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Branch Length Faults & Failures

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In order to appreciate branch success, branch failure should be examined. How do branches fail? When branches fail and are sealed-off, their history is embedded within the nodal area. (Coder 2019a) Branch failure is a common event in trees. In one study of branch failures during a major storm, branch failures were caused by: 5.4% included periderm (bark) unions; 9.7 % lion's tailed or severly end-weighted foliage concentration; 9.8% forks or codominant branches; 11.6% branch cavities; 18% dead branches; 25.8% overextended branches (low taper / high slenderness); and, 33.3% branch decay. (Koeser et al. 2020)

In another study, branch failures were caused by: branch or branch union decay (3%); codominant branches (10%); lack of pruning care & lion's tailing (10%); branch base periderm inclusions, cracks, and sharp bends (23%); and, simply excessive wind / snow / ice loads (54%). (van Haaften et al. 2021) Branches fail for a variety of reasons.

Branch Length Issues

Branch structural stress and strain increase with branch length whether the branch is tapered, non-tapered, or curved. Figure 1. Both length and branch weight conspire to generate stress at rest under gravity and when moving in wind. (Coder 2021a) A simple means of examining this branch length and weight issue is given in Figure 2. For branches of all the same length and weight, branch angle can also impact stress. Because all branches do not have the same weight and length, determining branch weight can help define stress. Figure 3 provides a means for estimating branch weight by determining branch volume. Figure 4 shows, for branch segments between 1 and 13 feet long and diameters between 2 and 25 inches, branch volume in cubic feet. Branch weight is estimated by multiplying cubic volume of branch segments by greenwood density for each tree species.

For example, green wood density (pounds per cubic feet of volume) of five different sample species include: live oak = 89.9; black locust = 68.0; sweetgum = 60.3; loblolly pine = 51.3; and, black cherry = 46.9. These values suggest long horizontal branches and/or large diameter branches are under large loads from gravity alone. Coupling gravity loads with wind, ice, or snow loads reveals a tremendous mechanical adjustment required in branch bases and stem nodes in order to support any branch. (Coder 2021c) Holding a load with the least investment of food materials invested is the dilemma for a tree. A branch slenderness ratio can suggest failure points. Figure 5.

Stress Focus

As a primary branch accumulates more mass and sail from higher order branches, branch failure increases. (Kane & Finn 2014) Branches tend to break at nodes either close to the stem / branch confluence or near the primary growth interface at tip. (Walkden 2016) At the branch base and stem flange area, strain is distributed evenly across the entire attachment zone without any local concentrations. The result is a branch-stem junction area stressed well below the failure point of its woody tissues. (Muller et al. 2006)

When branches do fail, they tend to crumple or collapse on the under side and crack on the upper side away from the attachment point. (Mattheck et al. 2015) Wood density within a branch influences the type of failures. (Gardiner et al. 2016) Branch wood failures are due to strength on the upper tension side linearly increasing with wood density, and strength on the lower compression side increasing exponentially with wood density. (James et al. 2017) In other words, as species wood density increases, failure potential quickly shifts with branch growth to the upper tension side of branch. Figure 6. Branches usually fail with green-stick fractures on the upper side in more dense wood species, and with lower side buckling in lighter density wood species. (Gardiner et al. 2016)

Wood Density Impacts

Tree species with low density wood tend to fail on the compression side and buckle. (van Casteren et al. 2012) Species with moderate wood density sustain “green stick fractures,” where initial yielding is on the compression side but the tension side laterally breaks and quickly forms a crack running along the center of a branch. (Ennos & van Casteren 2010; van Casteren et al. 2012) Trees with high wood density tend to fail by tension side lateral cracking. (James et al. 2017) Figure 7. Tree species with branches of very dense wood can crack across the whole diameter. (Ennos & van Casteren 2010) Longitudinal cracks expand and travel near the center of branch away from crossing rays, and either along annual increment boundaries or along earlywood / latewood tissues in ring-porous trees, where material is weaker. (van Casteren et al. 2012)

