Failure is Good:

Perforation Patterns and Stretchy Paper Towels

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***Abstract**: Engineering analyses are often targeted to help design parts and systems that provide a margin of safety against failure. More sophisticated models that include plasticity, damage, and failure help the analyst assess the part or system's ability to continue to serve its intended function safely in a partially-damaged state. However, at Kimberly-Clark we like failure—specifically when consumers are tearing a paper towel off the roll (known as "dispensing" in the parlance of consumer packaged goods). By utilizing Abaqus, the essential roles the mechanical behavior (including failure) of the towel and the perforation pattern have in dispensing has become clearer.*

In 2014, Kimberly-Clark launched a new, stretchable paper towel, VIVA® Vantage® (denoted Vantage). Vantage towels are unique in that they can stretch about four times further than other paper towels before tearing. To explore dispensing performance, the towels were modeled with a neo-Hookean hyperelastic model combined with a plasticity model, damage initiation criteria, and a damage evolution rule. New mechanical tests were developed to calibrate the material model. Perforation patterns were parameterized to investigate the interplay of the mechanical properties and the perforation pattern. Both the material calibration process and the perforation pattern analysis were accelerated through programmatically generating models through the Abaqus Python API. Developing the method for simulating VIVA Vantage dispensing performance provided additional value for the corporation after other paper towel and bath tissue product teams integrated modeling into their workflow.

***Keywords**: Damage, Failure, Mechanical Testing, Material Modeling, Scripting.*

1. Introduction

Consumer packaged goods companies that supply rolled products (such as toilet paper and paper towels) face a challenge in creating an experience for the consumer that effortlessly delivers a practical amount of product. The experience is called dispensing, and it is critical to "get it right". Getting it right means deliberately weakening the product to identify *sheets* that are torn off the roll (Figure 1). The weak regions are called *perforations* and the size and spacing between perforations is the *perforation pattern*. If the perforation pattern does not sufficiently concentrate stress, a product will tear somewhere other than the perforations or the tear may propagate away from the perforations. If the perforation pattern concentrates stress too effectively, tears may happen in unintended locations (such as intending to pull off multiple sheets but only dispensing a single sheet). Clearly, good dispensing will delight the consumer.

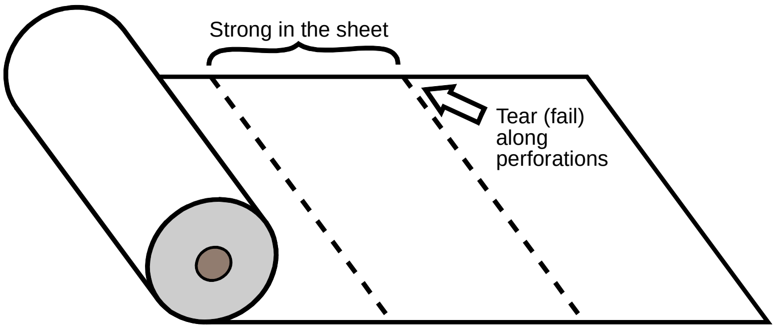

Figure 1: Rolled products are separated into sheets by providing lines of intermittent cuts called perforations.

In 2014, Kimberly-Clark launched a new paper towel, the VIVA Vantage® (simply denoted "Vantage" in the report). Vantage is a unique product because of its ability to stretch further than many paper towels (3-4 times the permanent strain before failure). The large permanent strain enables the towel to absorb more energy before tearing (the "toughness" of the sheet). The product development engineers at Kimberly-Clark recognized the high toughness of the product would require a different type of perforation than previous products. The product development team reached out to the Corporate Research and Engineering Modeling Team to answer the question: "How can we design the perforation pattern so the Vantage towels dispense along the perforations?"

To address this particular question through finite element analysis, it was essential to deliberately and accurately model the material. Since the model evaluated dispensing, a damage/failure model was necessary. Since the question entailed evaluating the possibility of a solution, it was essential to allow rapid iteration through perforation patterns, so the model was parameterized using the Abaqus Scripting Interface and other Python scripts.

