Predicting Non-woven Web Compression Performance from Fiber Properties

Theodore T. Tower Ph.D., Antonio Carrillo Ph.D.

Kimberly-Clark Corporation, Neenah, WI 54956

***Abstract**: Nonwoven webs are a critical component to many of K-C's disposable absorbent articles. For example, some webs are responsible for fluid intake and distribution, and therefore must remain sufficiently open even under compressive loading. Material development can be accelerated by predicting functional web performance from experimental fiber data. A finite element model was developed to evaluate compression resistance of a non-woven web as a function of fiber properties.*

We will also outline examples of using an open-source computer graphics package, Blender, to more effectively communicate simulation results to the broader organization. With careful application, simple rendering approaches can help disseminate and market the use of simulation.

***Keywords**: Nonwoven, Fiber, Compression, Fluid Distribution, Beam, Diaper, Absorbent Article*

1. Introduction

Disposable absorbent personal garments, such as diapers, is a multi-billion dollar industry. To continue to deliver performance and value to consumers and, ultimately, an attractive return to shareholders, we must continue to deliver innovations in marketing, manufacturing, and materials. The performance of diapers in absorbing body waste and preventing leakage is critically dependent on several performance materials. Whereas urine is absorbed in superabsorbing materials in an absorbent pad, most diapers also contain a cellulosic or nonwoven layer above the pad to serve as a temporary reservoir for the fluid coming into the product and act as a distribution layer over the absorbent pad.

This distribution layer serves a critical purpose, and likewise has very demanding criteria for successfully accomplishing that purpose. First, it serves as a temporary reservoir, thus requires a very high porosity (>95%). However, because of its use in absorbent garments, it is often subject to compression from the wearer sitting on it. As such, second, it must have sufficient mechanical compression resistance in order to maintain an adequate porosity. A third factor is the wettability characteristics of the material, which is also important for fluid handling. In this paper, we will examine the use of non-woven fibers and the structure of that non-woven in delivering the mechanical aspects of an absorbent article distribution layer, specifically on webs made of staple (i.e. cut) fibers.

Non-woven web mechanical behavior is dependent on many factors. The fiber material properties, thickness (or fiber denier), construction (e.g. monocomponent, sheath-core bicomponent, etc) all impact the effecting bending modulus of a fiber. Since non-woven webs are typically bonded in some fashion, we look at uniformly bonded web such as from an oven or through air dryer. This brings to light network aspects of the structure, including, but not limited to, fiber orientation, bonding density, strut length between bonds, and fiber mix (i.e. when multiple fiber types are used).

In practice, it can be difficult to definitively characterize the thickness of a non-woven, so we will plot thickness vs the applied load (stress). We can extrapolate this to approach the unloaded thickness, but in designing for fluid handling, it is often more useful to use the thickness at a given load. This thickness, together with the basis weight of the non-woven and the polymer density can be used to calculate the empty space (void volume) in the structure at any load. Maximizing this void volume at a given basis weight is our goal. Some example non-woven compression curves of carded webs are shown in Figure 1. They tend to follow an exponential decay-like behavior.

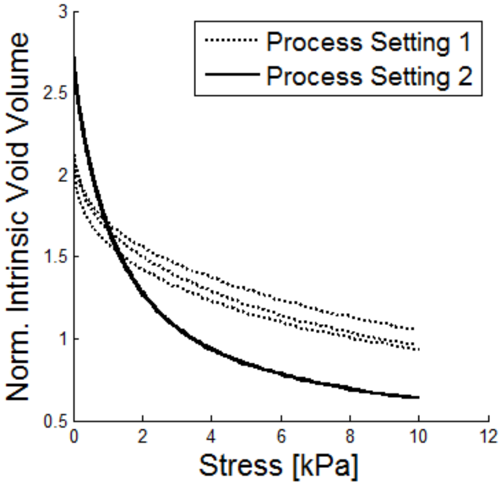

Figure 1: Measured compression curves for some example carded webs.