Strong branch tapering away from the base changes how fractures form. Branches with no taper tend to crack down the center (longitudinal fracture) in both directions starting at a lateral tension fracture on the upper side. (Ennos & van Casteren 2010) In tapered branches, a longitudinal crack will form under a lateral tension fracture on the upper side and tend to run toward the tip until it encounters a node when it could crack laterally again. (Ennos & van Casteren 2010) Figure 8. When a branch develops a longitudinal crack down the middle toward the distal end generating two half-round segments, the branch cross-section has roughly 28% of the bending and torsion resistance of a non-fractured circular branch. (Coder 2019b)

Failure Forms

Some unique tree branch failure categories observed have included:

-- Curved branches lifted too far by wind crack down the middle (Ennos & van Casteren 2010);
-- Branches with near 90^{o} branch angles develop shear cracks down the middle (Mattheck et al. 2015);
-- Foliage concentration at the branch tip (lion’s tailing) leads to multiple cracks and failures (Mattheck et al. 2015);

-- Extreme ovalization of branches can lead to cracks forming along the branch middle across the short axis of cross-section (Mattheck et al. 2015);
-- Because of variability in decay progression from branch to stem, and from stem to branch, cavity defect estimations do not work in branches as they would in upright stems (Mattheck et al. 2015); and,
-- Branches with excessive slenderness can generate both cracks and buckle, with critical buckling length depending upon branch length and radius (buckling length = branch length X (branch radius)$^{0.67}$). (Mattheck et al. 2015; Dahle & Grabosky 2010)

With all discussions of branch fractures and failures, it should be remembered for a majority of tree branches which fail under strong wind loads, most are not defective. Most branches fail in bending or shear, with only 22% of failures associated with defects. (Kane & Finn 2014) For example, branch failure causes associated with defects include weak confluences (80%), decay (12%), or a combination (4%). On the other hand, branches not failing had significant defects of weak confluences (78%), decay (13%), and a combination (4%). (Kane & Finn 2014) These values suggest branches fail when overloaded, regardless of defects. (Coder 2019c)

Lessons From CODIT

Long multiple studies of tree wound compartmentalization provide a number of important results for proper branch attachment, pruning, and tree health care. Specifications for size of pruning cuts by tree species are becoming more common. Recommendations suggest cut branches should be less than 2" in diameter for weak compartmentalizing species, and less than 4" in diameter for effective compartmentalizing species. (Dujesiefken & Liese 2015) In removing branches, stem flange areas should be carefully conserved and never cut or injured, regardless of its visible length outward along a branch. Timing of branch pruning should always be concentrated during the vegetative growth periods (April to August in the Northern hemisphere) for effective tree defense. (Dujesiefken & Liese 2015)

For proportionally large branches or codominant branches, pruning techniques need to be modified to allow for more effective tree defense. Reduction pruning cuts are the preferred cutting method on codominant branches (BR >0.66), rather than removal. (Dujesiefken & Liese 2015) Abridge large or codominant branches -- not remove. (Coder 2021b) Reduction pruning cut angles should be changed as branches approach and exceed branch ratio (BR) values above 0.66, due to the loss of an effective stem flange and defensive zone. (Dujesiefken & Liese 2015) If no stem flange area is visible at the branch base, and/or BR >0.66, cut outside the top of stem flange area and downward at an angle to the stem designed to minimize wound surface area and allow water to run off. (Dujesiefken & Liese 2015)

Conclusions

Knowing how branches are attached to stems, and how they begin to fail, can assist tree health care providers manage risk. The strength of branch attachment can be compromised by many things. Structural tissue areas around a branch and stem flange must be protected and conserved.