2. Material Characterization

Consider a consumer pulling a paper towel off the roll by pulling from one side to the other. The bonds "pop" neatly one at a time as the tear propagates from one side of the towel to the other (Figure 2). From this thought experiment it is clear the model of the material behavior must capture four different phenomena: the loading behavior, the unloading behavior, plastic strain accumulation, and the failure of the material. The loading behavior is required because dispensing is primarily applied tensile load. The unloading and plastic behavior are important to understand stress redistribution as bonds pop. Finally, the damage and failure behavior are required to understand bonds weakening and popping. All of these behaviors can be observed from two tests: a cyclic tensile test and a modified trapezoid tear test (ASTM, 2015).

2.1 Cyclic Tensile Test

The cyclic tensile test was conducted on a rectangular test specimen without perforations with a 3:5 aspect ratio. The specimen was pulled to 5% engineering strain and then returned to the initial position in the first cycle. In each successive cycle it was pulled 5% strain further (Figure 3).

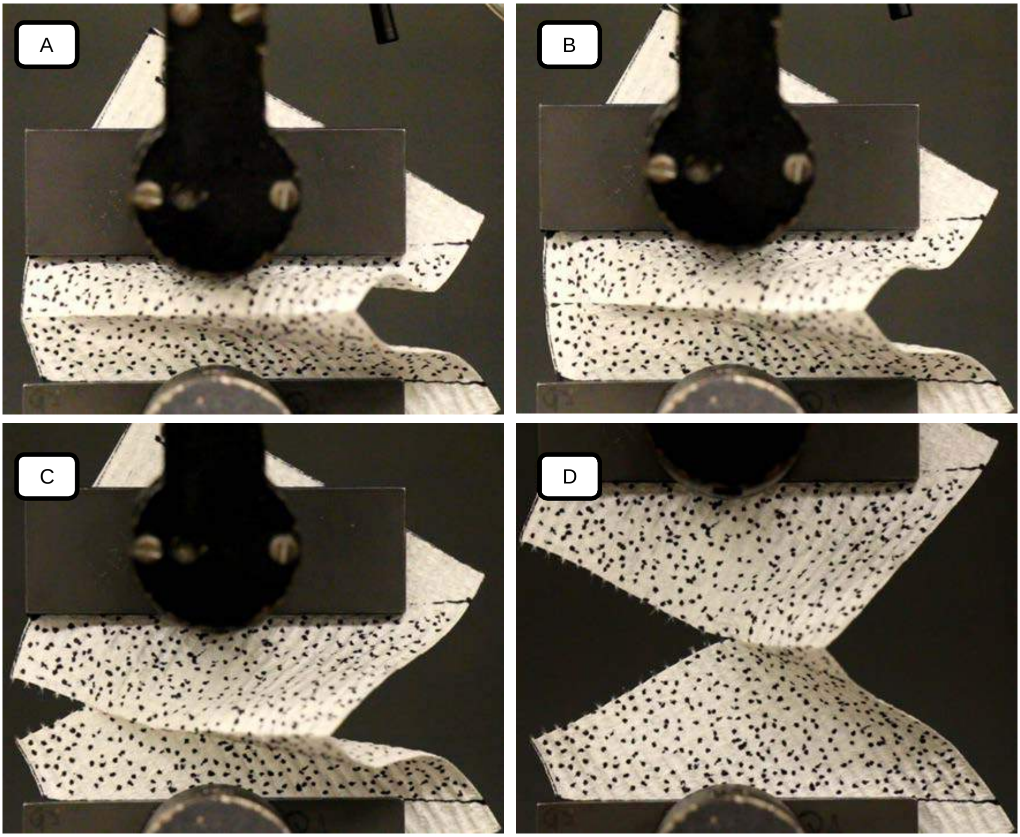

Figure 2: The trapezoid tear test applies the load preferentially to one side of the specimen, allowing the tear to propagate in a controlled fashion from one side to the other.

From a generic stress-strain curve (Figure 3), it is clear the cyclic tensile test captured the plastic strain, loading, and unloading behaviors.

2.2 Trapezoid Tear Test

The trapezoid tear test was adapted from the ASTM standard and consists of loading a rectangular specimen into the specimen grips with the edges of a transcribed trapezoid aligned with the specimen grips (Figure 4). This results in a specimen with buckled material at the trailing edge and a relatively flat configuration at the leading edge (Figure 2A). When the test is conducted, the test applies stress preferentially at the leading edge and has the load transfer across the sheet to the trailing edge as bonds pop, similar to how a consumer would dispense the sheet.

