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Implementation of Modeling and Simulation of Textile Seam and Joints for Parachute Design Applications

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The standard approach to validate parachute textile joint losses has been through destructive tensile testing. A typical joint loss is determined by the creation of test samples of the joint in question, performing tensile testing to failure and then comparing the joint load capacity results with control breaks of the base structural member. As samples and testing can be costly, a statistical analysis is completed from a determined sample size to determine a joint loss factor used in parachute design factors. Although widely accepted in the parachute industry, this method can prove to be rather costly in terms of schedule and program cost as the design matures and as design changes are implemented. In addition, the testing is typically limited to final visual inspections of the breaks and tensile measurements, and lacks a quantitative method of determining localized stress and strain information to provide a greater understanding of the loaded joint.

This paper reviewed an alternate method of study to evaluate seam and joints through modern computational simulations. An LS-DYNA model was developed to describe overlapping joints with varying stitch patterns. The model simulated the standard joint testing setup and attempted to replicate the failure models observed in testing. The results are then compared with actual test samples for validation of the simulation and to understand the feasibility of a seam and joint simulation. In addition, using the described results, the analysis method will be evaluated at a system level as either a replacement to current test methods, or to help drive design decisions with regard to joint composition.

The results of this modeling effort show a good correlation to prediction of failure in the threads comprising the sewn joint (within 15% of the breaking strength observed in testing). Further test data correlation, joint characterization and model improvements will only act to bolster the validity of this approach as a valuable tool for the parachute designer.

Nomenclature

a	=	*Aging Degradation Factor*
AL	=	*Applied load*
c	=	*Line Convergence Factor*
δ	=	*Shift in Substrate*
DF	=	*Design Factor*
DF_T	=	*Thread Design Factor*
e	=	*Abrasion Loss Factor*
E	=	*Young's Modulus*
ES	=	*Minimum Element Strength*
FEA	=	*Finite Element Analysis*
k	=	*Fatigue Degradation Factor*
L_o	=	*Initial Measured Length*
L_S	=	*Total Length of Stitching*
m	=	*Dynamic Load Factor*
$M\&S$	=	*Modeling and Simulation*
MOS	=	*Margin of Safety*
N_P	=	*Number of Plies*
o	=	*Contamination Degradation Factor*
φ	=	*Thread Pull Angle at Failure*
P_S	=	*Stitch Load Capacity*
s	=	*Asymmetric Load Distribution Factor*
SF	=	*Safety Factor*
SPI_{ACT}	=	*Effective Stiches per Inch*
SPI	=	*Stiches per Inch*
S_T	=	*Min Thread Tensile Strength*
t	=	*Temperature Degradation Factor*
t_{sub}	=	*Substrate Thickness*
u	=	*Joint Loss Factor*

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I. Introduction & Test Objectives

A widely accepted approach in determining parachute element structural losses in joined textile elements is to complete destructive tensile testing of textile joints. This is a well-established means of characterizing the joint capacity, but lacks crucial information regarding the joint capability for tensile load transfer between joined members of the base substrate material. Destructive tensile testing does provide some qualitative visual evidence of the load transfer between joined items, but offers little in terms of direct solutions to ineffective joint designs. There are standard stitch calculations that are commonly applied to sizing a sufficiently strong joint; however, relying solely on these calculations hinders optimization and further maturation of the joint design. Obtaining a quantitative relationship of the load transfer via modern computational methods enables the designer to better evaluate the joint and improve or optimize the joint in order to fit the structural needs of the system. In addition, if such an analysis could be completed, the ultimate capacity of the joint may also be predicted; thereby potentially reducing costly (in terms of program schedule, labor and material) tensile testing, while also advancing the textile design process. Thus, a method of this nature could be construed as a more effective means of the joint maturation process by developing the joint through computational methods rather than iterations of trial and error or experienced-based destructive tensile testing prior to final joint qualification.

This study was completed to compare current testing methods with modeling and simulation (M&S) results in order to understand the feasibility of conducting computational analysis to aid in the design of the textile seams and joint, and/or as a verification technique with final destructive tensile testing. An initial set of goals and objectives were identified and are shown in Table 1. This study will be limited to standard parachute joints and constructions as described in PIA-P-7567, and the required work will be limited to completing the goals described in Table 1. The design aspects of this paper will focus on an overlap joint using parachute standard stitch patterns and structural materials.

Table 1. Goals and Objectives of Study

Goals	Objectives
1.0 Define an approach to describe the textile joint load transfer using modern computational methods	*1.1 Model various parachute textile lap joints* *1.2 Simulate loading characteristics of the joint*
2.0 Define a quantitative analysis technique to estimate the failure and of the joint using modern computational methods	*2.1 Identify the ultimate load capacity of the joint elements via M&S* *2.2 Identify the failure location(s) through M&S*
3.0 Declare the feasibility of using these analysis techniques to improve on existing joint design processes and techniques	*3.1 Obtain destructive testing and M&S joint results* *3.2 Provide insight into opportunities and/or potential limitations of M&S technique*

II. Seam & Joint Background

In the design of parachute systems, the structural capacity of each element is evaluated to show sufficient capability above the identified applied load (AL). The structural Margin of Safety (MOS) is given by Eq. (1). where the element design factor (DF) is a combined factor intended to compensate for various degradation of the substrate; this is described by Eq. (2).

$$MOS = \frac{ES \cdot NP}{DF \cdot AL} - 1 \tag{1}$$

$$DF = SF \cdot \frac{m \cdot s \cdot c}{u \cdot e \cdot k \cdot o \cdot t \cdot a} \tag{2}$$

Textile materials can be particularly susceptible to environmental and operational degradation; as such, the parachute industry has identified the following factors to contribute to structural losses in the material and are used in the determination of textile component MOS.

- ***Dynamic Load Factor (m):*** Intended to account for differences in static and dynamic loading conditions.
- ***Asymmetric Load Distribution Factor (s):*** Used to account for asymmetries in construction and loading in operational environments.
- ***Line Convergence Factor (c):*** Accounts for any cosine/sine amplification factors into the item under load.
- ***Joint Loss Factor (u):*** Degradation factor accounting for losses associated with joining textile items.
- ***Abrasion Loss Degradation Factor (e):*** Meant to account for abrasion experienced during operation.
- ***Fatigue Degradation Factor (k):*** Accounts for structural losses due to multiple use items.

- ***Contamination Degradation Factor (o):*** Degradation factor accounting for environmental contamination due to ultraviolet radiation exposure, humidity, oils, salt, etc.
- ***Temperature Degradation Factor (t):*** Accounts for structural losses due to temperature exposure
- ***Aging Degradation Factor (a):*** Factor accounting for structural losses due to storage and aging
- ***Safety Factor (SF):*** Additional factor intended to account for other uncertainty within the system

The loss factors described above are determined through testing, analysis, heritage or other methods. Once the factors have been identified and agreed upon, the component DF can be calculated.

When designing systems with high performance textiles, material constructions of cord, webbing, tape, or cloth are cut and joined together in various ways in order to achieve a desired design intent (i.e. riser termination, suspension line attachment, etc.). Joining is typically accomplished through sewing, and during this process the structural capacity of the joined material is degraded as compared to original manufactured structure. This reduction is described by the joint loss factor (u) and typically requires extensive manufacturing of samples and tensile testing over the life of the program to establish the factor.

The structural decomposition of textile seams and joints comprises of the joining material, typically threads, and the base structural material. The standard method of joining the elements is completed by the lock-stitch, which effectively ties the structural element(s) together between the fibers. Figure 1 depicts a sample joint comprised of a straight stitch (Type 301) with a lock-stitch for reference.

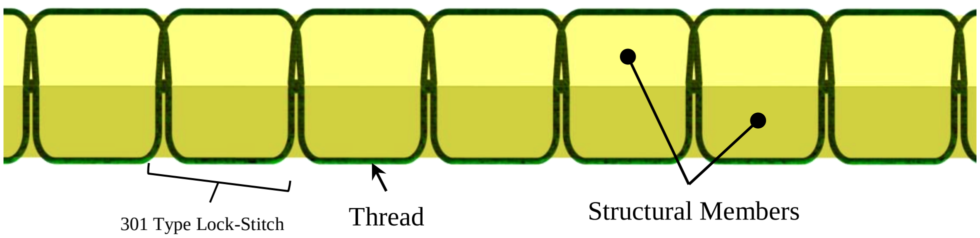


Figure 1. Straight Stitch (Type 301) Lock-Stitch Visual Reference

When the joined system is loaded in tension, the lock stitch tends to skew towards the pull directions in each of the plies and acts to transfer the loads between plies. In the case of a joined textile tape, the stitch transfers load between the fill fibers in the base materials, and applies tension to the warp fibers, as described Figure 2. Loading the fibers through the stitching generates localized stress risers in the base material, ultimately leading to premature failure of the base material with respect to the un-joined strength. This premature failure is represented by the joint loss factor (u). The load sharing between the joined plies, characterization and determination of stress risers and subsequent load sharing between the structural members and the threads is not easily determined. A proper design methodology for joined textile components should attempt to optimize the stitch pattern, stitch density, and joint materials in order to reduce the overall stresses in the system.

