Spring Orthosis Analysis – Finite element modeling and optimization of a composite material

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Abstract: This paper covers finite element (FE) analysis and optimization of a spring orthosis, constructed from a pre-impregnated carbon-fibre epoxy composite material. The spring orthosis is one of the most advanced aids that are used in the orthopedist industry. The work has been performed in collaboration with Ortopedteknik, Borås Hospital, at FS Dynamics in Gothenburg.

The purpose of the analyses was to find weaknesses of how the orthosis is built today and to give suggestions of how to change its properties and behaviour. The orthosis has two major interesting areas, the spring and the toe. Both of these areas were analyzed regarding rotation angles of the plies and ply stacking sequence. The geometry of the orthosis, material type and number of composite plies in toe and spring were kept constant during the analysis. The material was modeled as a balanced orthotropic lamina, with a plane stress assumption. To validate the material model a four point bending test of a composite plate was modeled in Abaqus/CAE and compared with experimental data. The interactive Tsai-Wu failure criterion was used as a relative stress measurement. The FE model of the orthosis was created from a scan of the real orthosis. From this the front surface was extracted and used as a thin shell model. The composite layup of the orthosis was created in the way to best imitate the manufacturing procedure used by the engineers at Ortopedteknik.

To be able to analyze the orthosis a walking cycle was recorded from a person wearing the orthosis. This walking cycle was then applied to the model in Abaqus by prescribing reference points and using boundary conditions and multi point constraints. The maximum Tsai-Wu values in the toe and spring part during this walking cycle indicate that the orthosis is not close to failure. The Design Of Experiment (DOE) methodology was used to analyze how the stacking sequences of both the spring (18 plies) and the toe (5 plies) affect the bending stiffness. This was done using the four point bending test in Abaqus where the vertical reaction force was used as stiffness measure. It was found that the angle variation of the outermost plies of the spring has the most effect on the bending stiffness. For the toe the rotation of the two outermost plies are almost alone deciding the bending stiffness of the toe.

From the DOE data approximations were created and then used to optimize stacking sequences based on requested bending stiffnesses.

Keywords: Abaqus CAE, Carbon fibre, Composite material, Composite modeler, Design of experiment, Draping, Finite element analysis, Four point bending test, Isight, Laminate, Optimization, Orthosis, Ply, Shell and Tsai-Wu.

1. Introduction

This work covers FE-analysis and optimization of a spring orthosis. A spring orthosis is one of the most advanced walking aids that are used in the orthopaedist industry today. The work has been performed in collaboration with Ortopedteknik, Borås Hospital, Sweden. The orthoses are designed individually to match the needs of each unique patient. The orthosis is made from a pre-preg material (pre-impregnated carbon fiber with epoxy) and is manufactured by hand by the engineers at Ortopedteknik. Today experiences from previously built orthoses form the ground of how new orthoses are built. In order to develop the product further and deeper, analysis is needed, which includes calculations using FEM. A deeper understanding would improve the possibilities of creating a better aid for each individual patient.

Figure 1 shows how the orthosis looks when it is ready to be used and when the buckles have been removed. The attached reflectors in were used when recording the walking cycle with position cameras.

1.1 Purpose

The purpose of the FEM analysis is to find weaknesses of how the orthosis is built today and to give suggestions in order to change its behaviour and properties. The orthosis has two major interesting areas, the spring part and toe part, marked in Figure 1. In these areas the main part of the deformation occurs.

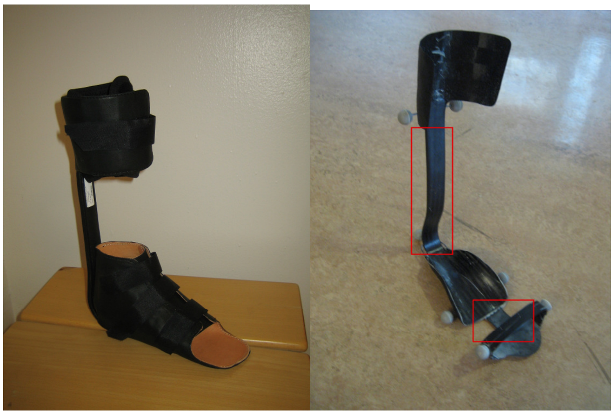

Figure 1. The spring orthosis with and without buckles. The red areas mark the two areas of interest, the spring and the toe.

The following questions are investigated:

- Where and when do the largest stresses occur during an ordinary walking cycle?

- How does the orientation of the composite plies change the bending stiffness of the spring and the toe?
- Which plies have most impact of the bending stiffness of the toe and the spring?
- Is there a way to obtain a ply stacking sequence based on requested bending stiffness?

2. Modelling the material

The spring orthosis is made from a pre-impregnated (pre-preg) high strength carbon fibre composite material. The composite is woven as a 4x4 twill, see Figure 2, with material parameters according to **Error! Reference source not found.**.