3. Material Model and Fitting Procedure

Vantage is an anisotropic, elastic-plastic material that has a specific damage and failure behavior. To keep up with commercial design cycles, it was essential to simplify the material formulation as

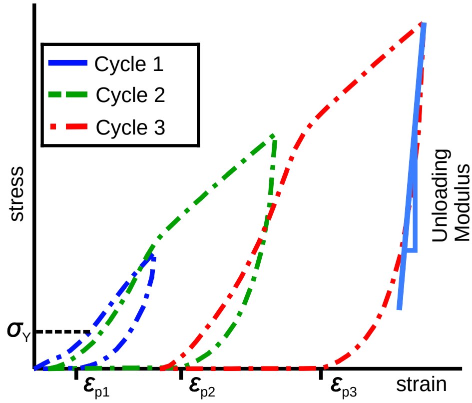

Figure 3: A generic cyclic tensile stress-strain curve shows how successive cycles are pulled to increasing strain and demonstrates the accumulation of plastic strain. The "yield stress" is also labeled on the plot.

much as possible and still capture the essential material behaviors. To accomplish this goal, Vantage was modeled as an isotropic material with a simple plasticity law and straightforward damage and failure behavior.

3.1 Cyclic Tensile Test

Vantage elastic behavior was modeled by assuming isotropic behavior with a neo-Hookean material model. The neo-Hookean parameters were arrived at by assuming a Poisson's ratio (ν) and adjusting the stress-strain curve's initial Young's modulus (E). These two properties can easily be recast as the bulk (k) and shear (G) moduli (Solecki & Conant, 2003, pp.105–6).

$$G = \frac{E}{2(1+\nu)} \qquad\qquad k = \frac{E}{3(1-2\nu)} \tag{1}$$

The neo-Hookean parameters C_{10} and D_1 can be calculated from the initial shear and bulk moduli (Abaqus Theory Guide, 2016).

$$C_{10} = \frac{1}{2}G \qquad\qquad D_1 = \frac{2}{k} \tag{2}$$

Due to plastic strain being accumulated at low total strain values (Figure 5), the initial modulus had a larger influence on the unloading behavior and plastic strain than the loading behavior. The early plastic strain accumulation also necessitated a low yield stress. The loading behavior above the yield stress was defined by the plasticity material model in a table of stress versus plastic strain.

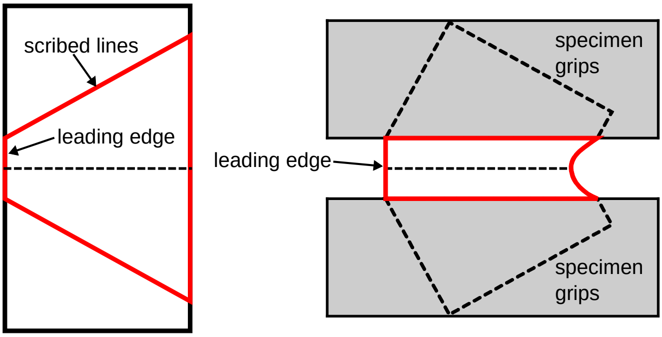

Figure 4: The trapezoid tear test is performed by loading a rectangular specimen into the tensile tester with the transcribed trapezoid's edges aligned with the specimen grips.

