ANALYSIS OF WEB WRINKLING IN ACCUMULATORS

B. K. Kandadai, N. J. Michal and A. Patil
Kimberly-Clark Corporation

ABSTRACT

Accumulators provide a large amount of web storage in a small space. They are used to allow start/stop events like an unwind splice or a transfer to a new roll on a winder. It is common to see a loss of productivity due to wrinkles and lateral movement of the web as it travels through an accumulator.

An explicit finite element model has been developed to study wrinkle formation and web steering inside of an accumulator. Four cases will be presented: perfect web / perfect accumulator; imperfect web / perfect accumulator; perfect web / misaligned accumulator; imperfect web / misaligned accumulator. Model results indicate that the misalignment required to cause wrinkles within the accumulator decreases with increase in number of misaligned rollers. Model results also indicate that the critical misalignment to cause wrinkles decreases if the web has imperfections in the form of thickness variations.

A seven roller accumulator set up was designed and built to study the wrinkling dynamics of a low modulus nonwoven web and to compare the model results. Measurements indicate that the model predictions compare reasonably well to experiments. The study highlights the criticality of acceptable limits for tolerance on misalignments within the accumulator for process robustness.

NOMENCLATURE

a, b	Half wave number, Web width
CD	Cross Direction (or) Cross Machine Direction
D	Stiffness Matrix
E_{11}, E_{22}, E_{33}	Modulus in principal direction
E_x, E_y, E_z	Modulus in principal direction
E, G (or) G_{12}	Elasticity, Shear Modulus respectively
MD	Machine Direction
R	Roller radius
T	Web tension
ZD	Thickness Direction
$\nu_{12, 13, 23, 21, 31, 32}$	Poisson's ratio (ν_{12} – '1' loading direction, '2' deformation direction)
ν_{xy}, ν_{yx}	Poisson's ratio (ν_{xy} – 'x' loading direction, 'y' deformation direction)
σ, ϵ	Principal stress and principal strain tensors respectively
γ, τ	Shear strain and shear stress tensors respectively
τ_{avg}, ϕ	Average shear stress, Shear parameter
σ_{ycr}, θ_{cr}	Critical stress, roller misalignment angle for wrinkles respectively

1. INTRODUCTON

Accumulators [1] provide a large amount of web storage in a small space. They are used to allow start/stop events like an unwind splice or a transfer to a new roll on a winder. It is common to see a loss of productivity due to wrinkles and lateral movement of the web as it travels through an accumulator.

Web tension is the most important parameter for any web process. Individual span tensions vary significantly within the accumulator during steady state operation. Individual spans undergo extreme tension differentials during the accumulator fill and feed process. Poor tension control within an accumulator can lead to waste and delay. Symptoms of poor tension control within the accumulator include web instability, web weave, wrinkling, and neck down. Failure modes include total web collapse and ultimately web breaks [1, 2]. Webs are stored in wound rolls under stress and spend most of the time in storage before being converted into a final product. The combination of stress and time cause the web to have floppy edges, baggy lanes, and web camber [3]. Accumulators must be capable of processing these non-ideal webs and lack thereof results in web instability as shown in Figure 1.

Figure 1: Cambered web and wrinkles in an accumulator

Fundamental research for web handling has been primarily limited to a single roller in an open span. There are several dozens of published papers that describe traction, air lubrication, and wrinkling. Shelton [4, 5] and Pagilla [6-9] along with a few others [10] have contributed the most to accumulator analysis. Equipment builders have not improved their designs based on published papers. As a result, most accumulators are operated using a trial and error approach.

In order to study the wrinkling mechanics of a nonwoven web within an accumulator, a seven roller accumulator was designed, built and installed between an unwind and a re-winder. Misalignment studies were completed using a lightweight nonwoven web, the properties of which are described in the following section. Based on the experimental results, a handful of cases were selected and modeled using explicit finite element procedure in order to further understand the underlying mechanics. Experimental results were then compared to the model results, the details of which are described herein.

2. FINITE ELEMENT MODEL

In a typical accumulator there will be several rollers in both the fixed and movable carriages [1]. However finite element modeling of an entire accumulator is not a computationally simple task. In order to gain basic understanding of the wrinkling mechanics of web behavior in multiple-spans such as that found in accumulators, a simpler model is considered herein.

2.1. Model Set Up

The model is set up such that the wrinkling mechanics of a moving web over multiple rollers in a manner such as that found in accumulators can be studied for various span lengths, roller misalignments, web properties, and surface interaction properties. Consider an initial configuration of the model wherein the web path through an accumulator is as shown in Figure 2.

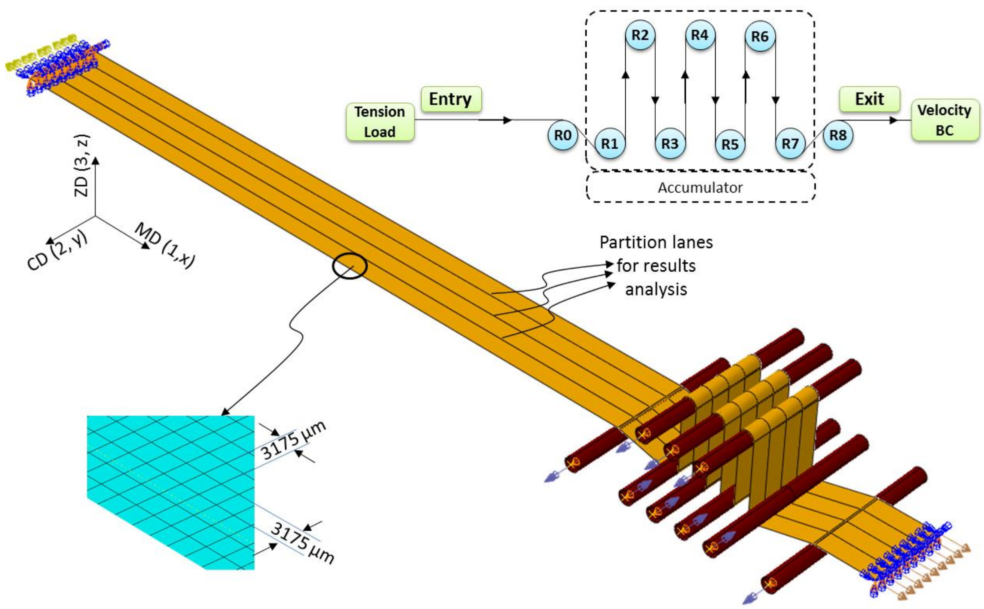

Figure 2: Schematic representation of the FE model set up

In this model, the web layer is modeled as an elastic layer while the rollers are modeled as rigid cylindrical shells. The model in the initial configuration is set up such that all the rollers are parallel to the y-axis as shown in Figure 2. Within the accumulator, rollers R1, R3, R5 and R7 represent the lower (fixed) carriage rollers while rollers R2, R4, R6 represent the moving (top) carriage rollers. Rollers R0, R8 serve to maintain a fixed web wrap angle entering and exiting the accumulator. All the rollers in the model can rotate about their respective axis but are constrained in all other directions. In order to keep the computational time to a reasonable level, the vertical motion of the top carriage rollers is not modeled. Instead the rollers are set at a fixed height from the rollers in the lower carriage and misaligned to a pre-determined value when studying the wrinkling dynamics of the web in a misaligned accumulator.

With this model, wrinkling analysis is performed as a function of time using a commercial FE application (Abaqus® Explicit). The model consists of two time steps.

1) In the first time step, a known value of load is prescribed at the left-end of the sheet on the entry side of the accumulator to simulate the web tension. The left end of the sheet is free to move in the MD, but constrained in all other degrees of freedom. When prescribing this load, the right-end of the sheet at exit side of the accumulator is constrained in all degrees of freedom. In addition, a constant moment that acts in the direction that is opposite to the rotational direction of the roller is prescribed to each roller to simulate bearing drag. It is difficult to accurately calculate/measure bearing drag. Hence it was estimated by experimentally measuring the increase in tension as measured by difference in tension measured at the entry and exit of the accumulator and dividing the load among all the rollers in the system.
2) In the second time step, the boundary conditions at the right end of the sheet are modified to allow motion in MD and CD, but not in ZD. In addition, a velocity boundary condition in MD is prescribed to the right end of the sheet to accomplish longitudinal motion of the web.

The model properties are summarized in Table. 1. The problem is analyzed as a quasi-static problem so that mass-related effects are negligible. The web is modeled as an elastic membrane using four-noded quadrilateral membrane elements in reduced integration mode with hour glass control [11].

Property	Value
Web length (L_w)	790.1 cm
Web thickness (h)	203.2 µm
Web width (Ww)	40.64 cm
Roller diameter ($D_{R1..9}$)	7.62 cm
Roller width (W_R)	97.2 cm
Web velocity (V_w)	9.14 m/min
Web/Roller Coefficient of Friction ($\mu_{Web/Roller}$)	0.22
Web tension (T_w)	0.75 N/cm
Roller moment (M_R)	0.003 N.m

Table 1: Accumulator model properties

Load, Moment and Velocity boundary conditions are ramped up to their final values using s-curve type functions in about one second in order to reduce mass-related effects. The mass density of web material was about 83.7 Kg/m^3. However the model density was appropriately scaled to ensure quasi-static conditions and in order to reduce the computational time yet maintaining computational accuracy. The model consists of 321,606 nodes and 318,994 elements with 964,845 variables that include degrees of freedom and any Lagrange multipliers.

