Load Transfer Analysis of SDS Wood Screw Connection in Multi-Ply Girder Trusses

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Abstract: ABAQUS/Explicit, combining with general contact, connector elements, distributed-memory processing (DMP), and digital signal processing (DSP) techniques, has a unique strength in solving some of the large quasi-static problems which involve large number of sliding contact pairs, highly nonlinear structural behavior. In this paper, a case is presented to show the successful application of ABAQUS/Explicit to solve the real-world problem in multi-ply girder truss load distribution testing.

Pre-fabricated wood floor trusses are cost-effective, engineered building components commonly used in single and multi-family home construction in North America. A girder truss is usually designed and engineered to carry loads transmitted from other structural members bearing upon it. Often a girder truss is made from multiple plies of trusses, which are nailed, screwed, or bolted together. The Simpson Strong-Drive® Screw (SDS), a ¼" diameter structural wood screw, is used to join four-ply trusses to form a girder truss. The ply-to-ply load transfer rate of a four-ply truss is the focus of this study.

The ply-to-ply load transfer behavior is first characterized by a connector element using a non-linear spring model based on shear testing of single SDS screws. The single shear model is validated for four-ply connection testing. Truss chord and web members are modeled using C3D8R wood elements with general contact for interactions. Truss metal connector plates are modeled using S4R elements, which are tied to the corresponding chord and web member surfaces. Steel rollers used in testing for out-of-plane deflection constraint are modeled using rigid surfaces. The model is completely created in ABAQUS/CAE, in which the assembly pattern feature greatly helps speedup the modeling process. The four-ply floor truss model is solved on the Linux-based cluster using DMP. DSP is used to filter out noise in the response measurement post-processing.

The model predicted ply-to-ply load transfer rates agree well with the test results. The calibrated model can be used for taking the place of some expensive lab tests, and it can be also used for evaluation of many design variations more efficiently.

Keywords: *Wood Truss, Multi-ply Girder Truss, SDS Wood Screw, Quasi-Static, General Contact, Connector Element, DMP, DSP.*

1. Introduction

Early this year, Simpson Strong-Tie Company introduced the next generation of Strong-Drive® Screw (SDS). The new SDS wood screw features a 4CUT™ tip and a double-barrier coating, which reduces installation torque, minimizes wood splitting during installation, and provides a level of corrosion resistance superior to galvanization (Simpson Strong-Tie Co., 2007). In order to expand the applications of the new SDS wood screw in the multi-ply wood truss applications, both numerical modeling and testing were conducted. In this paper, the finite element modeling using ABAQUS/CAE and ABAQUS/Explicit will be discussed. Comparison of FEA and testing results will be also presented.

1.1 Metal plate connected wood trusses

Wood trusses are widely used in single- and multi-family residential, institutional, agricultural and commercial construction. A truss is a structural frame relying on a triangular arrangement of webs and chords to transfer loads to reaction points. This arrangement gives them high strength-to-weight ratios, which permit longer spans than conventional framing, and offers greater flexibility in floor plan layouts. They can be designed in almost any shape or size, restricted only by manufacturing capabilities, shipping limitations and handling considerations. A metal plate-connected wood truss is a roof or floor truss whose wood members are connected with metal connector plates. The metal plate connected wood trusses are prefabricated by pressing galvanized steel truss plates into wood members that are pre-cut and assembled in a jig.

The metal connector plate is a metal plate (usually ASTM A653 G40 galvanized steel plate) used to connect coplanar wood members, so as to transmit forces from one wood member to another at the joint. It is connected to wood members using either integral teeth formed from the metal plate and subsequently embedded into the wood, or separately applied driven fasteners such as nails (ANSI/TPI 1-2002).

There are two basic types of trusses. The pitched truss or common truss is characterized by its triangular shape. It is most often used for roof construction. Some common trusses are named according to their web configuration. The chord size and web configuration are determined by span, load and spacing. The parallel chord truss or flat truss gets its name from its parallel top and bottom chords. It is often used for floor construction.

In the United States and Canada, most new houses are built with wood roof trusses. It is not surprising considering their:

- Strength: Trusses provide a strong and efficient structural wood system specifically engineered for each application.
- Economy: Through efficient use of wood and by providing a system that is installed in as little as half the time of conventional wood framing, wood trusses provide an economical framing solution.

- Versatility: Complex shapes and unusual designs are easily accommodated using wood trusses.
- Environmental Benefits: Wood, the only renewable framing material, has numerous environmental advantages. Wood trusses enhance wood's environmental advantages by optimizing wood use for each specific application.