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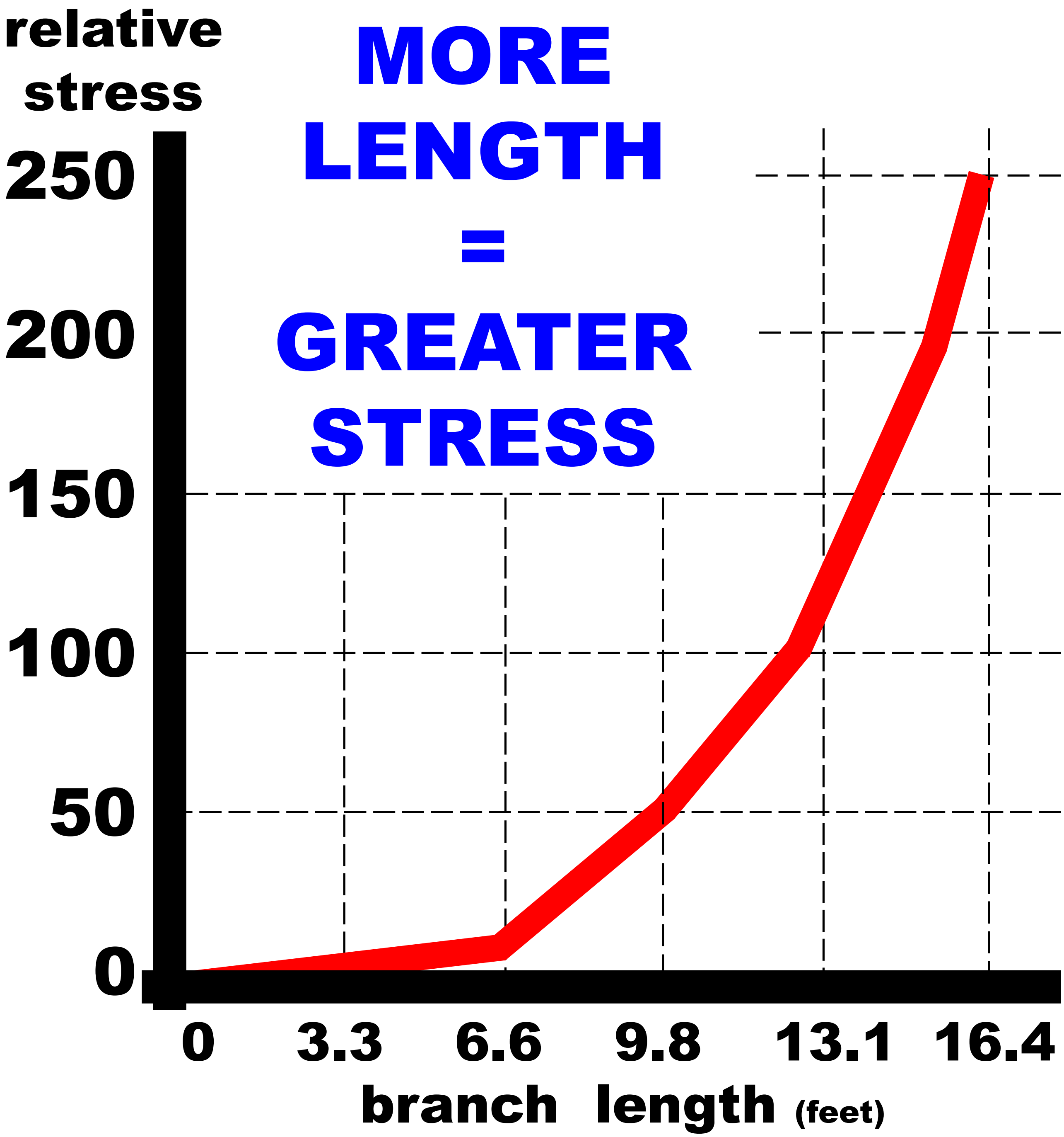

Figure 1: Composite curve for primary branch length in feet and its associated relative stress at failure for 21 tree species.
(after Evans et.al. 2008)

