EXPLICIT SIMULATIONS OF WRINKLE FORMATION DUE TO WEB NON-UNIFORMITY

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ABSTRACT

It is very common to laminate different materials together and then form, transport and process a web with non-uniform structure in the product manufacturing industry. The periodic media analysis (PMA) method in Abaqus/Explicit [1] has been applied to simulate web wrinkle formation due to web non-uniformity during web transportation. This is a further application of previous PMA simulation models [5]. In this work, an experiment has been conducted to test a web structure including two materials with significant differences in terms of thickness and material properties running through rollers. Wrinkles have been observed during the experiment. Based upon the experimental setup, a web handling model is generated using the PMA method. This model can capture wrinkle formation due to web non-uniformity which agrees with experimental observation. The model and information provided by this model can be used to study wrinkle formation due to similar root causes and explore solutions to prevent wrinkles from occurring in future applications.

INTRODUCTION

Abaqus/Explicit [1] has become a popular analysis tool to model different types of web handling problems for industrial applications. In the last several International Web Handling Conferences, there were many papers about web handling simulations using Abaqus/Explicit [2]-[6]. A relatively new simulation technique, PMA in Abaqus/Explicit, has been introduced to simulate web instability during transportation in [5]. This simulation technique first came out in the Abaqus 2011 version. PMA is a Lagrangian technique that offers a Eulerian-like view into a moving structure [1]. It can be used to effectively model systems that are repetitive in nature, which makes it very suitable for web transportation simulations. PMA models were successfully developed to study moment transfer, wrinkle formation due to roller misalignment, and web instability due to web non-uniformity [5]. PMA does not require excessively large meshes that traditional web handling models use, which enables it to speed up computational time significantly.

The schematic plot in Figure 1 shows how a PMA model works. As shown in Figure 1, the web length is not critical as long as it can run through the rollers modeled. A trigger plane is required for the PMA model to activate a periodic media procedure as shown in Figure 1. The five blocks shown in Figure 1 run like a loop during simulation: Block 5 is moved to the upstream side and tied to Block 1 after Block 1 passes the trigger plane and then Block 4 then is moved from the downstream end to the upstream end and so on. Re-using elements that have left the process zone via this shuffling process eliminates the need for additional element representing the web on the upstream end that traditional web handling models required for purely Lagrangian simulations. There are some special boundary condition set-ups required for the PMA model [1] which will not be described and discussed in this work. If steady state cannot be achieved by a set simulation time, a longer simulation time can be applied without modifying the model's geometry. Because of this special feature, PMA web handling models will save computational time significantly compared to traditional web handling models. Since it allows the web to be considered infinitely long, PMA makes high speed web line simulations available. Another benefit of the PMA model is that without long entry, the web can enter testing spans with consistent conditions. It is very important to have consistent conditions to simulate web non-uniformity related issues. This topic has been discussed in [4][5]. In the PMA model, this is straight forward to control.

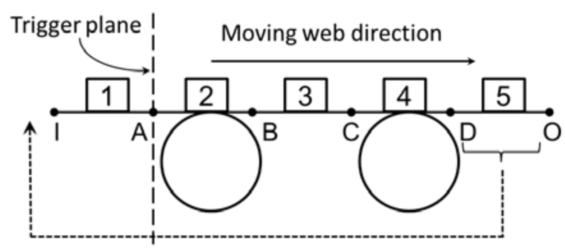


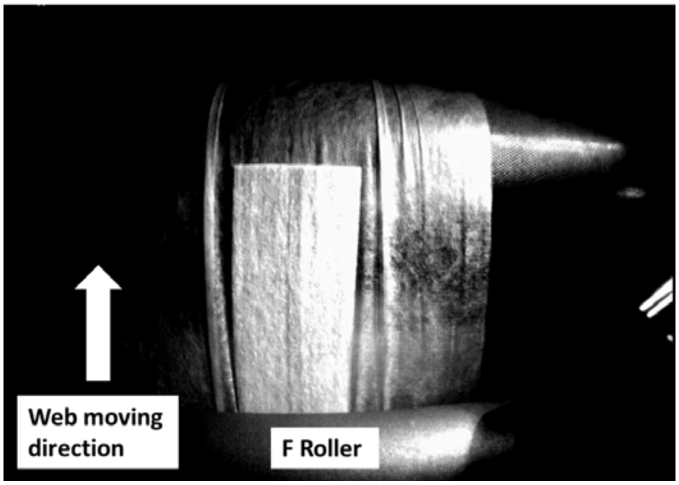
Figure 1 – Schematic Plots of PMA Web Handling Model

In web processing/converting, it is very common to laminate materials with significantly different material properties and/or geometry differences together to form a web and then transport and convert it to products. To handle this kind of non-uniform web can be very challenging due to more web instabilities introduced by non-uniformity of the web. Hence, wrinkles may have more potential to occur during converting of non-uniform webs. This work is a further application of PMA techniques: a PMA model is developed to simulate wrinkles due to web non-uniformity.