Wood floor trusses are the focus of this study.

1.2 Multi-ply girder trusses

A girder truss is usually designed and engineered to carry heavy loads transmitted from other structural members bearing upon it. Often a girder truss is made from multiple plies of trusses, which are connected together using nails, bolts, or screws. Four or more plies require bolts or other approved fasteners other than nails to develop continuity across the plies; in no case should a girder with four or more plies be connected only with nails (ANSI/TPI 1-2002).

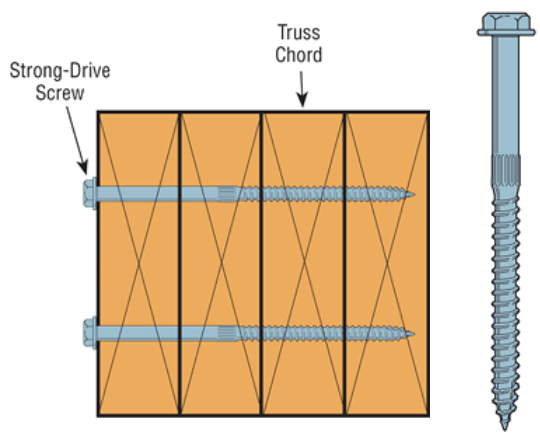

Figure 1. SDS Screw connection in four-ply truss.

The Simpson Strong-Drive® screw (SDS) is a ¼” diameter structural wood screw designed for various structural connector installations as well as wood-to-wood connections. It requires no pre-drilling, has a patented easy driving tip and a corrosion resistant coating. The SDS ¼”x6” can be used for ply-to-ply connections for four-ply girder trusses built with 2x members. Figure 1 shows a SDS screw and the cross-section view of four ply wood members joined by SDS screws.

For truss designers, the load distribution from the loaded ply to various plies of multi-ply girder trusses is an important design parameter. The goal of this study is to find out the load distribution from ply-to-ply for a four-ply floor girder truss joined by SDS screws.

The four-ply girder truss is built with the parameters shown in Table 1.

Table 1. Wood floor truss parameters.

Truss Component	Size
Truss Span	20’
Truss Depth	2’2”
Top Chord	2x4
Bottom Chord	2x6
Web	2x4
Center Web	2x10
Top Chord Fasteners	(10) SDS’s @ 24” o.c.
Bottom Chord Fasteners	(32) SDS’s @ 8” o.c. 2 rows

Figure 2 shows the four ply girder truss sketch used in this study. The top chord, bottom chord, and web members are connected by 28 (14 on each side) various sizes of metal connector plates at the joints. The metal connector plates are manufactured from minimum No. 20 gage ASTM A653 SS Grade 40 steel.

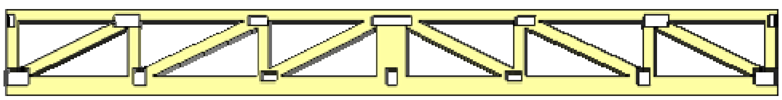

Figure 2. Four ply girder truss.

2. SDS wood-to-wood connection model

In order to simulate the shear transfer behavior of SDS screws in the ply-to-ply wood truss connection, single SDS screw shear tests were designed to characterize the load deflection responses of the interactions between the plies. The interaction pairs are 1^{st} ply/2^{nd} ply, 2^{nd} ply/3^{rd} ply, and 3^{rd} ply/4^{th} ply. Figure 3 shows the sketch of the test setup. Thin Teflon sheets were used in each ply interface to minimize the effect of friction.

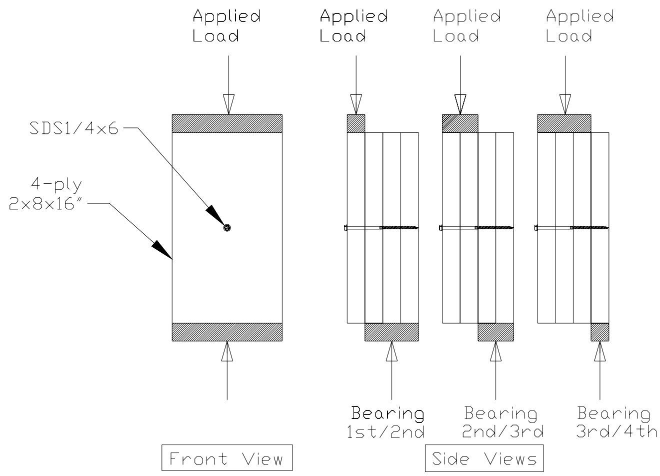

Figure 3. Single SDS screw ply-to-ply shear test.