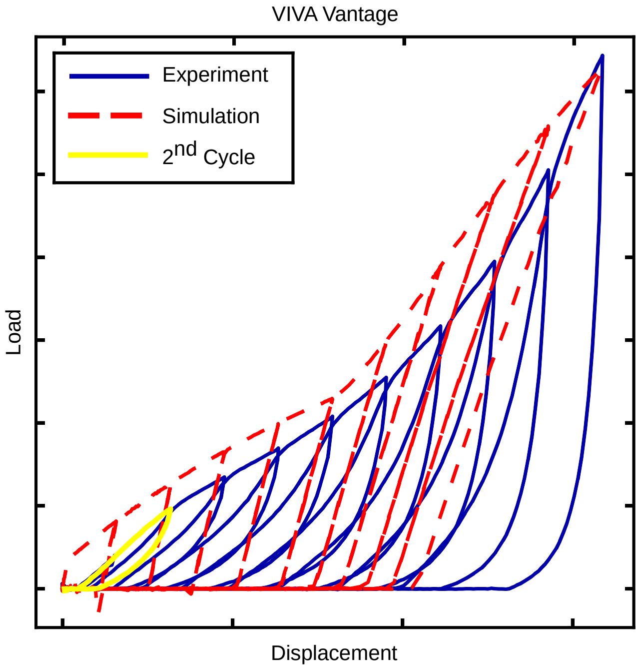

Figure 5: The Vantage cyclic tensile test stress-strain curve for the experiment (solid line) and the simulation (dashed line). The plastic strain is accumulating early in the experiment.

The challenge of having the initial modulus contribute to the plastic strain and the unloading behavior while the plastic properties define the loading behavior is the difficulty in creating an objective function for an optimization scheme to find model parameters. Therefore, the model parameters were found manually with these criteria: simulation results match the experimental plastic strain and then attempt to match the loading curve above the yield stress. Particular attention was also paid to more closely match the peak stress of the experiment. Two primary consequences of this strategy are there are deviations from the exact experimental data and the initial modulus is too stiff compared to the initial loading behavior.

Astute readers will have noted the material model was calibrated with load-displacement data rather than stress-strain data (Figure 5). In the author's experience, using force-displacement data requires the analyst to work closely with the test lab to ensure the test was conducted according to specifications. It also requires the analyst to carefully model the exact test conditions to have a valid comparison. This care would not necessarily be required if simply fitting stress-strain data. Since the force-displacement comparisons happen during post-processing, all of the model parameters are still adjusted for the stress-strain formulation.

3.2 Trapezoid Tear Test

The trapezoid tear test was used to calibrate the damage and failure model as well as provide predictions for perforation pattern performance. The damage and failure model are one method to model dispensing including when the bonds pop (tear).

The damage model was defined by a damage initiation parameter (plastic strain limit) and a damage evolution parameter defined as the energy dissipated by the fracture at failure. To illustrate how this model works, consider an isotropic material like an engineering steel. During a tensile test, the material has a linear response until it reaches the yield stress (σ_0), at which point

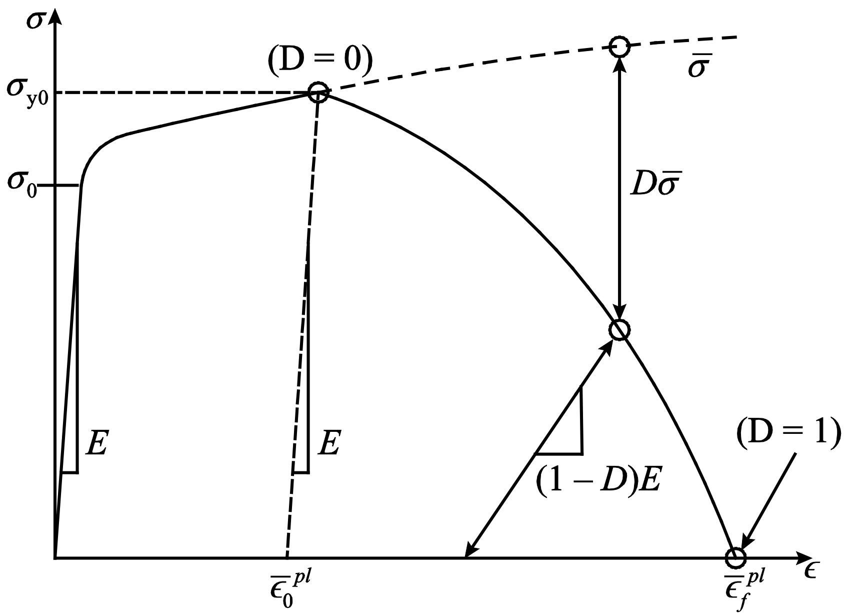

Figure 6: The damage and failure model is more easily demonstrated on a simple material (such as an engineering metal). Figure recreated from the Abaqus Analysis User's Guide (Abaqus Analysis User's Guide, 2016, fig.24.2.3-1).