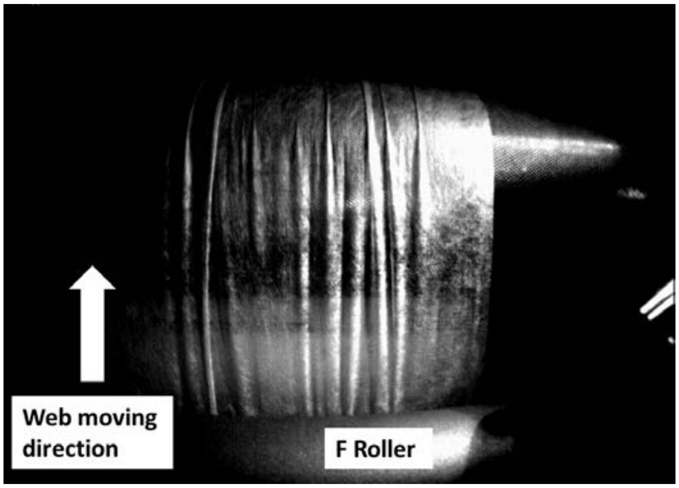
In following sections, a PMA model based upon experimental set-up will be described and validated. To explore causes of wrinkle formation, different parameters have been used to in the model to conduct a sensitivity study. Simulation results from these models will be discussed as well.

EXPERIMENT

This work will focus on studying a web that is made of a thin continuous web having discontinuous thick patches of a thicker, different material. The patches are attached in the center of the thin web along the cross machine direction (CMD); and along the machine direction (MD) they repeat periodically. After the patch is joined to the web material, the laminate is run through a series of rollers. Both of these materials are non-woven materials. The thick patch material is compressible in the thickness direction (ZD) which needs to be taken into account when modeling web instabilities. During the experiment, a high speed camera was installed to record the web movement at a designated location. Two snapshots, shown in Figures 2 (a) & (b), show wrinkles formed when the web passes the roller (it is named as "F Roller" in this experiment). A long span leads the laminated web into the F Roller and the thick patches contact the F Roller in this experiment. Web instability induced by the long span combined with a non-uniform web increases the potential for wrinkle formation. Due to space limitations, the high speed camera could not be set to record where the web enters the F Roller. The figures show the exit of the web from the F Roller, where wrinkles are still clearly observed. As shown in Figures 2 (a) & (b), wrinkles form near the boundary between the thicker patch and the thin web, and they propagate to the thin web after they occur.



(a)



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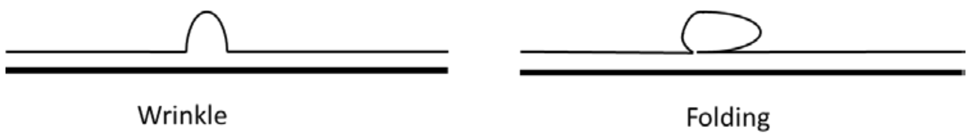


(c)

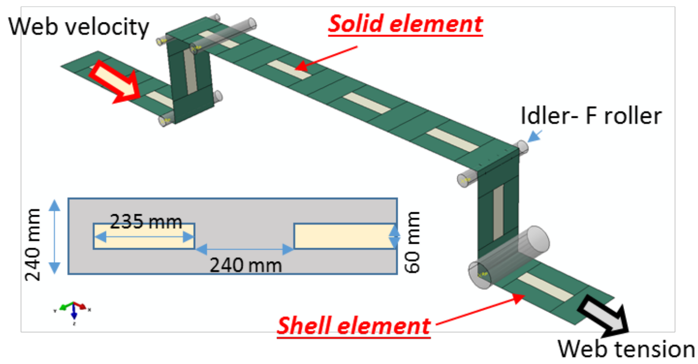
Figure 2 – (a) & (b): Wrinkle Formation Captured by High Speed Camera; (c) Schematic Plots of Wrinkle and Folding

It is worthy to note that throughout this work the word "wrinkle" is used to refer to not only deformations that follow the definition in [3], which is developed based on film, but also deformations traditionally referred to as "fold" which is not exactly the same as wrinkle in terms of its mechanical root cause. In [7], folding is defined as when the areas on either side of the buckled materials begin to contact and generate hollow channels beneath the surface plane of the materials. Schematic plots of wrinkle and folding are shown in Figure 2 (c). In [3], wrinkle is defined as a permanent deformation: it cannot recover. This definition of wrinkle is more applicable for materials such as film and metal sheets. Non-woven materials behave differently when wrinkles occur: web spreading equipment can still spread the web and eliminate wrinkles. Wrinkle is caused by high stress concentration induced by local buckling and the deformation is permanent. Folding may be different, and can be caused by structure buckling without really high stress concentrations. Different buckling behaviors are the result of differing material characteristics.