The load and bearing blocks are shown in Figure 3 to illustrate the testing utilized to capture the load deflection response of each ply interface. LVDT's were used to measure the ply-to-ply relative deflection.

2.1 Ply-to-ply single shear characterization

Since wood grain orientation has an effect on the bearing strength, the tests were conducted for two loading cases, one for perpendicular to grain loading, and the other for parallel to grain loading. Three samples were tested for each case. The load deflection curves were recorded and curve-fitted to find the average response for each interface. The curve-fitted load deflection curves were input into ABAQUS/CAE as non-linear springs. ABAQUS connector element was used to simulate the single shear behavior.

Figure 4 shows the curve-fitted single shear load deflection response of each ply interface for both parallel to grain and perpendicular to grain loadings. To simplify identification, "Perp to grain – 1" denotes the single shear load deflection response of the 1st ply to 2nd ply interface for the perpendicular to grain loading. "Perp to grain – 2" denotes the single shear load deflection response of the 2nd ply to 3rd ply interface for perpendicular to grain loading. "Perp to grain – 3" denotes the single shear load deflection response of the 3rd ply to 4th ply interface for perpendicular to grain loading. Likewise, "Para to grain – 1" denotes the single shear load deflection response of the 1st ply to 2nd ply interface for the parallel to grain loading condition. The same naming convention is used for other ply-to-ply interfaces.

Form the response curves in Figure 4 it can be observed that the shear behavior is very non-linear from the initial loading. Non-linear spring behavior can be employed to simulate this highly non-linear behavior. In ABAQUS, this can be simulated using a connector element with axial load deflection behavior the same as the curve-fitted response curve.

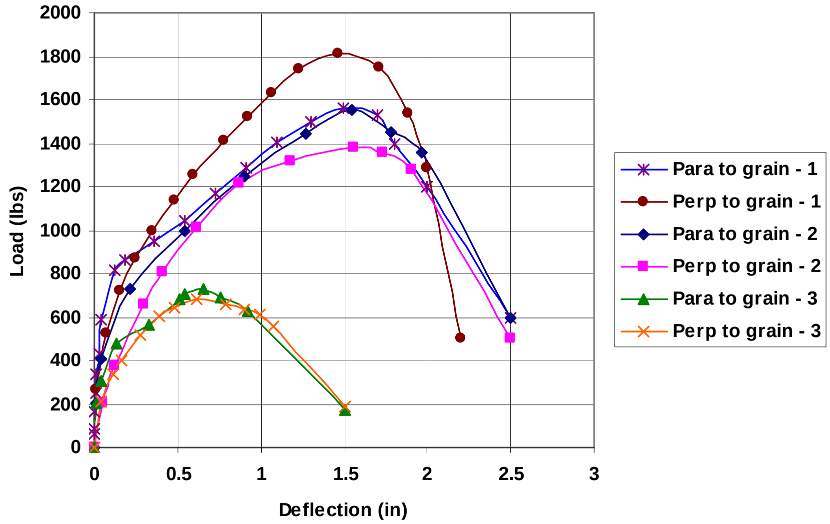

Figure 4. Curve-fitted load deflection for each ply interface.

2.2 SDS single shear model validation

To validate the SDS screw single shear model for ply-to-ply connection, a four ply 2x8x16 wood members joined by a single SDS screw was modeled and tested. The test setup is shown in Figure 5. The load is applied to the first ply through the loading block, and the bearing block is on the 4th ply. Two samples were tested for perpendicular to grain loading condition.

The test was simulated using the SDS single shear model. Three connector elements were used to simulate the non-linear load deflection behavior for 1st ply to 2nd ply, 2nd ply to 3rd ply, and 3rd ply to 4th ply connections. The model was solved using ABAQUS/Explicit with mass scaling for quasi-static analysis considering the large sliding contact area involved. The load deflection response was filtered using DSP to reduce the noise. Figure 6 shows the load deflection responses of FEA and the test. Figure 7 shows the ABAQUS model and an actual testing setup picture.