In an effort to screen potential distribution layer construction options, it would be advantageous to use a computational model to help reduce the number of approaches and physical trials that are evaluated. The use of theory or simulation to predict network properties has remained an active research area in academia since at least the 1980's [1,2]. Research covers a wide range of behavior, included predicting elastic behavior and compressive properties [3,4]. However, because of the complexity of different fiber morphologies, bonding behavior, and fiber mixtures an explicit, discrete fiber model seems the best option to gain reasonable insight into mechanical performance, with the greatest flexibility in the types of structures that could be created.

For the purposes of this paper, we propose two key hypotheses:

1) That a discrete, mixed fiber type model can give quantitatively reasonable compression behavior to real non-woven, staple fiber, webs.
2) That smaller diameter bondable fibers will result in a more compression resistant web.

2. Methods

We will attempt to answer our hypotheses using a discrete fiber finite element model in ABAQUS. This will allow us to independently test the effects of fiber mix, diameter, modulus, and so on. This section goes into many simulation practitioner aspect of model development for this generic and flexible bonded web model.

2.1 Model Assumptions

Carded webs are made from crimped staple fiber that become entangled and provide volume (i.e. loftiness) to the web. It is common practice to use bicomponent fibers with a sheath/core construction using a lower melting point polymer on the sheath that will enable bonding with similar fibers. Often, there is a second type of fibers used that have a higher melting point, and thus are not bondable at processing temperatures. These unbondable fibers remain stiffer and provide adequate loft to the web through the bonding process. During thermal-bonding, the crimped fibers relax enough that they no longer appear crimped, but rather form a continuous network of fibers (see Figure 2).

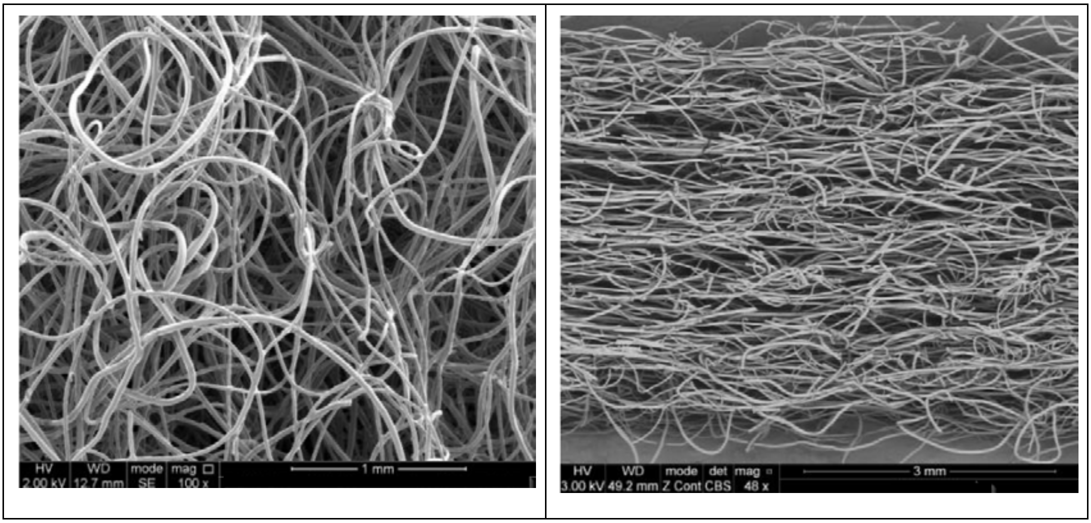

Figure 2: Example scanning electron microscopy (SEM) images of lofty non-woven used as a distribution layer in a diaper. Left: surface view. Right: cross-sectional view.

We assume that a network of finite element beams are adequate to represent the fibers, and the compression resistance of the entire network is a composite behavior of these fibers and the manner in which they are bonded. Several model assumptions related to the post-bonding network will degrade the compression resistance seen in physical validation. These include assumptions of a circular cross-section and uniform diameter, no macroscopic basis weight variations, and that the model is caliper independent. In physical experiments, the caliper of a given web is dependent on bonding temperature and the fiber resin, and as a result may experience shrinkage. Therefore, for the purpose of this work in predicting a best possible performance of a web, we assume that a web of a given caliper, can in fact, be manufactured.