2.2. Material Properties and Constitutive Relationship

A Polypropylene based spun bonded nonwoven web with a basis weight of 17 g/m^2 is used in this study. The anisotropy of this nonwoven SB material is characterized in the Table 2. Note that the modulus in the thickness direction was assumed to be equivalent to the modulus in machine direction. The shear moduli values were estimated from Equation 1 which was originally developed by St. Venant and later used by Cheng and Cheng [12]. The material orientation is shown in Figure 2 and the constitutive relationship used in the model is established by the compliance matrix is given in Equation. 2.

Material Constant	Value
E_{11}, E_{22}, E_{33}	62.8, 14.3, 62.8 MPa
ν_{12}, ν_{13}, ν_{23}	0.4, 0.01, 0.01
G_{12}, G_{13}, G_{23}	10.1, 10.1, 10.1 MPa

Table 2: Material properties of 17 gsm Spunbond nonwoven web.

$$G_{12} = \frac{E_{11}E_{22}}{E_{11}(1+\nu_{21}) + E_{22}(1+\nu_{12})} \tag{1}$$

$$\sigma = D:\epsilon; \quad \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & -\frac{\nu_{21}}{E_{22}} & -\frac{\nu_{31}}{E_{33}} & 0 \\ -\frac{\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & -\frac{\nu_{32}}{E_{33}} & 0 \\ -\frac{\nu_{13}}{E_{11}} & -\frac{\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 \\ 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \end{Bmatrix} \tag{2}$$

2.3. Surface Interaction Behavior

Surface interaction between the web and the roller is accomplished using general contact algorithm [11]. General contact uses the finite-sliding, surface-to-surface formulation. General contact uses the penalty method to enforce the contact constraints by default. The contact algorithm automatically accounts for thicknesses and offsets associated with shell-like surfaces. In general contact, contact definitions are greatly simplified and are primarily due to the relaxed restrictions on the surfaces that can be used in contact. Dynamic coefficient of friction between the web and the roller was measured at 0.22 and this value is used to define the contact interaction property between the roller surfaces and the web material.

2.4. Model Cases

In order to understand the wrinkling mechanics of a web in the accumulator, four different scenarios were developed. In all the scenarios, the web entering the accumulator is under a web tension of 0.75 N/cm and the distance between the fixed carriage rollers and the top carriage rollers are set nominally to 0.9 times the width of the web (36.6 cm).

Case (1): Perfect web, Perfect accumulator

This case provides an example of a perfect accumulator arrangement and behavior of a perfect web in the same. All the rollers are perfectly aligned in the accumulator and the web material does not have any defects.

Case (2): Perfect web, Imperfect accumulator

This case provides an example of an imperfect accumulator with a perfect web moving through it. The imperfect accumulator studied herein has one or more misaligned rollers within the accumulator. The degree of misalignment is varied to understand the wrinkling mechanics of the web within the accumulator.

Case (3): Imperfect web, Perfect accumulator

This case provides an example of an imperfect web moving through a perfect accumulator. The imperfection in the web is introduced as low thickness sections in the web with the same material properties as elsewhere in the web. Web thickness at the imperfection locations is about one fourth the thickness (50.8 micron) compared elsewhere (203.2 micron). At the start of the simulation all the imperfections are only present in the entering portion of the web and not within the accumulator. Once the web starts moving, these imperfections travel through the accumulator. Five imperfections each at a size of 3.81 cm x 3.81 cm (square section) with a repeat distance of 81.3cm are located at one quarter web width distance from one edge. Four imperfections each at a size of 2.54 cm x 2.54 cm (square section) with a repeat distance of 81.3 cm are located at three quarter web width distance from one edge. These imperfections are also offset from the first set by a distance of 40.6 cm. A schematic describing these imperfections is shown in Figure 3.

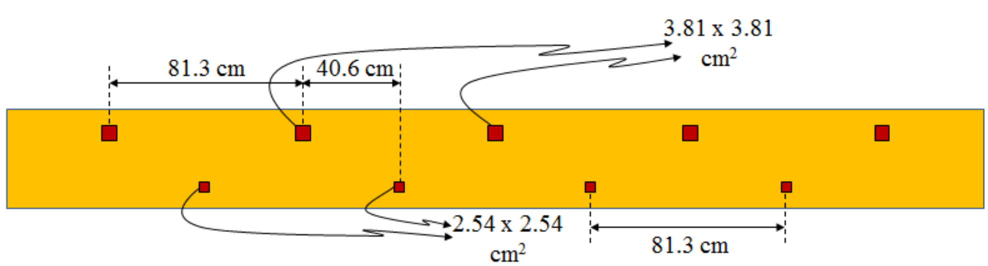

Figure 3: Schematic of imperfections in the web in the entering span

Case (4): Imperfect web, Imperfect accumulator

This case provides an example of an imperfect accumulator with an imperfect web moving through it. The imperfect accumulator studied herein has one or more misaligned rollers within the accumulator. The degree of misalignment is varied to understand the wrinkling mechanics of the web within the accumulator. The imperfections in the web are similar to that described in Case (3). Hence this case is a combination of Case (2) and Case (3) and thus constitutes the worst case scenario for a web and accumulator system.

3. FE MODEL RESULTS:

Case (1): Perfect web, Perfect accumulator

To facilitate easier analysis, MD web stresses along the length of the web are shown at the center line of the web in Figure 4. In this case, the tension increases from a nominal 0.75 N/cm in the entry span to about 0.92 N/cm at the exit span due to the bearing drag in the rollers of the accumulator and was expected.

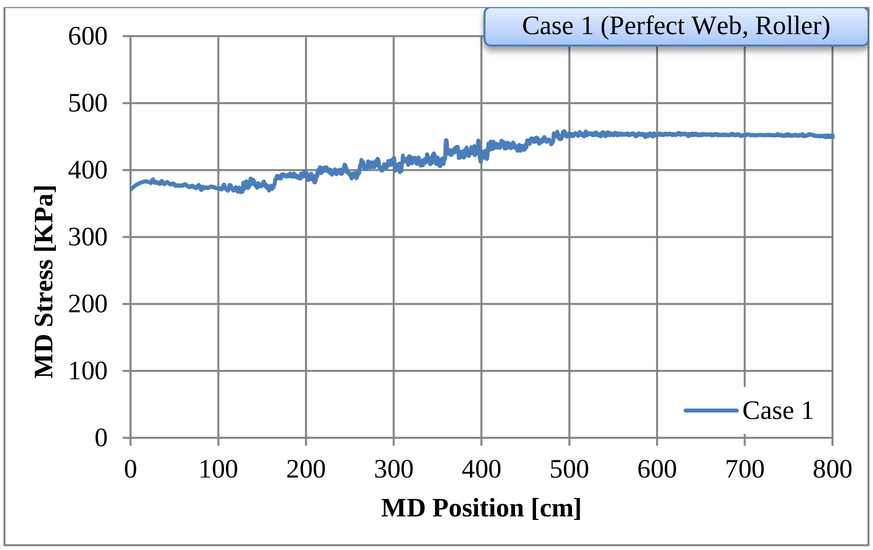

Figure 4: MD stresses in the web along its length at different CD locations for Case (1)

CD in-plane stresses at the entry of each roller in the accumulator are shown in Figure 5. The data indicates that the web is under compressive stress in each span. This is due to the Poisson contraction of the web in CD that arises from web tension. Critical stress to wrinkle as predicted by Good et al [13] that was derived from shell theory [14, 15] is shown in Equation 3. This value was calculated at 94 KPa. Note that the magnitude of the compressive stresses shown in the figure is very small and will not cause wrinkles since the stresses are significantly lower compared to 94KPa. The local minimum seen in Figure 5 at entry of Roller 1 is due to the long entry span prior to roller 1. This data is presented to illustrate the nature of the CD stresses in a perfect system thus serving as a bench mark for other cases presented henceforth.

$$\sigma_{ycr} = -\frac{h}{R} * \sqrt{\frac{E_x \ E_y}{3\left(1 - \nu_{xy}\nu_{yx}\right)}} \tag{3}$$

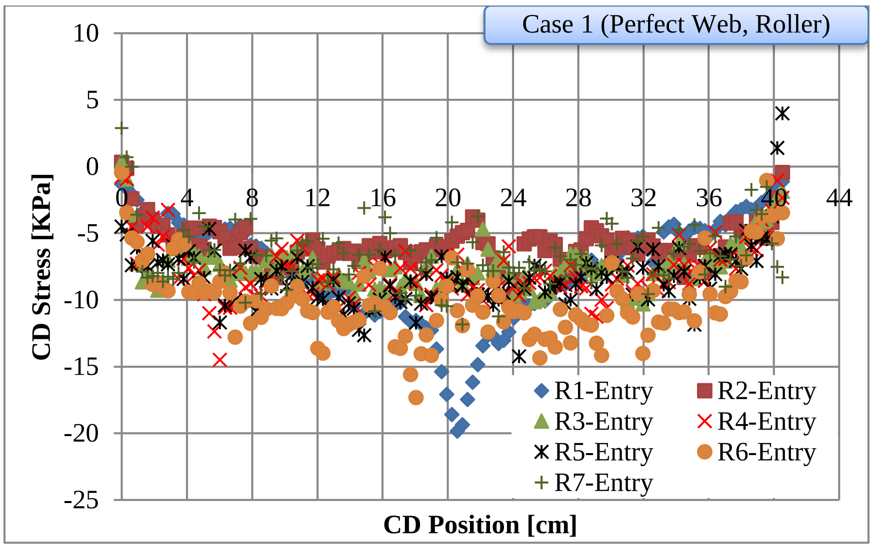

Figure 5: CD stress in the web at the entry of all rollers in the accumulator in Case (1)