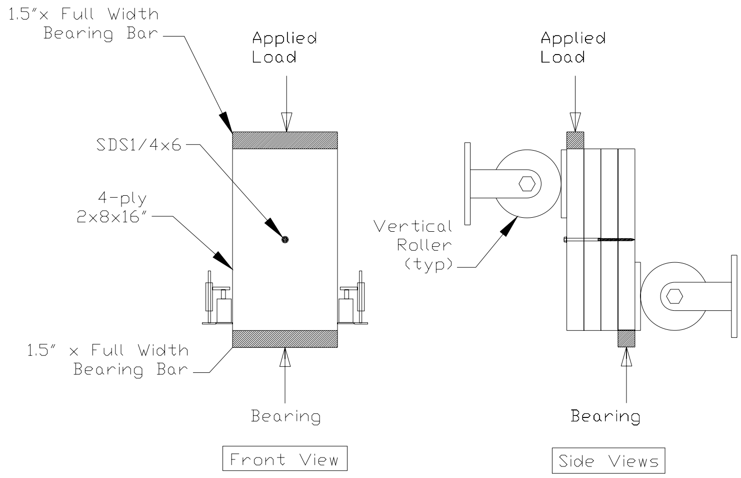

Figure 5. Single SDS in four ply shear test.

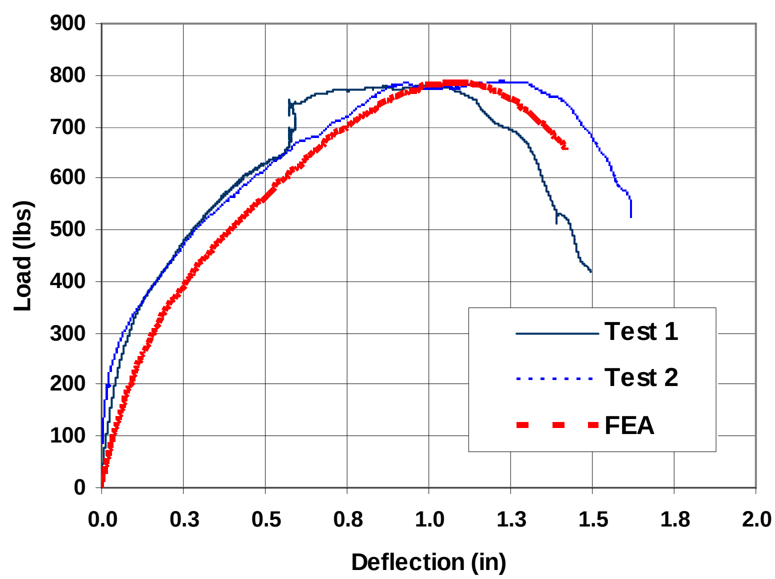

Figure 6. Response of single SDS in four ply shear (perpendicular to grain).

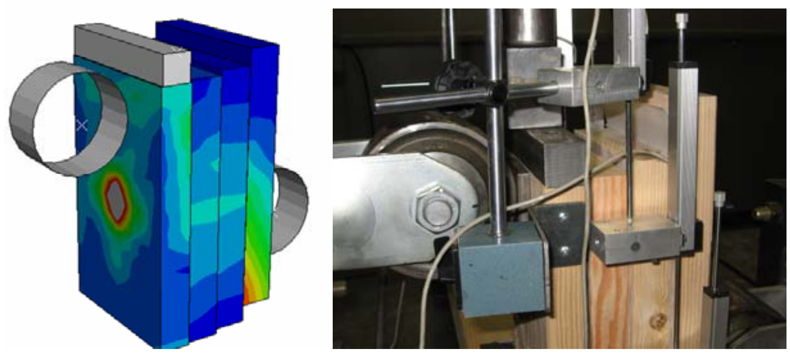

Figure 7. ABAQUS model of single SDS in four ply shear test.

Based on the load deflection response curve comparison between FEA and tests in Figure 6, we see the model can realistically capture the SDS behavior for load transfer in this four ply wood member connection. The initial stiffness of the FEA result is lower than that of the test. This is partly because the SDS clamping force effect (generated during installation) is not captured in the FEA model. However, the peak load and overall response agrees reasonably well with the test.

3. Single ply truss model

A single truss was modeled to simulate a truss stiffness test with a concentrated load of 1500lbs on the center of top chord. The individual truss wood members (top chord, bottom chord, and webs) were modeled using 3D solid elements C3D8R. There were a total of 15 2x wood members. The contacts among wood members at the joints were modeled using general contact. Metal connector plates were modeled using shell elements S4R. There were a total of 28 metal connector plates in this truss model. Each metal connector shell element was tied to the corresponding wood members at the joint using surface-to-surface tie constraint. Each truss ply was tested and supported at both ends of the bottom chord. Two steel rollers were employed to constrain the out-of-plane buckling at the truss center. Elastic response of the truss was observed due to the low applied load. Figure 8 shows the FEA model of a single ply truss stiffness test. The model was solved using ABAQUS/Explicit for quasi-static solution with mass scaling. The response was filtered using DSP to reduce the noise. Figure 8 shows the ABAUQS model of a single truss bending test.