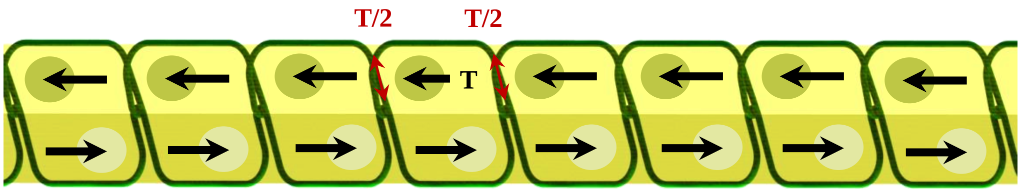


Figure 2. Load Characteristics for Straight Stitch (Type 301) Lock Stitch

For the thread element the estimated stitching load capacity (P_s) is determined using the following characteristics:

- Thread tensile strength (S_T)
- Number of plies per stitch (N_p) – two plies per lock stitch
- Thread design factor (DF_T) – see Eq. (2).
- Effective joint stitches per inch, (SPI_{ACT}), and the total length of stitching (L_S)

The parachute industry has described an acceptable range of required stitches per inch (SPI) for various stitching types and thread sizes, as described in Table 2. For zig-zag stitching, the SPI is counted along one side, therefore, two stitches comprise a single throw zig-zag (type 304) count and four stitches comprise a double throw zig-zag (type 308) count.

Table 2. Stitches per Inch Description

Stitch Type	SPI_{ACT}
301 Straight Stitch	SPI x 1
304 Single Throw Zig-Zag	SPI x 2
308 Double Throw Zig-Zag	SPI x 4

For each lock stitch there are two plies of thread that transfer the load between the structural members. The structural losses of the stitch can be represented by a loss factor, as described in Eq. (2). Therefore, the estimated strength of the stitch pattern is described by Eq. (3). An optimized joint design would ensure sufficient thread count so joint failure occurs in the structural base rather than in the joining stitches. Additionally, an optimized joint design would consist of a sewing pattern intended to reduce stresses on the fibers and facilitate load sharing between elements.

$$P_S = \frac{N_P \cdot S_T \cdot SPI_{ACT} \cdot L_S}{DF_T} \tag{3}$$

III. Test Sample Design Overview

For this study, a standard overlap joint was selected as there is a wider range of stitching patterns than with a cord or cloth. The selection of the structural element was limited by readily available materials; as such, a single layer 1.75 in Kevlar tape was selected. The material selected was 6,500 lbf Kevlar tape (PIA-T-87130, Type X, Class VII). The stitching patterns were selected from standard cross stitch (type 301) and zig-zag (type 308) with the inner and outer rows staggered. In addition, a new type of elliptical pattern (type 301) was added in order to study a non-traditional stitching pattern. The elliptical pattern consisted of four concentric ellipses. Each pattern selected the following thread types: Nylon, size 'FF' thread (specification A-A-59826), Nylon '3-cord' thread (specification A-A-59826), and Kevlar, size 'FF' thread (specification A-A-55220). For consistency each pattern was equally spaced to provide a stitched width of 1.50 in (W_S) and a theoretical breaking capacity above the estimated maximum capacity of the structural member. The ultimate capacity of the joined structure was estimated at 7,000 lbf. In addition, the degradation of the thread was estimated at 2.00. The test specimen pattern characteristics are shown in Figure 3 through Figure 5.

Table 3. Stitch Pattern Properties

Pattern	Thread Type	P_S [lbf]	Mean Values		N_p	DF_T	W_s [in]
			S_T	SPI_{ACT}			
4 Point Cross Stitch	Nylon, 'FF'	7000	17.5	7.50	2	2.00	1.50
4 Row, Staggered Zig-Zag	Nylon, 'FF'	7000	17.5	30.0	2	2.00	Not Required
4 Ellipses	Nylon, 'FF'	7000	17.5	7.50	2	2.00	1.50, 1.13, 0.75, 0.38
4 Point Cross Stitch	Nylon, '3 CORD'	7000	27.0	6.50	2	2.00	1.50
4 Row, Staggered Zig-Zag	Nylon, '3 CORD'	7000	27.0	22.0	2	2.00	Not Required
4 Ellipses	Nylon, '3 CORD'	7000	27.0	6.50	2	2.00	1.50, 1.13, 0.75, 0.38
4 Point Cross Stitch	Kevlar, '120'	7000	45.0	7.50	2	2.00	1.50
4 Row, Staggered Zig-Zag	Kevlar, '120'	7000	45.0	30.0	2	2.00	Not Required
4 Ellipses	Kevlar, '120'	7000	45.0	7.50	2	2.00	1.50, 1.13, 0.75, 0.38

The required stitching lengths (L_{REQ}) were calculated from the pattern characteristics in Figure 3 and solving Eq. (4) for L_S.

$$P_s = \frac{N_P \cdot S_T \cdot SPI_{ACT} \cdot L_S}{DF} \rightarrow L_S = \frac{DF \cdot P_S}{N_P \cdot S_T \cdot SPI_{ACT}} \tag{4}$$

Each of the particular patterns has a different equation associated with the specific geometry of the pattern. Figure 3 through Figure 5 depict each of the patterns characterized in this study, while Eq. (5) through Eq. (7) describes the equations used in determination of stitching.

