Workshop in Virtual Reality Interactions and Physical Simulation VRIPHYS (2008)
F. Faure, M. Teschner (Editors)

Seams and Bending in Cloth Simulation

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Abstract

Accurate modeling of bending behavior is one of the most important tasks in the field of cloth simulation. Bending stiffness is probably the most significant material parameter describing a given textile. Much work has been done in recent years to allow a fast and authentic reproduction of the effect of bending in cloth simulation systems. However, these approaches usually treat the textiles as consisting of a single, homogeneous material. The effects of seams, interlining and multilayer materials have not been considered so far. Recent work showed that the bending stiffness of a textile is greatly influenced by the presence of seams and that a good cloth simulation system needs to consider these effects.

In this work we show how accurate modeling of bending and seams can be achieved in a state-of-the-art cloth simulation system. Our system can make use of measured bending stiffness data, but also allows intuitive user control, if desired. We verify our approach using virtual draping tests and garments in the simulation and comparing the results to their real-world counterparts. Furthermore, we provide heuristics derived from measurements that can be used to approximate the influence of several common types of seams.

Keywords: computer animation, cloth simulation, physics based animation, bending force model

1. Introduction

The simulation of textiles has been a topic of extensive research in the computer graphics community for well over 20 years. The state of the art offers many fast and precise approaches, depending on the requirements of the task at hand. Realtime performance is crucial in applications like games, while virtual try-on applications require a faithful reproduction of textile characteristics [Krz06]. In both cases a viable trade-off between physical accuracy and performance has to be established.

A key component present in essentially all clothing has, however, so far received very little attention. Most cloth simulation techniques assume that the garment consists of only a single type of homogeneous material. While many of these systems may easily be extended to allow different materials in a single garment, the effects of seams, interlining and multilayer materials have not been studied in detail yet. Worse,

Figure 1: *A women's dress simulated using the techniques proposed in this paper, using measured tensile and bending material data.*

Ma et al. [MHB06] note that most sewing approaches in cloth simulation systems merely merge the border vertices of the seam line. This essentially creates a uniform mesh lacking realistic appearance.

In this paper, we focus on the simulation of seams and present an approach that can accurately represent the effects caused by their presence.

1.1. Related Work

Cloth Simulation The literature on cloth simulation is abundant and it is impossible to provide a complete list of related work due to space constraints. We refer the reader to the books by Volino and Magnenat-Thalmann [VMT00] and House and Breen [HB00] or the surveys by Ng and Grimsdale [NG96] and Volino et al. [VCMT05].

Bending Most cloth simulation systems take the approach to treat in-plane (tensile) deformations independently from out-of-plane (bending) deformations. We are mainly concerned with bending behavior. Good overviews covering the extensive literature on this topic can be found in [GHDS03], [TWS06] and [TW06]. Of particular interest with respect to this paper, Volino et al. [VCMT95] use the dihedral angle formed by two adjacent triangles to compute the bending force. Choi and Ko [CK02] propose a bending model that accounts for compression and buckling. Bridson et al. [BMF03] also use dihedral angles, but take care to use an independent bending mode that does not affect rigid-body transformations and in-plane deformations. Volino et al. [VMT06] present a simple and efficient linear approach, which is well suited for interactive systems.

Seams The influence of seams on the drape of garments is not yet well understood. In the field of computer graphics, Ma et al. [MHB06] propose a seam model that can simulate *seam pucker*, i.e. the distortion of textiles due to sewing. However, they are mainly interested in the visual effect of seams and are not concerned with the alteration of the draping behavior. In the textile research community, Hu et al. [HCL97] examine the effect of seams on the drapability. Further research by Masteikaite [Mas97] shows an interdependence of fabric bending stiffness and stitch type. Inui et al. [IOY01] examine how seam pucker is related to the mechanical properties of the fabrics and how it can be simulated, but they focus on the effect of the fabric on the appearance of the seam. Schenk et al. [SSR06] are the first to study the influence of seams on the bending stiffness of the surrounding fabric.