Case (2) Perfect web, Imperfect accumulator:

MD web stresses for the operator side edge, center line of the web and drive side edge of the web are shown for the case wherein the rollers R2, R4 and R6 in the accumulator are misaligned in the z-direction at 0.7 degrees. The misalignment on the rollers cause the drive side of the rollers R2, R4, R6 to be closer to the fixed carriage rollers resulting in web slackness on that side. The effect of roller misalignment on the MD stresses is evident from Figure 6. In order to achieve normal entry as the web approaches each roller in the accumulator, the web bends and steers laterally towards the slack side. This causes an uneven stress distribution such that the operator side is the “tight side” and the drive side is the “slack side”. However the nominal average web stress remains similar to that shown in case (1). Note that the peaks in the figure occur where the web contacts a roller within the accumulator.

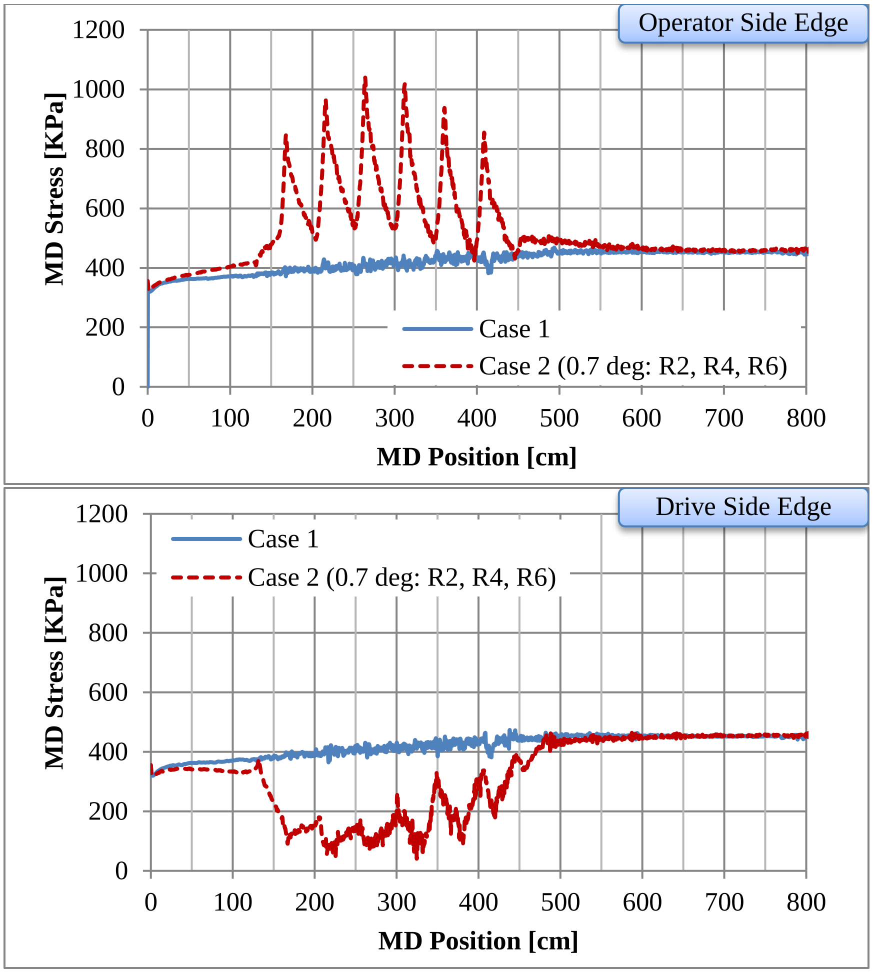

Figure 6: Comparison of MD stresses in the web along its length at different CD locations between Case (1) and Case (2)

CD stresses at entry of rollers R4 through R7 are shown in Figure 7 along with a contour plot of the stresses for rollers R1 through R7 for four different misalignment values. This figure indicates the CD stress behavior at one instance of time when the web has travelled a distance that is about 7.1 times width of the web. This is the last time step in the simulation. Four different values of 0.35, 0.45, 0.55 and 0.7 degrees were chosen to understand the level of misalignment needed to cause severe wrinkling in the accumulator. CD stresses for rollers R1 through R3 is not shown in the figure as wrinkles were not observed on these rollers for the levels of misalignment studied. For misalignment = 0.35 degrees, no wrinkles are formed. It is evident from the Figure 7[A] that the CD stresses are significantly higher than that predicted by Equation 3 at the entry of rollers R4-R6. For example, the minimum CD stress at R5 for case 2[a] is about 140 KPa as compared to the 94 KPa calculated using Equation 3.

When the misalignment is increased to 0.45 degrees, intermittent wrinkles appear sequentially from rollers R4 through R7 but disappear immediately as the web moves through the accumulator. In the last time step in the simulation, a wrinkle is formed on roller R7 as indicated by the circle in the contour plot in Figure 7[B]. CD stresses shown in Figure 7[B] indicate a minimum CD stress (maximum compressive CD stress) in the web at the entry of roller R7 as indicated by an arrow. This stress represents the magnitude of stress post the formation of the wrinkle. It is not the critical stress required to cause a wrinkle.

Similar trends are observed when the misalignment is increased to 0.55 degrees. However the intermittent wrinkles that appear on rollers R4-R7 stay for a longer time period (about 3 seconds) before disappearing. In the last time step, a wrinkle is present on roller R7 as indicated by the circle with a solid line. The CD stresses post wrinkle formation are smaller than that seen for the case of misalignment=0.45 degrees. Once the wrinkle forms, the instability is characterized by lowering of the CD stresses at the wrinkle site as well as the adjoining regions. For this misalignment, while a wrinkle is not seen on roller R6 at this time step, it does appear that the minimum CD stress at the entry of this roller is significant as indicated by the arrow in the graph and by a dotted circle in the contour plot as shown in Figure 7[C].

When the misalignment is further increased to 0.7 degrees, persistent wrinkles that "walk" from one side to the other form on rollers R4 through R6. The CD stresses at the entry of rollers R4-R6 are lower compared to that observed for the case of misalignment=0.55 degrees. Observe that a wrinkle is seen on each roller from R4 to R6 with two wrinkles seen on R7. As explained above, once the wrinkle forms, the instability is characterized by lower CD stresses around the wrinkle (Compare the magnitude of stresses at the entry of each roller in figures 7[C] and 7[D])

Individual Roller –vs- Accumulator Misalignment:

In order to further understand multi-span wrinkling, analyses were completed for a misalignment of 0.7 degrees in rollers as laid out in the following cases:

Case 2(e): Perfect web, only one misaligned roller (R2)
Case 2(f): Perfect web, rollers R2, R4 are misaligned
Case 2(d): Perfect web, rollers R2, R4, R6 are misaligned (shown in Figure 7[D])

CD stresses at the entry of rollers R4-R7 are shown in Figure 8 for the analyses described above. When only one roller is misaligned at 0.7 degrees, wrinkles do not form on any of the rollers (Case 2(e)). When two rollers are misaligned at 0.7 degrees, wrinkles are present on rollers R6, R7 at the last time step (Case 2(f)). At that same time step, in the case wherein all three accumulator top carriage rollers are misaligned at 0.7 degrees (R2, R4, R6) wrinkles are present on rollers R4-R7.