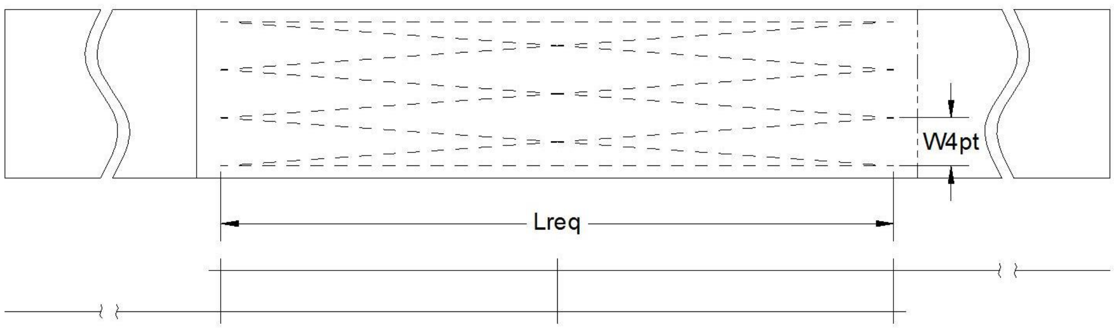


Figure 3. 4 Point Cross-Stitch Pattern Drawing

$$L_S = 6 \cdot \sqrt{w_{4pt}{}^2 + L_{REQ}{}^2} + 2 \cdot L_{REQ} \tag{5}$$

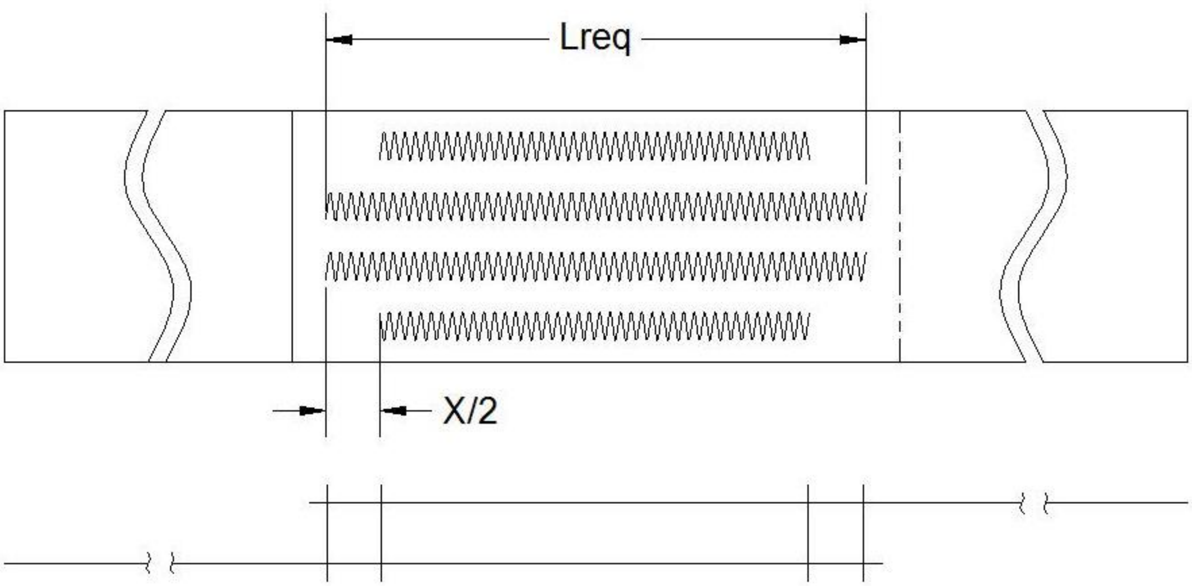


Figure 4. Staggered Zig-Zag Pattern Drawing

$$L_S = 2 \cdot L_{REQ} + 2 \cdot \left(L_{REQ} - x\right) \tag{6}$$

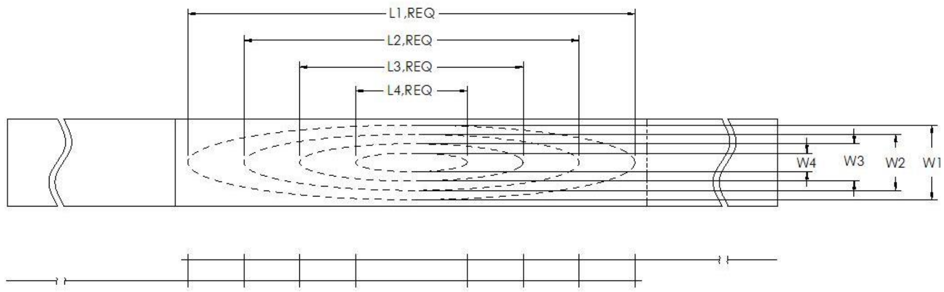


Figure 5. Concentric Elliptical Joint Pattern Drawing

$$L_S = \pi \cdot \left(\frac{L_{x,REQ} + W_x}{2}\right) \cdot \left(1 + \frac{3 \cdot h_x}{10 + (4 - 3 \cdot h_x)^2}\right) + \cdots$$
$$Where\ h_x = \frac{\left(\frac{L_{x,REQ} - W_x}{2}\right)}{\left(\frac{L_{x,REQ} + W_x}{2}\right)}, x = 1, 2, 3, 4\ (number\ of\ ellipses) \tag{7}$$

Table 4. Estimated Stitch Pattern Required Lengths

Pattern	L_{REQ} [in]	L_{ACT} [in]	Notes
4 Point Cross Stitch	6.66	7.00	None
4 Row, Staggered Zig-Zag	3.33 (AVG)	3.38 (AVG)	None
4 Ellipses	10.50, 7.88, 5.25, 2.63	9.00, 6.75, 4.50, 2.25	Sewing machine maximum length is 9.00
4 Point Cross Stitch	5.00	7.00	Maintained same dimensions for consistency
4 Row, Staggered Zig-Zag	3.00 (AVG)	3.38 (AVG)	Maintained same dimensions for consistency
4 Ellipses	7.50, 5.63, 3.75, 1.88	9.00, 6.75, 4.50, 2.25	Maintained same dimensions for consistency
4 Point Cross Stitch	2.57	7.00	Maintained same dimensions for consistency
4 Row, Staggered Zig-Zag	1.30	3.38 (AVG)	Maintained same dimensions for consistency
4 Ellipses	3.50, 2.63, 1.75, 0.875	9.00, 6.75, 4.50, 2.25	Maintained same dimensions for consistency

The average thread pull angle is estimated form the shift between the substrate plies as described in Eq. (8). Though thread pull angle is not typically a key characteristic of concern for joint construction, the results of this study imply that perhaps degradation of the stitching may be more significant than originally understood.

$$\theta = \tan^{-1}\left(\frac{t_{sub}}{\delta}\right) \tag{8}$$

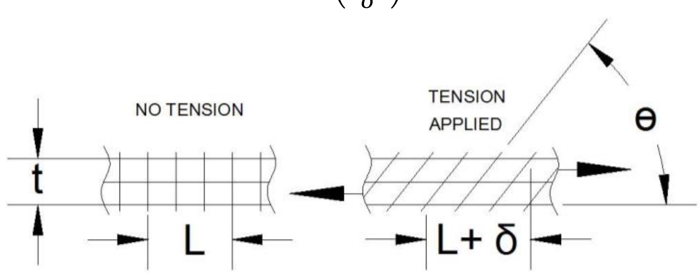


Figure 6. Thread Pull Angle Definition

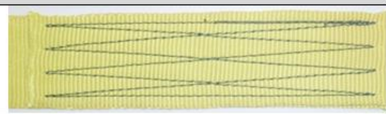
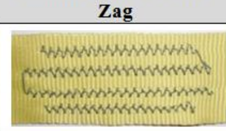
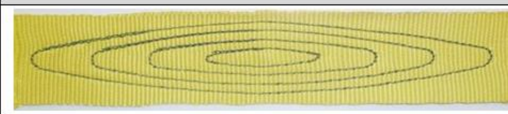
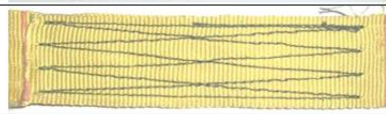
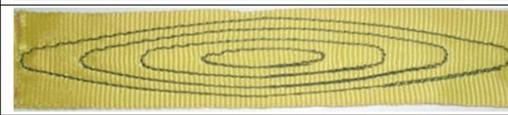
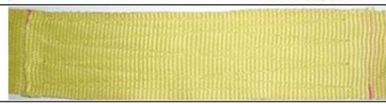
Consistency in the sewn geometry is important to obtain a direct comparison with the simulation geometry. Table 5 defines specified strengths and stitch per inch requirements for each of the thread types used in the manufactured samples. The average SPI values are used to define the width and length of the pattern.

Table 5. Thread Specification Properties

Thread Size	Nylon (A-A-59826)	Kevlar (A-A-55220)	Type 301, Straight			Type 308, Zig-Zag, Double		
	MIN (lbf)	MIN (lbf)	MIN SPI	MAX SPI	AVG SPI	MIN SPI	MAX SPI	AVG SPI
FF	17.5	45.0	6	9	7.5	6	9	7.5
3	27.0	NR	5	8	6.5	4	7	5.5

A programmable stitching machine is utilized to guarantee that each stitch pattern has the same geometry and total stitch count. The constructed test samples are depicted in Table 6, note the 'FF" Kevlar cord is difficult to discern due to its similar color to the base Kevlar tape material.

Table 6. Constructed Test Samples

	4-Point Cross Stitch	4 Rows Staggered Zig-Zag	4 Concentric Elipses
Nylon 'FF'			
Nylon '3' Cord			
Kevlar 'FF'			

Though only a single sample of each of the constructed joints are shown in Table 6, each of the individual samples is relatively interchangeable.

IV. Testing Overview

In order to provide comparison and verification to M&S studies, destructive testing must be completed. Nine variations of a simple overlap joint were constructed. Three stitch patterns were sewn using three types of thread typical for this type of substrate. As described in Section III, the base substrate chosen was 1.75 in, 6500 lbf Kevlar tape because of its simple single layer construction, sufficient width that allows deformations to be clearly observed during testing and perhaps most importantly due to its availability.

Because of the variance in test results due to material setup in the tensile test machine and stitching variations, five samples were manufactured to provide a more robust average breaking strength value. Five destructive control tests for the substrate and two for the threads are required in order to provide a basis for comparison for joint efficiency, as well as to provide load verses elongation curves to be input into the models. All control samples are from the same material lots to ensure a direct comparison is made. Additionally three tests characterizing the strength degradation to lock stitched threads will provide inputs into models and calculations that cannot be easily obtained theoretically.

Two of the stitch patterns chosen are typical designs used for overlaps: four rows of zig-zag and 4 point cross-stitch. One of the purposes of developing an M&S method to analyze joint designs is to be able to quantitatively, but inexpensively, test the feasibility of new joint designs. Using a correlated M&S tool allows for a designer to relatively quickly study effects of different materials, stitch patterns, stitch densities on textile joints. This ability to quickly assess the joints has the potential to reduce the overall cost and schedule associated with a typical system level design cycle. To reflect this, a novel design utilizing four concentric ellipses was chosen to test the exploratory nature of the M&S methods. A complete summary of the test samples that were constructed is listed in Table 7.

