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An investigation of branch stresses induced by arboricultural operations

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a method for assessing the safety of tree branches subject to unorthodox climbing approaches and possible falls. The method entails finite element modeling of the tree branch, experimentally or analytically determining loads associated with an ascending or falling climber, and computing stresses and safety factor along the length of the branch using dynamic structural analysis. A case study example is presented for an *Ulmus americana* L. branch on the campus of the University of Massachusetts, Amherst. This tree and branch were climbed using an unorthodox and controversial method during a competition in 2014. Case study models demonstrate that during an ascent, a climber's skill has a significant effect on branch stresses, and during a simulated fall, the climber's mass and fall distance are the key determinants of branch stresses. For loads induced during an ascent, safety factors for branches ranged between 3 and 4; for loads induced during a fall, safety factors were as low as 1.2. These values are dangerously low given the uncertainty of branch material properties. Climbers should be extremely cautious when attempting unorthodox climbing techniques.

1. Introduction

Arboriculture is a dangerous profession in which 14.1 fatalities per 100,000 workers involved in tree work [1] were reported in 2003, much greater than the overall population rate of 4.0 fatalities per 100,000 workers (Wiatrowski, 2005). Of the 1285 arboriculture worker fatalities between 1992 and 2007, 44% occurred while pruning or trimming trees, and 34% involved a fall (Castillo and Menéndez, 2009). The Center for Disease Control's National Institute for Occupational Safety and Health (NIOSH) explicitly recommends, "checking the condition of tree branches before…climbing," (Castillo and Menéndez, 2009), but: (1) climbers cannot carefully inspect a branch until they are close to it, (2) climbers cannot assess internal structural defects or ascertain the severity of external structural defects without sophisticated measuring devices and (3) there is a lack of robust data quantifying the safety of branches under expected or "worst-case-scenario" loads.

This paper introduces a method for assessing the safety of a branch when loaded by an ascending or falling climber, and shows how the stresses depend on the type of ascent and parameters of the fall. Following description of the method, results are presented for an example branch subject to a variety of ascending and falling loads. The findings point to ways in which arborist safety can be enhanced even in the absence of engineering analysis of the tree branch.

The work presented here is motivated by observations of an unorthodox and potentially dangerous ascending technique during a competition in 2014 in Massachusetts. To encourage worker safety, safe work practices are strongly emphasized at contemporary climbing competitions (http://www.itcc-isa.com/about/missionhistory/history.aspx, http://www.itcc-isa.com/resources/about_Eventdescriptions_MastersChallenge.pdf). During a Masters' Challenge event in 2014 in Massachusetts, a competitor installed the rope over a distal portion of a branch and footlocked the doubled rope (Adams, 2007) to reach one of the work stations in the event rather than ascending to the top of the tree and limb-walking in the conventional fashion (with the anchor point over a branch and around the main stem (Fig. 1) at a central point near the top of the crown (Lilly, 2005). Conventional limb-walking facilitates lateral movement throughout the crown with continuous rope support from a point higher in the crown. Limb-walking provides maximum stability for a climber and minimizes the bending moment on the branch (because the rope carries part of the climber's weight).

Prior to the competitor's ascent, judges conferred about the safety of the unorthodox approach and allowed the competitor to continue since the branch was large and *Ulmus americana* L. is considered to have strong wood. The branch supported the applied loads during ascent and descent without failure or apparent damage. Thankfully, the climber did not fall, but loads induced by a falling climber would be much greater, and the event inspired this study. The objective of this paper is to define a method for assessing branch safety using the case study of the *U. americana* branch. The results of the analyses provide guidance to climbers about branch safety during ascent or a fall.

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Fig. 1. Proper tie-in for work-positioning: a climber's rope passes over a lateral branch (on the right) and around the main stem.

2. Methods

The method used to address the objective of this paper consists of four steps: (i) definition of general branch geometry and section properties, and the internal forces, stresses and safety factors in general terms; (ii) description of the branch analyzed in this paper, including wood properties; (iii) determination of ascending and falling loads by experimental or analytical methods; (iv) development of a finite element model for the purposes of static, modal, and dynamic time history analysis. This method applies generally to the analysis of tree branches subjected to loads that could occur during an ascent or a fall, and is useful because it provides a framework for continued research into climber safety. The following sub-sections describe the four steps.

2.1. General definitions

Throughout the text, the branch described in the introduction is referred to as the primary branch—a branch that arises from the main stem or trunk. Lateral branches arising from the primary branch are referred to as secondary branches. The geometry of a primary branch can be defined by the parameterized coordinates ($x(s_1)$, $y(s_1)$, $z(s_1)$), where s_1 is a local, curvilinear coordinate that has its origin at the attachment of the branch to the trunk. The coordinate system is defined such that z is positive upward and the x and y coordinates define a plane parallel to the ground. The local coordinate specifies, for $0 < s_1 < l_1$, position along the length of the main branch, which has a total length l_1. The geometry of secondary branches is described by ($x(s_{2,i})$, $y(s_{2,i})$, $z(s_{2,i})$), where $0 < s_{2,i} < l_{2,i}$ is the local curvilinear coordinate for the ith secondary branch that is of length $l_{2,i}$ and has its origin at the attachment point to the primary branch $s_{1,i}$.