1.2. Overview and Contributions

The remainder of the paper is organized as follows: First, we describe our bending model and several issues related to it. Then we examine the influence the presence of seams has on samples of textiles. We specify the selection of seams used in our tests and introduce our new seam model. We show how to deal with cases where the mesh resolution is too low to properly model the seam. We use a virtual bending testing device to show that the seam model is accurate. To demonstrate the effect of seams on garments, we compare simulations of draping tests with actual results from such tests. Finally we examine how the seam model enhances the realism of the simulation of a women's dress by comparing it to its real-world counterpart. We close with a critical analysis of the strengths and shortcomings of our approach and point to promising future work directions.

Our main contributions are a bending model that makes use of measured moment-curvature data and a seam model that significantly improves the realism of garment simulations.

2. Cloth Model

As many other cloth simulation systems, we take the approach to treat the in-plane (tensile) deformations independently from the out-of-plane (bending) deformations. Out-of-plane deformations will be treated in more detail in Section 3. In-plane deformations are handled using a continuum mechanics formulation of linear elasticity theory. The central quantities in this case are strain, which is a dimensionless deformation measure, and stress, which is a resulting force per area. These two variables are related to each other through a material law. The resulting partial differential equation is discretized using a linear finite element approach as described in [EKS03]. For dynamic simulation, inertia effects have to be included, as well as viscosity and possibly external forces. We use an implicit backward Euler method for numerical time integration. Our simulator can use regular or irregular triangular meshes.

3. Bending Model

Our treatment of out-of-plane deformations is, as are many other models, based on the dihedral angle formed by two adjacent triangles (a *bending element*).

3.1. Bending Stiffness

Our approach is related to the one proposed by Bridson et al. [BMF03]. However, the elastic bending stiffness parameter used by Bridson et al. lacks a physical foundation and it is not clear how one would compute the parameter for a given textile sample in their approach. We therefore propose a bending model based on the moment-curvature relationship of fabrics. This allows us to accurately reproduce the bending behavior of cloth using measured data, which can be acquired using a technique first suggested by Clapp et al. [CPGE90].

For the readers convenience, we briefly summarize their approach. They propose to indirectly measure the moment-curvature relationship using a cantilever beam test. Cartesian (x,y)-samples along the textiles' profile are collected, converted to polar coordinates and a standard least-squares fitting is used to obtain a smooth fifth-order polynomial. From this, moments and curvatures along the polynomial representation of the curve can be derived. The extracted moment-curvature relationship can then be used to approximate the nonlinear bending stiffness B, which is defined as the change in moment divided by the change in curvature:

$$\mathbf{B}(\kappa) = \frac{\mathbf{dM}}{\mathbf{d}\kappa}$$

A quadratic regression and a linear regression are taken from the moment-curvature curves. From these, a continuous function is constructed that combines the quadratic and the linear parts. The quadratic regression is used for small curvatures and approximates the nonlinear *initial bending stiffness*, while the linear regression is used for the *ultimate bending stiffness*. Thus,

$$M = \begin{cases} b_1\kappa + c_1\kappa^2 & \text{if } |\kappa| \leq \kappa_0, \\ M_0 + b_2\kappa & \text{if } |\kappa| > \kappa_0. \end{cases} \tag{1}$$

where

$$\kappa_0 = \frac{\mathbf{b_2} - \mathbf{b_1}}{\mathbf{2c_1}}$$

$$\mathbf{M_0} = (\mathbf{b_1} - \mathbf{b_2})\kappa_0 + \mathbf{c_1}\kappa_0^2$$

The material bending stiffness is then defined by the constants $\{b_1, b_2, c_1\}$. In the following, we will describe how to extend common bending models to allow the use of these constants for cloth simulation.