Table 7. Destructive Test Matrix

Test	Number of Tests Planned
Controls	
Substrate Control	5
Nylon ‘FF’ Thread	2
Nylon ‘3 CORD’ Thread	2
Kevlar ‘120’ Thread	2
Test Specimens	
Lock Stitch, Nylon ‘FF’	2
Lock Stitch, Nylon ‘3 CORD’	2
Lock Stitch, Kevlar, ‘120’	2
4 Point Cross Stitch, Nylon ‘FF’	5
4 Row, Staggered Zig-Zag, Nylon ‘FF’	5
4 Ellipses, Nylon ‘FF’	5
4 Point Cross Stitch, Nylon ‘3 CORD’	5
4 Row, Staggered Zig-Zag, Nylon ‘3 CORD’	5
4 Ellipses, Nylon ‘3 CORD’	5
4 Point Cross Stitch, Kevlar ‘120’	5
4 Row, Staggered Zig-Zag, Kevlar ‘120’	5
4 Ellipses, Kevlar ‘120	5

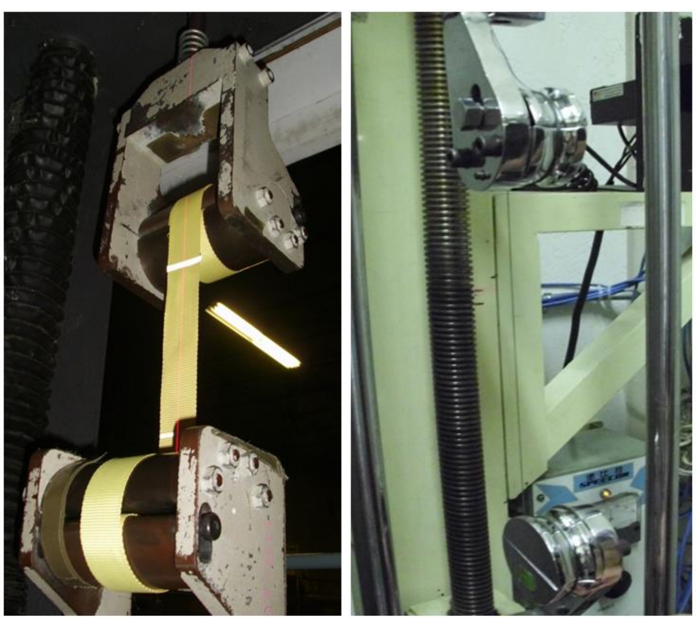


Figure 7. (Left) – Tensile Testing of Control Sample with Extensometer. (Right) – Tensile Testing Lock-Stitch Thread

The objectives for destructive testing are to obtain breaking strengths; elongation values, high speed videos, and still photographs of samples at various loads and after failure. The goal of destructive testing is to provide all actual values needed to verify the simulated values obtained by M&S methods. A 30,000 lbf capacity Tinius-Olson tensile testing machine equipped with a non-contact laser extensometer is used to break all of the substrate samples. The laser extensometer utilizes reflective tape on the specimen to record the differential motion between the two plies of material. All samples are pulled at a rate of 12 inches per minute. This test setup is depicted in Figure 7.

A 300 lbf capacity thread testing machine was used to break the thread controls as well as lock stitch samples. This particular test setup is also depicted in Figure 7

V. Modeling

Using the commercially available transient dynamic finite element analysis (FEA) software LS-DYNA, a model was developed to replicate the test samples and testing methodology described in Section IV. The Kevlar tape was modeled using 2-D shell elements with thicknesses reflective of the base material. Given that standard material specifications for textiles typically specify minimum values with respect to load capability, and that this particular attribute varies significantly from one lot of material to the next, in-house testing was necessary in order to determine the base material strength of the samples. The results of these tests are described in Section VI; and as one can quickly discern, the average breaking strength of the Kevlar tape is approximately 35% greater than the minimum specified material strengths as referenced in PIA-T-87130.

In addition to acquiring sample appropriate breaking strengths, an extensometer was employed to acquire accurate data on the material elongation properties from initial loading through failure. These data were used to define the specific material properties within the LS-DYNA model, particularly the Young's modulus, E, of the material.

Based on the construction of the Kevlar tape, the warp direction of the tape has an inherently higher fiber density; as such, it is assumed for the scope of this analysis linear fiber density correlates directly to material strength. As such, the Young's modulus for the warp direction, E_{warp}, is defined using Eq. (9).

$$E_{warp} = \frac{F_{break}}{e_{break} \cdot A_o} \tag{9}$$

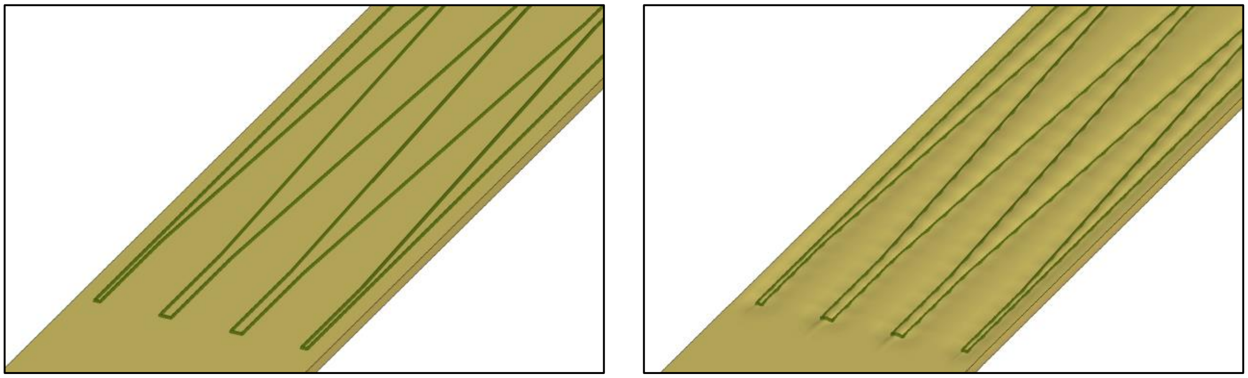
The Kevlar tape was modeled using the LS-DYNA *MAT_FABRIC material model. Given the construction of the Kevlar tape, a unique Young's modulus for both warp and fill directions should be included into the material model definition. The 1.75 in Kevlar tape does not lend itself to an obvious or accurate test method for directly determining the tape strength in the fill direction. As such, a ratio of the total fibers (normalized on a per inch basis) was used to define a Young's modulus, E_{fill}, as described using Eq. (10).

$$E_{fill} = \frac{F_{break,warp}}{e_{break} \cdot A_o} \cdot \left(\frac{n_{fill}}{n_{warp}} \right) \tag{10}$$

As one of the goals of this paper was to characterize the behavior of sewn textile joints while correlating an FEA model to relevant test results, attention to the specifics of the joint construction is central to the accuracy of the model. In addition to characterizing the Kevlar tape, a proper treatment of the joint at a quasi-microlevel is also necessary. Though the interest was to characterize the behavior of the sewn joint, at this point it is worth noting that the scope of this paper is not to necessarily model the direct interaction between individual fibers in the substrate materials and the sewn threads; instead, the base material is assumed to be relatively homogenous and the emphasis of this paper is instead placed on accurately modeling the individual stitches that comprise the textile joints and their influence on the base material.

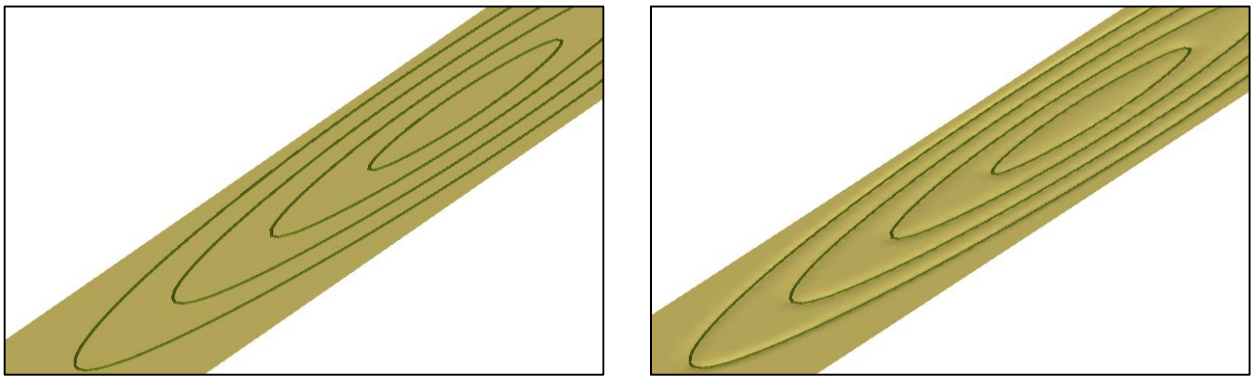
As described in Figure 8 through Figure 10, each of the individual samples is modeled. The individual joint threads are modeled in LS-DYNA using the 1-D element *ELEMENT_SEATBELT. This particular element model was selected on the basis of its ability to incorporate inherent pre-tension in the elements prior to commencement of the simulation. In this case, that is a particularly useful trait given that the sewn joints are held together by threads in tension. This pre-tension is accomplished using a negative slack length which causes the nodes comprising the 1-D element to contract. This contraction imparts a tension into the element appropriate with the material force/elongation properties.

