Effects of Emerald Ash Borer Infestation on the Structure and Material Properties of Ash Trees

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Abstract. Emerald ash borer (EAB), an invasive insect borer on ash trees, currently occurs in the United States and Canada. In many regions, large populations of ash trees are affected with many trees exhibiting partial to full canopy dieback. Several cases exist in northwest Ohio, U.S., where EAB infested ash branches or stems fail prematurely during deadwood pruning or whole tree removal. This study was initiated to resolve the effects of EAB on the material properties of ash branches and stems. Visually non-infested ash trees and trees with recent and advanced EAB activity were examined. The data from static loading tests on primary branches indicate that maximum bending stress at failure was not significantly lower in EAB infested trees compared to non-infested trees. Examination of the fracture zone, however, revealed that wood moisture was significantly lower and more cracking was observed in wood sections of branches taken from EAB infested trees. During static loading, branch failure at the union occurred only in the EAB infested trees. In a wood resistance evaluation of infested and non-infested ash stems, significantly lower resistance was observed in advanced EAB infested ash stems when drilled at the base compared to drill sites 1 m above. This was not observed at similar drill site heights in the visually non-infested ash stems. These data may help identify risk elements associated with structural and material degradation of ash wood as early as one to two years after infestation by EAB.

Key Words. Anchor Points; Biomechanics; Branch Failure; Emerald Ash Borer; Resistance Drilling; Static Loading; Zone of Fracture.
• Group III: Five ash trees that after confirmed EAB infestation had dead canopies (there were no signs of life in terminal branches). All trees had small amounts of epicormic sprouting at the base. Based on the city forester’s records, it is estimated that initial EAB infestation may have been three to four years earlier.

The ultimate fracture force, moments, and bending stresses at the point of fracture were determined by applying static loads to an approximate center of gravity (visually estimated) of selected branches. Three branches from each of five ash trees in each group were loaded until failure. Forty-five branches were thus broken in this study. Pre branch-breaking measurements that were recorded included: DBH using an arborist diameter tape and branch diameter at the branch collar using a hinged caliper (12.5 cm) (Forestry Supplies, California, U.S.). Visual estimates (based on initial measurements of first few branches) of the approximate angle of the branch attachment (branch to stem attachment angles ranged from 10 to 60 degrees upward slope) were also recorded. Only first order branches that were directly attached to the main trunk were selected. Branches were between 3 to 10 cm in diameter and any with apparent defects were not used in the trial.

Study Part 1. Static Loading of Branches
A 2,925 kg, 1.27 cm, three-strand rope (New England Ropes) was tied around the base of the target tree using a clove hitch knot [Rope A] (Figure 1). A 1,000 kg hand winch or ‘come along’ (Lug All Corporation, Morgan, Pennsylvania, U.S.) [C] was connected to rope A using a 3,960 kg, 8 mm spliced loop (Sherrill Tree, Greensboro, North Carolina) [D] and a six-coil Prusik knot. The hook in the come along could then go through the loop made in the spliced loop. Rope A was connected to the rear mounted hitch of a stationary truck (Ford F-150) and pulled taut using the come along. Rope A formed a firm horizontal anchor line to which a 3,825 kg, 7.62 cm rigging pulley (CMI, Franklin, West Virginia, U.S.) [E] was connected, using a 3,645 kg, 1.27 cm blue streak spliced loop (Samson Ferndale, Washington, U.S.) [F].

A second rope system [Rope B] consisted of a 4,005 kg yellow endless polyester strap (Buckingham) [G] that was looped using a girth hitch around the target branch at an estimated (visually) approximate center of gravity (CGV). A Dillon 500 kg dynamometer (Dillon Quality Plus Inc., Kansas City, Missouri, U.S.) [H] was connected using a 5,058 kg steel rigging double locking carabiner (International Safety Components, Ltd, Bangor, Gwynedd, UK) [I]. At the bottom of the dynamometer, another rigging double locking carabiner [J] was connected to a three-strand rope (3,200 kg) with an anchor bend. The rope was then threaded through the 7.6 cm rigging pulley [E] that was attached to Rope A. Rope B was then wound around the 900 kg capacity Good Rigging Control System (GRCS, Greg Good, Wisconsin, U.S.) [K] and mounted on a platform connected to a standard trailer hitch on the rear of the truck. The GRCS was used to apply the static load. Upon limb breakage, an arborist climber used a hand saw to prune off the entire broken limb at the point of union with the trunk. The branch was then lowered to the ground. Six main post branch-breaking measurements that offered meaningful relationships in the study were retained for further calculations:

1. Ultimate fracture force (F) determined from the dynamometer at time of breakage
2. Entire length of the broken branch (L_B) measured along the branch
3. Distance (L = lever arm) between the projection (vertical to a horizontal plane) of the load application point and the projection (vertical to a horizontal plane) of the fracture point along a horizontal line (Lilly and Sydnor 1995)
4. Diameter (D) of the branch as close to the fracture as possible and on the branch and stem-union side. Two measurements on opposite orientations were taken and a mean value was computed.
5. Distance of fracture point from branch union (L_{FU}) along the branch
6. L_{FU} as a percentage of the entire branch length L_B (%L_{FU}L_B)

Calculation of Moments and Bending Stresses
The moment (M) and maximum bending stress (σ) at failure were calculated according to Lilly and Sydnor (1995). Moments (M) were calculated using the formula: \( M = F \cdot L \); maximum bending stress (σ) at failure was calculated using the formula: \( \sigma = \frac{4FL}{\pi r^2} \). Radius (r) used was determined from diameter (D).

The Zone of Fracture
A region of the branch consisting of the visually identified fracture (usually within approximately 30 cm on either side of the break zone) was sawed off, photographed, and labeled. This region was considered the zone of fracture (ZF) in the study. Visual checks were made on all failed branches to ensure that no areas of decay or cankers that could potentially compromise the evaluations were present. Branch cross section discs measuring 2.54 cm thick were cut 48 hours after severing the ZF from trees using a 25.4 cm compound miter saw. Discs were taken as close to the fracture point as possible and towards the branch collar. Discs were weighed to

![Figure 1. Schematic outline of the ropes and equipment configuration used for static loading branches from visually un-infested and EAB-infested green ash trees in an evaluation of the material properties of ash trees in northwest Ohio in 2009. (A) Horizontal anchor rope, (B) tension rope, (C) hand winch, (D) six-coil Prusik knot, (E) rigging pulley, (F) blue streaked splice loop, (G) polyester strap, (H) dynamometer, (I and J) double locking carabiner, (K) Good Rigging Control System.](image-url)
the nearest 0.1 g to obtain green weights (Gw). The discs were
dried in an oven at 104°C for 24 hours and reweighed to obtain
dry weights (Dw). The oven dry volume (V_Dw) of each disc was
determined by first dipping the entire 2.54 cm wood sections
in molten paraffin wax and allowed to drip dry to ensure only
a thin wax seal remained (the ratio of the volume of wax to that
of the wood was considered negligible and is one limitation of
this protocol). The wood discs were then totally submerged in a
graduated (cm³) container of water the volume of the displaced
water represents the oven dry volume (V_Dc) of the wood disc.

Two evaluations were carried out as per standard wood measure-
ment protocol (USDA; Forest Products Laboratory 1987; also
Farrell 2003) on disc samples extracted within the ZF:

(i) Percent moisture (P_moist) = [(Gw - Dw) / Dw] × 100
(ii) Spec. Grav. (oven dry basis) (SG_Dw) = (oven dry weight Dw
(g) / VD (cm³)) / 1 g/cm³ (density of water)

Total Linear Cracks
Cracks present on the surface of the cross section of the wood
disc samples that faced the fracture point were measured after
first dusting with talc powder and shaking excess powder off.
Visible cracks were then measured using a divider and added
cumulatively to produce a total linear value (cm) (TLC).

Statistical Analysis
Moments and bending stresses at the fracture point, % (LFU = o),
were calculated using a Scheffe Grouping, SAS statistical software
compared across treatments using ANOVA. Means were sepa-
rated using the Scheffe Grouping, SAS statistical software
(SAS Institute, Cary, North Carolina, U.S.). Percentage data
for (% LFU L_B) was square root transformed before analysis.