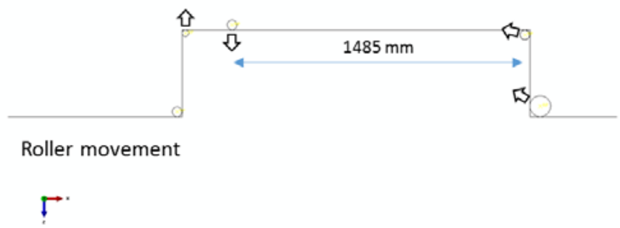
An Abaqus model using periodic media analysis will be generated based upon this experimental setup as shown in Figure 3 schematically and described in the next section.

FINITE ELEMENT MODEL

In this PMA model, blocks are used to generate the web model. Each block has a non-uniform structure: a central thicker patch is generated on the top of a thinner web, which means there are two layers of materials in the center of the laminated web. The thickness of the thin web is 0.09 mm and that of the thick patch is 1.7 mm. In each block, the dimensions of the thin web are 475 mm (MD) × 120 mm (CMD) and those of thick patch are 235 mm (MD) and 60 mm (CMD). The initial set-up of blocks is shown in Figure 3 (a). All of the blocks are connected together and form a continuous web. To avoid the complexity of creating blocks with flat and curvature regions, all blocks are originally identical, and the curvature regions wrapping on the rollers are not initially modeled. All the rollers are modeled using an analytical rigid and cylindrical shape, but the diameters are different. As a result, there are two steps in this simulation: simulation times are 0.6s and 4s for 1^{st} and 2^{nd} steps respectively. The web model consists of nine blocks, but curvature parts are not included in the initial set-up as shown in Figure 3 (a). In Step 1, four rollers (the roller at the upstream end does not move) will be moved into expected positions (directions shown as arrows in Figure 3 (b)) to match the web span lengths to experimental settings. In addition to that, a 21 N tension is applied to the outlet control point based upon the test settings. To move the web, a velocity of 1.28 m/s is applied to the inlet control point. Since there are not any rate dependent properties or boundary conditions, web velocity is used only to move the web forward. Web tension and contact force will deform the blocks to form the curvature shape wrapping on the rollers. Figure 3 (c) shows the set-up after pre-stretch, after the rollers are moved into expected positions and after applying web tension. Periodic media analysis stays inactive through Step 1. In Step 2, the periodic media analysis will be activated and the web starts moving along the direction shown in Figure 3 (a). General contact is used for interaction between the web and the rollers: the friction coefficient between the web and rollers is set to 0.4.



(a)



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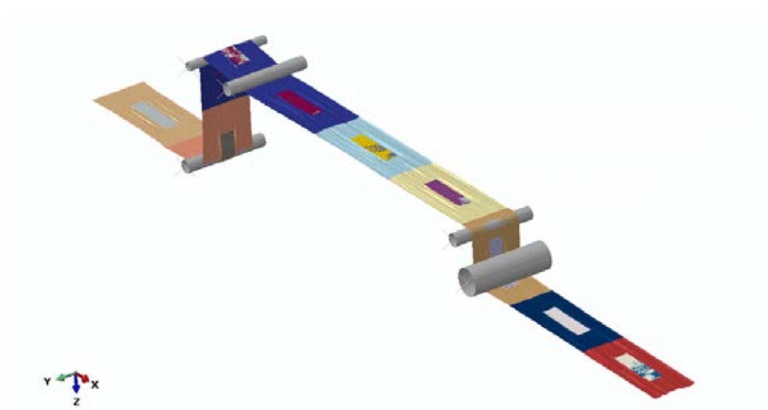


(c)