Woven composites are often assigned one warp and one weft direction, where the weft direction is transverse the warp direction (often, but not necessarily, perpendicular to each other) (Åström 1997). Depending on how the weft fibres are woven relative the warp fibres different properties can be obtained in different directions. The 4x4 twill has no differences between the warp and weft direction.

Figure 2. 4x4 twill

Table 1. Material parameters for 4x4 twill

$E_1^{tensile}$	60.0	GPa
$E_1^{compressive}$	54.1	GPa
$E_2^{tensile}$	60.0	GPa
$E_1^{compressive}$	54.1	GPa
Tensile strength	700	MPa
Compressive strength	541	MPa
ν_{12}	0.08	
G_{12}	3.87	GPa
In plane shear strength	95.5	MPa
Inter laminar shear strength	71 4	MPa

The spring orthosis is created from 24 separate plies, or laminas, together forming a laminate. Of these plies, 18 are used to construct the spring, whereas the rest 6 plies are mainly to provide comfort for the user. The toe part consists of 5 out of the 18 plies used to create the spring. The plies forming the spring are cut to rectangular strips from a large sheet of carbon fibre received from manufacturer. Each ply is then separately applied onto a cast of the patient's foot, this procedure is called draping. Since this is done by hand the draping procedure varies from one job to another, depending on who is performing it and the variation of pressure applied by the constructing engineer.

Results from a four point bending test were used to verify the material model. The test specimen consists of 18 plies, stacked [45°/0°], and they were hand made in the same way as the orthosis is. Figure 3 shows the test setup.

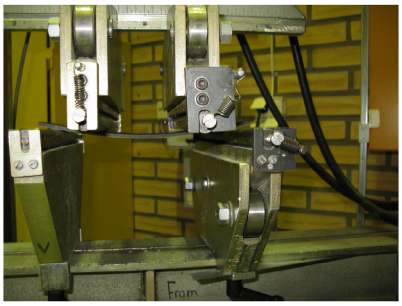

Figure 3. Set-up of four point bending test.

The load was applied on the two middle supports until failure occurred, i.e. when the test specimen lost all its strength. The displacement as well as the applied force was recorded throughout the entire test period until the ultimate failure occurred, see Figure 4. To be able to verify the material model the four point bending test was reconstructed in Abaqus/CAE.

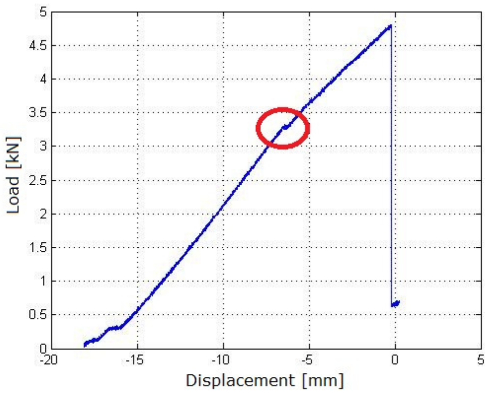

Figure 4. Force displacement curve from the four point bending test. The highlighted area shows where the assumed failure of the top lamina occurred. The sharp drop in stiffness represents a brittle failure, which is typical for carbon fiber composite.

A compressive failure of the top ply was assumed to have occurred, as can be seen as a small dip in Figure 4. The force, 3.3kN, and the displacement, -11.3mm, recorded at this dip were used as a reference state. The material was modelled as a balanced orthotropic lamina with $E_1 = E_2$. This corresponds to the material model "lamina" in Abaqus/CAE which is a plane stress orthotropic elasticity material model. Required parameters in this model are E_1(= E_2), ν_{12}(=ν_{21}), G_{12} and G_{13}(= G_{23}). The out of plane shear moduli G_{13}(= G_{23}) are needed for the out of plane stiffness needed to model the transverse shear deformation. Since G_{13} and G_{23} are not given in the material data sheet they were tuned so that the vertical reaction force would match the force obtained from the test.

The Tsai-Wu failure criterion was used as an equivalent stress measure, the cross product term coefficient was chosen to be -0.5. This failure criterion was used when comparing different test parameters and to investigate where and when failure has occurred.

From the material data sheet one can see that Young's modulus differs in compression and tension. To compensate for this an average of E_1 and E_2 was calculated accordingly:

$$E_{1,2} = \frac{1}{2}\left(E_{1,2}^{compressive} + E_{1,2}^{tensile}\right)$$

The stacking sequence used is the same as for the original layup of the spring, 18 plies with [45°/0°], see Figure 5.

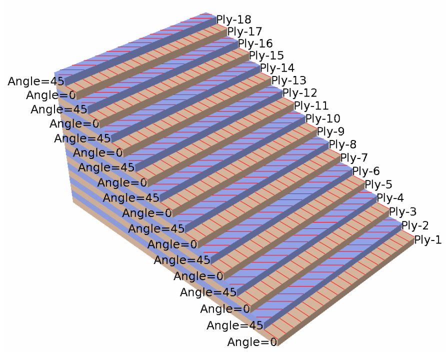

Figure 5. Ply stack plot of the composite layup of the plate.