Study Part 2: Evaluation of the Resistance of
Stem Tissue at Two Drill Heights in Two Groups
of Ash Trees
Ash trees ranging in diameter at breast height from 30 cm to 50
cm were selected in recreation park environments in and around
the city of Perrysburg, Ohio. Two groups were selected for this
trial similar to Group I and Group III trees in Part 1 of this study.
Each group consisted of five trees. Trees used in Study Part 1
were not used in Study Part 2. An F400-S model (IML, Atlan-
ta, Georgia, U.S.) was used to evaluate the resistance to drill-
ing in the stems of the two ash tree groups. Measurements were
taken in two directions (north to south and east to west) at the
base and at 1 m height of stems of all tree replicates. An air-
spade (155 cm³) was used to excavate around the base to provide
clear access if needed. Stem diameter at each drill height was
measured using an arborist diameter tape. The height resistance
readings (from chart printouts) were read in millimeters at 1.27
cm increments into the stem (reflected as a percentage of the
stem diameter at successive increments). Resistance (mm) val-
ues obtained for drill points (NS or EW) at the base or at the
1 m height for trees in Group I were plotted separately against
the corresponding incremental increase in percentage stem di-
ameter. Separate scatterplots were thus obtained for each height
(and direction) of drill point for all trees in Group I. This was
repeated for resistance (mm) values obtained for drill points
at the two stem heights of the trees assessed in Group III.

RESULTS AND DISCUSSION

Study Part 1
Moments and Bending Stresses
Moments and bending stresses calculated at branch fracture
were not significantly different (F = 0.47, DF = 3, 38, P = 0.70
and F = 0.74, DF = 3.38, P = 0.53, respectively) among the three groups of ash trees tested (Table 1). These data are further discussed within the context P_moist and TLC.

Comparison of Percentage Distance from Fracture Point to
Union to Entire Branch Length (%LFU L_B) Across Groups
The %LFU L_B comparisons from broken branches were signifi-
cantly different (F = 63.00, DF = 3, 18, P < 0.0001) different among the groups (Table 1). The mean ± SE %LFU L_B values were highest in Group I trees and lowest in Group III trees which may suggest a possible shift in fracturing towards the union. Good-
fellow (2009) identified a critical zone of failure within twenty
percent of the branch length to the union with the main stem.
The frequency of branch breakage also peaked in this region in this study (Figure 2). Of the 45 branches broken in total, six fractures or 13.3 % occurred at the point of union
with the stem (L_FU = o), these branches were all within a range of
3 to 7 cm in diameter. Interestingly three branches were
from Group II trees and three originated from Group III trees.

The Zone of Fracture for P_moist, SG_Dw, and Wood Strength
P_moist was significantly (F= 10.80, DF= 3, 38, P < 0.001) lower in Group III trees compared to P_moist from sample discs cut from
trees in Groups I and II, which were statistically homogenous
with each other (Table 1). Despite variable wood moisture content
this did not directly affect maximum stress at failure or strength
upon static loading. Farell (2003) reported similar findings
between variable moisture content with harvest date but found
similar stress at breaking was observed in sawtooth oak (Quer-
cus acutissima Carruthers) and red maple (Acer rubrum)
crotchles. Wood moisture decreases have generally been more aligned
with increase in strength of harvested wood in the traditional
sense. In the context of living trees, drier wood may not neces-
rarily constitute a stronger tree. Significantly lower wood moisture
coupled with rotational forces from wind loading or incidental
loading from snow or ice could increase risk of wood failure.

SG_Dw calculated for wood disc samples taken from the
ZF of the three groups of ash trees was not significantly dif-
f erent among groups (F = 0.73, DF = 3, 37, P = 0.54) (Table
1). While specific gravity of wood may be correlated with
strength in trees (Zoebel and van Buijtenen 1989; Niklas
1997), other studies, such as Lilly and Sydnor (1995), found
that although Norway maple (Acer platanoides L.) had a sig-
nificantly higher specific gravity than silver maple (Acer
saccharinum L.), no significant variation was observed in bend-
ing stresses at fracture point between the two maple species.

Statistical Analysis
Regression analyses with height of drill point as
an indicator variable were conducted for each
group of trees using SAS statistical software.

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Total Linear Cracks
The TLC (cm) in wood disc samples from the ZF was significantly different among the tree groups ($F = 17.64, DF = 3, 38, P < 0.0001$). Wood discs taken from Group III trees had highest total cumulative linear cracking while discs taken from Group I trees had least cracking (Table 1). The linear cracks increased with decrease in moisture ($Y = -0.33 + 20.6; r^2 = 0.32$) (Figure 3). Total cracks present may be indicative of the wood integrity in the ZF. While this may not be entirely representative of true branch strength, it underscores the significant variability of ash wood behavior after EAB interaction as early as two years of infestation.