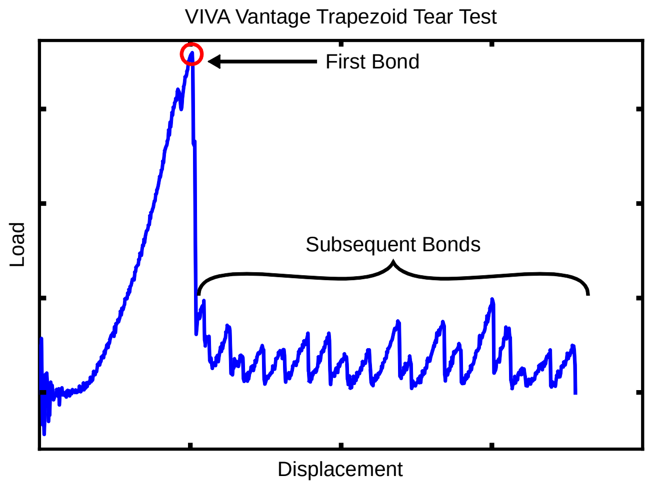

Figure 7: Experimental data for the trapezoid tear test for VIVA. The peak force required to pop a bond comes at the first bond failure.

the material begins to accumulate plastic strain and the stress-strain curve becomes nonlinear (Figure 6). The stress continues to increase until it reaches the ultimate tensile strength (σ_{y0}). At any point before the ultimate tensile strength, if the specimen was unloaded, the unloading curve would exhibit the Young's modulus (E) and the strain when the stress reached 0 would be the plastic strain up to that point $(\bar{\varepsilon}^{pl})$. In addition, the damage (D) up to this point would be zero. The damage parameter is tracked on an element by element basis. At the ultimate tensile strength, the plastic strain is $\bar{\varepsilon}_0^{pl}$ and the damage would start to increase. If the damage did not increase, the stress-strain curve would follow the nominal stress path $(\bar{\sigma})$. The damage evolution law is a linear increase of the damage parameter between the ultimate tensile strength $(D=0)$ and when the strain energy in the element reaches the user-specified energy dissipated by crack growth $(D=1)$. The damage parameter affects the stress-strain curve by scaling the stress by this relationship:

$$\sigma = D\bar{\sigma} . \tag{3}$$

Beyond the ultimate tensile stress, if the specimen was unloaded the modulus would also be scaled as follows: $(1-D)E$. Eventually, the element will completely fail $(D=1)$ and the plastic strain at failure is $\bar{\varepsilon}_f^{pl}$. When an element fails, Abaqus "deletes" it from the mesh. Thus crack propagation (or, in our case, the tear across bonds) is simulated by successive element removal.

The force-displacement curve for the trapezoid tear test is unique in that the force required to pop the first bond is several times higher than the rest of the perforations (Figure 7). Subsequent bond failures are seen in the saw-tooth profile of the force displacement data. The criteria for fitting the trapezoid tear data was to match the maximum force. Similar to the curve fitting for the cyclic tensile test, the fitting for the trapezoid tear test was done manually. After finding the properties, it became clear the damage initiation parameter was primarily responsible for the peak force and the damage evolution parameter needed to be kept low to avoid mesh distortion and simulation errors. The calibration was only able to reach about 80% of the peak stress. However, holding the parameters constant allowed comparisons between perforation patterns.

4. Scripting and Parameterization

The material calibration and the subsequent perforation pattern exploration were facilitated by the Abaqus Scripting Interface (ASI), which is essentially Python with additional data classes defined. Through the Abaqus Scripting Interface, the complete models for the cyclic tensile and trapezoid tear tests were built (Figure 8). Each run (whether the cyclic tensile model or the trapezoid tear model) read in parameters from a spreadsheet (Excel 2013, Microsoft Corporation, Redmond, WA), built the model through the ASI, ran the model on a high performance computing cluster, and automatically post-processed the results. Since each run was defined by a line in the spreadsheet, multiple simulations can be set-up and run with a single command. The ability to run multiple models in a batch process accelerated both the manual material model calibration and the perforation pattern analysis.