Lastly, if all the fibers are oriented nominally in the machine direction, we assume there will be less cross-direction bonding and the structure will be weaker in through-thickness compression. In reality, we know that certain manufacturing processes can produce a strong fiber orientation in the machine direction, but for the purposes of the through-thickness compression, we shall ignore it. Taken together, each of these assumptions should give rise to a predicted void volume that is higher than we could achieve in reality, thus the model acts as an upper limit or the best that could be achieved with a given structure.

In addition to assumptions related to the fibers and the overall network structure, we assume that a 5x5 mm virtual model is a representative portion of the web and that 3-5 simulations of the web model replicates using different random seeds for network generation will be an adequate assessment of web variability. From experience, we find we get reasonably good results from scaling simulations of ½ thickness of our typical distribution layers.

2.2 Network Generation

Since we are interested in the mechanical performance of the thermally-bonded web, we strived to generate a computer model that represents a similar structure. The fibers are generated using a pseudo-random walk algorithm, where fibers midpoints are seeded in space and “grown” in both directions. Additional model terms govern the fiber trajectory’s predisposition to be in the plane of the web. A larger initial web area is generated to minimize edge artifacts, and post generation, the domain is cropped down to sample dimensions. Although typical staple fibers are 25mm or more, we utilize 10mm fibers because of the small representative volume (5x5x ~3 mm). Since these webs are often greater than 95% porous when unloaded, we assume true intersections are rare, and thus each fiber is generated independently (i.e. ignorant of fibers around it). During simulations, they will contact and interact with each other as the porosity decreases.

The network structure is an essential element to the mechanical response of the structure to compression. Admittedly, exact reproductions of network geometry might be achievable through micro/nano-computer tomography. However, given the variability of the material, the difficulty in geometry extraction and assignment, and the goals of the effort (i.e. finding the relative importance of various construction parameters), we felt a plausible recreation of the network from the top and cross-sectional views was appropriate. Figure 3 shows an example simulated network in the top and cross-sectional views. In comparison with Figure 2, the simulated network nominally has a similar curvilinear appearance from the top view and a nominal planar view in cross-section. These same network generation parameters were used for all simulations.

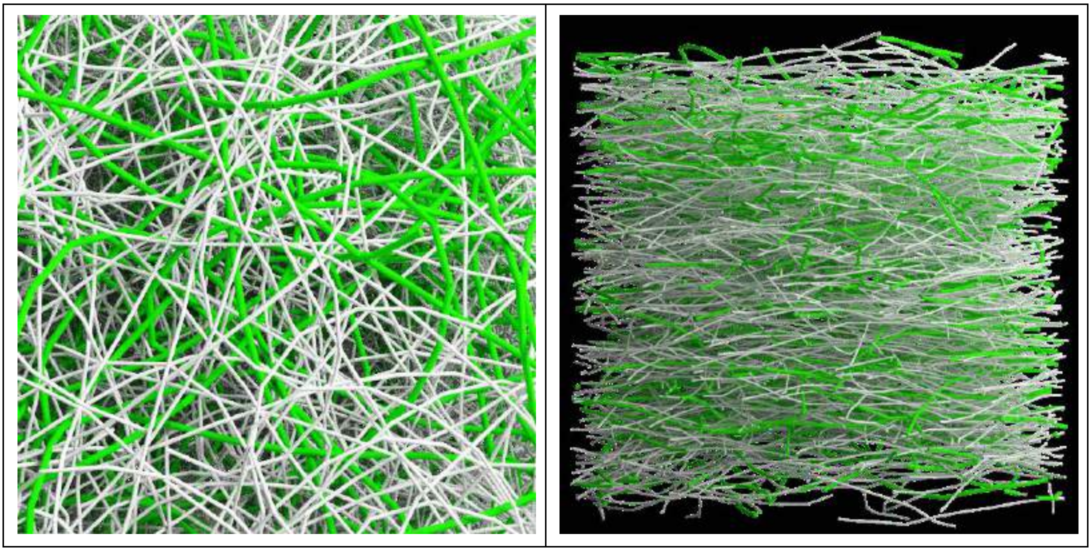

Figure 3: Simulated fiber networks. Bondable fibers (white) and unbondable fibers (green).