3.2. Bending Force Computation

Due to its simplicity and the intuitive control that it offers, the bending model of [BMF03] is widely used in computer graphics. Though convenient for general animations, two aspects render the integration of measured material data a non-trivial task: the deformation measure used is a function of the sine of the dihedral angle and forces follow directly as a linear function thereof. By contrast, fabric measurement devices usually deliver curves in which bending moment per length $(N \cdot cm \cdot cm^{-1})$ is plotted against curvature (cm^{-1}). The first issue is readily dealt with by replacing the sinusoidal deformation with the discrete mean curvature measure by Grinspun et al. [GHDS03]. Here, the mean curvature of a deformed bending element is computed as

$$\kappa = \frac{(\theta - \bar{\theta})}{\bar{h}_e} \tag{2}$$

where θ and $\bar{\theta}$ refer to the dihedral angle in current and rest state and $\bar{h}_e$ is the average of the two triangles' heights in the rest state.

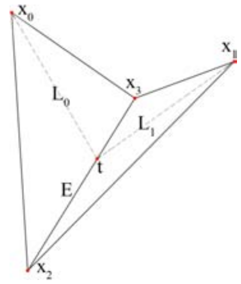


Figure 2: *A bending element consisting of two adjacent triangles.*

The solution to the second problem follows by simple geometric considerations. Given the curvature κ represented by a bending element (Figure 2), we can now compute the bending moment M using equation 1. From the moment, we compute the force, given the lever handle from the nodes x_0 resp. x_1 to the closest point on the edge E connecting x_2 and x_3:

$$\mathbf{t} = \frac{(\mathbf{x_0} - \mathbf{x_2}) \cdot \mathbf{E}}{\mathbf{E} \cdot \mathbf{E}}$$

where t is the barycentric coordinate of the point on the edge E. From this we can compute the bending force, for $i \in \{0,1\}$:

$$\mathbf{F_i} = \frac{\mathbf{1}}{\mathbf{2}} \frac{\mathbf{M}}{|\mathbf{L_i}|} \frac{\mathbf{E} \times \mathbf{L_i}}{|\mathbf{E} \times \mathbf{L_i}|} |\mathbf{E}| \tag{3}$$

where L_i is the vector from $x_2 + tE$ to x_i and the factor $\frac{1}{2}$ follows from the fact that $A_i = \frac{1}{2}|E||L_i|$. Conservation of linear and angular momentum requires that the sum of the forces acting on the nodes as well as the sum of the torques be zero. We can thus deduce the force in x_2 and x_3 from F_0 and F_1 as

$$\mathbf{F_2} = -(\mathbf{F_0 t} + \mathbf{F_1}(\mathbf{1} - \mathbf{t})) \tag{4}$$

$$\mathbf{F_3} = -(\mathbf{F_0}(\mathbf{1} - \mathbf{t}) + \mathbf{F_1 t}) \tag{5}$$

Not surprisingly, the direction of the forces as well as their relative magnitudes coincide with those derived in [BMF03]. Hence, our formulation also shares the desirable properties of [BMF03]: It does not affect rigid-body transformations and in-plane deformations, and is relatively independent of the mesh resolution and mesh anisotropy. A damping bending force can easily be added based on the rate of change of the curvature, analogously to [BMF03]. An extension to allow different bending properties in weft and warp directions is also straightforward.

3.3. Resolution Independence

The bending forces are computed as a function of discrete mean curvature. The associated bending energy is fairly (though not completely) independent of the mesh used for discretization and it converges to its continuous counterpart under refinement (see [GHDS03]). We verified this property for our bending model using a sequence of irregularly refined meshes and conclude that, on the visual scale, the behaviour does virtually not depend on resolution (see Fig. 3).