To enable the process to work, the entire model had to be parameterized. Due to the nature of the ASI, most of the model parameters were fairly straightforward to determine (mesh seed size, for example). The geometry, however, was more challenging to parameterize, particularly the perforation pattern. Perforations typically consist of co-linear slits in a material with a repeating pattern. A uniform perforation pattern can be described mathematically with three parameters:

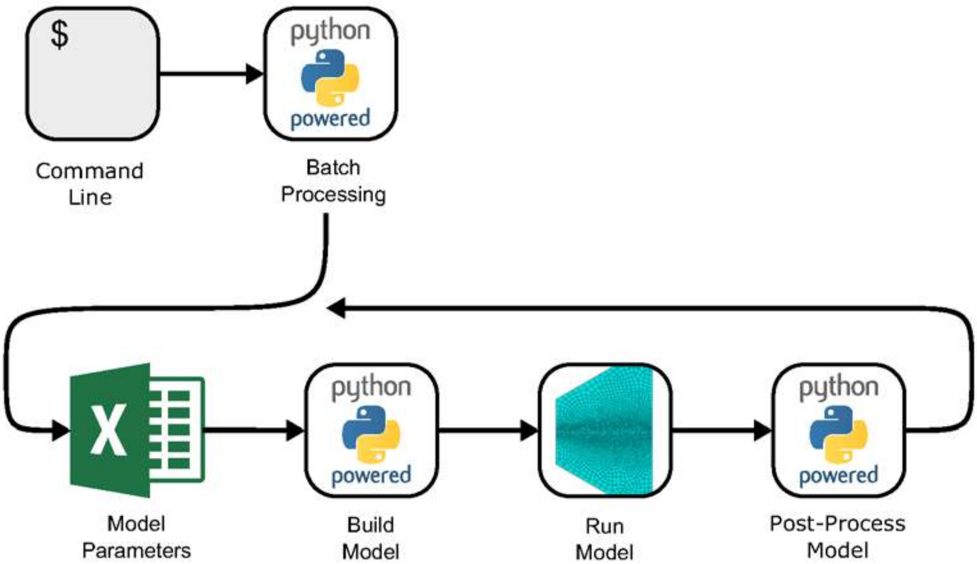

Figure 8: Rapid iteration of the models for calibration and perforation pattern exploration followed this flow chart: calling a batch-processing Python script resulted in reading model parameter s from a spreadsheet, building the model, runing the model on the HPC, and automatically post-proecessing the results.

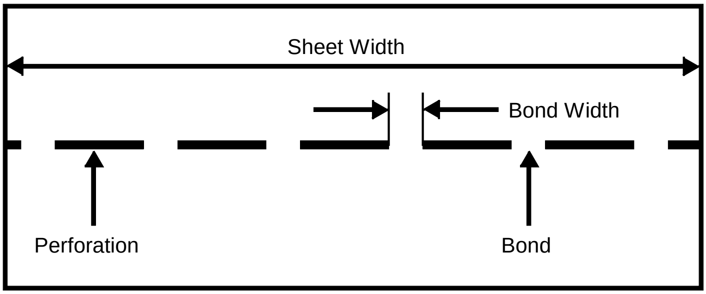

Figure 9: The perforation pattern is parameterized by the sheet width, the bond width, and the bond fraction.

sheet width, bond width, and bond fraction (Figure 9).

5. Dispensing Model

The trapezoid tear simulations followed the experiment closely. The simulation started with loading the specimen into the grips (Figure 10A, Figure 10G star). As the specimen was pulled apart, the sheet resisted more force until the first bond popped (compare Figure 10 B and C, and correlate the contour plots with the force-displacement curve in Figure 10G). Once the first bond popped, the rest of them failed with much lower force (Figure 10D-F and Figure 10G), similar to the experimental data (Figure 7).

Good dispensing was defined as having the appropriate stress concentration such that the tear happens along the line of perforations and between the appropriate sheets. The model predicted successful dispensing for some of the perforation patterns (Figure 10). Other perforation designs had the failures initiate at the specimen grips or deflect away from the perforations. In addition, the damage model allowed the tear to propagate across the sheet in a realistic fashion. Thus the model was able to capture the behavior exhibited in reality. From the perforation patterns analysis, the product developers received a series of design principles for perforation patterns. Based on the success with Vantage, there have been two follow-on for perforation pattern analyses with other rolled-products.

