Using Computer Models To Predict the Performance Of Structural Glued Laminated Timber

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Abstract

Several computer models are available today for estimating the mechanical properties of structural glued laminated timber (glulam). These models are useful for glulam manufacturers who are interested in the efficient use of available lumber resources. The most popular model used by the glulam industry in the United States is a deterministic model based on the so-called I_k/I_g concept originally developed in 1950s. APA - The Engineered Wood Association / Engineered Wood Systems (*APA EWS*), whose members produce approximately 70% of glulam production in North America, has developed a computer model based on the principles set forth in ASTM D3737 to predict the performance of glulams. This model, known as GAP (Glulam Allowable Properties), has been recognized by the major building codes in the United States as an alternative method for determining layup combinations and assigning design stresses for glulams. This paper discusses the procedures implemented by *APA EWS* using the GAP model to establish new glulam layup combinations. Three case studies are given to demonstrate this practice. The acceptability of the GAP model in predicting the performance of glulams is confirmed. Considerations for adopting a probability-based model are also discussed.

Keywords: Structural Glued Laminated Timber, Glulam, Computer Models, GAP, LVL-Glulam, Durango Pine, Eastern Spruce.

Introduction

Model simulation techniques have had a significant contribution to the advancement of a variety of engineered products. For the structural glued laminated timber (glulam) industry in the United States, the most well known model is the conventional I_k/I_g model, as originally developed by Freas and Selbo in the 1950s and subsequently adopted in ASTM D3737 (1996) as a national consensus standard. This model uses knot data of the laminating lumber to predict the mechanical properties of glulam members. As the model predicts a single strength value for a given glulam layup combination, it is deterministic in nature.

In the United States, there are several probability-based models that have been developed specifically for glulams. Unfortunately, none of these models is recognized in ASTM D3737. As a result, APA - The Engineered Wood Association / Engineered Wood Systems (*APA EWS*), whose members produce approximately 70% of glulam production today in North America, has developed a deterministic computer model based on the principles set forth in ASTM D3737 to predict the performance of glulams.

"GAP" Model

This model, known as GAP (Glulam Allowable Properties), has been recognized by the major building codes in the United States as an alternative method for determining layup combinations and assigning design stresses for glulam members (NES 1994). In the past few years, this model was used by *APA EWS* in developing several commercially significant layup combinations for use by its glulam producing members. Currently, research is being undertaken by *APA EWS* to revise the allowable bending stresses when the compression zone is stressed in tension (upside-down beams) based on the values predicted by the GAP model. It has been proven over the years that this model provides a great flexibility for glulam manufacturers in customizing the available lumber resources, while maintaining the structural integrity needed for glulam designs. Implementation procedures for developing a new *APA EWS* layup combination based on the GAP model are described below.

Implementation Procedures

APA EWS has established implementation procedures when a new layup combination is deemed desirable. In most cases, targeted design values for the layup combination and available species or grades of laminating lumber are pre-defined in accordance with market needs, economical considerations and other factors. In general, a request from an *APA EWS* producing member will initiate the following typical processes:

Feasibility Study -- *APA EWS* staff will work with the producing member to conduct a feasibility study, which may be a simple stress analysis or a complicated study on the available lumber resources, appropriate laminating lumber grades, as well as a preliminary GAP analysis based on the existing knot data obtained from similar lumber species/grades. Limited preliminary full-scale tests may be necessary at this stage to optimize the candidate layup combinations.

Knot Data -- Characteristic knot sizes are required for a GAP analysis. If the knot data of the candidate laminating lumber are not available, a knot survey will be conducted by *APA EWS* staff in accordance with the provisions given in ASTM D3737. Results from the knot survey are then analyzed and the characteristic knot sizes established for use in the GAP database.

Model (GAP) Analysis -- In addition to knot data, other mechanical properties, such as clear wood stress index values and stress modification factors, are required for GAP to predict the performance of glulams made with a specific layup combination. These mechanical properties will be established by *APA EWS* staff in accordance with the provisions given in ASTM D3737. Once established, these values will become part of the GAP database and form the basis for the subsequent GAP analysis. Results from the model analysis provide optimum layup combinations that will meet the targeted design values.