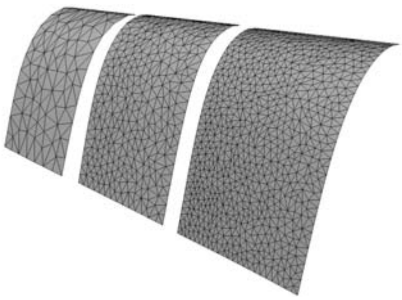


Figure 3: *A stiff piece of cloth, simulated using three different mesh resolutions (150 faces, 574 faces, 1408 faces). The bending behaviour is virtually independent from resolution*

3.4. Linear Bending Stiffness Factor

The ability to make use of measured bending stiffness data is of vital importance to applications in the apparel industry, e.g. in virtual try-on settings. However, cloth simulation is also important in the field of computer animation, where it is required to have intuitive control over the key aspects of the simulation. Our bending model can easily be extended to allow this kind of control, i.e. allowing the animator to make a fabric behave more stiff or more flexible. To this end, we introduce a new material property β, the *linear bending stiffness factor*. From this we can compute

$$\alpha(\kappa) = \beta + \frac{(\beta - \mathbf{1})\mathbf{c_1}\kappa}{\mathbf{b_1}} \quad , \quad \beta > \mathbf{0}$$

and scale the bending stiffness parameters b_1 and b_2:

$$\mathbf{b_1} = \alpha(\kappa)\mathbf{b_1}$$

$$\mathbf{b_2} = \beta\mathbf{b_1}$$

This approach allows us to scale only the linear part of the bending stiffness, without introducing any unwanted changes into the second derivative. Figure 4 demonstrates the effect of varying β.

4. Influence of Seams

4.1. Bending Stiffness Tester

Bending rigidity of textiles is usually measured using the *Kawabata Evaluation System of Fabrics* (KES-FB) [Kaw80]

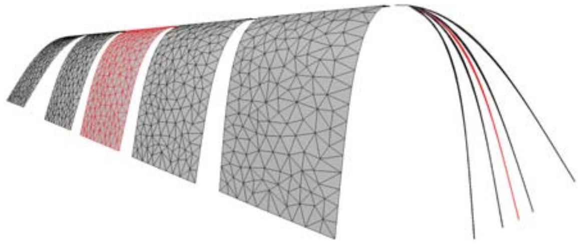


Figure 4: *A piece of fabric (290 faces) simulated using varying linear bending stiffness factor* β*, from left to right:* 2.0, 1.2, 1.0, 0.8, 0.5. *The orthographic projection to the right shows the intuitive control over the bending stiffness that is achieved.*

or the manual cantilever method [Pei30]. The KES-FB-2 method measures the moment-curvature relationship using a fabric sample of $1cm$ width, which is not enough to capture the influence of seams on the surrounding fabric.

The cantilever approach, which is e.g. used in the *FAST-System* [Min95], is known to be very error-prone, since the results are dependent on the individual traits of the person executing the test. Rödel et al. [RSS07] propose the new bending stiffness testing device *ACPM200*, which remedies the shortcomings of the manual testing method. It also uses the cantilever principle, however it is largely automated to reduce the influence of the human operators' traits. A piece of fabric (up to 20cm wide) is moved at a constant speed of $12\frac{cm}{min}$ until the fabric front passes through the IR light barrier, which is oriented at $41.5°$. The light barrier consists of 17 individual sampling rays, which are used to record the profile of the fabric front.

4.2. Seam Model

The two most common textile weaves are *plain* weave and *twill* weave. In plain weave, warp and weft threads form criss-cross patterns, i.e. weft threads go over warp threads and then under the next warp thread, and so on. In twill, offsets are used and weft threads pass under two or more warp threads, which creates a characteristic diagonal pattern.

Seam	ISO	Cloth layering	Cross section	Layers	Applications
A	1.01.01			2	Joining seam between clothing patterns
B	2.02.04			3	Safety seam, used in dresses, shirts, working clothes
C	2.04.05			4	Double lap seam, used in working clothes and sportswear

Table 1: *Selected seam types.*

From the large number of seams that are used in the apparel industry, three common types are chosen, as depicted in Table 1. These seams connect two, three and four layers of textile together.