The test was set up in Abaqus/CAE using symmetry in x- and z-direction. When tuning in the unknown material parameters a thick continuum shell model with the element type SC8R was used. For the analysis of how the composite layup of the toe and the spring affects the bending stiffness a thin shell model with the element type S4R was used. The test set up with boundary conditions are shown in Figure 6. The friction coefficient was chosen to be 0.2.

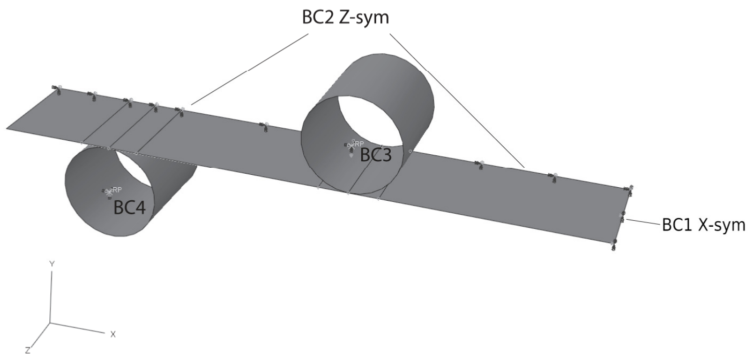

Figure 6. Test setup in Abaqus. The boundary conditions for the test setup are also shown. BC4 is fixed while BC3 is prescribed 11.3mm in negative y-direction.

3. Orthosis model

The spring orthosis was scanned to get the FE model. From the scanned geometry the front surface was extracted and used in the analysis, see Figure 7. The model was meshed with the first order shell elements S4 and S3. The second order element S8R was rejected due to poor convergence properties of the analyses performed.

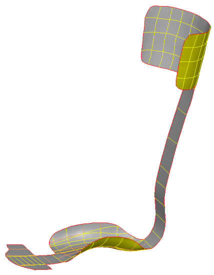

Figure 7. Front surface of the scanned geometry.

The composite layup was created in Composite Modeller (CM). CM allows you to create composite plies with varying properties and orientations. An advantage of CM compared to creating a composite layup in Abaqus/CAE is that it allows you to choose how the plies are draped onto the model. One option is to let a ply orientation follow a seed curve. Figure 8 shows the difference between applying a ply with and without seed curve.

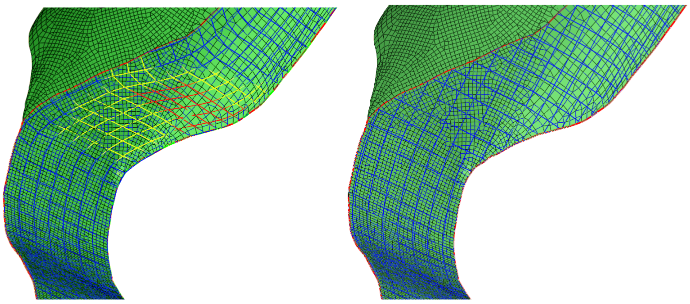

Figure 8. The difference between using a seed curve (left) and not using a seed curve.

3.1 Creating original composite layup

Based on interviews and observations of the engineers at Ortopedteknik the draping procedure was reproduced, this is later referred to as the original layup. The spring orthosis consists of 24 separate plies draped onto various regions. Different element sets were created to match the areas where the different plies are draped onto. 18 plies are used to build the spring and toe. Figure 9 shows the corresponding sets or regions that were used.

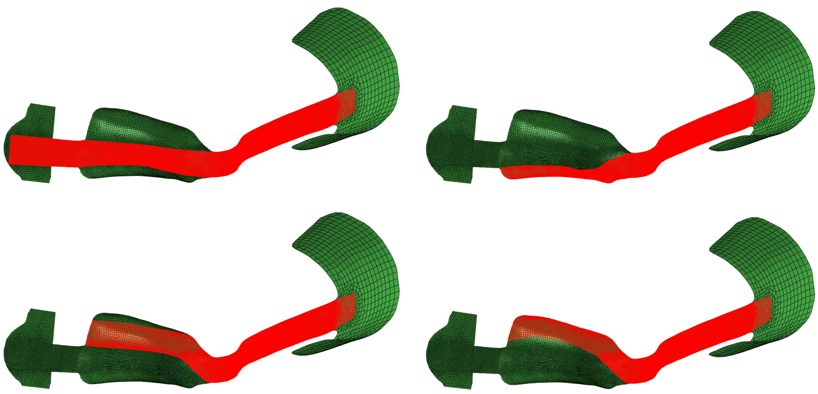

Figure 9. Illustration of different draping regions used when creating the composite layup.

The sets in Figure 9 were created such that they have approximately equal width all the way from the top of the spring to the toe. The seed curves used can be seen in Figure 10. The regions of interest during the analysis are the spring and the toe. These element sets are illustrated in Figure 11.