Qualification -- In-plant qualification tests are required if the lumber species or grades to be used for the candidate layup combinations have not been previously qualified under the provisions of *American National Standard for Wood Products -- Structural Glued laminated Timber, ANSI A190.1-1992*. Typical qualification tests include cyclic delamination and shear tests for face bonding, and full-scale tension tests for end joints. When necessary, laminating lumber may have to be qualified by full-scale tension tests (applicable to a certain type of special tension laminations) or static long-span E tests (applicable to E-rated laminating lumber). All these qualification procedures are designed to ensure the components of a glulam member be made to comply with the provisions given in *ANSI A190.1*.

Full-Scale Verification Tests -- These verification tests are not required by ASTM D3737, but are implemented by *APA EWS* to confirm the model analysis and provide assurance of quality products. Based on the candidate layup combinations, full-scale glulam beams for each layup combination will be manufactured under the supervision of *APA EWS*, and shipped to the APA Research Center in Tacoma, WA, for testing. Depending on the test results, the layup combinations may be accepted or may need further modifications. Additional full-scale verification tests are usually required when significant modifications are made to the layup combinations.

Database Maintenance -- When the layup combinations are accepted based on the results of full-scale verification tests, the model analysis is essentially validated. As a result, the new knot data collected during the development of the new layup combination will become part of the GAP database, which could be used for the modeling of other new layup combinations. As the knot data play a significant role in the GAP analysis, it is imperative that the database be monitored on the on-going basis. After the establishment of a new laminating lumber grade, *APA EWS* staff will conduct a periodical knot survey and knot data evaluation in accordance with the provisions given in ASTM D3737. If a significant change in the characteristic knot data is noted, a re-evaluation of the existing layup combinations followed by full-scale verification tests is usually required.

Quality Assurance -- Once being approved, the new layup combinations will be audited on the on-going basis by *APA EWS* in accordance with the *APA EWS Quality Assurance Policy for Glued Laminated Timber Products*. An *APA EWS* trademark, as shown in Fig. 1, will be issued to signify the glulam product is produced to the requirements of *ANSI A190.1* and supported by comprehensive services for quality validation, product research, testing, and marketing of *APA EWS*.

APA EWS

B IND	**DOUGLAS-FIR**	**117-93 24F-V4**
MILL 0000		**ANSI A190.1-1992**

Figure 1 -- Typical *APA EWS* trademark.

Case Studies

The following three cases are selected to demonstrate the use of the GAP model in developing new layup combinations for *APA EWS* producing members. Through these cases, the acceptability of the GAP model in predicting the performance of glulams manufactured with a wide array of species and layup combinations is confirmed.

Case I: LVL-Glulam

An *APA EWS* producing member was interested in the development of a composite, high strength glulam layup combination. Due to its relative high tensile strength, laminated veneer lumber (LVL) was chosen to replace the traditional solid-sawn special tension laminations. The core materials and the laminations in the compression zones remained to be solid-sawn laminating lumber. The targeted allowable bending stress for this LVL-glulam was pre-selected at 20.0 MPa (2900 psi) with a targeted modulus of elasticity of 13.1 GPa (1.9×10^6 psi).

As the knot data for LVL are difficult to characterize, a GAP analysis had to be performed by *APA EWS* staff using the "equivalent" knot data, as shown in Table 1. These knot data were estimated based on the "equivalent" values published by Braun and Moody (1977), and further adjusted 10% down for the characteristic knot sizes and 7% down for the bending stress index value to reflect the LVL grade intended for use in the layup combination (Yeh 1992c). For comparison purposes, Table 1 also shows the L1 grade (a high grade) of Douglas-fir laminating lumber.

Table 1 -- LVL and L1/DF data[a] for used in the GAP analysis.

Grade	Long-Span E, GPa (10^6 psi)	$\bar{x}$, % width	h, % width	Bending Stress Index Value, MPa (psi)
LVL	14.5 (2.10)	5.5	16.5	25.9 (3750)
L1/DF	14.5 (2.10)	7.6	30.1	24.1 (3500)

[a] Long-span E = Modulus of elasticity based on a span-to-depth ratio of 100,
$\bar{x}$ = average knot size,
h = difference between the 99.5 percentile and average knot size, and
Bending stress index value = a value established in ASTM D3737.

Based on the results of the GAP analysis and preliminary full-scale beam tests, a feasible layup combination was identified (Yeh 1992b). Using this layup combination, a total of 206 full-scale LVL-glulam beams manufactured in various sizes was subsequently tested by *APA EWS* to derive the design values. Results from these tests supported an allowable bending stress of 20.0 MPa (2900 psi) with a modulus of elasticity of 13.1 GPa (1.9×10^6 psi).