Notice the joint construction before/after the negative slack is applied, as shown in Figure 8 through Figure 10. The inclusion of negative slack allows for a more accurate coupling between the Kevlar base material and the associated joining threads. The thread material is modeled using the data described in Table 10. Using the simple lock stitch data described in Section VI, a joint efficiency for the individual threads was derived. This derived joint efficiency is then assumed to be representative of the threads that comprise the joints. Notice the similarity between the as-constructed and as-simulated joints shown in Figure 11 through Figure 13, test samples on top and simulation results on bottom.



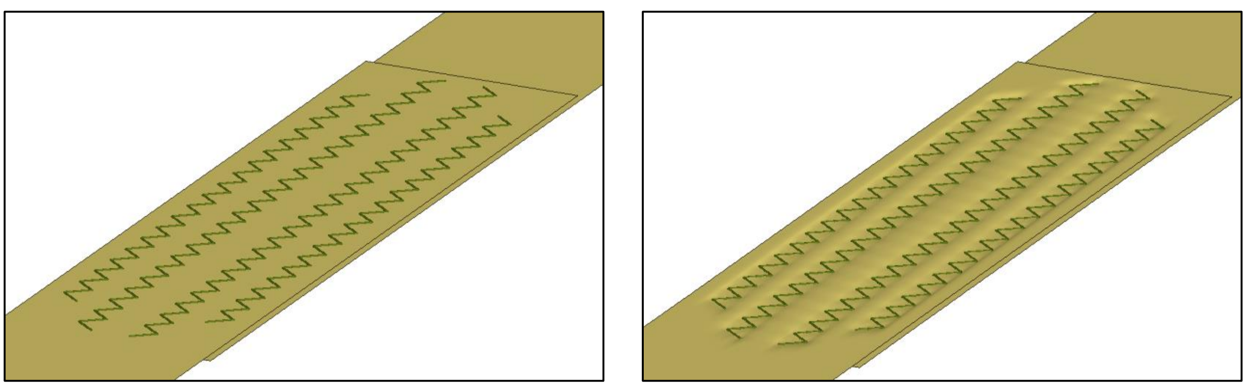
Before Pre-Tension Applied After Pre-Tension

Figure 8. 4 Point Cross-Stitch Simulated Joint



Before Pre-Tension Applied After Pre-Tension

Figure 9. Concentric Ellipse Simulated Joint



Before Pre-Tension Applied After Pre-Tension

Figure 10. Zig-Zag Simulated Joint

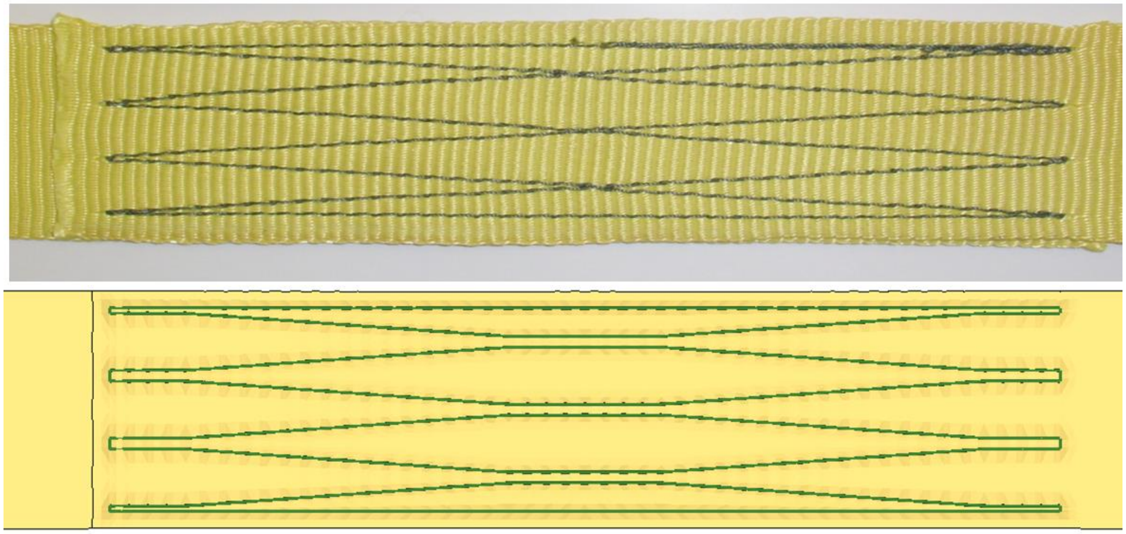


Figure 11. 4 Point Cross-Stitch Sample and Simulation

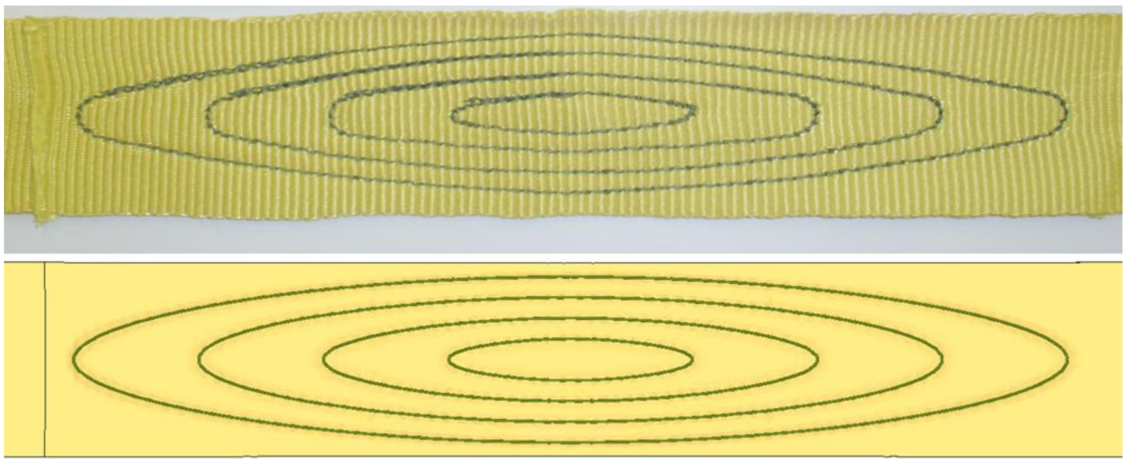


Figure 12. Concentric Ellipse Sample and Simulation

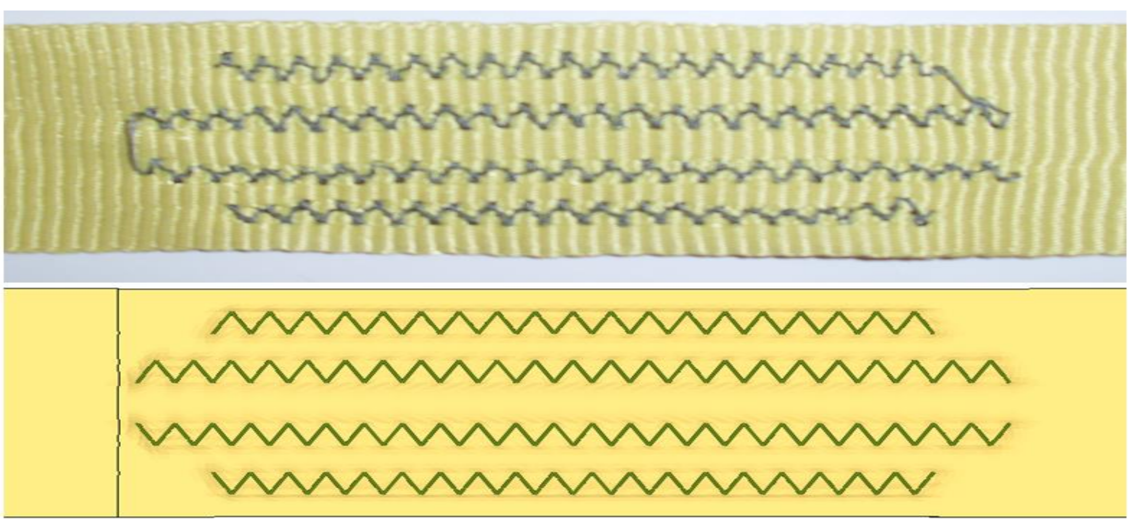


Figure 13. Zig-Zag Sample and Simulation

The model uses the same loading methodology as is reflected in the test setup. The bottom ply is constrained on one end while the opposite end of the top ply is stretched. The nodes at the end of the top ply are displaced using a *BOUNDARY_PRESCRIBED_MOTION card in LS-DYNA with a displacement rate that closely resembles the test fixture head displacement speed. At the onset of the simulation no displacement is imparted initially, this is to allow the sufficient damping time for the negative slack effects prior to commencement of the actual test conditions. The simulation setup is depicted in Figure 14.