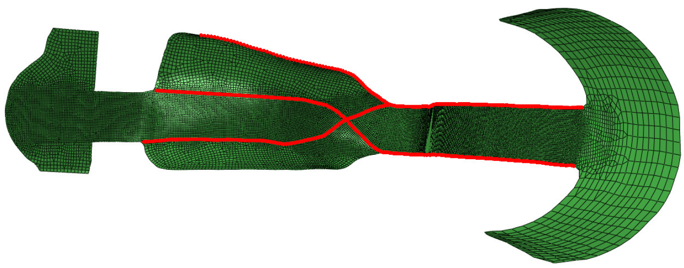

Figure 10. Seed curves used when creating the composite layup.

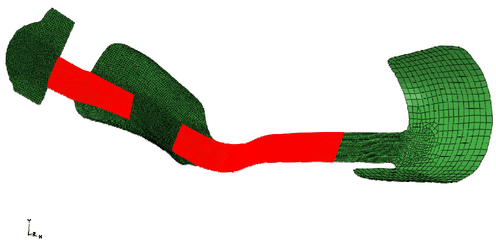

Figure 11. Element sets used for analysis, toe element set and spring element set.

4. Walking cycle

A walking cycle was recorded at Ortopedteknik to see how the orthosis deforms when being used. There were 7 reflectors attached to the orthosis, with positions and numbering according to Figure 12. The reflectors were connected by steel connectors glued onto the orthosis. As the patient walked through the room, there were 8 cameras recording the positions of each reflector. To obtain only one step cycle, 0.88 seconds of the recorded time was extracted, containing 213 time steps. This resulted in 3 time histories each for all 7 reflectors, one for x-movement, y-movement and z-movement.

Figure 12. Positions and numbering of reflectors.

In the Abaqus model the reflectors were replaced by reference points. To control the movement of the reference points each point was assigned three boundary conditions, one for each translation direction. The MPC beam was used to transfer the motion from the reference points to node sets created on the orthosis. Point 2,4 and 6 were used to control the motion. Usage of more than three reference points caused unwanted stress concentrations. To make the orthosis "walk" a general static analysis was performed. The step time period was set to 1 and maximum time increment was set to 1/213 = 0.0046948. This made sure that each of the 213 recorded time steps will be present in the results. A python script was used to extract the states with highest Tsai-Wu value in both the toe and spring. It also showed in what ply the highest value was located.

5. Laminate stacking sequence analysis

This chapter describes analyses created to show how different stacking sequences, ply angles and draping methods affect the behaviour of the spring orthosis. To get an understanding of how the laminate stacking sequence and lamina orientation affect the stiffness of the composite the four point bending test described in section 2 was used. The reaction force was used as a relative measure, i.e. the original layup has a relative stiffness (RS) of 1. A stacking sequence with relative stiffness larger than 1 has a larger stiffness than the original layup and vice verse. A copy of the four point bending test but with 5 plies was also created. The displacement of the roll was still 11.3mm in the y-direction. The reaction force obtained from this model was used as a relative measure for the toe, i.e. the relative stiffness of the toe equals 1 when all plies are oriented 0°.

To get an understanding on how the different plies affect the stiffness the Design Of

Experiment (DOE) methodology was used. The DOE technique makes it possible to extract as much information as possible from a limited number of test runs. This was done using Isight. Both the spring and the toe setup were analysed where each ply in the stack can be rotated between 0° and 45°. This means that the numbers of variables in the two analyses are 18 and 5. To cover the different possible stacking sequences for the 18 layers it would be needed almost infinite number of sequences for continuous parameters. The same holds for the 5 layer stacking sequences. There are different methods to pick these stacking sequences to get the best possible design space. For these analyses the Latin hypercube sampling was used. The sample size, and type of analyses that were made are presented in Table 2. From the DOE a regression analysis output was requested together with basic statistics. These data were then analysed to find interaction properties between the different plies. The different tools that are available for analysis in Isight are described in (Isight manual). The tools that were used in this analysis are;

- Pareto plot.
- Correlation plot
- Main effect plot

The tools listed above were not used individually to determine the interaction properties between the plies. By evaluating all tools together an indication of how the different plies affect the response was obtained.

Table 2. DOEs that were analysed.