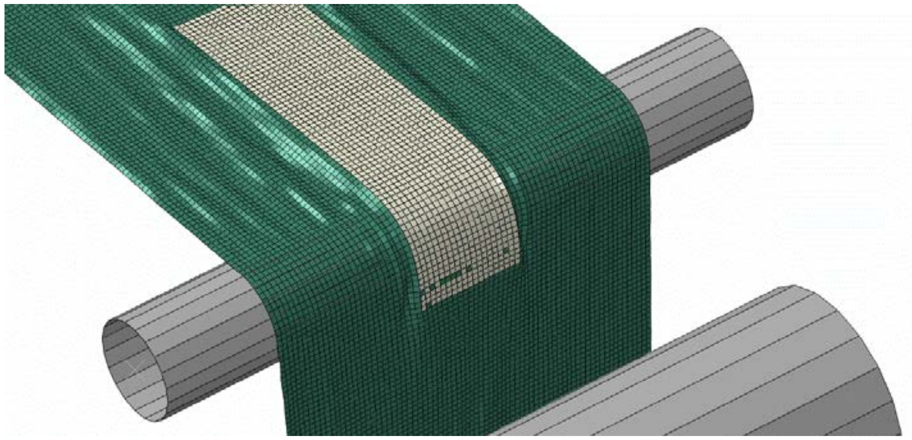
Figure 3 – Explicit PMA Model of a Web Transiting Four Rollers: (a) PMA Model Set-up Step 1; (b) Roller Movements in Step 1; (c) PMA Model Set-up after Step 1.

As mentioned in the previous section, both materials are non-woven materials. Web handling models using non-woven properties are not yet fully developed. The major issue is that constitutive relationships developed in continuum mechanics may not be fully applicable for non-woven materials. In this work, an orthotropic linear elastic material model is used to describe the materials. The assumption is that the strain induced by web tension is still within the linear region. For the thin web in this study, Young's moduli and Poisson's ratio are: $E_{MD} = 30.3\ MPa$, $E_{CD} = 3.3\ MPa$ and $\nu_{MD} = 2.8$. Shell elements are used to model the thin web. For the thick patch, Young's moduli and Poisson's ratio are: $E_{MD} = 13.3\ MPa$, $E_{CD} = 10.3\ MPa$, $E_{ZD} = 0.5\ MPa$ and $\nu_{MD} = 1.0$. Solid elements are used to model the thick patch. It is worth noting that solid elements can be compressed along the ZD direction. Since the thick patches are 1.7 mm thick, they will be compressed and deformed when they contact any rollers. This is considered important to understanding the cause of wrinkle formation. In the experiment, wrinkle formation was observed to occur on F Roller as shown in Figure 2. The location of this roller is shown in Figure 3 (a). The F Roller radius is 27 mm. The element size used in this model is 3.15 mm × 3.15 mm. This model was generated using Abaqus/Explicit 2016 and was parallel process using 24 CPUs.

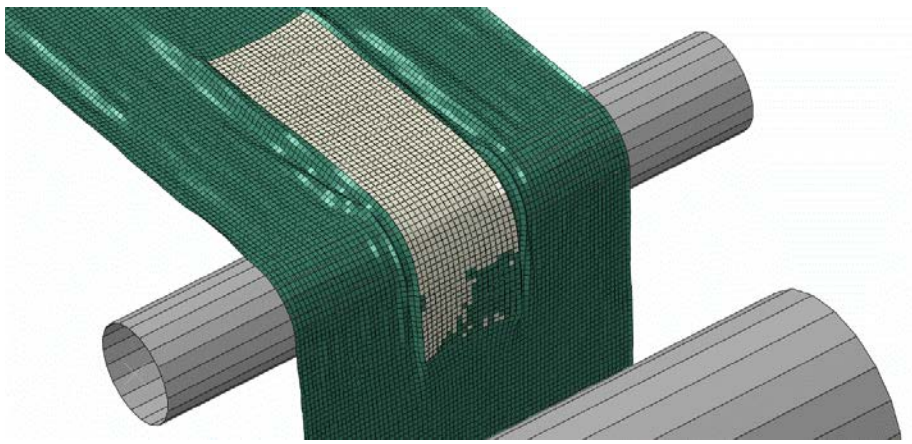
SIMULATION RESULTS AND DISCUSSIONS

A few snapshots at different simulation times are shown in Figure 4. Wrinkles do not occur at the beginning of the simulation as shown in Figures 4 (a) to (c), however troughs in the web span are clearly indicated in these figures. Particularly, Figure 4 (b) shows really severe troughs which almost convert to wrinkles but have been flattened out temporarily. At later time (Figure 4 (c)) no wrinkles are seen. Wrinkles occur in Figures 4 (d) and (e) and once wrinkles on the roller occur, they cannot be flattened out in the future. These results imply that wrinkle formation takes time to develop in the simulation. Troughs caused by web non-uniformities cannot be avoided but the frictional force on the F Roller battles against them and tries to prevent wrinkle generation. Due to the periodic configuration of the thick patches, disturbances from these patches keep coming when they pass the rollers. Eventually frictional force is not enough to overcome the disturbances and wrinkles occur.