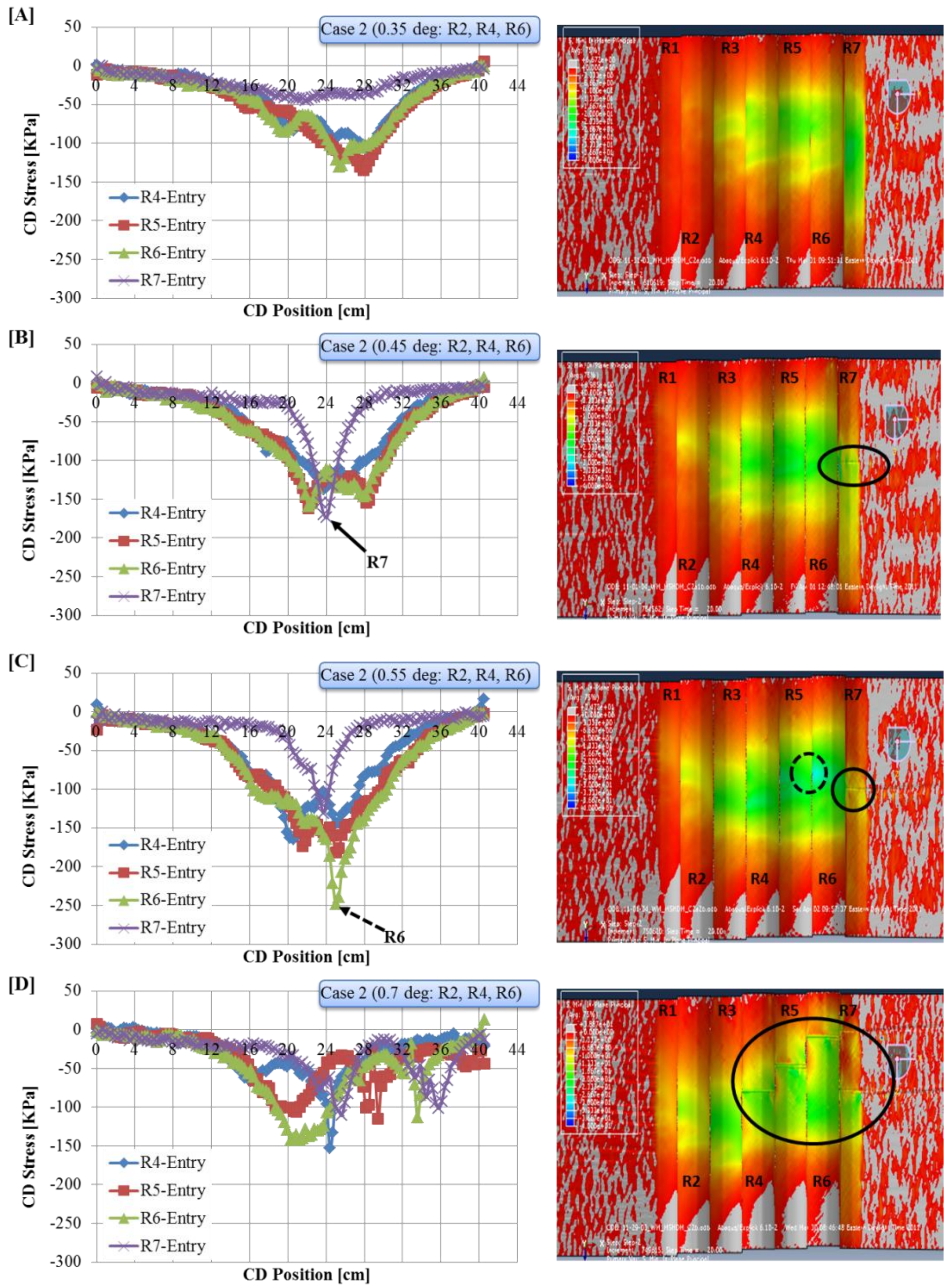

Figure 7: CD stresses in the web at the entry of rollers R4-R7 and contours of CD stresses in the web for rollers R1-R7.

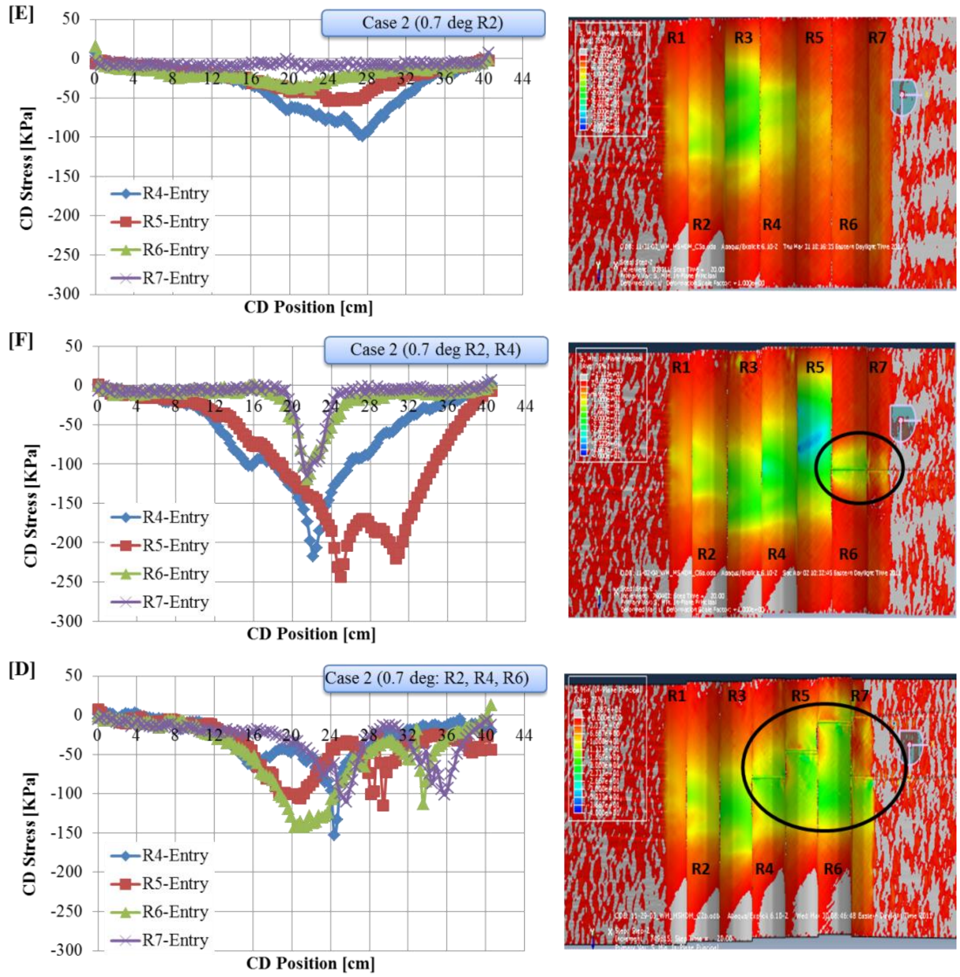

Figure 8: Comparison of CD stresses for cases wherein one, two or all three top carriage rollers are misaligned. [*Case 2(d) is included for comparison purposes and contains the same data as presented in Figure 7[D]*]

The behavior of minimum CD stress for wrinkle formation and post wrinkle formation is similar to that described in the preceding section. It is evident from the figure that for a given accumulator, roller misalignment required to produce severe wrinkling decreases with increase in number of rollers that are misaligned in the system. In the accumulator discussed herein, the web encounters a misaligned roller in both the entry and exit spans with misalignment in the same direction (see Figure 9 for visual interpretation) thus causing wrinkling behavior to get progressively worse. Hence the web steers continuously to only one side.

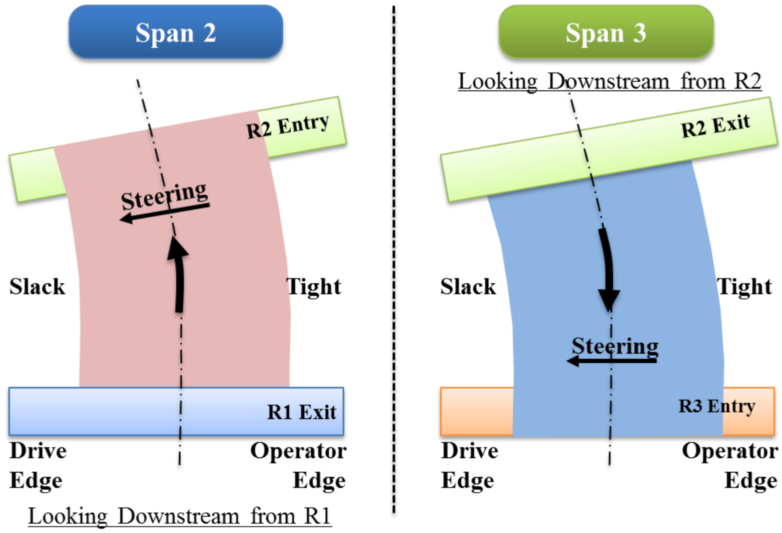

Figure 9: Schematic of web behavior in spans 2 and 3.

When one of the movable carriage rollers, namely R2, is misaligned, the web steers laterally towards the slack side to achieve normal entry into roller R2 as shown in Figure 10. (also schematically shown in Figure 9). Note that the analysis does not indicate that the overall steering at the exit of the accumulator has reached steady state. While the wrinkling mechanics of the web doesn't change, it is likely that the web will get steered to one side till equilibrium is reached. When two of the movable carriage rollers R2 and R4 are misaligned, the web steers significantly to slack side as compared with the case when only R2 is misaligned. Observe that the steerage of web is significant as it enters the misaligned rollers R2 and R4. However it is low as it exits roller R2 and moving toward roller R3 and also when it exits roller R4 and moving toward roller R5. When all three rollers R2, R4 and R6 in the movable carriage are misaligned, the overall steering is much higher than in the previous cases. The steerage of web is significant as it enters the misaligned rollers R2, R4 and R6 but low as it enters roller R3 and R5. The amount of steering within the accumulator thus describes the compounding effect of several misaligned rollers within the accumulator.

Case (2): Summary

The simulation results for case (2) indicate that a misalignment of about 0.7 degrees is needed to create continuously moving wrinkles ("walking wrinkles") on rollers R4 through R7. Also, the data indicates that a minimum of 0.45 degrees of misalignment is required to form wrinkles on any of the rollers.

Based on analyses of case (2), it can be summarized that:

- When the accumulator carriage is misaligned, Figures 7, 8 and 10 indicate that the level of misalignment required to cause a wrinkle/s is much less in an accumulator as compared to individual rollers.