Using the *ACPM200*, a number of experiments with seam types *A*, *B* and *C* on both plain and twill weave textiles allow us to approximate the change in bending stiffness as a function of the distance *d* from the seam. The bending stiffness of the textile itself, without any seam, can easily be determined using a photo of the profile of the sample. Standard image processing techniques were used to extract a profile curve from the image, allowing us to use the approach outlined in Section 3 to compute the bending stiffness.

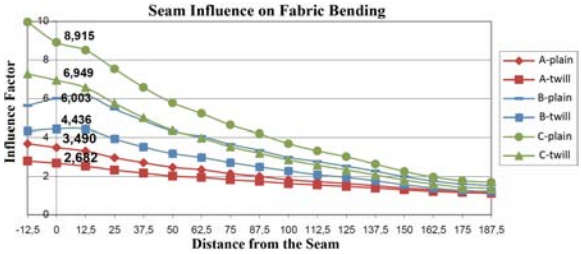


Figure 5: *Influence of seams A, B and C on different types of fabrics, measured using the* ACPM200*. The influence factor describes the increase in stiffness in relation to the fabric without any seams.*

Seam	bending stiffness factor $B_f(d)$
A-plain	$\mathbf{5.0 \times 10^{-5} d^2 - 0.0211d + 3.46}$
A-twill	$\mathbf{2.0 \times 10^{-5} d^2 - 0.0127d + 2.64}$
B-plain	$\mathbf{4.0 \times 10^{-5} d^2 - 0.0322d + 5.92}$
B-twill	$\mathbf{4.0 \times 10^{-5} d^2 - 0.0287d + 4.37}$
C-plain	$\mathbf{2.0 \times 10^{-4} d^2 - 0.0702d + 9.07}$
C-twill	$\mathbf{1.0 \times 10^{-4} d^2 - 0.0524d + 6.86}$

Table 2: *Seam influence factor $B_f(d)$ for plain and twill weave, as a function of the distance d in mm from the seam.*

Using Table 2 the bending stiffness multiplier *S* for every mesh face can be calculated, which is easily done as a preprocess.

$$\mathbf{S = 1 + (B_f(d)(B_f(0) - 1))}$$

Combining *S* and equation 3, we arrive at our final bending model which also includes the seam influence:

$$\mathbf{F_i = \frac{1}{2} \frac{M}{|L_i|} \frac{E \times L_i}{|E \times L_i|} |E| S} \ , \quad \mathbf{i \in \{0, 1\}} \qquad (6)$$

Depending on the type of seam, we additionally scale the fabric weight for the nodes on the proportionally to the number of layers of the seam, i.e. a double lap seam stitches 4 layers of fabric together, thus we scale the weight of the seam by 4.

4.3. Adaptive Refinement

The aim of cloth simulation is to reproduce the behavior of textiles as accurately as possible and as fast as possible. Depending on the application requirements, one needs to find a good trade-off between these two goals. Often, meshes of relatively low resolution are used to facilitate fast computation. Since the seam influence varies greatly with the distance from the seam, this can lead to very abrupt changes in the bending stiffness between neighboring bending elements. To remedy this, one could increase the resolution of the whole textile until the bending stiffness varies smoothly enough. This, however, incurs a great computational burden and is not really needed. Adaptive refinement, can be used to locally increase the mesh resolution so that the seam influence can be reproduced smoothly. In our system, we found it useful to subdivide triangles according to their area and proportional to the bending stiffness factor, as described in Table 2. A triangle is then refined into $\lceil B_f \rceil$ new triangles. Figure 6 shows an example.