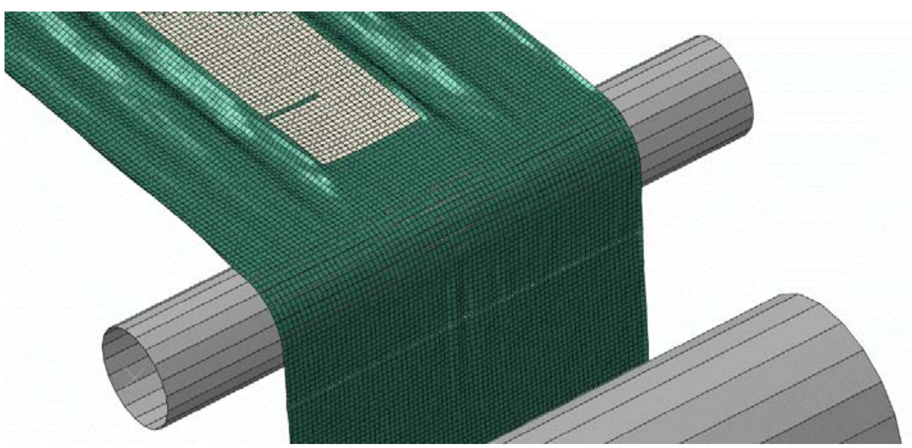
As mentioned in the Experiment section, more studies may be needed to study wrinkles on nonwoven materials. Figure 4 (b) shows clear buckling of the thin web on the F Roller, but there is no folding over of the web until later in the simulation as shown in Figures (d) and (e). Frictional force causes wrinkle formation, but characteristics of non-woven materials may change the way the web buckles.