- Hence more rollers within the accumulator will require more precision on alignment.
- The CD stresses in Figure 7, 8 indicate that Equation. 3 underestimates the critical CD stress required to cause wrinkles for the nonwoven web that was studied.
- If the movable carriage of the accumulator is misaligned, the web steers towards the slack side in each span causing an overall gross movement of the web material at the exit of the accumulator.

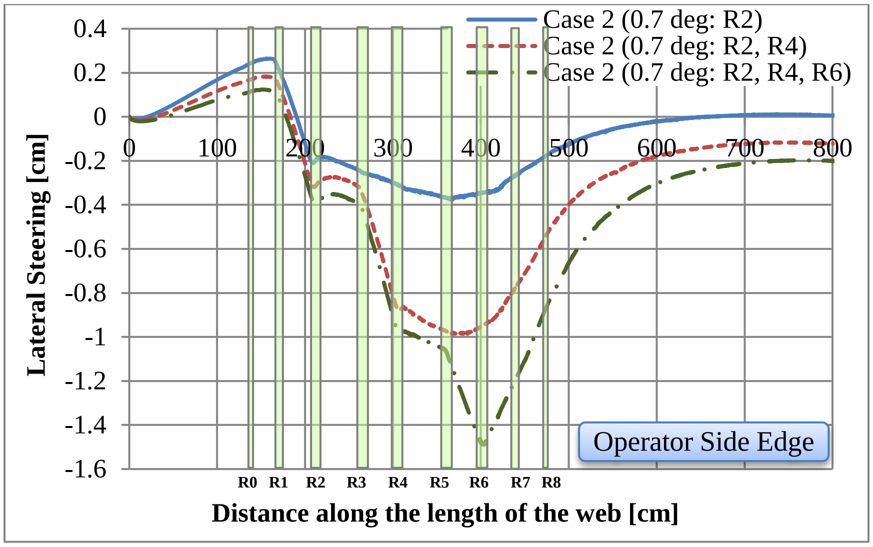

Figure 10: Comparison of lateral steering for cases wherein one, two or all three top carriage rollers are misaligned.

Case (3) Imperfect web, Perfect accumulator:

A web with a hole approaching a roller was presented by Good et al [13] using nonlinear finite element analysis. They showed that the CD compressive stresses in the web approach a minimum value on either side of the hole. This stress was shown to cause troughs on either side of the hole in the open span and wrinkles on the roller. In this research, web imperfections as shown in Figure 2 moving through an accumulator is studied. CD stress contours in the open span prior to web motion as well as at the last time step (7.1 times web width distance) within the accumulator are shown in Figure 11. Similar to that was observed by Good et al., troughs exist on either side of an imperfection. These imperfections also have two minimas for CD compressive stress on either side of the imperfection in the open span. As the web starts moving, the compressive stresses on either side of the imperfections increases as the imperfection nears the roller. When the critical buckling stress is reached wrinkles form on the roller.

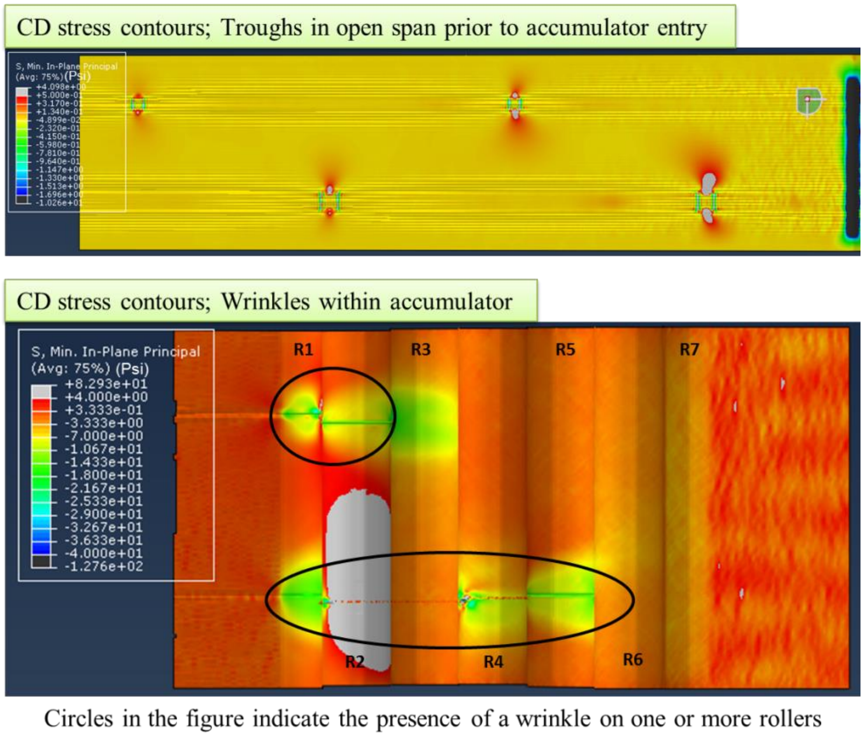

Figure 11: CD stresses due to web imperfections at the entry of rollers R1-R5.

CD stresses at the entry of each roller at the time step when the web has moved 7.1 times the width the web is shown in Figure 12. Wrinkles are present on rollers R0 (not shown in Figure 11), R1, R2, R4 and R5 as indicated by the minimum CD stress at each of these rollers. Note that the CD stresses are not substantial to produce a wrinkle on Roller R3 (Also, observe Figure 11 for contour plot). Note that the staggered arrangement of imperfections cause parallel wrinkles on rollers R1 and R2. Figures 11 and 12 indicate that an imperfect web can form wrinkles even if perfect alignment of rollers can be achieved within an accumulator.

Case 3: Summary

The following observations can be made based on the results presented in Case 3 for an imperfect web moving through a perfect accumulator:

- An imperfection in the web causes CD stresses to reach a minimum value on either side of the imperfection. This causes troughs to form that run parallel to MD on either side of the imperfection.
- As the imperfection nears a roller, the CD compressive stresses increase resulting in a wrinkle formation on the roller when the value reaches critical buckling stress.

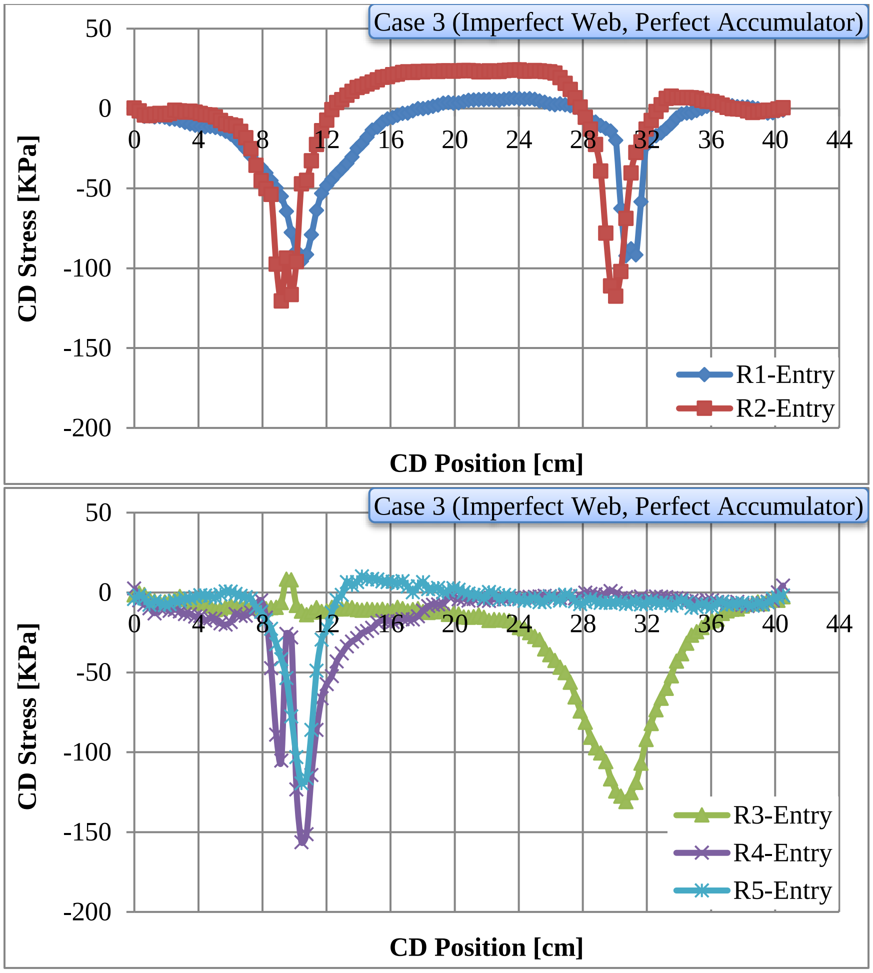

Figure 12: CD stresses due to web imperfections at the entry of rollers R1-R5.