Study Part 2: Evaluation of the Resistance of Stem Tissue at Two Drill Heights in Two Groups of Ash Trees
The resistance of stem wood tissue at 1 m above the base was not significantly different ($F = 2.63, DF 2, 453, P > 0.05$) compared to drill points at the base when measured for trees in Group I (visually un-infested ash trees) (Figure 4). Resistance at drill points observed for trees in Group III (EAB infested trees) was significantly ($F = 44.22, DF 2, 464, P < 0.001$) higher at 1 m compared to drill points at the base (Figure 4). These data suggest that the variation in the integrity of the wood at the base of ash tree stems compared to 1 m above may indicate material degradation with advanced EAB infestation. Material degradation may be indicative of strength loss and may introduce potential risk factors. Further research is needed especially to further evaluate the behavior of EAB infested ash stems to dynamic loads.

Table 1. Mean ± SE of post branch breaking parameters determined after static loading branches from visually non-infested and EAB infested green ash trees after static loading in an evaluation of the material properties of ash trees in northwest Ohio in 2009.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
<th>P-value</th>
<th>F Value</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moments Nm</td>
<td>959 ± 142</td>
<td>2423 ± 459</td>
<td>1546 ± 441</td>
<td>0.70</td>
<td>0.47</td>
<td>3, 38</td>
</tr>
<tr>
<td>Bending stress N/mm²</td>
<td>497 ± 115</td>
<td>653 ± 83</td>
<td>650 ± 106</td>
<td>0.53</td>
<td>0.74</td>
<td>3, 38</td>
</tr>
<tr>
<td>% LFULB</td>
<td>5.62 ± 0.11A</td>
<td>4.42 ± 0.11b</td>
<td>3.13 ± 0.13C</td>
<td>&lt;0.0001</td>
<td>63.00</td>
<td>3, 18</td>
</tr>
<tr>
<td>Percent moisture</td>
<td>59.17 ± 5.44A</td>
<td>52.90 ± 5.52a</td>
<td>27.68 ± 5.18C</td>
<td>&lt;0.0001</td>
<td>10.80</td>
<td>3, 38</td>
</tr>
<tr>
<td>TLC (cm)</td>
<td>4.69 ± 1.15 c</td>
<td>10.26 ± 1.18 b</td>
<td>15.72 ± 1.10 a</td>
<td>&lt;0.008</td>
<td>17.64</td>
<td>3, 38</td>
</tr>
<tr>
<td>SGDw</td>
<td>0.59 ± 0.27 a</td>
<td>0.48 ± 0.25 a</td>
<td>0.70 ± 0.18 a</td>
<td>0.54</td>
<td>0.73</td>
<td>3, 37</td>
</tr>
</tbody>
</table>

Notes: Asterisk (*) indicates untransformed means represented. Significant variation among groups is indicated by different letters in a row; ANOVA means separated by Scheffe’s grouping at 5% level.

SUMMARY
These data are based on the effects caused by the interaction of EAB with its preferred ash tree host over time. Ellison (2005), in a quantified tree risk assessment study, remarked of environment and biological entities that “precise quantification of potential for tree failure is unlikely to be achievable”; the researchers of the current study could not agree more. The data from this study identify that EAB-infested ash trees are compromised as early as two years after initial infestation and basal decline may occur with advancing infestation. Hauer et al. (1993), in an evaluation of ice storm damage to urban trees, concluded that deadwood present in the crown predisposes trees to further wind damage. Canopies of ash trees after early to intermediate EAB infestation often suffer die-back resulting in substantial deadwood accumulation. James and Kane (2008) cautioned that forces exerted by winds on branches may cause failure not predicted by static loading tests. The authors have found indication that branch failure may sometimes occur closer to the union in EAB infested ash trees under static loading. In addition to wind and ice and snow loading, climbing
and rigging activity will exert variable forces at single or multiple points on branches or basal stems of EAB infested ash trees. Detters et al. (2008) indicated that failure of the load bearing structure (branches and stems of trees) may occur during rigging and dismantling because of strength loss due to biotic effects. With advancing age of the EAB infestation, the risk concern of forces exerted by rigging and dismantling will exceed that emanating from the single load point responses we have observed in this study.

