sheet cross section can be obtained by using the new technique developed in this thesis. Then the series of images can be used to reconstruct the 3-D image of the paper structure using new image analysis software, such as ImagePro. The 3-D image will show more information of fibre-fibre contacts.

Dent (Dent 2001) has shown that from theoretical analysis the free fibre length should be a general gamma distribution. It is recommended to use the data in this thesis to test the gamma distribution in the future work.

It has been shown that some fibre-fibre bonds break before the fracture of paper. The bond strength affects the bond breakage and therefore the load transfer between fibres and the value of $r$. This is how the bond strength comes into the simple fibre fracture model for the tensile strength of paper. The bond strength in this thesis was estimated by fitting the experimental data to the Page equation where the bond strength was treated as a fitting parameter. The literature has shown that there is no technique available to measure the bond strength so far. Development of techniques for measuring the bond strength is an important topic in the future work in this area.

It has been shown that the bond breakage simulation model is very promising. Refining the bond breakage model by including the fracture of fibre and other factors as discussed in Chapter 8 is expected to be able to predict the fracture of paper and therefore to generate correct values of $r$ in the simple fibre fracture model of the tensile strength of paper. This can be done by:

- Allowing fibres crossing at $90^o$ to contribute to load transfer via shear mechanism. Major difficulty here is how to treat the shear contribution of fibres not crossing at $90^o$.
- Allowing crossing fibres at broken bonds to continue to contribute force to fibre via a friction mechanism. In the current model, it is assumed that once a bond

breaks then that crossing fibre is completely removed from the simulation. In reality, such fibres are likely to continue to transfer some load by fibre-fibre friction even after they have broken.

- Introducing plastic deformation into the fibre of interest. This will reduce the load at the fibre-fibre bonds for a given level of external strain.
- Including fibre fracture in the simulation.

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