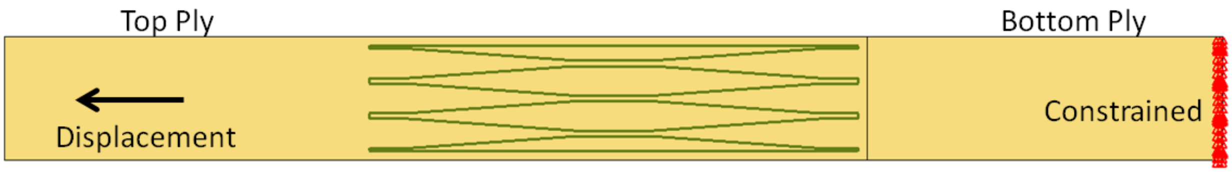


Figure 14. Simulation of Testing Methodology

As mentioned previously, each of the individual stitches that are included in the construction of the joint are modeled as 1-D seatbelt elements, as depicted in Figure 15.

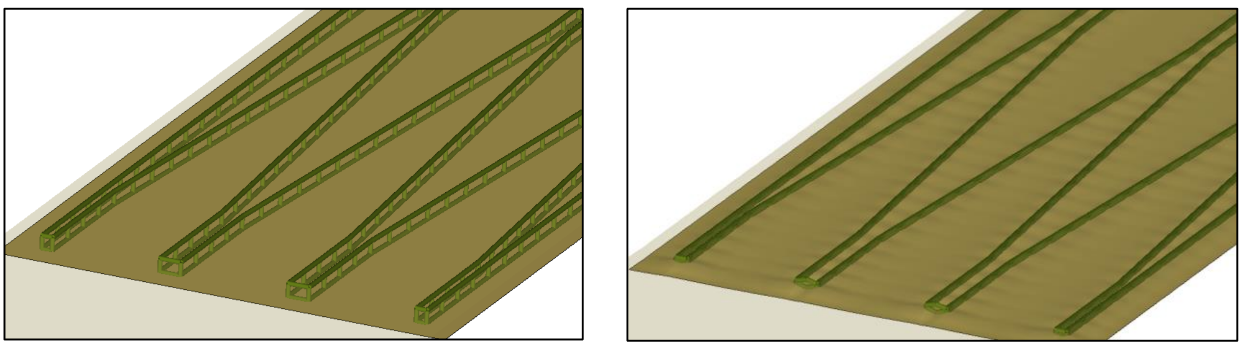


Figure 15. Modeling of Individual Stitches Comprising the 4 Point Cross-Stitch

During the simulation, the forces in all of the stitches are tracked along with the stress/forces in the Kevlar substrate material. In order to simplify the modeling of the joints, the force/elongation relationship for the threads follows the appropriate test data until the breaking strength is exceeded; upon which the material force/elongation relationship allows the threads to stretch.

The PIA-T-87130 specification for Kevlar tape lacks several of the key material characteristics required for modeling the material within LS-DYNA. The Kevlar tape was modeled using the LS-DYNA *MAT_FABRIC material model, as such the inputs described in Table 8 were derived. No direct measurement was performed to derive the E_{fill}; as such, a simple ratio of the number of fibers in the warp/fill directions was used to scale the E_{warp}.

Table 8. Material Properties used in LS-DYNA Model

Material Property	Value	Units
E_{warp}	$3x10^6$	psi
E_{fill}	$7x10^5$	psi
Fabric Density	$2.2x10^{-4}$	lb/in^3

The fabric was modeled using 2-D shell elements with a shell thickness of 0.033 in, a value derived from several measurements of the Kevlar tape in the test lot of material. To ensure no adverse impact of model results derived solely from the fidelity of the finite element mesh, a mesh sensitivity study was conducted before finalizing the overall mesh size used in this study.

VI. Tensile Testing Results

Table 9 lists the actual tests completed, as compared to the planned tests listed in Table 7. It is imperative that all material tested is from the same manufacturing lot. Due to trial and error in the manufacturing process, there was only enough material available to conduct four tests of each of the stitch patterns rather than the five originally planned.

Table 9. Destructive Tests Completed

Test Specimens	Number of Tests Completed
Lock Stitch, Nylon 'FF'	0
Lock Stitch, Nylon '3 CORD'	1
Lock Stitch, Kevlar, '120'	1
4 Point Cross Stitch, Nylon 'FF'	5
4 Row, Staggered Zig-Zag, Nylon 'FF'	4
4 Ellipses, Nylon 'FF'	5
4 Point Cross Stitch, Nylon '3 CORD'	4
4 Row, Staggered Zig-Zag, Nylon '3 CORD'	4
4 Ellipses, Nylon '3 CORD'	4
4 Point Cross Stitch, Kevlar '120'	4
4 Row, Staggered Zig-Zag, Kevlar '120'	4
4 Ellipses, Kevlar '120	4

The stitch patterns designed for this test were created to be able to safely sustain 7000 lbf. of tensile load (P_s) The substrate control material broke around 35% higher than the specified strength. Worth noting is the standard deviation of breaking strength of the substrate verses the thread. The testing methodology required for a high strength, low elongation tape introduces more variables than the low strength, high elongation thread samples. The results of the control sample destructive tests are detailed in Table 10.

Table 10. Control Breaking Strengths

Test Specimen	Specification	No. of Tests	Specification Strength (lbf)	Breaking Strength (lbf)	
				Mean	STDEV
Substrate Control	PIA-T-87130, Type X, Class VII	5	6500	8790	418
Thread, Nylon 'FF'	A-A-59826	2	17.5	21.0	0.000
Thread Nylon '3 Cord'	A-A-59827	2	27	32.0	0.000
Thread Kevlar 'FF'	A-A-55220	2	45	63.5	0.707

A standard method of characterizing the efficiency of a sewn joint in parachute applications is to compare the breaking strength of the samples with the control material. Eq. (11) is a direct comparison of the averages of the sample and control breaks.

$$Mean\ Efficiency = \frac{Average\ of\ sample\ breaks}{(Average\ of\ control\ breaks)(Number\ of\ plies)} \tag{11}$$

Eq. (12) however, takes the standard deviation of the sample breaks into account. Because of its conservative nature, the standard efficiency is more commonly utilized in the parachute industry than the mean efficiency.

$$Standard\ Efficiency = \frac{Average\ of\ sample\ breaks - standard\ deviation\ of\ sample\ breaks}{(Average\ of\ control\ breaks)(Number\ of\ plies)} \qquad (12)$$

The resulting joint efficiencies for each of the constructed joints are detailed in Table 11. In most every case, the failure mode occurred as a result of the failed stitching joining the Kevlar plies together. These results will be directly comparable to the output results from the LS-DYNA simulations. In each case, the zig-zag stitching was the strongest of the samples tested and the concentric ellipses and cross-stitch were similar in capacity.

Table 11. Joint Efficiencies with respect to the Kevlar Substrate

Test Specimen	Thread Type	No. of Tests	Breaking Strength (lbf)		Joint Efficiency wrt Substrate (%)		
			Mean	STDEV	N_p	Mean	STDEV
4 Point Cross-Stitch	Nylon, 'FF'	5	4150	163	1	47.2%	45.4%
4 Row, Staggered Zig-Zag	Nylon, 'FF'	4	4470	138	1	50.9%	49.3%
4 Concentric Ellipses	Nylon, 'FF'	5	3790	240	1	43.1%	40.4%
4 Point Cross-Stitch	Nylon, '3 CORD'	4	5390	398	1	61.3%	56.8%
4 Row, Staggered Zig-Zag	Nylon, '3 CORD'	4	5940	276	1	67.6%	64.4%
4 Concentric Ellipses	Nylon, '3 CORD'	4	4730	410	1	53.8%	49.1%
4 Point Cross-Stitch	Kevlar, 'FF'	4	5040	261	1	57.3%	54.4%
4 Row, Staggered Zig-Zag	Kevlar, 'FF'	4	6190	90.0	1	70.4%	69.4%
4 Concentric Ellipses	Kevlar, 'FF'	4	5120	428	1	58.2%	53.4%

As mentioned previously in Section III, the pull angle of the threads relative to the direction of pull (as defined by Figure 6) was determined by applying Eq. (8) to the results recorded by the non-contact laser extensometer. This angle is important in characterizing losses in stitch strength as a result of localized cosine amplification of the stitches. A reflective tape was placed at the edge of the stitching on each ply to capture the mean elongation due to thread angles between layers of substrate. The initial length between each reflective tape was not recorded, and assumed to be placed at the ends of the stitch pattern in order to derive an estimate angle. The measured joined sample thickness was 0.065 inches and assumed constant. Further evaluation of the pull angle would include actual measurements. Table 12 reports the average estimated pull angles of each stitch pattern variation.