As shown in Table 2, these design values were in excellent agreement with the GAP prediction of 20.3 MPa (2948 psi) for the allowable bending stress and 12.8 GPa (1.86×10^6 psi) for the modulus of elasticity. The predictability of the LVL-glulam performance using the GAP model was within ± 2% of the results obtained from full-scale bending tests.

Table 2 -- Predictability of the LVL-glulam.

	F_b[a], MPa (psi)	E_x, GPa (10^6 psi)
GAP	20.3 (2948)	12.8 (1.86)
Test Results	20.0 (2900)	13.1 (1.90)
Predictability	0.98	0.98

[a] The allowable bending stress obtained from test results is rounded to the nearest 100 psi in accordance with ASTM D3737.

This information was submitted to and accepted by the major building codes in the United States and the LVL-glulam products are now available in the market place bearing the trademark of *APA EWS*.

Case II: Durango Pine Glulam

Durango Pine (DP) is a combination of softwood species, including *Pinus durangensis* (predominant species), *Pinus leiophylla, Pinus teocote, Pinus cooperi*, and *Pinus englemanni*, which are grown in the Durango area of Mexico. Interest in producing E-rated Durango Pine glulams for North American construction markets initiated the development of a layup combination for this new species group. The targeted allowable bending stress and modulus of elasticity was 16.5 MPa (2400 psi) and 12.4 GPa (1.8×10^6 psi), respectively. To be more specific, the primary goal was to develop a layup combination similar to the 24F-E1 of Southern Pine glulams.

Due to the lack of knot data for Durango Pine laminating lumber, *APA EWS* staff worked with the plant personnel in conducting necessary knot surveys. Results of the knot surveys suggested that the characteristic knot sizes for Durango Pine were compared favorably with the same grade of E-rated Southern Pine (Yeh 1995a). Along with the knot surveys, *APA EWS* staff also evaluated the tensile strength and long-span E of the various grades of E-rated laminating lumber. This practice was beyond the requirements of ASTM D3737, but was deemed necessary for a new species group to be used in glulam manufacturing.

Based on the knot data, a GAP analysis was performed and the 24F-E1/SP layup combination was confirmed to be applicable to Durango pine in terms of the targeted design values. In the meantime, the glulam plant demonstrated its ability to comply with the requirements of *ANSI A190.1* through a series of successful qualification tests. Consequently, full-scale verification tests were undertaken by *APA EWS*. Results from these tests (Yeh 1995a) strongly supported the targeted allowable bending stress of 16.5 MPa (2400 psi) and the modulus of elasticity of 12.4 GPa (1.8×10^6 psi).

As shown in Table 3, an excellent predictability was obtained for the allowable bending stress using the GAP model. On the other hand, the predicted E_x value was somewhat conservative when compared with the test results. This outcome might seem unusual as the transformed section method used by the GAP model has been known to be reasonably accurate in estimating the modulus of elasticity of glulam beams. However, it is important to note that the predict E_x value given in Table 3 was based on the nominal long-span E for the E-rated laminating lumber. For example, the 2.1E-6 laminating lumber was assumed to have a mean long-span E of 14.5 GPa (2.1×10^6 psi) for modeling purposes. In reality, due to the lumber sorting practice at the glulam plant, the mean long-span E for this grade of laminating lumber might be 15.9 GPa (2.3×10^6 psi) or higher. As a result, it is understandable that the model prediction was conservative on the modulus of elasticity of the glulams.

Table 3 -- Predictability of the DP glulam.

	F_b[a], MPa (psi)	E_x, GPa (10^6 psi)
GAP	19.4 (2817)	12.5 (1.82)
Test Results	19.3 (2800)	14.5 (2.11)
Predictability	0.99	0.86

[a] The allowable bending stress obtained from test results is rounded to the nearest 100 psi in accordance with ASTM D3737.

For conservative reasons, the Durango Pine glulams manufactured in accordance with the 24F-E1/DP layup combination were assigned an allowable bending stress of 16.5 MPa (2400 psi) and modulus of elasticity of 12.4 GPa (1.8×10^6 psi). These design values have been submitted to the major building codes in the United States for acceptance as part of NER-486 (NES 1994).

Knot data for the E-rated Durango Pine laminating lumber established from this study are now part of the GAP database. Other Durango Pine layup combinations can be readily developed based on these characteristic knot sizes when needed. For quality assurance purposes, *APA EWS* staff continues to conduct periodical knot surveys to monitor the characteristic knot data.