This work represents the first documented study that uses static loading and resistance drilling techniques to study the material degradation of tree wood caused by wood borers. Further work should be carried out on this EAB–ash tree complex as it pertains to tree structural and material integrity. This is especially relevant when large numbers of tree hosts occur in close proximity to each other or are prevalent species in community greenspaces.

Acknowledgements. The authors wish to express gratitude for the support from the city of Perrysburg, OH; Joe Tommasi and the safety department of the Davey Tree Expert Co., Kent, OH; John Goodfellow of BioCompliance Consulting, Inc. Redmond, WA; and Andreas Detters of Brudi & Partner TreeConsult, Germany.

**LITERATURE CITED**


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Persad et al.: Effects of Emerald Ash Borer Infestation on Tree Structure

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Résumé. L’agrile du frêne, un insecte épidémique chez les frênes, est couramment présent aux États-Unis et au Canada. Dans plusieurs régions, d’importantes populations de frênes sont affectées avec de nombreux arbres qui présentent des défoliations partielles à un état de dépérissement généralisé. De nombreux cas sont survenus, dans le Nord-Ouest de l’Ohio aux États-Unis, où des branches et des tiges infestées par l’agrile du frêne sont tombées prématurément lors de travaux d’élagage de sécurité ou d’abattage. Cette étude a été initiée afin de résoudre la question des effets de l’agrile du frêne sur les propriétés structurelles des branches et des tiges du frêne. Des frênes non infestés visuellement ainsi que d’autres avec des infestations récentes ou avancées ont été examinés. Les données provenant de test de charge statique sur les branches primaires ont indiqué que la résistance maximale à un stress de flexion jusqu’au point de rupture n’était significativement pas différente entre les arbres infestés par l’agrile du frêne de ceux non infestés. Cependant, l’examen des zones de fracture a révélé que le taux d’humidité du bois était significativement plus faible et le nombre de fissures plus élevé pour les sections de branches recueillies d’arbres infestés par l’agrile du frêne. Lors des tests de charge statique, les bris de branches au point d’attaque survenaient seulement chez les arbres infestés par l’agrile du frêne. Lors d’une évaluation de la résistance du bois chez des frênes infestés et d’autres non infestés, une résistance significativement plus faible a été observée sur les tiges de frêne infestées à un stade avancé par l’agrile du frêne lorsque des trous étaient forés à la base des zones d’infestation comparativement à 1 m au-delà. Cette situation n’était pas observée lors de forage de trous à des hauteurs similaires au sein de frênes sans signes visuels d’infestation. Ces données pourraient aider à identifier les éléments de risques associés avec la dégradation structurale du bois chez les frênes, et ce aussi tôt que une à deux années après l’infestation par l’agrile du frêne.

Zusammenfassung. Der smaragdgrüne Eschenbohrer (EAB, für seine siglas en inglés), ein insekt invasivo de árboles de fresno, ocurre actualmente en los Estados Unidos y Canadá. En muchas regiones, grandes poblaciones de fresnos son afectados con muchos árboles presentando muerte regresiva de las copas parcial o totalmente. Existen varios casos en el noroeste de Ohio, U.S., donde ramas o tallos infestados por EAB fallan prematuramente durante la poda de madera seca o la remoción completa del árbol. Este estudio fue iniciado para resolver los efectos de EAB en las propiedades del material de ramas y tallos de fresno. Se examinaron visualmente árboles de fresno no infestados y otros con reciente y avanzada actividad de EAB. Los datos de cargas estáticas en ramas primarias indican que la máxima flexión a la falla no fue significativamente más baja en árboles infestados por EAB comparados con árboles no infestados. El examen de la zona de fractura, sin embargo, reveló que la madera húmeda fue significativamente más baja y más quebradiza, lo que se observó en secciones húmedas de las ramas tomadas de árboles infestados por EAB. Durante la carga estática, la falla de las ramas en la unión ocurrió solamente en los árboles infestados por EAB. En una evaluación de la resistencia de la madera de ramas infestadas y no infestados cuando se taladraron en la base, comparados con sitios taladrados 1 m arriba. Estos datos pueden ayudar a identificar elementos de riesgo asociados con degradación estructural y material de madera de fresno en los primeros dos años después de la infestación por EAB.

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