The approach to bonding in the model was a simple brute force global search between bondable fibers at their nodes. Large bonding radii gives rise to a very cobweb-like appearance (see Figure 4, left and middle), which did not agree visually with SEMs (Figure 2). A smaller bond distance, in the range of 80um, seemed to much more realistic (see Figure 4, right), and was used for all simulations.

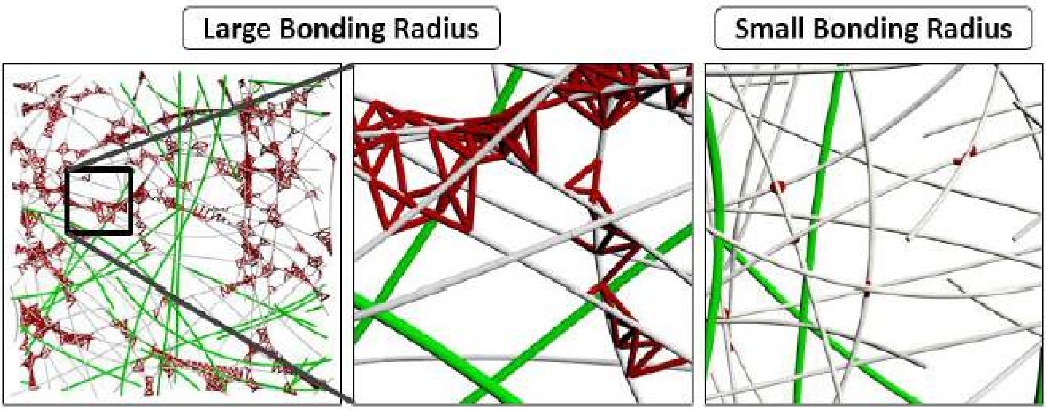

Figure 4: The effect of bonding radii in a mixture of bondable (white) and unbondable (green) fibers. Resultant bonds shown as red struts.

While various approaches to generating “bonds” are possible (e.g. elements, connectors, geometry modification), we found that Abaqus ties between fiber nodes were the most robust, efficient, and simple to implement.

2.3 Effective Fiber Properties

In order to simplify the simulation, we homogenize the mechanics of the fibers, using the sheath and core properties and geometry to determine effective mono-component properties and dimension. Composite elastic regime tensile behavior is determined by the modulus and the cross-sectional area of the sheath and core, solving for an effective fiber diameter and modulus that has the same tensile and simple beam-bending behavior as the sheath-core fiber.

2.4 Compression Simulation

Because a compression test is a complex contact problem, the necessary calculations and time-steps can be quite restrictive. In order to achieve a more economical solution, we speeded up the simulation where possible. Because we wish to avoid platen/fiber intersections at the beginning of the simulation, we placed the compression platens 4 web-calipers apart and moved them together at 5m/s until they reached 1.3x separation, followed by a compression speed of 1m/s. Mass scaling was applied to elements whose stable time increment was smaller than 1e-5ms. The high speed and the mass scaling results in greatly increasing the inertia of the simulation, although in practice we find this does not appreciably alter the resulting compression curve when compared to 4x slower simulations, implying that the system dynamics propagate reasonably fast.

However, occasionally, the initial structure and inertial effects will generate spikes and compression curves that are not monotonic. These simulations were discarded and a new random sample was generated. Moreover, the inertial and system dynamics can cause the sample to translate in x and y, so the sample is confined to a box with a 50um margin on each side, which again, has not been shown to alter results, since the effective Poisson’s ratio of the web is almost zero.

In use, one metric of interest is the fluid handling capacity of the non-woven as a function of mass of the non-woven (i.e. we want to maximize capacity for a given mass). We will refer to this as the void-volume per gram. To be relevant to how the product is used, this is often evaluated at a certain compression, or pressure. Ideally, the non-woven will remain highly porous, even under a physiologically relevant pressure, such as a child sitting on the absorbent core. For convenience, we will evaluate the void-volume per gram evaluated under 2kPa compression.