The predicted truss deflection was compared with the tested result. It was found that the FEA model over-predicted the stiffness of the truss. This was expected due to the stiffness variation of wood members, the way metal connector plates were modeled, and the tie constraint used between metal connector plates and wood members at the joints.

Because of the orthotropic nature of wood, the stiffness of wood members perpendicular to grain and parallel to grain is quite different. For instance, the stiffness of compression perpendicular to grain is about 10% of the stiffness of compression parallel to grain for Douglas-fir (Forest Products Laboratory, 1999). The tension stiffness is also usually lower than the compression stiffness for wood members. It is known that the truss members are under different loading conditions for top chord, bottom chord, or webs. Some of them are under tension, others are in compression. Some of them are loaded parallel to grain, and others are loaded perpendicular to grain.

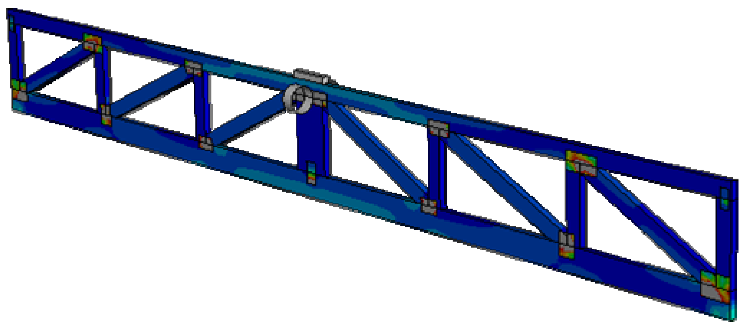

Figure 8. Single ply truss stiffness test.

The tie constraint between metal connector plates and wood members also over-estimates the stiffness at the joint.

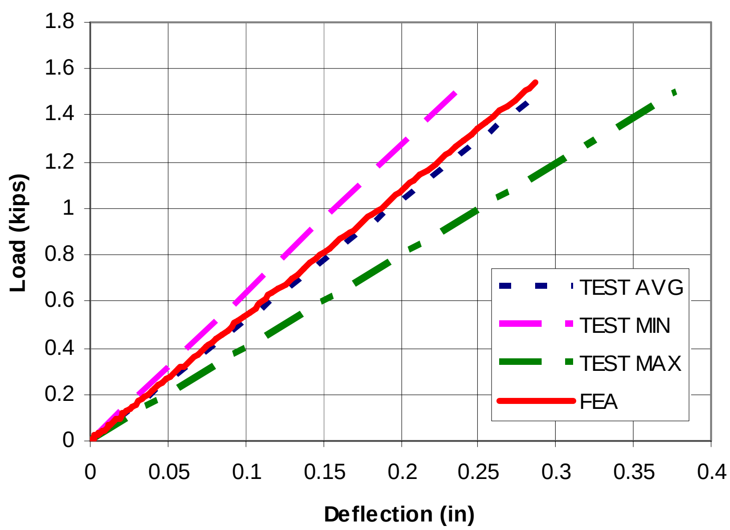

Figure 9. Load deflection of single ply truss stiffness test.

In view of the fact that it is almost impossible to model each wood members properties and joint properties under different loadings, an overall effective stiffness approach was used to correlate single truss stiffness. First the original material stiffness was used to run the analysis to obtain the baseline stiffness. The ratio of the baseline stiffness over the tested average stiffness was calculated. The ratio then was applied to the material stiffness (both wood members and metal connector plates) to proportionally reduce the overall stiffness. Figure 9 shows the load deflection response of the calibrated single ply truss bending model, which agrees well with the tested average stiffness. The calibrated effective material stiffness was later used in the four-ply girder truss modeling.

4. Four-ply girder truss model

Once the single ply truss model is created, the four-ply girder truss model can be created by joining the four single ply trusses using ABAQUS connector elements. ABAQUS/CAE instance patterning feature was employed to duplicate four identical single ply trusses. If the stiffness of the single ply truss needs to be varied to model the stiffness variations from ply-to-ply, the ABAQUS/CAE instance merge/cut feature can be employed to create a single truss part, and re-assign material properties. It turns out these two features of ABAQUS/CAE significantly reduced the modeling time for this application.