Number of layers	Number of variables	Number of samples	Parameters	Name
18	18	400	$0° \leq \theta \leq 45°$	DOE A
5	5	100	$0° \leq \theta \leq 45°$	DOE B

5.1 Creating approximation

From the DOEs presented in Table 2. approximations, i.e. metamodels, were created. In Isight there are two different types of approximations to choose from; response surface method (RSM) and radial basis function (RBF). The response surface model approximates the surface with polynomials up the fourth order according to

$$F(x) = a_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_i^2 + \sum_{ij(i<j)}^{N} c_{ij} x_i x_j + \sum_{i=1}^{N} d_i x_i^3 + \sum_{i=1}^{N} e_i x_i^4$$

where N is the number of model inputs, x_i is the set of model inputs and a, b, c, d and e are the polynomial coefficients. The accuracy of the prediction relies on the amount of data used when constructing the polynomial, the shape of the exact response function that is approximated and the volume of the design space in which the model is constructed. The RBF method uses radial basis function to approximate the function. The RSM and RBF methods in Isight are described in (Isight manual). To validate how good an approximation created out of the estimation is, different error estimation graphs and error estimation numbers will be analysed. A cross validation error analysis procedure was used with 20 randomly chosen points from the data set Four different types of error estimations were considered that are available in Isight; average, maximum, Root mean square and R-squared. The graph used to analyse the error estimation in Isight was;

- **Response fit**. This graph shows the actual versus the predicted values. The diagonal line represents a perfect fit. If all points fall on or close to the line the approximation model predicts well based on the error points.

Those plots show how the predicted results deviate from the actual results graphically. From those values the error estimation numbers are computed, for more information see (Isight manual). To determine which approximation method to use, a comparison between an RBF and a 1st and 2nd order RSM approximation were made for both DOE A and B. Higher order approximations were not considered since they were likely to give unphysical behaviour between the curve fitted data points. In Table 3 the error estimations for the chosen approximations for DOE A and B are shown. The intervals of the relative stiffness that was captured in the test data for the approximation are also shown. The approximation will not be used to predict responses outside those intervals. In Figure 13 the response fit for the approximations of these sets are shown.

Table 3. Error estimations for DOE A and B.

Run	Method	Average	Maximum	Root mean square	R-squared	Interval
A	RSM 2nd order	0.04411	0.08344	0.05061	0.97046	0.56≤RS≤1.13
B	RBF	0.02802	0.06551	0.03352	0.98767	0.34≤RS≤0.96

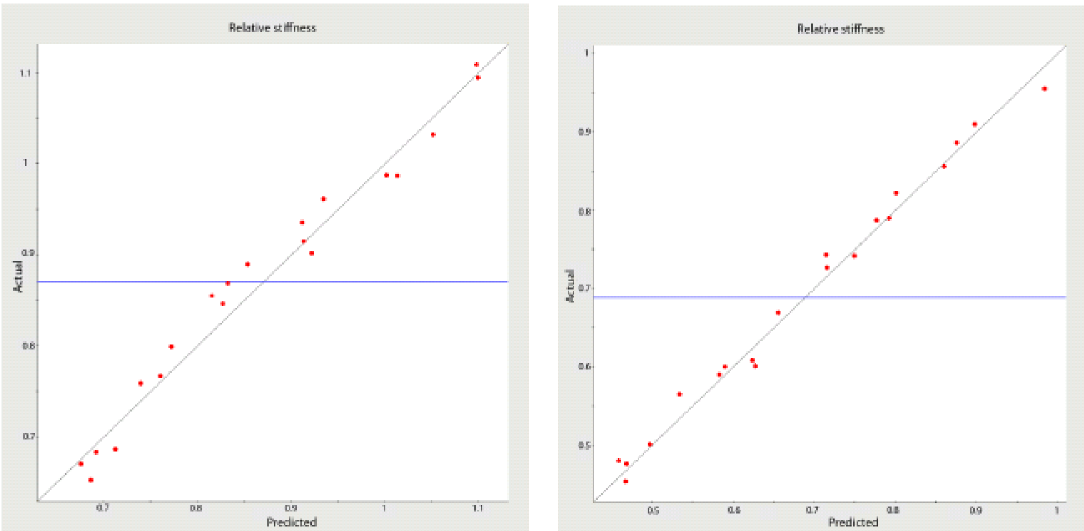

Figure 13. The response fit for DOE A (left) and B. The dots represent the 20 randomly chosen points in the cross validation error analysis procedure.

5.2 Stiffness optimization

The approximations created were used to create optimization loops to generate a stacking sequence for a predefined value of the relative stiffness. This is then compared to the result for the same stacking sequence in Abaqus. The optimization algorithms used for this are Multi-Island GA and ASA, described in (Isight manual). The criteria that were used when choosing these algorithms were that they should be stable and generate values close to the target. If the target is reached the optimization method works. Outside those loops a DOE are running where it is possible to define a matrix of values that should be generated and compared. The Design Gateway from Isight that shows the optimization schedule is shown in Figure 14. Discrete parameters were used in the optimization of stacking sequences. This was done due to the fact that the plies are cut by hand. The chosen parameter values are θ = 0°, 15°, 30°, 45°. Note that one could also use continuous parameters.