Case (4) Imperfect web, Imperfect accumulator:

Data presented in Case (2) indicates that a minimum misalignment of 0.45 degrees on rollers R2, R4 and R6 is required to initiate wrinkles within the accumulator when the incoming web material has no imperfections. When an imperfect web enters a misaligned accumulator, data presented in Figure 13 indicates that a misalignment of 0.35 degrees is enough to cause significant wrinkling within the accumulator. A misalignment of 0.35 degrees on a 97.2 cm wide roller is equivalent to a distance of 0. 6 cm for vertical offset on one side. This data indicates that the misalignment required to cause severe wrinkling of webs in accumulators is much less when the incoming web has imperfections in the form of thickness variations or material property variations (not studied in this paper).

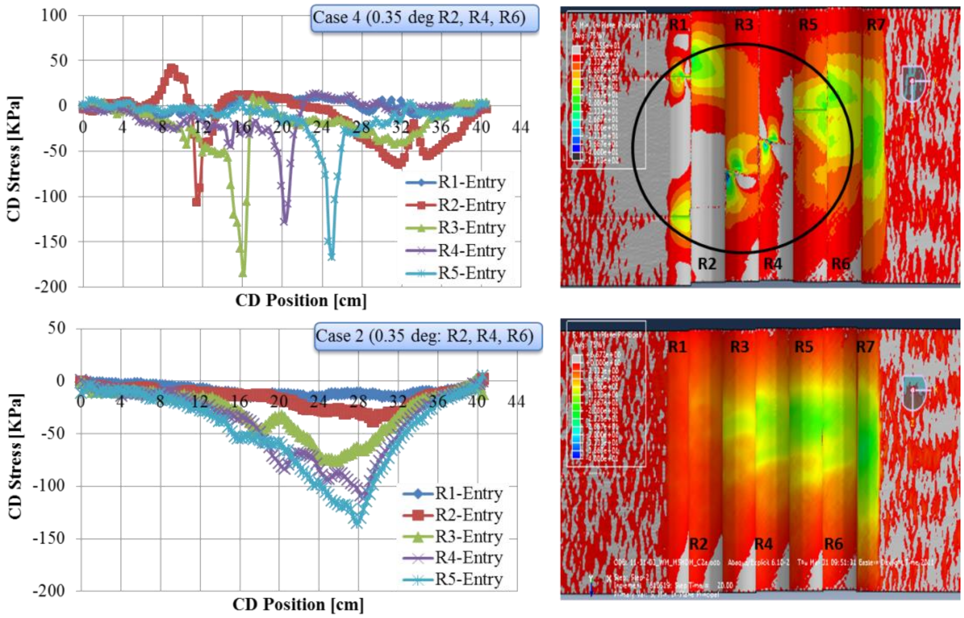

Figure 13: CD stresses due to web imperfections and misaligned rollers within accumulator.

Case 4: Summary

The following observations can be made based on the results presented in Case 4 for an imperfect web moving through an imperfect accumulator:

- A misalignment of 0.35 degrees is enough to cause severe wrinkling within the accumulator when the incoming web has imperfections in it.
- In case 2 (a), wrinkles were not observed for a misalignment of 0.35 degrees when the incoming web was perfect. A misalignment of 0.7 degrees was required to cause severe wrinkling within the accumulator in that case. However, when the incoming web is imperfect, severe wrinkling is observed within the accumulator at even 0.35 degrees of carriage misalignment as illustrated in Figure 13.
- Thus the data presented for Case 4 highlights the criticality of alignment when dealing with delicate nonwoven webs that are inherently non-homogenous and imperfect.

4. EXPERIMENTAL COMPARISON

Behavior of a light weight nonwoven SB web in an accumulator is described herein along with comparison between model results and experimental measurements.

4.1. Accumulator Set Up

A seven roller accumulator was designed for use on a pilot line with three rollers on the top representing the "moving carriage" rollers [1] and four rollers on the bottom representing the fixed position rollers with load cell feedback from the entrance and exit rollers. The rollers were 3.0" diameter aluminum dead shaft idlers. They were mounted on support rails that could be raised to different heights (four in this study) to achieve length to width ratios that ranged from 0.69 to 2.96. Experiments were completed at two different tension set points (0.44 N/cm, 0.75 N/cm) at four different heights as mentioned above. The framework was fabricated out of modular aluminum framework. Corner braces were installed to provide additional rigidity. The framework was attached to the floor at the four corners to insure it did not move during the trial. The four hard stops (see dotted circles in Figure 14) for the vertical adjustment were leveled to each other using a precision level. All of the rollers were then aligned using a precision level and machined blocks. The two load cell rollers were calibrated using standard weights.

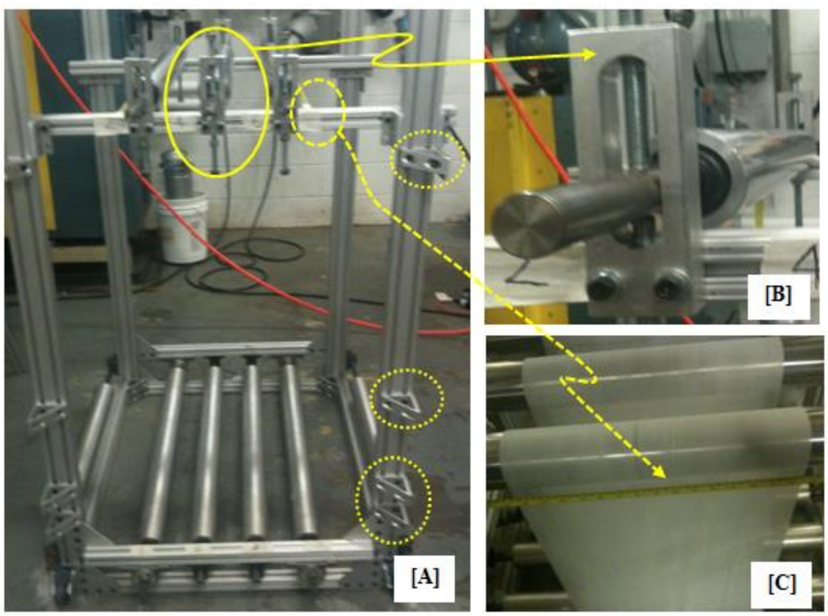

Figure 14: Accumulator Module

The top rollers were mounted in a bracket that allowed vertical adjustment at both ends as indicated by the solid circle in Figure 14[A] with the details indicated in Figure 14[B]. The thread pitch of the adjuster bolts and the number of turns were used to calculate individual roller misalignment during the study. Typically the adjustments were made on the front side by turning the hex bolts one half turn at a time (180 degrees) which was equivalent to a vertical motion of about 0.1 cm. Scales were mounted at the entrance and exit (as indicated by dashed circle in Figure 14[A] with details indicated in Figure 14[c]) to document the position of each edge and to calculate width loss and/or shift in web position after misalignment.

A driven unwind with an air loaded dancer was used to provide the nonwoven web at a target tension to the accumulator module. Web material that exits the accumulator is then wound into a roll form using a re-winder. Only new rolls of material were used for the all the studies described herein. While conducting the misalignment studies, the following trial sequence was used.

1. Set the height for the upper rollers for pre-determined span ratio
2. Check the alignment of each roller in the top carriage & realign if needed
3. Thread up web from unwind through the accumulator to the winder
4. Start the line up
5. Set line tension by adjusting air pressure on the dancer
6. Document line speed, tension at entrance and exit
7. Document width and position at the entrance and exit
8. Adjust the misalignment of the top rollers and allow the process to stabilize
9. Observe for troughs or wrinkles and document the location of troughs or wrinkles by span position
10. Identify the type of wrinkle as intermittent or frequent or intermittent walking or continuous walking wrinkle
11. Repeat steps for different span heights

The lightweight web that we used for the study was made previously on a pilot line. There was a significant amount of variability noted across the width and in the longitudinal direction. No effort was made to optimize formation or basis weight profile on purpose for the study.

4.2 Results & Discussion

Given a span height, when the misalignment was increased, wrinkles were observed first on the last carriage roller R6. When a continuously moving wrinkle (walking wrinkle) was seen on this roller, the condition is designated as “Onset”. With more misalignment we observed that continuous walking wrinkles formed on all the carriage rollers (R2, R4, R6). This was identified as “Complete” because all of the rollers had continuous wrinkles. Due to bearing drag, the tension at the exit of the accumulator increased compared to the entrance tension. For an average entry tension of 0.44 N/cm (“low tension”) and 0.76 N/cm (“high tension”), the average exit tension was about 0.57 N/cm and 0.88 N/cm respectively. This range of tension was selected based on common settings used in nonwoven converting processes. The average tension through the accumulator was about 0.51 N/cm and 0.81 N/cm for the low and high tension cases respectively. Thus the “high tension” case represents an increase of about 59% in average web tension from the “low tension” case. The amount of misalignment required to form wrinkles within the accumulator for the low and high tension cases are summarized in Table 3 for different span heights and graphically represented in Figure 15.