Except where noted, the computer simulations were conducted with the following:

Independent variables: Fiber mix and diameter.
Fiber Type. Bicomponent fibers (nominal 20um diameter, 50:50 sheath: core construction) and monocomponent fiber (36um diameter, hollow)**.**
Dependent variable: Void volume [cc/g] at 2kPa nominal pressure load.
Controlled variables: Basis weight, web size, loading protocol
Uncontrolled variables: Fiber trajectories determined by random walk, bounded by caliper.
Method: A 5x5mm 28gsm discrete fiber web composed of bondable and unbondable fibers or nominal 1mm thickness was created using Abaqus 6.14-2 (scaled down version of 85gsm, 4mm thick web). Virtual compression test was conducted (N=3 or N=5).
Hardware & Problem Size: Simulations were conducted on two 12-cpu servers running at 3GHz and generally took 20-40 minutes depending on fiber mix. Number of variables were between 50,000-100,000.

2.5 Visualization

In addition to visualization of simulation results through Abaqus Viewer, we can leverage advances made in the computer graphics industry through the use of Blender, an open-source package for realistic rendering of materials and lighting. Here, we exported Abaqus simulation results as Virtual Reality Markup Language (VRML) files for each simulation frame. In Blender, these were rendered as still images, such as in Figure 3. These files could also be used as key frames, where additional frames could be interpolated, providing a final animation that was much smoother than that afforded by the frames stored in the ODB. In this way, we could reliably produce high quality animations, while minimizing the ODB size.

3. Results

3.1 Validation

There are many process variables in the manufacture of BCW which are not taken into account in the network generation step for the simulation, including the cards used, lapping, needle-punching and other intricacies to different assets. However, Figure 5 shows very good correlation of some experimental test data (black) and the baseline simulation (blue). The red and green curves show the relative impact of reducing the basis weight and increasing the bondable fiber diameter while maintaining caliper, both which reduce the void volume at various evaluation stresses, and qualitatively agrees with experimental experience. While this is only one dataset from a variety of conditions, it is encouraging and the simulation data agrees so well with the magnitude and shape of the curve without any fitting.

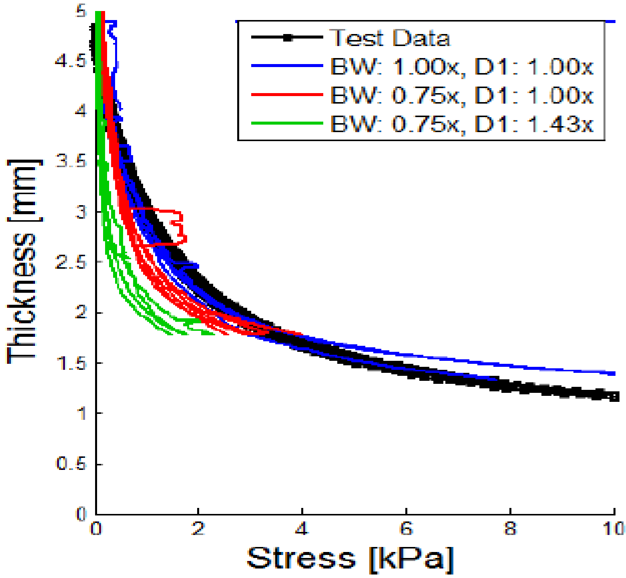

Figure 5: Compression test data vs simulation. Control simulations (blue), reduced basis weight (red), and reduced weight and increased fiber diameter (green).

3.2 Diameter

Simulations were run of a 50:50 mix of bondable and nonbondable fibers over a range of bondable fiber diameters. Figure 6 shows the normalized intrinsic void volume (i.e. volume per mass at 2kPa stress) decreases with increasing bondable fiber diameter. This is expected since larger fibers consequently mean fewer fibers at the same fiber mix, and fewer fibers have fewer opportunities to generated bonds.