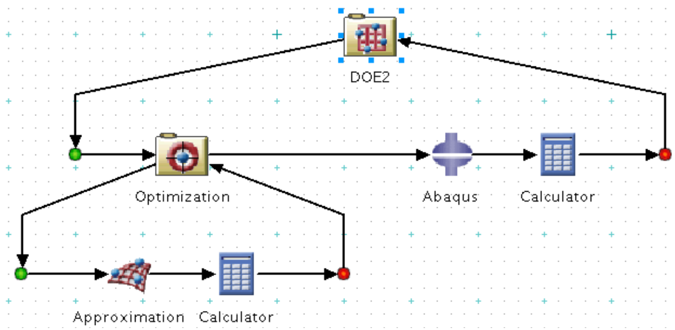

Figure 14. Optimization loop in Isight. The main loop generates relative stiffnesses that will be targets in the optimization of stacking sequences from the curve fitting approximation created from data in the DOE A or B. The resulting stacking sequences are then compared to the result using the same stacking sequence in Abaqus.

To see if the approximations would give predicted values close to the actual values, 30 different relative stiffnesses were chosen for the spring part. These values were equally distributed from the lowest to the highest value in the approximation, see Table 3. The same thing was done for the toe part with 5 plies but with 10 different relative stiffnesses. The stacking sequences generated from the optimization based on these values were compared to the actual results from Abaqus.

6. Results

In this chapter the results from the analyses described in section 3, 4 and 5. The results from Abaqus simulations presented as averaged contour plots are plotted as max absolute envelopes.

6.1 Maximum Tsai-Wu during walking cycle

Figure 15 shows an envelope plot of the maximum absolute Tsai-Wu value. The maximum Tsai-Wu value for the toe element set is 0.4657 located in the top ply. This ply is subjected to compressive stresses due to bending. The location of the maximum is just by a ply drop off. The time frame for this value is 176 which corresponds to a time 70.03 % of the total step time. This is around where the patient uses his/her toes to push off the ground.

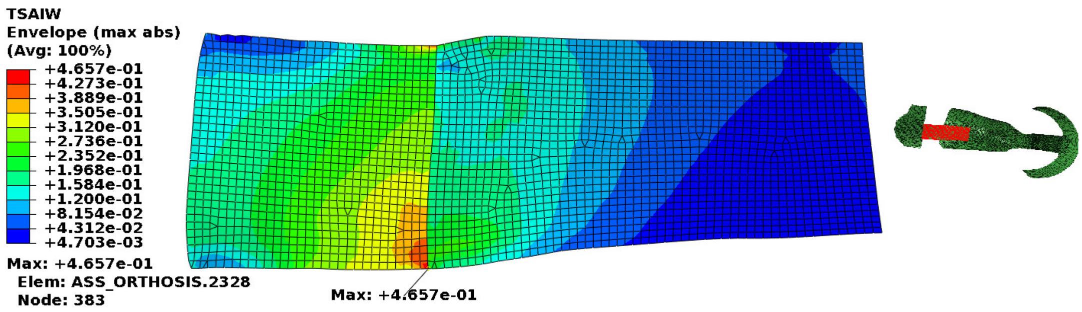

Figure 15. Plot of maximum Tsai-Wu value in toe element set.

The highest Tsai-Wu value for the spring element set can be seen in Figure 16.
The maximum value of 0.3505 is located in the top ply. This ply is subjected to compressive stresses due to bending. The time frame for this value is 201 which corresponds to a time 81.77 % of the total step time. This is around the time where the heel leaves the ground.

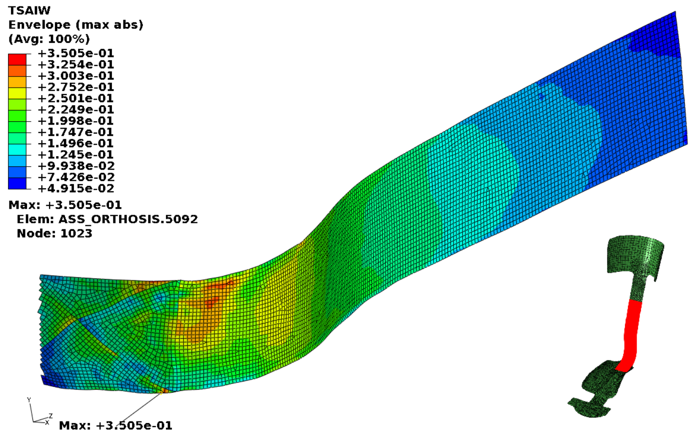

Figure 16. Plot of maximum Tsai-Wu values in the spring element set.

6.2 Laminate stacking sequence

In Figure 17 correlation coefficients for the approximation are shown for DOE A and B. In these figures only the plies with the largest correlation are shown. All the correlations are negative which means that a larger angle has a negative influence on the relative stiffness. The correlation for DOE A shows that the outermost layers have the largest correlation to the response. Note that the inner plies are not represented. For DOE B one can see the same trend.