Ignoring shear deformations, the spatially varying moment of inertia $I(s)$, torsional constant $J(s)$ and cross-sectional area $A(s)$ are the complete set of section properties for a circular branch, and depend on the branch diameter $d(s)$. Tree branches are not generally circular, with the depth often exceeding the width. Circularity of the cross section is assumed here, though the approach could be readily adapted to treat branches with elliptical or other cross sections. Details about the validity of this assumption for the example tree are given in Section 2.2.

In this paper, only the response of the primary branch is considered, and the key response quantities are the: (i) displacements ($u(s_1,t)$, $v(s_1,t)$, $w(s_1,t)$) corresponding to the (x, y, z) coordinate directions where z is the downward direction and the x and y directions are in the plane parallel to the ground, (ii) bending moments ($M_p(s_1,t)$, $M_q(s_1,t)$) which correspond to vertical and lateral bending of the branch, and (iii) axial force $N(s_1,t)$. The two bending moments act with respect to orthogonal, cross-sectional coordinates (p, q) and can be combined into a resultant bending moment $M_r(s_1, t) = \sqrt{M_p(s_1, t)^2 + M_q(s_1, t)^2}$. The axial force and resultant bending moment generate stresses that can be combined to yield a maximum compressive stress, which acts along the longitudinal axis of the branch and occurs in the outer wood fibers at the bottom of the branch cross-section:

$$\sigma_{c,max}(s_1, t) = \left|\frac{M_r(s_1, t)d(s_1)}{2I(s_1)}\right| + \left|\frac{N(s_1, t)}{A(s_1)}\right| \tag{1}$$

The maximum stress that occurs at any point along the branch and at any time of the analysis is $\sigma_{c,max} = max_{(s_1,t)}(\sigma_{c,max}(s_1, t))$ and the location at which that maximum stress occurs is $s_{1,max} = \text{argmax}_{s_1}((\sigma_{c,max}(s_1, t)))$. Safety is checked by evaluating the safety factor $FS = \sigma_{c,all}/\sigma_{c,max}$. If $FS \geq 1$ the limb is safe, if $FS < 1$ the branch is unsafe and is predicted to fail under the current set of assumptions. Shear and torsional stresses were neglected in this analysis because the primary branch is slender (span:depth ratio > 30) and torsional loads are minimal since the branch was relatively straight between the trunk and the load point.

2.2. An example tree and branch

The *U. americana* tree that inspired this study is shown in Fig. 2. The branch was measured at increments of $\Delta s_1 = 1$ m out to $s_1 = 11$ m, and a final measurement was taken at $s_1 = 11.5$ m, which is the point of load application (s_{load}) and the point at which the primary branch divided into two secondary branches. At each increment, the depth and width, azimuth and elevation angle of the primary branch were recorded. Subsequently, the azimuth and elevation angle were converted to Cartesian coordinates ($x(k\Delta s_1)$, $y(k\Delta s_1)$, $z(k\Delta s_1)$), $k = 1, 2, \ldots, 11, 11.5$ with $\Delta s_1 = 1$m (Table 1). The cross section is approximated as circular and the diameter reported in Table 1 is the average of the measured width and depth. This assumption simplifies the analysis and, for the example tree, results in an error in cross section moment of inertia of no more than 7% (in only 1 segment). In 3 of the measured segments the cross section width and depth were equal.

Three secondary branches were present, including extension of the primary branch past the final measurement point. Secondary branch measurements were limited to (i) the location of their attachment point ($s_{1,1}$, $s_{1,2}$, $s_{1,3}$), (ii) the diameter at that point, and (iii) the distance to the distal end of the secondary branch (Table 2). This distance is used to approximate the secondary branch lengths ($l_{2,1}$, $l_{2,2}$, $l_{2,3}$). Since cross-sectional measurements of the secondary branches could not be practically obtained, the secondary branches were approximated as cones with diameter that tapered linearly from the proximal to the distal end so that the diameter of each secondary branch is given by $d(s_{2,i}) = d(s_{2,i} = 0)\,((l_{2,i} - s_{2,i})/l_{2,i})$. While this conical form does not exactly represent secondary branch geometry it is adopted as a simple approach to including secondary branch mass distribution in dynamic analysis.

Branch diameters shown in Tables 1 and 2 were measured outside of the bark. To avoid unnecessary wounding, bark thickness was measured at four points along the branch (rather than every meter). From these measurements, the bark thickness t_b is assumed to be

$$t_b(s_1) = \begin{cases} 1.25\,\text{cm} & s_1 < 3\,\text{m} \\ 0.60\,\text{cm} & 3\text{ m} < s_1 < 6\,\text{m} \\ 0.40\,\text{cm} & 6\text{ m} < s_1 < 9\,\text{m} \\ 0.20\,\text{cm} & 9\text{ m} < s_1 < 11.5\,\text{m} \end{cases} \tag{2}$$

Assuming that bark does not contribute to structural stiffness, the moment of inertia is $I(s_1) = \pi(d(s_1) - t_b(s_1))^4/32$, the cross-sectional area is $A(s_1) = \frac{\pi(d(s_1) - t_b(s_1))^2}{4}$, and the torsional constant is $J(s_1) = \pi(d(s_1) - t_b(s_1))^4/16$. Bark thickness was assumed constant at 0.20 cm for secondary branches.

The compressive bending strength of branch wood parallel to grain, $\sigma_{c,all}$, was assumed to be 75% of the MOR reported in Kretschmann (2010) for green *U. americana*. The reported value of MOR is 50 MPa