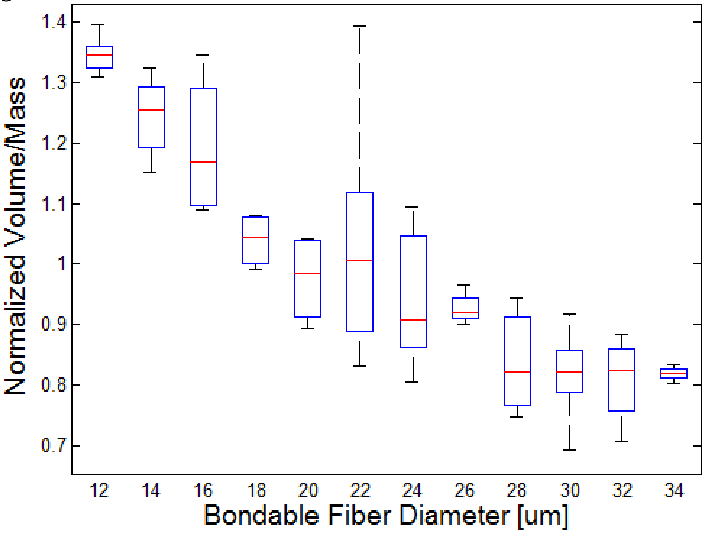

Figure 6: Normalized void volume vs bondable fiber diameter.

3.3 Fiber Mix

Figure 7 shows the variation of normalized intrinsic void volume as a function of fiber mix between 2 bondable fiber types and one nonbonding type. The lowest void volumes are when the matrix is dominated by the nonbonding fibers. The highest void volumes are with the smallest diameter bondable fiber. However, in practice, 100% of the small diameter bondable fibers end up collapsing during bonding, so a mixture of bondable and unbondable fibers is necessary. These simulations show what could be possible if the structure could be made, but does not address feasibility of manufacture.

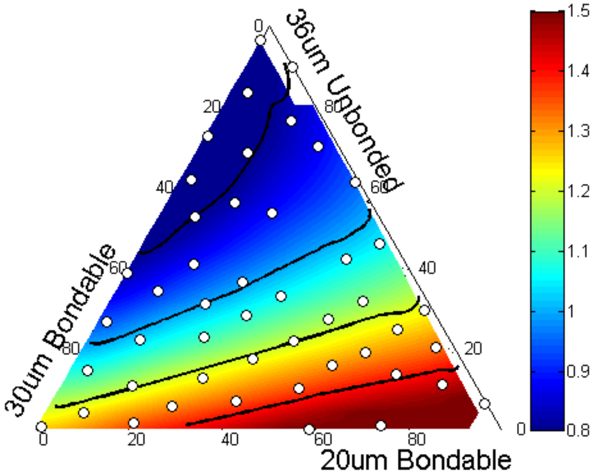

Figure 7: Normalized intrinsic void volume as a function of fiber mix.

4. Discussion

As we have seen and expect, increasing the mass fraction of bondable bicomponent fibers and reducing fiber diameter both result in more bondable fibers and more bonds. A consequence of that is a more resilient structure leading to higher void volume. Fluid handling might further be examined by using the resulting porosity together with empirical relationships to estimate fluid flow characteristics.

Although not shown here, there have been cases where physical trial results come back significantly underperforming model predictions. In these cases, subsequent investigation normally finds that one or more of the model assumptions is no longer true (e.g. long residence time or elevated temperatures leads to collapse of the web). This, in turn, gives the material developer additional information whether process settings are or are not appropriate for the target web construction.

In addition to the metrics such as intrinsic void volume, scientific visualization can play an important role in technology development. As we've briefly demonstrated here, the Blender computer graphics package can be used to visualize Abaqus ODB results, as well as provide unique opportunities for interaction with simulated structures.

5. Summary

Discrete fiber simulations of webs is an important research area in developing performance materials for diapers and other consumer goods. Here, we have outlined one approach to evaluating the mechanical performance of a thermally bonded non-woven web of staple fibers using a discrete fiber finite element simulation in Abaqus. Using appropriate assumptions, we believe these simulations portray the upper limit of what might be achievable if a particular web construction could be manufactured.

Moreover, these results have been promising and continue to guidance in distribution layer development.

6. References

1. Ostoja-Starzewski, M, “On the Elasticity of Isotropic Fiber Systems,” IPST Technical Paper Series, 1996.
2. Ostoja-Starzewski, M., and D. Stahl, “Random Fiber Networks and Special Orthotropic Elasticity of Paper,” IPST Technical Paper Series, 1999.
3. Picu, R.C., “Mechanics of random fiber networks—a review,” Soft Matter 7(15): 6768–6785, 2011.
4. Picu, R.C., “Mechanical Behavior of Non-bonded Fiber Networks in Compression,” Procedia IUTAM 3: 91–99, 2012.