Table 12. Estimated Thread Pull Angles (Geometrically Derived)

Stitch Pattern	Thread Type	Elongation (%)		Length (Lo)	Est. Delta (δ)	Est. Pull Angle (φ)
		Mean	STDEV	Inches	Inches	Degrees
4 Point Cross Stitch	Nylon, 'FF'	4.37	1.36	7.00	0.306	12.0
4 Row, Staggered Zig-Zag	Nylon, 'FF'	6.23	0.64	3.38	0.211	17.2
4 Ellipses	Nylon, 'FF'	4.92	1.43	9.00	0.443	8.35
4 Point Cross Stitch	Nylon, '3 CORD'	4.02	0.94	7.00	0.281	13.0
4 Row, Staggered Zig-Zag	Nylon, '3 CORD'	6.80	0.48	3.38	0.230	15.8
4 Ellipses	Nylon, '3 CORD'	4.97	0.63	9.00	0.447	8.27
4 Point Cross Stitch	Kevlar, '120'	3.78	0.80	7.00	0.265	13.8
4 Row, Staggered Zig-Zag	Kevlar, '120'	5.33	1.20	3.38	0.180	19.8
4 Ellipses	Kevlar, '120'	4.27	1.01	9.00	0.384	9.60

The standard efficiency equation described by Eq. (12) gives a parachute designer a good idea as to how a certain joint will perform in a parachute system. In order to determine global stitching degradation factors for certain stitch patterns and threads, rather than for one specific joint, the breaking strength must now be compared to the strength of the thread rather than the substrate. This is done by utilizing the control strengths of the thread. The design factors derived from these efficiencies can be utilized to create stitch patterns where the thread strength surpasses the strength of the substrate.

The standard efficiency utilizing the control strength of the threads and the thread angle is defined below in Eq. (13). The thread angle, θ, was included to compensate for the cosine amplification of the thread.

$$Standard\ Efficiency = \frac{Average\ of\ sample\ breaks - Standard\ deviation\ of\ sample\ breaks}{(Average\ of thread\ control\ breaks) \cdot (No. of\ plies\ of\ thread\ in\ pattern) \cdot (Cos\ \theta)} \tag{13}$$

The joint efficiencies with respect to the threads as derived through testing are detailed in Table 13. Though these values are not explicitly used in this study, they are shown here for completion.

Table 13. Estimated Joint Efficiencies with respect to the Threads

Test Specimen	Thread Type	No. of Tests	Breaking Strength (lbf)		Joint Efficiency wrt Thread (%)			
			Mean	STDEV	N_{pt}	Est Pull Angle (φ)	Mean	STDEV
4 Point Cross Stitch	Nylon, 'FF'	5	4150	163	782	12.0	25.8%	24.8%
4 Row, Staggered Zig-Zag	Nylon, 'FF'	4	4470	138	810	17.2	27.5%	26.7%
4 Ellipses	Nylon, 'FF'	5	3790	240	700	8.35	26.0%	24.4%
4 Point Cross Stitch	Nylon, '3 CORD'	4	5390	398	677	13.0	25.5%	23.6%
4 Row, Staggered Zig-Zag	Nylon, '3 CORD'	4	5940	276	594	15.8	32.5%	31.0%
4 Ellipses	Nylon, '3 CORD'	4	4730	410	607	8.3	24.6%	22.5%
4 Point Cross Stitch	Kevlar, '120'	4	5040	261	782	13.8	10.5%	9.9%
4 Row, Staggered Zig-Zag	Kevlar, '120'	4	6190	90.0	810	19.8	12.8%	12.6%
4 Ellipses	Kevlar, '120'	4	5120	428	700	9.60	11.7%	10.7%

Additionally, high-speed photography was incorporated into the test setup for two of the sample tests. The intent was to capture the failure propagation using the high speed camera; unfortunately, the event was too fast for the highest frame rate of the high speed camera available. With that, the camera stills do prove valuable from a qualitative standpoint as they compare to the highly stressed states predicted in the LS-DYNA simulations. A comparison between the model and the test specimens can be found in Section VII.

VII. Simulation Results

As described in Section V, failure in the LS-DYNA simulation is defined as the point at which the force in the Kevlar tape substrate exceeds its breaking strength or when the forces imparted into the 1-D stitching elements exceeds their breaking strength, whichever occurs first. In each of the test cases analyzed in this study, the stitches failed prior to the failure of the Kevlar substrate. Construction of test samples such that the substrate materials are intended to fail before the threads is a subject intended for future work.

In each of the simulation results, the thread forces are monitored, once the force exceeded the breaking strength of the thread, that time was cross-referenced with the force applied in the system. The force in the system is considered to be the breaking strength of the combined system. The methodology is illustrated in Figure 16. The resulting principal stress tensors are overlaid with the principle elemental stresses, the results of these for each type of stitch pattern are shown in Figure 17. In each of the cases, the predicted failure points occur at the transition from the stitched joint to the Kevlar tapes, the highly red regions detailed in Figure 17.