6. References

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7. Acknowledgment

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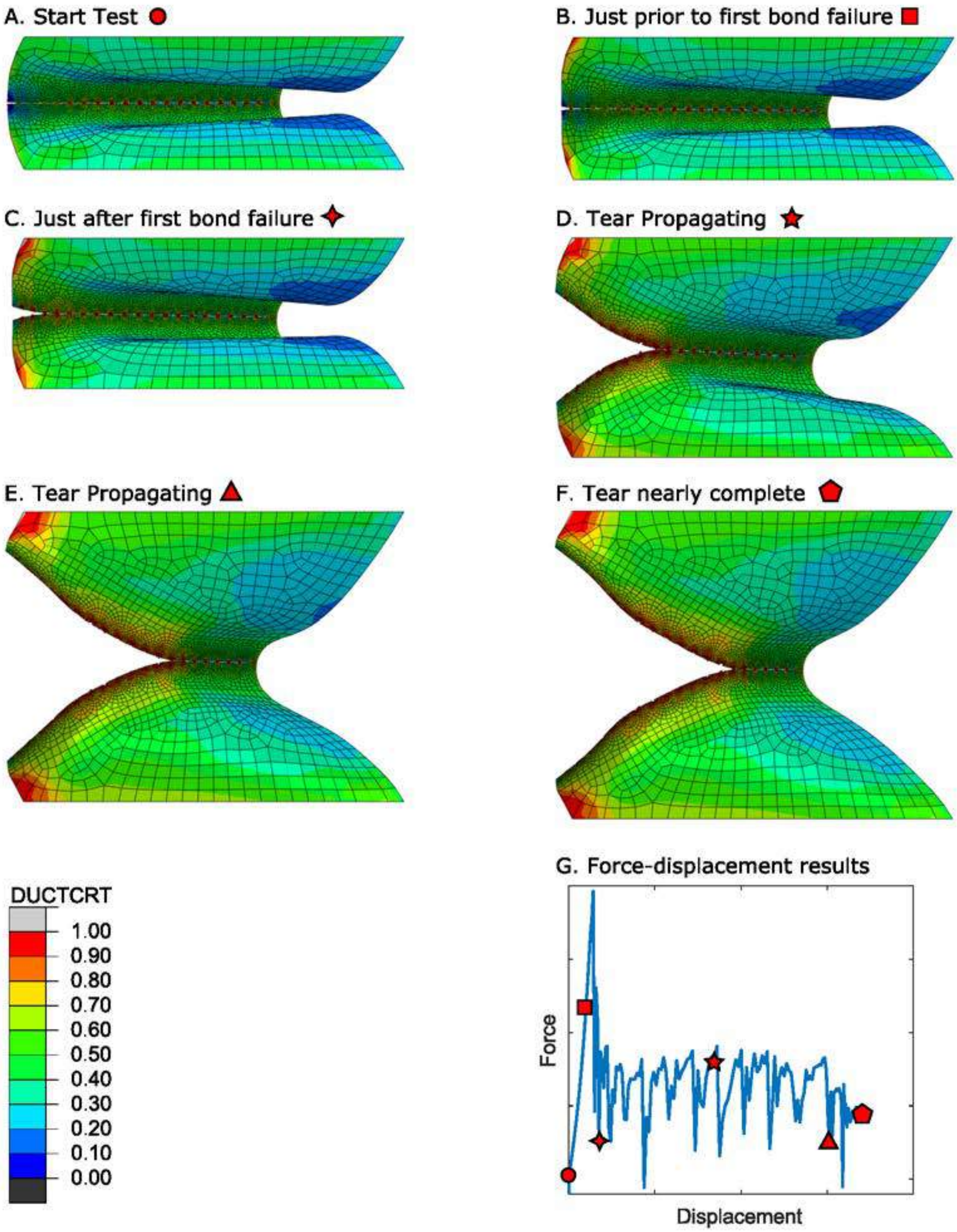

Figure 10: The trapezoid tear test simulation results were similar to the experimental data.