Table 1 indicates how the four-ply girder truss is joined by a number of SDS screws. Each SDS screw connection was modeled using a connector element with non-linear spring behavior. Since the SDS screws were only installed on the top chord and the bottom chord, the curve-fitted load deflection behavior of the ply interface for perpendicular to grain was used to model the SDS screw connections. A total of 30 connector elements were used to simulate the 10 SDS screw connections on the top chords, and a total of 96 connector elements were used to simulate the 32 SDS screw connections on the bottom chords considering the fact that there are three shear interfaces for each SDS screw. Figure 10 shows the ABAQUS model of the four-ply girder truss load transfer test and an actual testing picture.

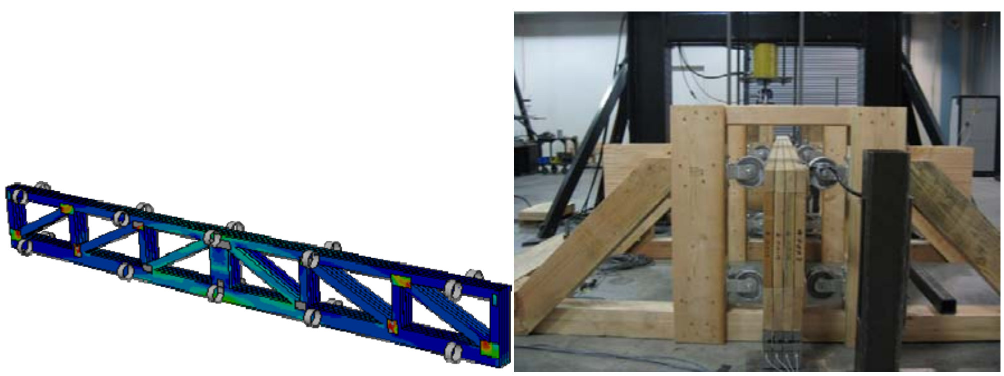

Figure 10. Four Ply Girder Truss Load Transfer Test

A concentrated load was applied at the center of the 1st ply side face to simulate the loading from a face-mounted hanger such as the THGQ3 manufactured by Simpson Strong-Tie (Simpson Strong-Tie Co., 2007). As shown in Figure 10 a total of 20 steel rollers (10 on each side) were used to prevent the four ply girder truss from out-of-plane buckling. Each roller was modeled as a rigid body surface with only rotational degree of freedom about its axis. Each end of the bottom chords of each single ply trusses were supported vertically. The reaction load from each ply was measured using two load cells (one on each end) during the test. The load transfer rate was calculated based on the total load applied and the reaction load from each truss ply. Table 2 shows the load distribution on each ply. FEA predicted result is very close to the tested result.

Table 2. Four Ply Girder Truss Load Transfer % for Concentrated Loading.

Description	1st Ply	2nd Ply	3rd Ply	4th Ply
Test	30	27	25	18
FEA	30	26	24	19

Several factors may affect the load transfer from ply to ply, such as the type of fastener used to connect the plies together, the fastener spacing, and the characteristics of individual plies. A notable observation from unpublished test results is that the stiffness of individual plies has a large effect on the percentage of load carried by the plies, depending on the relative stiffness of the various plies (ANSI/TPI 1-2002). For the test result in Table 2, a stiffer ply was used for the first ply. In the FEA model, a stiffer 1st ply was also used to reflect the testing conditions.

The model size was about 300,000 DOF. It was solved by ABAQUS/Explicit on an AMD Opteron-based Linux cluster. Again, mass scaling was used to speed-up the quasi-static solution. The solution time was about five hours on 4 CPU's using MPI-based distributed memory processing (DMP).

5. Conclusions

The four ply girder truss modeling approach presented in this paper proved to be feasible, and the predicted result correlated well with the test result. The model added another tool for the multi-ply truss design and analysis in addition to physical testing. This model could also be used to evaluate multi-ply truss design variations and loading conditions where it is expensive to achieve using physical testing.

ABAQUS/Explicit, combining with general contact, connector elements, distributed-memory processing (DMP), and digital signal processing (DSP) techniques, has a unique strength in solving this kind of large quasi-static problems which involve a large number of sliding contact pairs, and highly nonlinear structural behavior

ABAQUS/CAE's patterning feature and merge/cut feature proved to be efficient tools for this modeling effort.

6. References

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7. Acknowledgement

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