Case III: Eastern Spruce Glulam

Eastern Spruce (ES) has been used in the glulam manufacturing for years. By definition, this species group includes *black*, *red*, and *white spruce* that are grown in the United States or Canada and graded in accordance with the requirements in Canadian Standards Association (CSA) *Standard O122* (1989).

According to the glulam design specification (AITC 1987), there is only one Eastern Spruce layup combination, unbalanced 20F-E8/ES, available for glulam manufacturers who are interested in producing Eastern Spruce glulams. The allowable bending stress for this layup combination is merely 13.8 MPa (2000 psi) with a modulus of elasticity of 10.3 GPa (1.5×10^6 psi). A request was made by an *APA EWS* producing member to develop an unbalanced Eastern Spruce layup combination capable of an allowable bending stress of 16.5 MPa (2400 psi) and modulus of elasticity of 11.7 GPa (1.7×10^6 psi). For the given design values, this layup combination is customarily called 24F-1.7E/ES in the United States.

Based on a preliminary GAP analysis, it was noted (Yeh 1995b) that the highest achievable allowable bending stress using the existing Eastern Spruce lumber grades was limited to 15.9 MPa (2300 psi) with a modulus of elasticity of 11.0 GPa (1.6×10^6 psi). As a result, a laminating lumber grade that is higher than the existing ones had to be developed for the 24F-1.7E/ES layup combination. A 1.9E-6 E-rated lumber grade was selected in accordance with the experience of *APA EWS* staff on the development of similar layup combinations for Canadian Spruce-Pine-Fir glulams (Yeh 1992a). Requirements for this grade of E-rated laminating lumber followed the same rules applicable to other wood species (AITC 1993).

Knot surveys on the 1.9E-6/ES laminating lumber were conducted by *APA EWS* staff at the glulam plant based on randomly sampled lumber from the lots of several lumber mills. It was noted that the characteristic knot sizes for the 1.9E-6/ES laminating lumber were significantly smaller than those established in the GAP database for the existing lower grades of E-rated Eastern Spruce laminating lumber.

In accordance with these new knot data, a feasible layup combination, as shown in Table 4, was determined using the GAP model. It is important to note that for the modeling purposes, the bending stress index value for the 1.9E-6/ES laminating lumber was assumed to be 22.4 MPa (3250 psi), which was about 8% higher than the value specified in ASTM D3737 for the same grade of E-rated laminating lumber. This assumption was made based on experience and was required to be validated by means of full-scale verification tests.

Table 4 -- Optimized 24F-1.7E/ES layup combination[(a)].

Beam depth	Outer Tension Zone	Inner Tension Zone	Core	Inner Compression Zone	Outer Compression Zone
4 lams	5% 1.9E-6/ES	--	B/ES	--	5% 1.9E-6/ES
5 lams to < 30 cm	25% 1.9E-6/ES	10% C4/ES	D/ES	10% C4/ES	15% B/ES
≥ 30 cm	25% 1.9E-6/ES	10% C4/ES	D/ES	10% C4/ES	20% B/ES

(a) Assumed a bending stress index value of 22.4 MPa (3250 psi) for the 1.9E-6/ES laminating lumber.

Full-scale verification tests were conducted at the APA Research Center in Tacoma, WA, using the glulam beams manufactured in 3 different production runs. *APA EWS* staff was present at each run to verify lumber grades and witness the beam manufacturing. All test beams were manufactured following the provisions of *ANSI A190.1*. The end joints for the tension laminations were previously qualified under *APA EWS* at a qualification stress level of 17.9 MPa (2600 psi).

Results from the full-scale verification tests (Yeh 1995b) supported the allowable bending stress of 16.5 MPa (2400 psi) and modulus of elasticity of 11.7 GPa (1.7×10^6 psi). As shown in Table 5, the GAP model provided excellent predictions to the glulam performance. This outcome also validated the assumed bending stress index value of 22.4 MPa (3250 psi), which was previously used for the 1.9E-6/ES laminating lumber in the GAP analysis.

This information has been submitted to the major building codes in the United States for acceptance as part of the layup combinations recognized in NER-486 (NES 1994). The knot data for the 1.9E-6 laminating lumber is now in the GAP database and can be readily used to develop other layup

Table 5 -- Predictability of the ES glulam.

	F_b[a], MPa (psi)	E_x, GPa (10^6 psi)
GAP	16.9 (2457)	11.4 (1.66)
Test Results	17.2 (2500)	12.3 (1.79)
Predictability	0.98	0.93

[a] The allowable bending stress obtained from test results is rounded to the nearest 100 psi in accordance with ASTM D3737.

combinations when needed. As part of the quality assurance program, the knot data are monitored by *APA EWS* staff on the on-going basis.