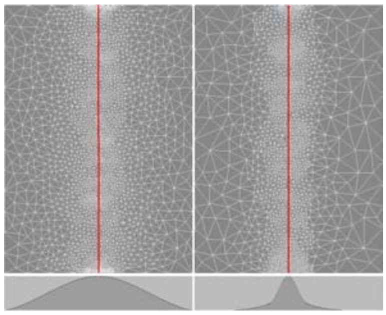


Figure 6: *Adaptive refinement depending on the seam bending stiffness factor, which is visualized over the width of the textile below.*

5. Results

To demonstrate the validity of our approach, we perform three kinds of tests. First, we recreate the bending stiffness tester *ACPM200* in our simulation environment and verify the output of our seam model. Secondly, we perform draping tests using the simulation and compare their outputs to actual draping experiments. Thirdly, we simulate a complete women's dress that has been faithfully reproduced inside the simulation environment, and again compare the results to the real garment. Since we are interested in the simulation of fabrics using measured material properties, the linear bending stiffness factor is set to $\beta = 1.0$ for all simulations presented in this section and thus does not have any influence.

5.1. Bending Tester Simulation

We used the bending stiffness tester *ACPM200* described in Section 4.1 to acquire bending stiffness and seam influence data. We constructed the device in our simulation environment and simulated the fabrics using the measured data. Figure 7 shows the results for two types of textiles, a plain fabric and then the same fabric with interlining. We also show the seam influence that is caused by a double lap seam.

5.2. Draping Tests

A circular piece of cloth (radius 15cm) is draped onto a circular disk (radius 9cm) recreating the widely used *Drapemeter* test. Figure 8 shows the results of several draping experiments, both with and without seams. The influence of simulated seams is significant and closely matches those reported from actual Drapemeter experiments by [HCL97] and [Sei07].

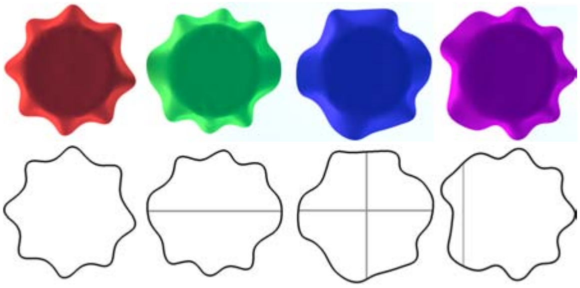


Figure 8: *Drapemeter simulation. From left to right: no seam, a single seam along the weft direction, two seams aligned along weft and warp directions, and a seam that has been shifted to the side. The fabric bending stiffness parameters are* $\{b_1 = 0.1,\ b_2 = 0.0892,\ c_1 = -0.0092\}$*, the seam is simulated as a double lap seam.*

Figure 9: *A comparison between a real garment and the simulation, using our proposed techniques and actual measured data for tensile and bending stiffness. The fabric bending coefficients are* $\{b_1 = 0.0973,\ b_2 = 0.0973,\ c_1 = 0.0453\}$*, and the fabric with interlining is simulated using* $\{b_1 = 0.5168,\ b_2 = 1.8856,\ c_1 = 2.2683\}$.

Model	Bending force evaluation
Volino et al.	6.3ms
Bridson et al.	51.1ms
Our model	65.0ms

Table 3: *Bending computation times for a* 0.5m *by* 0.5m *piece of fabric fixed at one border and bending under its own weight (3600 faces).*

5.3. Comparison with real garments

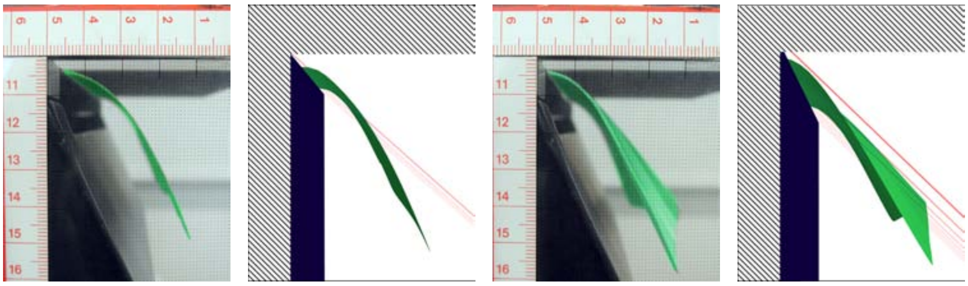
Figure 9 shows a women's dress that has been constructed both as an actual garment and inside our simulation. The tensile material parameters were acquired using the KES-FB system, while for the bending parameters we used the techniques described in this work. The dress uses some interlining in the upper parts, around the neck and the arms. The main seams are of type A. The simulation matches many aspects of the real garment very well, e.g. the location of the main folds and their shape. However, some discrepancies remain, which is unavoidable for such a complex task, since many parameters of the real garment cannot be properly estimated, e.g. the friction coefficient of the avatar or local imperfections.