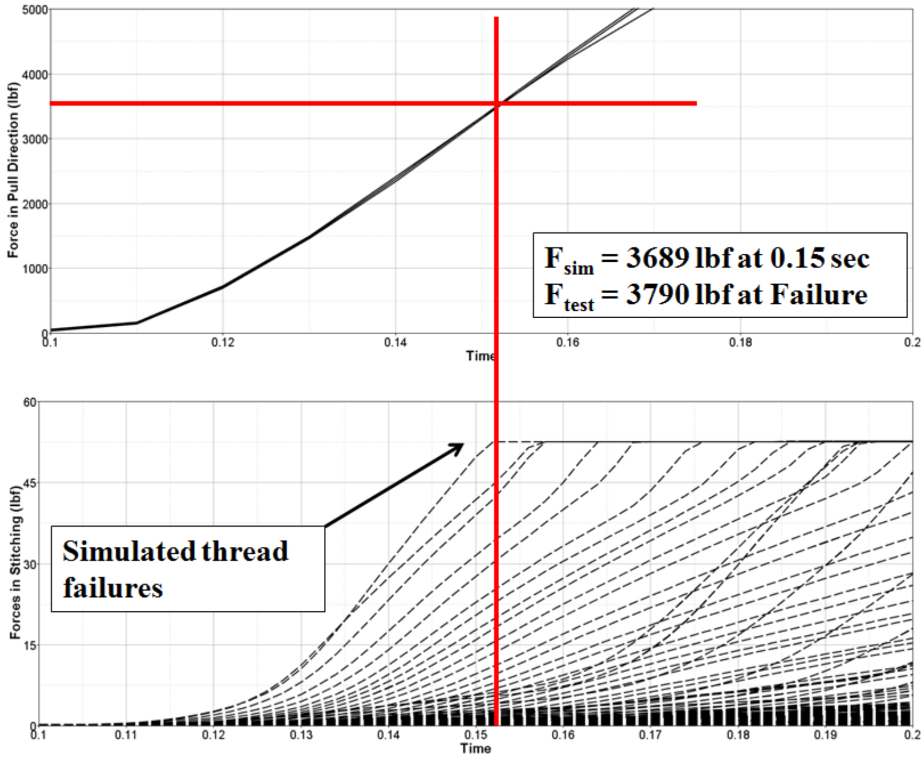


Figure 16. Cross-Referencing Force in Pull Direction at Time of Stitch Failure

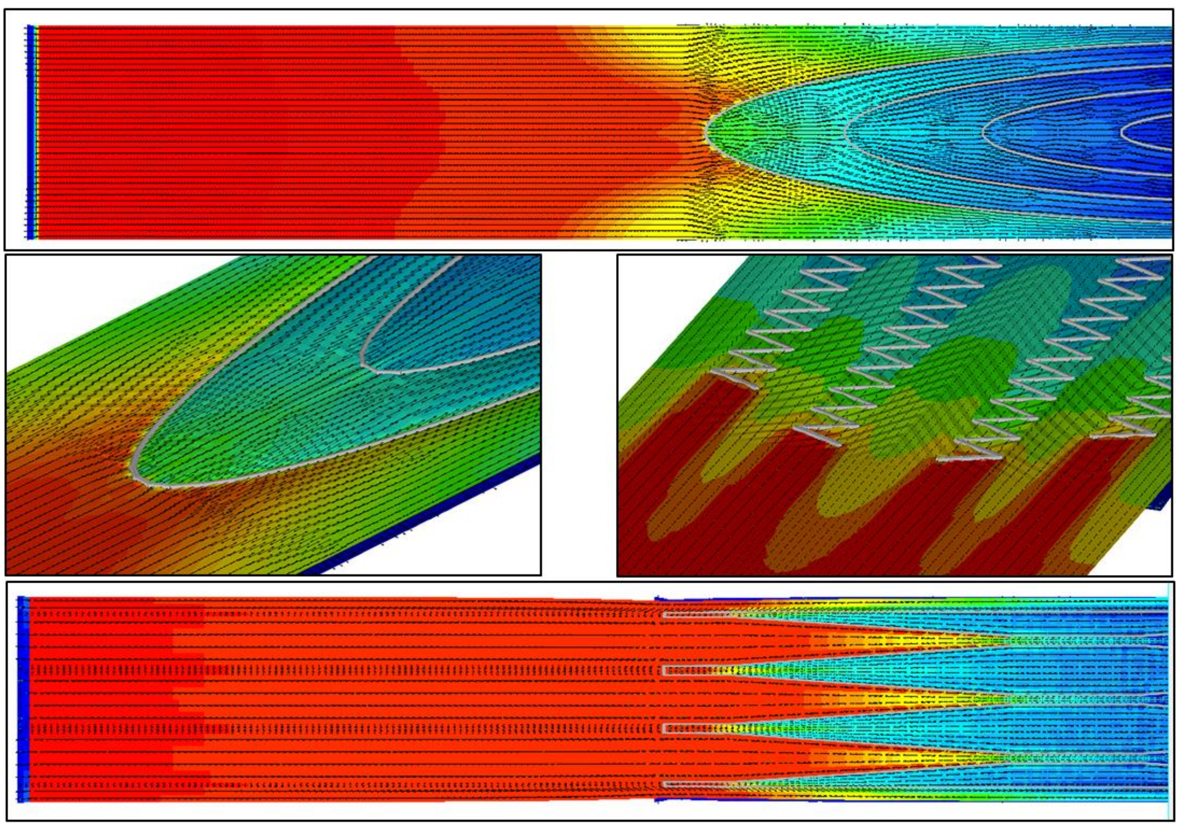


Figure 17. Stress Contours with Principal Stress Tensor Overlays for each of the Test Samples

A side-by-side comparison of the high-speed video (500 fps) and the moment of failure in the simulation are shown in Figure 18. The overall behavior is replicated well through simulation means; however, one of the notable differences is the presence of the interior stitches of comprising the cross-stich "popping" prior to catastrophic failure during the high speed testing. No interior stitch failures are noted in the simulation results, this could suggest these stitches are failing due to asymmetries not present in the model as-constructed.

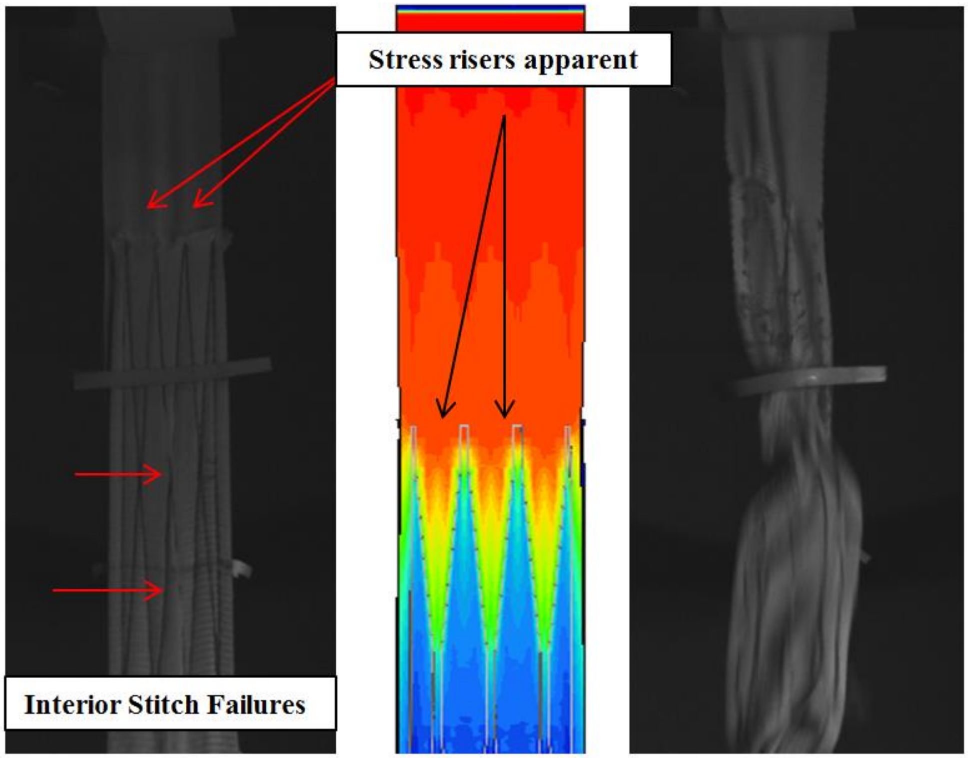


Figure 18. High-Speed Video and Simulation Result Comparison (4 Point, Cross-Stich, "FF" Nylon)

The complete simulation results are tabulated in Table 14, and the overall correlation between the test data and the model was highly encouraging. The largest variation between the simulation results and the test results was observed in the Kevlar "FF" thread simulations and the zig-zag stitch simulations. In each of those cases, the simulation predicted a higher force capacity for the sewn joint than was observed during the test. Continued testing and further material and stitching model correlations can only work to improve the predictive capability of the simulation. The model predicts the joint failure within 15% of the tested results; knowing that, this model can be used to help drive overall joint design by allowing a designer to directly interrogate the causes of stress risers within the fabric sewn joint.

Table 14. Simulation Results Compared Directly to Testing Results

Stitch Type	Nylon "FF" Thread			3-Cord Nylon			Kevlar "FF" Thread		
	Sim	Test	% Diff.	Sim	Test	% Diff.	Sim	Test	% Diff.
Concentric Ellipses	3689	3790	2.7%	4290	4730	10.3%	5510	5120	-7.1%
4 Point Cross-Stitch	4123	4150	0.7%	5344	5390	0.9%	5890	5040	-14.4%
Zig-Zag Stitch	5048	4470	-11.5%	6419	5940	-7.5%	6731	6190	-8.0%

VIII. Conclusions and Recommendations for Future Work

Further work will continue on this modeling methodology to better understand the coupling between the threads and substrate materials. Airborne Systems plans to conduct additional testing to further develop this already promising modeling tool. The next series of testing will include substrate materials that will failure prior to the stitched joint; this will allow for further correlation and expanded capability of the simulation. Other areas of interest for future work on this subject include:

- Simulation of dynamically loaded joints with the intent of understanding impact on shock loading with respect to stress risers and overall constructed joint efficiency
- Expansion of this methodology to include broadcloth and textile cords
- Additional base material sizes to expand the overall capability of the simulation
- Interrogation of manufacturing influence on constructed joints; for instance, conducting sensitivity studies to the pre-tensioned thread that would cover normal operational ranges of sewing machines for a given sewn joint and understanding the potential adverse influences of standard practices such as back-stitching

An exploration into the cause of the interior stitch popping prior to the peak force that is not present in the simulation but was present in all of the tests is also worth considering. These local asymmetries, whether they are imparted through slight anti-parallel forces from the test fixture or due to sewing techniques, could be the cause of local stress risers in the base Kevlar material.

Additionally, more data will allow for further study into the importance of the thread angle as described by Figure 6 with the results tabulated in Table 12. As noted, the thread angle for each sample was approximately 70 degrees, at this time it is not fully understood if that angle would dramatically change if different substrate materials, joining threads, or joint stitch patterns were employed.

All of the objectives listed in Table 1 were sufficiently met; with that, further work is required to correlate the model to the existing test data set and for use on other joint construction.

Acknowledgments

The authors would like to thank Airborne Systems for allowing us the opportunity to conduct these tests and pursue development of this simulation tool, they would also like to thank Scott Hilton for his help sewing samples into the wee hours of the night.