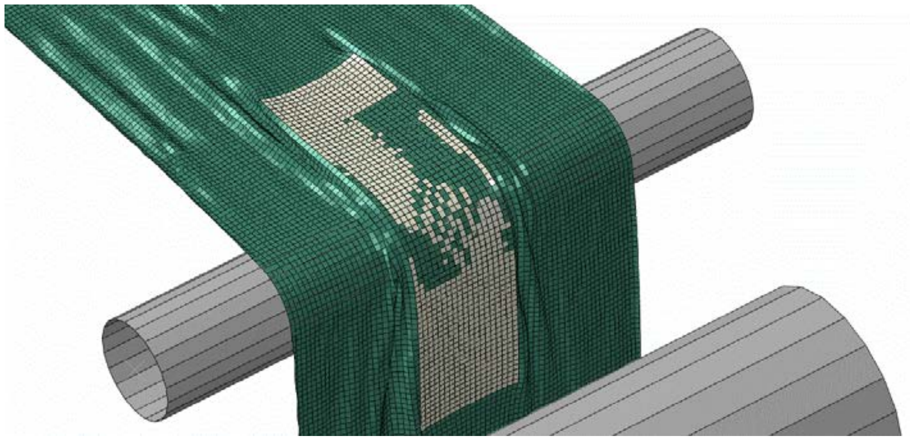
(a) Total Simulation Time = 1.1s



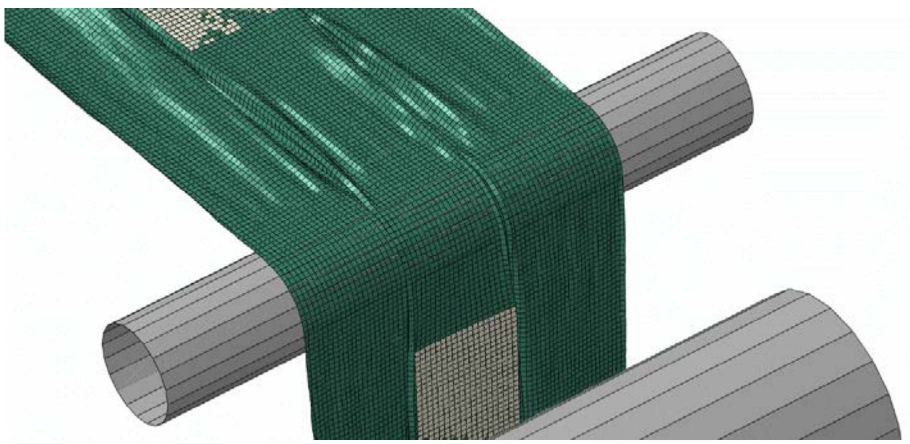
(b) Total Simulation Time = 2.6s



(c) Total Simulation Time = 3.6s

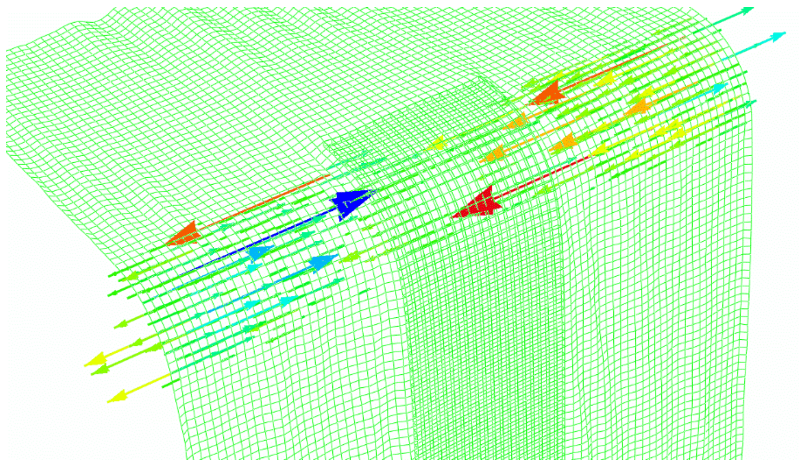


(d) Total Simulation Time = 4.1s

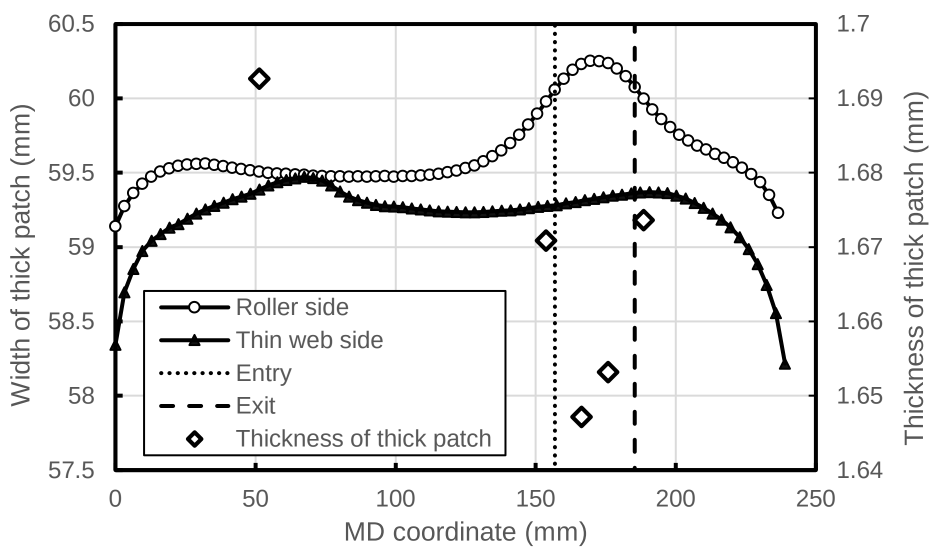


(e) Total Simulation Time = 4.6s

Figure 4 – Deformation of Web on F Roller at Different Simulation Time



(a)



(b)

Figure 5 – (a) CSHEAR 2 (CMD) Distribution; (b) Thick Patch Width and Thickness

Figure 5 (a) shows CSHEAR along the CMD direction. CSHEAR 2 is the simulation output of contact shear force. The arrows in this figure indicate the direction of force and the size of arrows imply the magnitude of force. This is a snapshot from a moment when wrinkles have not been fully developed yet. The CSHEAR forces near the boundary between the thick patch and the thin web are towards the inside, which indicates the tendency to buckle the web. Figure 5 (b) shows thick path width and thickness at the same moment as Figure 5 (a). Since solid elements are used to model the thick patches, the width is measured on both sides of each thick patch: Roller side (bottom) means the side of the thick patch contacting the F Roller and Thin web side (top) means the side of the thick patch laminated to the thin web. Entry and Exit indicate where the thick patch enters and exits the F Roller. Thicknesses from different locations on the thick patch, scaled using the axis on the right hand side, are also shown in Figure 5 (b). It appears the side that contacts the roller has a wider width than the original width 60 mm, but the opposite side has a narrower width. This implies the thick patch is under a bending moment, which could be caused by a combination of pressure induced by web tension and frictional forces from contacts between the thin web, the thick patch, and the roller. CSHEAR forces in Figure 5 (a) show compression of the web along the CMD, and these compressive forces generated on the thin web are transmitted to the top side of the thick patch. Thicknesses shown in the figure indicate that the thick patch is compressed when it contacts the roller. Due to compression of the thick patch, it expands along CMD, which explains why the width of the thick patch increases on the side contacting the roller. Width increase is also impacted by Poisson's ratio. Overall, the use of compressive solid elements to model the thick patches is very important for the capability of this simulation in predicting and analyzing wrinkle formation.