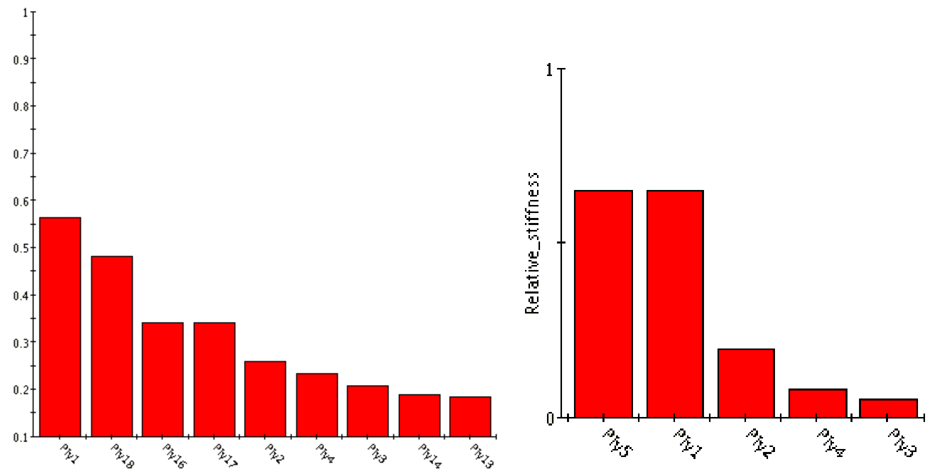

Figure 17. Correlation of DOE A and B.

Pareto plots for DOE A and B are shown in Figure 18. These plots have been computed from the coefficients of the second order polynomial fits from the regression data. The bars pointing to the left give a negative effect to the response (relative stiffness) for an increasing angle and vice versa. For DOE A the linear terms of the outer most plies have the largest effect, i.e. ply 1 and 18. After that the effect of the linear terms are decaying for ply 2,3,16 and17 but they are still affecting nearly as much as the two outer plies. The second order coefficients for ply 1,2,17 and 18 have almost the same affect but positive. For DOE B one can see that the outer most plies are dominant compared to the other plies.

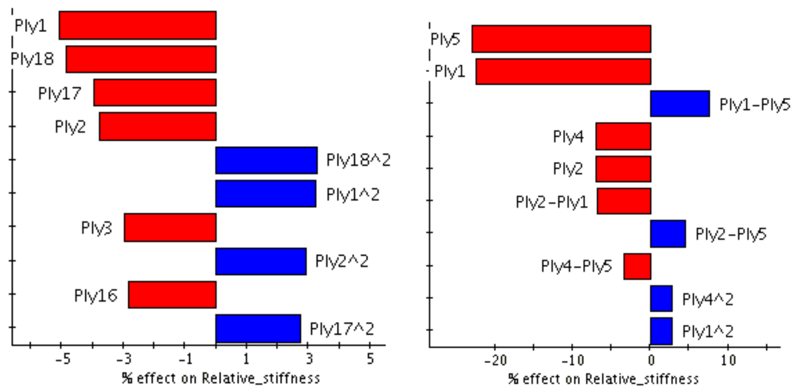

Figure 18. Pareto plots for DOE A and B.

In Figure 19 main effect graphs are shown. These graphs can be seen as estimation on how a change in angle will influence the response. It seems like an increased angle leads to a lower relative stiffness for almost all plies. Also in this plot one can see that the outermost plies have more effect on the relative stiffness of the laminate for both DOE A and B.