5.4. Performance

The performance of our proposed model is comparable to that of other methods based on the dihedral angle, with a slight additional cost due to the evaluation of curvature. The linear approach proposed by [VMT06] is much faster, however as they note in their paper and as we demonstrate in Section 5.5, this performance comes at a price.

5.5. Bending Quality

Figure 10 shows the bending force in normal direction for a varying opening angle of a bending element. We compare our proposed model and two popular recent approaches by Bridson et al. [BMF03] and Volino et al. [VMT06]. Bridson et al.'s model is based on the sine of the dihedral angle and exhibits a smooth, monotonically rising bending force. [VMT06] is optimized for performance and its main drawback, as is noted in their paper, is evident from the plot curve. The bending force increases monotonically up to 90 degrees and then drops off again. This introduces unwanted tensile (in-plane) compression effects, which also might lead to an increased number of self-collisions later on. We show two materials from [CPGE90], simulated using our method. The first one exhibits an almost linear bending force, something that cannot be reproduced with the other methods, while the second one is similar to the material simulated using Bridson et al.'s approach.



(a) Fabric with interlining in the bending testing device

(b) Simulation of (a)

(c) Fabric with interlining and seam B in the bending testing device

(d) Simulation of (c)

Figure 7: *A comparison of results obtained using our bending and seam model with results using the bending stiffness tester* ACPM200. *The fabric sample* (20cm *wide) with interlining is simulated using bending coefficients* $\{b_1 = 0.5168,\ b_2 = 1.8856,\ c_1 = 2.2683\}$ *obtained from measurements. The seam is of type B, a safety-seam.*

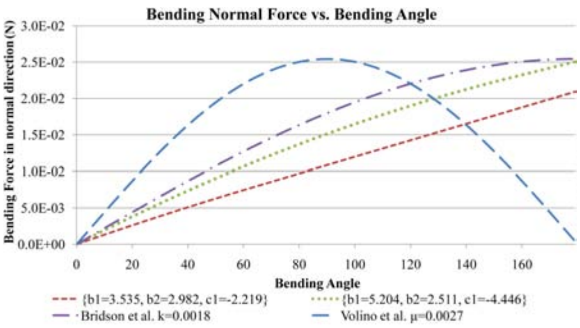


Figure 10: *Bending force in normal direction for a single bending element using different bending models.*

6. Conclusion and Future Work

We have described an approach that can be used to model bending and seams in cloth simulations. The approach is general, thus it should pose no difficulties to integrate it into other cloth simulation systems. While it is generally difficult to prove the correctness of the method, comparisions to experiments suggest that the method is indeed capable of capturing the essence of the non-linear bending behaviour of fabrics. The performance impact is minimal. We have presented a way to simulate the important influence of seams in textiles. Again, experimental evidence and data demonstrate that our approach is able to capture key aspects of the effects that the presence of seams in textiles cause.

However, seams and fabric bending are far from being fully understood, and thus a number of promising directions for future work remain. For example, [MHB06] proposed a way to visualize seam pucker, but the effect of puckering on the mechanical properties and how it can be integrated into cloth simulation systems has not yet been examined. Also, the effect of seams that are not oriented along warp or weft directions is not yet fully understood.

Acknowledgments

We would like to thank our anonymous reviewers for their insightful comments. This work was supported by DFG grants STR465/21-1 and RO1303/10-1.

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