L/W	Misalignment [Degrees]			
	Onset (0.44 N/cm)	All Rollers (0.44 N/cm)	Onset (0.74 N/cm)	All Rollers (0.74 N/cm)
2.96	0.23	0.46	0.29	0.58
1.5	0.35	0.46	0.35	0.69
0.92	0.23	0.46	0.35	0.58
0.69	0.46	0.58		0.58
Average	**0.32**	**0.49**	**0.33**	**0.61**

Table 3: Summary of misalignment required to form wrinkles in accumulator

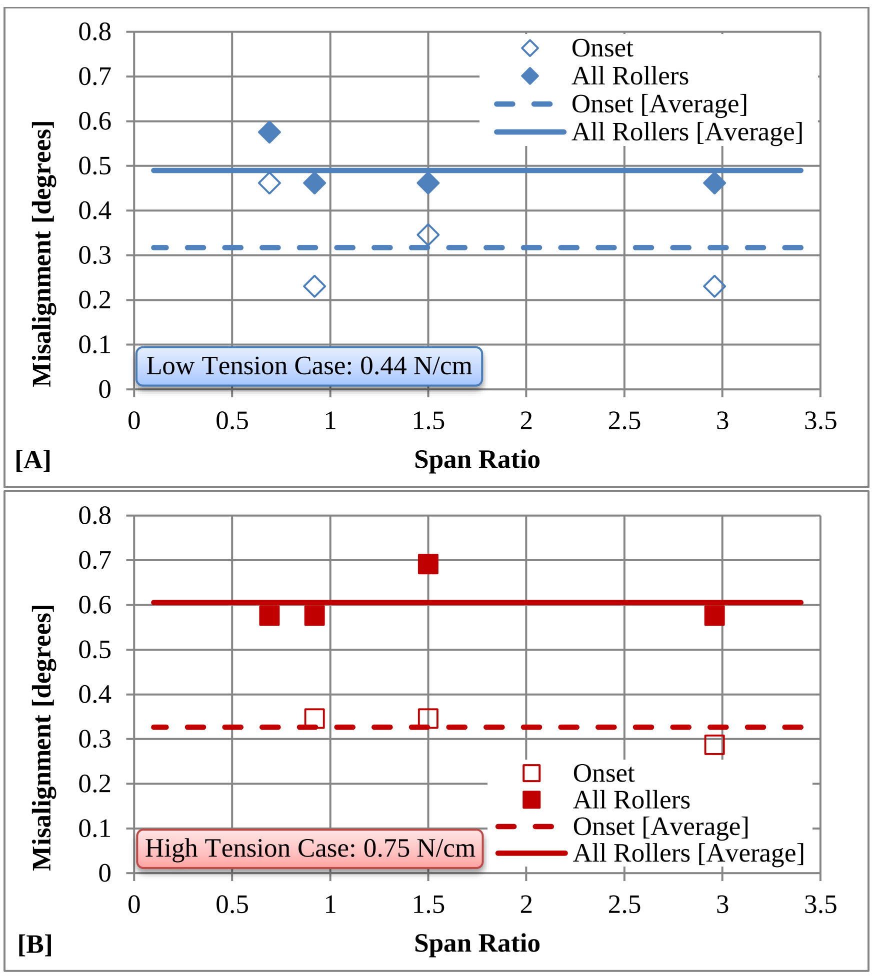

Figure 15: Misalignment needed to cause wrinkles within accumulator at different span heights and tensions

Based on the data shown in Figure 15, following general observations can be summarized:

- Misalignment of the top carriage rollers that is required to initiate wrinkles on one roller (last roller R6) is significantly lower than that is required to cause continuous walking wrinkles on all rollers.
- For both low and high tension cases, the misalignment required to initiate walking wrinkles on roller R6 ("Onset") is about 0.32 degrees.
- Misalignment required to cause continuous walking wrinkles on all the rollers increased to about 0.49 and 0.61 degrees for low and high tension cases respectively.
- This increase is considered small and hence the effect of web tension on critical misalignment required to form wrinkles in accumulator for the nonwoven studied is minimal.
- For the nonwoven web that was studied, the misalignment required to cause continuous wrinkles on all the spans is more or less independent of the span distance between the rollers.
    - This is inconsistent with observations made by previous researchers for single span roller misalignment for other nonwoven materials [13]. Good et al observed that the misalignment required to cause troughs in a single span for one misaligned roller as calculated using Equation 4 increased with increase in span ratio. In a separate study, Webb [16] showed that the misalignment required to cause wrinkles is two times that required to cause troughs thus following trough behavior.
    - The disagreement is likely because due to low friction coefficient between web and roller observed in the study.

$$\theta cr, \tau avg = \frac{6(5b^6E^2h^2 + a^4T(5bGh + 3T)(1+\emptyset) + a^2b^3Eh(25bGh + T(6\emptyset - 4)}{5G\left(5b^6E^2h^2 + 9a^4T^2(1+\emptyset)\right) + 2a^2b^3EhT(13+3\emptyset))}\sigma_{ex} \tag{4}$$

    - The difference in behavior is further illustrated in Figure 16. Data presented in Figure 16 illustrates that Equation 4 cannot be applied directly for calculating the critical misalignment required to cause wrinkles on all rollers within an accumulator.
    - Note that the wrinkle criterion calculated by multiplying Equation 4 by a factor of two compares well the experimental data for a single roller.
    - However this equation does not take into consideration the compounding effect of misalignment in multiple rollers thus over estimating the critical misalignment for accumulators.

Comparison of FE model to the experimental results is shown in Figure 17 and the associated data is shown in Table 4. Note that the model was completed only for the case of high web tension (0.74 N/cm) and a span height of 0.9. In addition, note that the model showed continuous walking wrinkles on rollers R3-R7 in the case of a perfect web moving through the accumulator while the experiments showed continuous walking wrinkles on roller R1-R7. The increase in misalignment needed to cause wrinkles on rollers R1-R7 compared to the misalignment needed to cause wrinkles on rollers R3-R7 was typically about one half to one full turn of the adjuster bolts in experiments. One half turn of the adjuster bolt is equivalent to a misalignment of 0.057 degrees. The nonwoven web used in this study was inherently inhomogeneous and imperfect. For the case of imperfect web moving through an accumulator model results indicate that even at 0.35 degrees of misalignment continuously walking wrinkles can be observed through most of the accumulator. Overall the experimental values fall between the model results for perfect and imperfect web scenarios analyzed thus giving credibility to the model results.

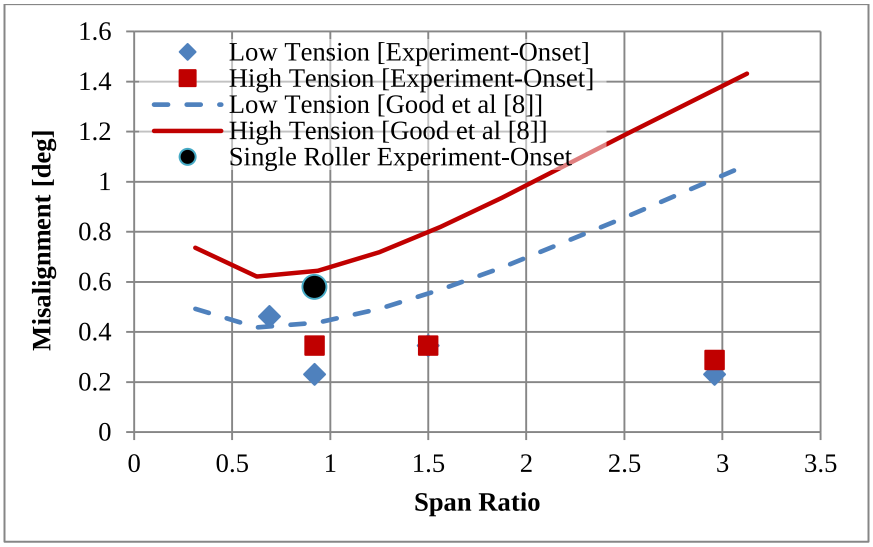

Figure 16: Misalignment needed to cause wrinkles within accumulator at different span heights and tensions

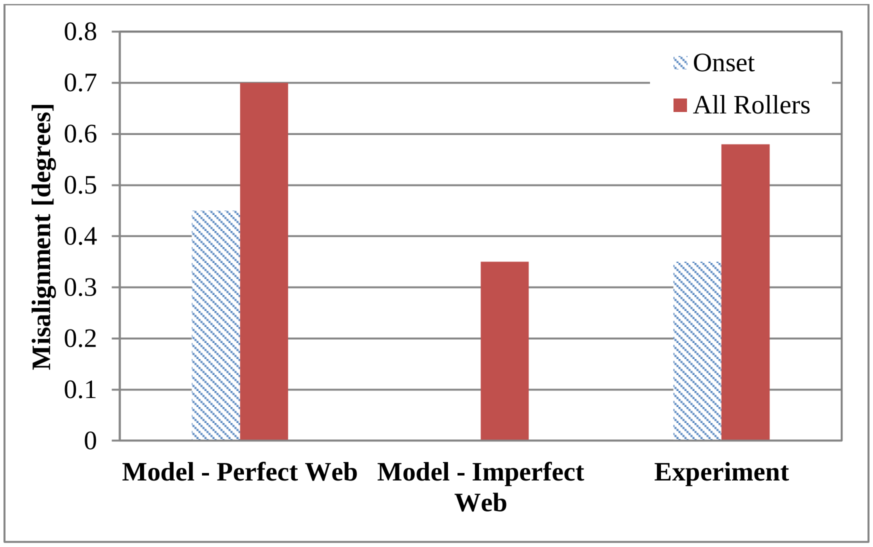

Figure 17: Misalignment needed to cause wrinkles within accumulator at different span heights and tensions

High Tension - 0.74 N/cm			
	L/W	**Onset**	**All Rollers**
Model – Perfect Web	0.9	0.45	0.7 (rollers R3-R7)
Model – Imperfect Web	0.9	N/A	0.35 (rollers R1-R5)
Experiment	0.92	0.35	0.58 (rollers R1-R7)

Table 4: Comparison of Model and Experimental results

Another experiment was conducted to understand the difference between one roller being misaligned as compared to all of the top rollers. The span height was set to provide a length to width ratio of 0.92. Tension was set to the previous high tension case of 0.74 N/cm. A single roller required 0.58 degrees of misalignment to initiate wrinkle within the accumulator. Recall that all three rollers only needed 0.35 degrees of misalignment to initiate a walking wrinkle (Figure 16 & 17). This experimental result points to the model results described previously. For the accumulator described in Michal [1, 2], practical experience indicates that severe wrinkling only requires 0.075 degrees of misalignment for an eight roller carriage arrangement for a similar nonwoven web. Figure 18 illustrates the impact of number of rollers on critical misalignment required to cause severe wrinkling within the accumulators. It appears that the critical misalignment required to cause severe wrinkling within the accumulator is inversely proportional to the number of rollers.