Probability-Based Models

Although the deterministic I_k/I_g model has served the glulam industry in the United States very well, there are concerns on the validity of the fundamental equations used by the model due primary to the fact that the model relies significantly on the empirical relationship between knot sizes and the strength of laminating lumber. This is especially important when considering the changing lumber resources in recent years. Furthermore, as the design of timber structures is moving toward a reliability-based format, the need for a stochastic model capable of simulating statistical distributions of glulam strength and stiffness becomes apparent.

Among the models that have been developed in the United States, two computer models, the Probability Based Design Method (PBDM®) and PROLAM, receive the most attention from *APA EWS* and its producing members. A brief review of these models is given below. It is, however, important to note that the mechanical properties, which may be predicted by these probability-based models, are limited to bending strength and stiffness. All probability-based models available today are not designed to simulate shear strength, compression and tension parallel to grain, and compression perpendicular to grain. On the contrary, these mechanical properties can be estimated using the GAP model based on the provisions given in ASTM D3737.

PBDM® Model

This model, as developed by Weyerhaeuser Company, uses the ultimate tensile strength and flatwise long-span E of the laminating lumber to predict the bending strength and stiffness of glulams (Stone 1990). Based on Monte-Carlo type computer simulations, a complete data distribution (up to 5000 beams) can be obtained and the characteristic strength and stiffness determined. The initial database used for the simulations can contain as low as 50 pieces of full-length (2.4 m or 8 ft) laminating lumber for each grade and width. The size of this database will grow with production as destructive tests are required as part of on-going in-plant quality control processes,

PBDM® had been successfully implemented in commercial productions until the company closed down its glulam plant in 1992. In the United States, this is the only probability-based model that has ever been used in commercial productions. The strength of this model lies in the relative ease of database establishment and maintenance. However, as similar to other proprietary products, complete algorithms and precision of the model have not been made public and remained in the black box even when the company is no longer involved in the glulam production.

PROLAM Model

PROLAM was developed at Texas A&M University (Hernandez *et al*. 1992). This model uses the characteristic statistics of each grade of laminating lumber and end joints as basic input. The correlations between the modulus of elasticity and tensile strength of the lumber as well as end joints are established based on the actual measurements of 60-cm (2-ft) segments along the lumber length. Due in part to these finite segments, the model prediction on the bending strength of Douglas-fir glulams was reported to be quite accurate (Hernandez *et al*. 1992).

This model depends heavily on the correlation matrix between the tensile strength and modulus of elasticity of the laminating lumber and end joints. The strength of PROLAM lies in the requirement to physically test most properties of the constituent elements for a glulam member, including lumber and joints, in small segments. Unfortunately, from a manufacturing viewpoint, this may become too expensive to implement as extensive measurements are required for establishing and verifying the model database. In addition, the database maintenance represents a significant drawback as new data must be analyzed by sophisticated statistical "series correlation" procedures. Due to this complexity, those data obtained from on-going quality control procedures (full-scale destructive tests) may not be readily incorporated into the model database.

Most concerns given above are not too difficult to resolve. Several improvements, such as the use of the data collected from continuous lumber testers (CLT's) to substitute for or augment the PROLAM database, have been investigated. Nonetheless, an effort is needed to streamline the existing PROLAM database for Douglas-fir and Southern Pine glulams. For other species, a significant effort is needed for the establishment of the initial database. Most of all, this model could not be implemented at the production level without being adopted in some ways by ASTM D3737. As a result, it is possible that the glulam industry will work with the model developer to move this model forward in the near future.

Conclusion

Computer models can be a useful tool for glulam manufacturers who are interested in the efficient use of available lumber resources. Based on the I_k/I_g concept originally developed in 1950s, the GAP model has been used by *APA EWS* in developing several commercially significant layup combinations. The predictability of glulam performance using the GAP model is confirmed to be excellent by the three case studies given in this paper.

Although the deterministic model has served the glulam industry in the United States very well, the need for a stochastic model is apparent. However, the model developer must be concerned with not only the accuracy of the model prediction, but the implementation of the model in a practical manner. Ultimately, the model must be adopted in some ways by ASTM D3737 before it can be implemented in commercial productions. As a result, the glulam industry and the model developer must work together to make the implementation of a probability-based model a reality.

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