Tension was measured during the experiment, and about 21 N. Tension was used as an input condition as shown in Figure 3. Figure 6 shows the reaction force along the MD on the F Roller from the simulation and the load cell reading. It can be seen that the reaction force has an average value of about 21 N but oscillates more than what is seen in experimental measurements. This can be partially caused by numerical errors of the explicit method. It can be also induced by the periodic thick patches entering the F Roller and generating instabilities. The model may not be able to dampen all these instabilities as the web does in reality. In this case, steady state may never be able to be reached due to web non-uniformity in the simulation.

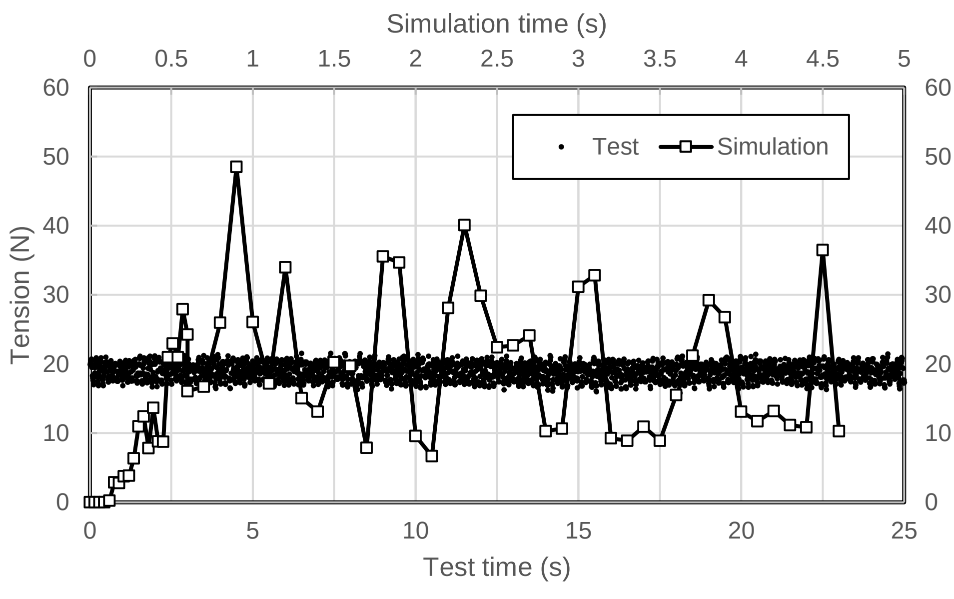


Figure 6 – MD Reaction Force from Simulation and Measured Web Tension from Test

Timoshenko's shell buckling theory [8] has been used to study wrinkle failure [3] for films. To capture wrinkles in the model, it is important to have a fine enough mesh so that equation {1} can be used.

$$\lambda = 3.44 \cdot \sqrt{Rt} \qquad \{1\}$$

The radius of F Roller is 27 mm and the thickness of the thin web is 0.09 mm. The calculated wavelength is about 5.36 mm. The mesh size is 3.15 mm which should be considered slightly coarse to generate wrinkles. However, wrinkles can still be simulated in this model. This behavior should be considered as in between wrinkling and folding. Figure 2 also shows this phenomenon. This may be due to non-uniform structure and non-woven material properties. It can be argued that wrinkle failure theory developed in [3] may not be able to accurately explain wrinkles of non-woven materials. Essentially, a non-woven material is a structure consisting of fibers, which may lead to a different definition of wrinkle failure. Based upon observation of non-woven processing, wrinkles that occur on non-woven materials tend to be a hybrid of wrinkle and folding which may not be permanent either. This area is definitely worth further study.

The buckling of the web is caused by the combined effect of web non-uniformity and frictional force. A sensitivity study has been conducted to understand effects of the different parameters. All the parameters are shown in Table 1, which also includes whether a wrinkle is generated or not. The first row contains parameters used in the model discussed in previous sections.