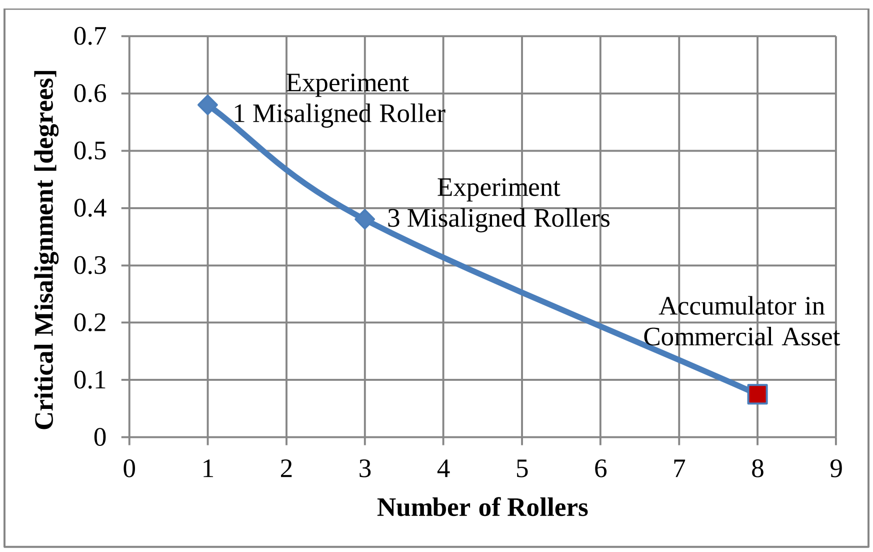

Figure 18: Critical misalignment needed to cause wrinkles within accumulator for different number of rollers

5. OVERALL SUMMARY

Based on the experimental results and finite element analyses presented in the study, overall observations and conclusions can be summarized as follows:

- Explicit finite element modeling is a powerful tool to better understand wrinkling mechanics for non-ideal webs and/or industrial accumulators.
- Wrinkles will first appear at the exit of an accumulator due to misalignment. More misalignment is required to form continuous wrinkles across all of the rollers within the accumulator.
- Existing closed form solution for a single roller in an open span over estimates the critical misalignment required to cause wrinkles in accumulators for delicate webs such as the nonwoven Spunbond web studied herein.
- Experimental results are in general agreement with FE model results. For the nonwoven web studied herein, the critical angle of carriage misalignment is independent of length / width span ratio.
- An imperfect web will wrinkle at smaller angles of carriage misalignment as compared to a perfect web.
- Accumulators require better alignment to avoid wrinkles as compared to a single misaligned roller. The required precision appears to be linear with the number of rollers within the accumulator.
- The critical angle for carriage misalignment appears to be inversely proportional to the number of rollers in the carriage for an imperfect nonwoven web.

6. FUTURE WORK FOR INDUSTRY NEEDS

The work described in this paper illustrates the impact of delicate webs and imperfect equipment on the convertibility of the material in commercial processes. Finite element modeling of the mechanics presented herein provides a glimpse of how powerful these tools are and what can be studied with them. However the work is very narrow in focus.

Delicate webs such as nonwovens can pose significant processing and converting challenges. Several areas need to be investigated including but not limited to the following:

- Understanding the fundamental mechanical behavior of these delicate nonwoven webs that are inherently inhomogeneous and imperfect
- Analytical solutions for multi-span, multi-roller imperfections
- Understanding the air/web dynamics within an accumulator and the impact of speed on the same
- Impact of basis weight and imperfect formation on web dynamics
- Understanding traction within accumulators; effect of roller COF, diameter, contact pressure and air lubrication at high speed

A combination of fundamental and applied research is needed to develop value priced robust solutions. Increase in price of oil emphasizes the need for lighter materials and higher converting/processing speeds. Higher operating speeds gravitate towards tighter processing window which in turn limits the capability to tolerate any web imperfections. Understanding the impact of the different variables on process capability for unwinds and accumulators is more critical than ever.

Open innovation is needed. Strategic partnerships between OEM's, research organizations and end use customers are desired to develop solutions that meet the needs of industry.

7. ACKNOWLEDGMENTS

The authors would like to thank Anthony Lamanac, Jodi Smith, Donovan Bowen and Charles Mull for their help to get the pilot line accumulator up and running. We would like to thank Eric Kepner, Joel Edwards, Sue Sudbeck, Charles Morell, and Bob Stargel at Kimberly-Clark Corporation for their support of open innovation at the Web Handling Research Center. We would like to thank Chris Pieper and Ted Tower in the Kimberly-Clark Corporation's modeling team for their help with Abaqus job management and input. Finally we would like to thank Dr. Keith Good, Dr. Prabhakar Pagilla, Dr. John Shelton, Bruce Feiertag, Ron Markum and Dr. Karl Reid at the Web Handling Research Center for the development of first order principles that have provided Kimberly-Clark a competitive advantage.

7. REFERENCES

1. N. J. Michal., "Web Tension in an Industrial Accumulator and Industry Needs for Future", Proceedings of the Tenth International Conference on Web Handling, Stillwater, Oklahoma, 2009.
2. N. J. Michal., "Practical Considerations for Zero Speed Splice Unwinds", Proceedings of the Second Applied Web Handling Conference, May 2008
3. D. R. Smith., "Roll and Web Defect Terminology", Second Edition, TAPPI Press, 2007.
4. J. J. Shelton., "Dynamics of a Web Accumulator," Proceedings of the Fifth International Conference on Web Handling, pp. 423-442, Stillwater, Oklahoma, 1999.
5. J. J. Shelton., "Improvement of Control of a Web Accumulator," Proceedings of the Tenth International Conference on Web Handling, Stillwater, Oklahoma, 2009.
6. P. R. Pagilla, E. O. King, L. H. Dreinhoefer, and S. S. Garimella., "Robust Observer-Based Control of an Aluminum Strip Processing Line", IEEE Transaction on Industry Applications, Vol. 36, No. 3, May/June 2000
7. P. R. Pagilla, E. O. King, L. H. Dreinhoefer, and S. S. Garimella., "Dynamics and Control of Accumulators in Continuous Strip Processing Lines", IAS Annual Conference Rome, 2000.
8. P. R. Pagilla, E. O. King, L. H. Dreinhoefer, and S. S. Garimella., "Dynamics and Control of Accumulators in Continuous Strip Processing Lines", Proceedings of the IEEE transactions on Industry Applications, Vol. 37, No. 3, May/June 2001
9. P. R. Pagilla, I. Singh, and R. V. Dwivedula., "A Study on Control of Accumulators in Web Processing Lines", ASME Journal of Dynamic Systems, Measurement, and Control September 2004, Vol. 126 / 453,

10. H. Koc, D. Knittel, M. de Mathelin, G. Abba, and C. Gauthier., “Web Tension Control in an Industrial Accumulator,’’ Proceedings of the Fifth International Conference on Web Handling, pp. 411-422, Stillwater, Oklahoma, 1999.
11. Dassault Systèmes Simulia Corporation., "ABAQUS 6.10 Documentation," 2010.
12. S. Cheng. and C. C. Cheng., "Relation between E, ν, G and Invariants of the Elastic Coefficients for an Orthotropic Body," The Winter Annual Meeting of the American Society of Mechanical Engineers, Dallas, Texas, Applied Mechanics Division and the Materials Division, ASME, vol. 112, pp. 63-65, 1990.
13. Good, J. K., Biesel, J. A., and Yurtcu, H, “Predicting Web Wrinkles on Rollers”, Proceedings of the Tenth International Conference on Web Handling, Web Handling Research Center, Stillwater, Oklahoma, 2009.
14. S. P. Timoshenko and S. K. Woinowsky., “Theory of Plates and Shells”, Second Edition, McGraw-Hill, 1959.
15. S. G. Lekhnitski., “Anisotropic Plates”, Gordon and Breach, 1968.
16. Webb, D. K., “Prediction of Web Wrinkles due to Misalignment of a Downstream Roll in a Web Span”, Master’s Thesis, Oklahoma State University, Dec 2004.