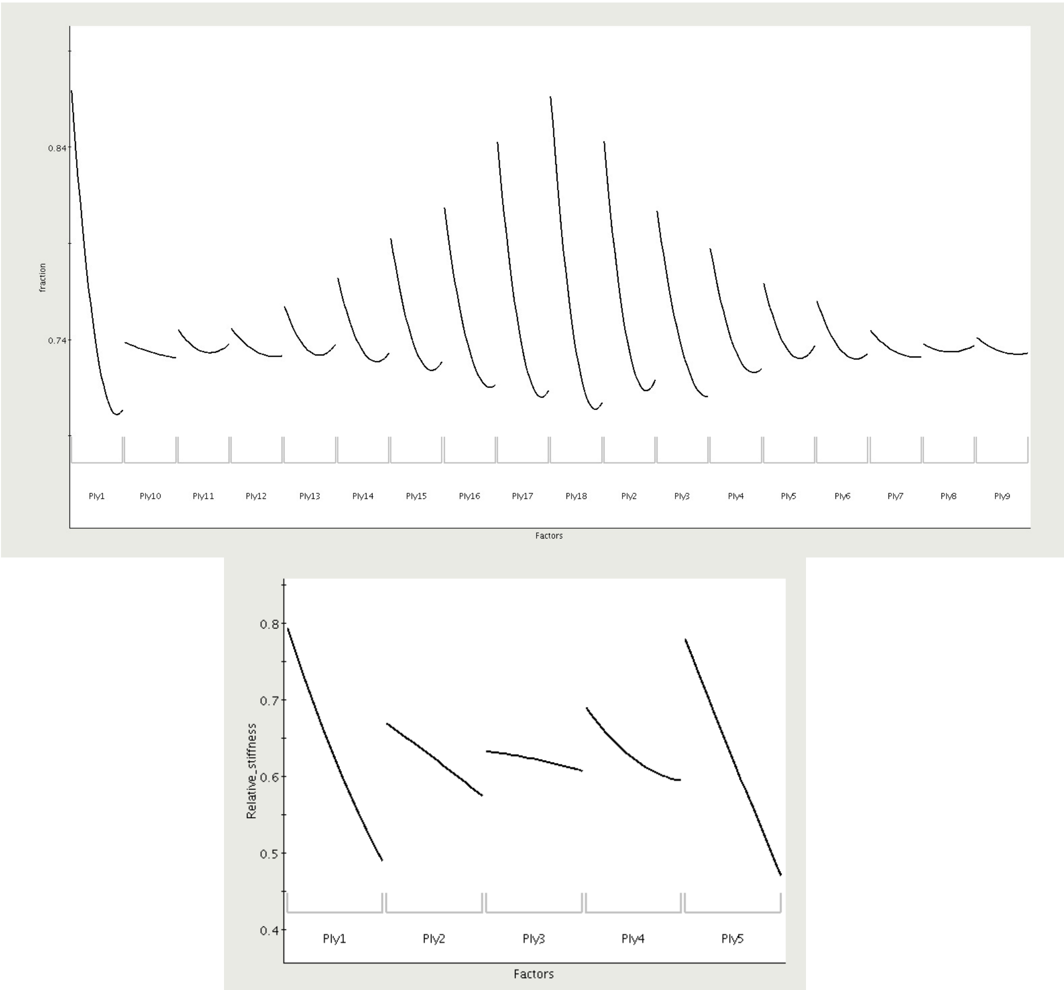

Figure 19. Main effect graphs for DOE A and B.

By using the results of the plots in Figure 17-19 the engineers should be able to see which plies to change manually in order to obtain an orthosis with varying stiffness. The Isight loop in Figure 14 was used to obtain a ply stacking sequence, by entering a requested relative stiffness. How well it predicted a requested relative stiffness can be seen in Figure 20 and Figure 21. The stiffnesses were selected to cover the entire span of the both approximations, for a more detailed description of how the comparison was made see section 5.2.

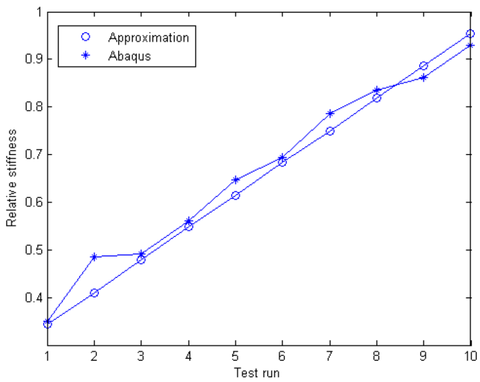

Figure 20 Comparison of relative stiffness response between the approximation and Abaqus. Spring, 18 plies.

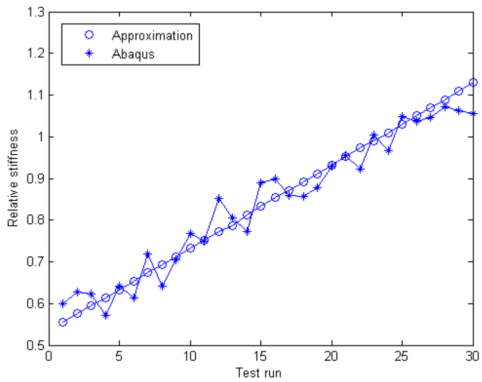

Figure 21 Comparison of relative stiffness response between the approximation and Abaqus. Toe, 5 plies.

7. Conclusions

The maximum Tsai-Wu value of the orthosis model during a walking cycle is located in the toe as can be seen in Figure 15. The maximum Tsai-Wu value in the entire model is not close to 1 which indicates that the model is not close to failure during an ordinary walking cycle.

The laminate stacking sequence analysis shows that the outermost plies of the spring have the largest effect on the bending stiffness. This seems reasonable considering that the strain magnitude of these plies is larger than the innermost. The results also showed that it is possible set the innermost plies to arbitrary angles without obtaining any significant change of bending stiffness. Since the orthoses are manufactured by hand other factors with larger impact than what the change of these plies entails will be added.

Another conclusion is that increasing a ply angle will lead to a weaker bending stiffness. This is also quite reasonable since a cross-woven ply has a larger Young's modulus along the fibres.

When using the optimization loop to obtain stacking sequences for requested relative stiffnesses one cannot always be certain of that the requested stiffness is obtained. As seen in Figure 20 Figure 21 the actual relative stiffness for a stacking sequence can differ from the predicted. However this difference might not be of importance since previously stated factors from manufacturing may cause an even larger error. The most important feature of this model is that it is possible to create an orthosis where one can modify the stiffness within reasonable tolerances.

8. References

[1] Åström, B.,T. (1997): Manufacturing of polymer composites. Chapman & Hall, London, England.

[2] Isight manual, version 4.0