	COF-F Roller	**COF-else**	**Thin web thickness (mm)**	**Thin web Poisson's ratio**	**Thick patch Poisson's ratio**	**Wrinkle**
1	_0.4_	_0.4_	_0.09_	_2.8_	_1_	_Yes_
2	0.4	0.4	0.1	2.8	1	No
3	0.4	0.2	0.09	2.8	1	Yes
4	0.3	0.2	0.09	2.8	1	No
5	0.35	0.2	0.09	2.8	1	Yes
6	0.34	0.2	0.09	2.8	1	Yes
7	0.33	0.2	0.09	2.8	1	Yes
8	0.33	0.2	0.09	1.8	1	No
9	0.34	0.2	0.09	1.8	1	No
10	0.4	0.2	0.09	1.8	1	No
11	0.4	0.2	0.09	1.8	0.9	No
12	0.4	0.2	0.09	1.8	0.85	Yes

Table 1 – Parameters Used in Sensitivity Study

In the first attempt (Case 2), the thickness of the thin web was increased from 0.09 mm to 0.1 mm, and all other parameters were held constant. In this simulation, wrinkles did not occur even though clear troughs were generated near the entry to the F Roller. Apparently, a laminated web's tendency to wrinkle is very sensitive to thickness differences between components of the laminates. In the rest of the cases, the thickness of the thin web was maintained at 0.09 mm while other parameters were changed. In Case 3, the friction coefficient on all the rollers was changed to 0.2, except for the F Roller. Wrinkles were still generated in this case. This implies that the friction coefficient on other rollers was not critical to wrinkle formation. As mentioned earlier, the long web span between the F Roller and the upstream roller can generate more dynamic effects which induce more web instabilities. This is the reason why wrinkles are only observed on F Roller during experiments. Since the friction coefficient on other rollers does not impact wrinkle much, it was kept at 0.2 in the rest of the cases. Cases 4 to 7 were used to study friction coefficient on the F Roller. First, friction coefficient was reduced to 0.3 on F Roller. The simulation did not show any wrinkle formation. Then friction coefficients 0.35, 0.34 and 0.33 were applied on the F Roller in the next three cases respectively. These three cases all showed wrinkles formed. This indicates that a higher friction coefficient is another key cause of wrinkles, in addition to structural non-uniformity. Beyond thickness differences, material properties can influence wrinkle generation as well. To study this, Cases 8 and 9 had a lower Poisson's ratio for the thin web (1.8 compared to 2.8 used in previous cases). Parameters in Cases 8 and 9 are the same as those in Cases 6 and 7, except for the Poisson's ratio of the thin web. It turns out that wrinkles did not occur in Cases 8 and 9. A higher friction coefficient 0.4 was used in Case 10, and no wrinkle was seen. Lower Poisson's ratios for the material used for the thick patch were tested in Cases 11 and 12. Wrinkles regenerated when the Poisson's ratio of the thick patch material was lowered to 0.85 (Case 12). It appears that the difference in Poisson's ratio between the thin web and the thick patch is another important factor in web wrinkling: the bigger difference is, the more potential to form wrinkles. An explanation of this is that two materials laminated together that have different Poisson's ratios neck differently under the same tension. In this model setup, the patch in the center is much thicker, and also having a lower Poisson's ratio resists compression along the CMD caused by necking of the thin web. When this resistance is large enough, it will cause wrinkles along the boundary between the thin web and the thick patch.

In reality, there might not be flexibility to use materials which have characteristics to resist wrinkles for certain processing and converting procedures. However, learning from these or similar models can be used to pre-check or troubleshoot web wrinkle issues. Wrinkle reducing equipment or different web paths can be possible solutions to eliminate wrinkles, which all can be simulated using models before actual trials to save time and cost.

CONCLUSIONS

- Simulation models can capture wrinkle formation due to web structure non-uniformity. Mechanical root causes of wrinkles on non-woven materials may not be the same as those on film/metal webs. It appears that "wrinkles" on non-woven materials are a combination of wrinkle and folding. More studies in this area should be conducted to explore further.
- Solid elements are used to model the thick patch and enable ZD compression which turns out to be a very important influence on web buckling. Shell elements are used to model thin web.
- The friction coefficient is a key factor affecting wrinkle formation: wrinkles occur within higher friction coefficients.
- Wrinkles are sensitive to thickness non-uniformity: non-uniform webs lead to higher likelihood of wrinkles.
- The difference of Poisson's ratio between thin web and thick patch affects wrinkle formation: a greater difference intends to generate more wrinkles.

ACKNOWLEDGEMENTS

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