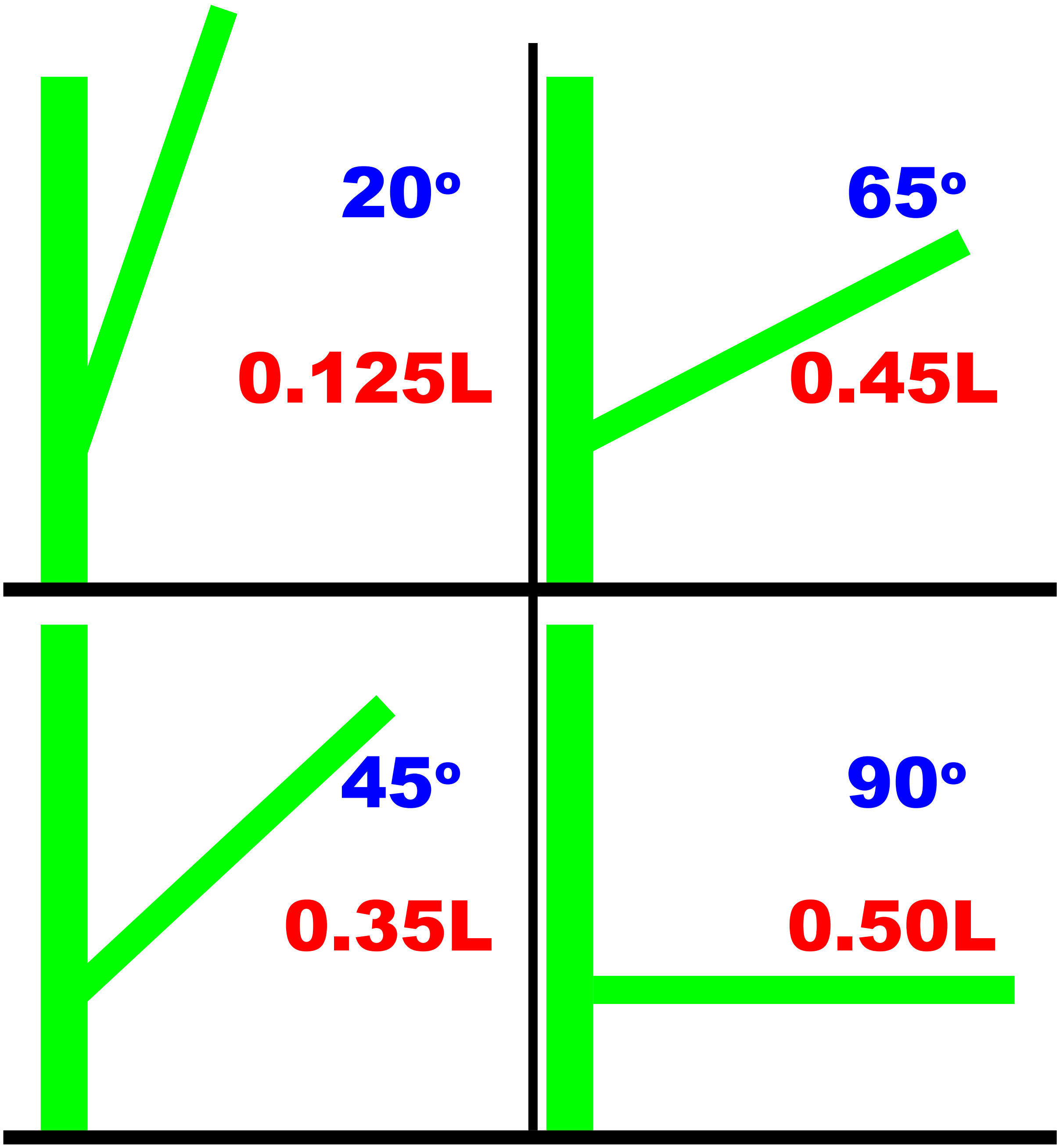

Figure 2: Force (in red) pulling downward on branches of the same length based upon various branch angles in degrees.
Branch length = L (from Loehle 2016)

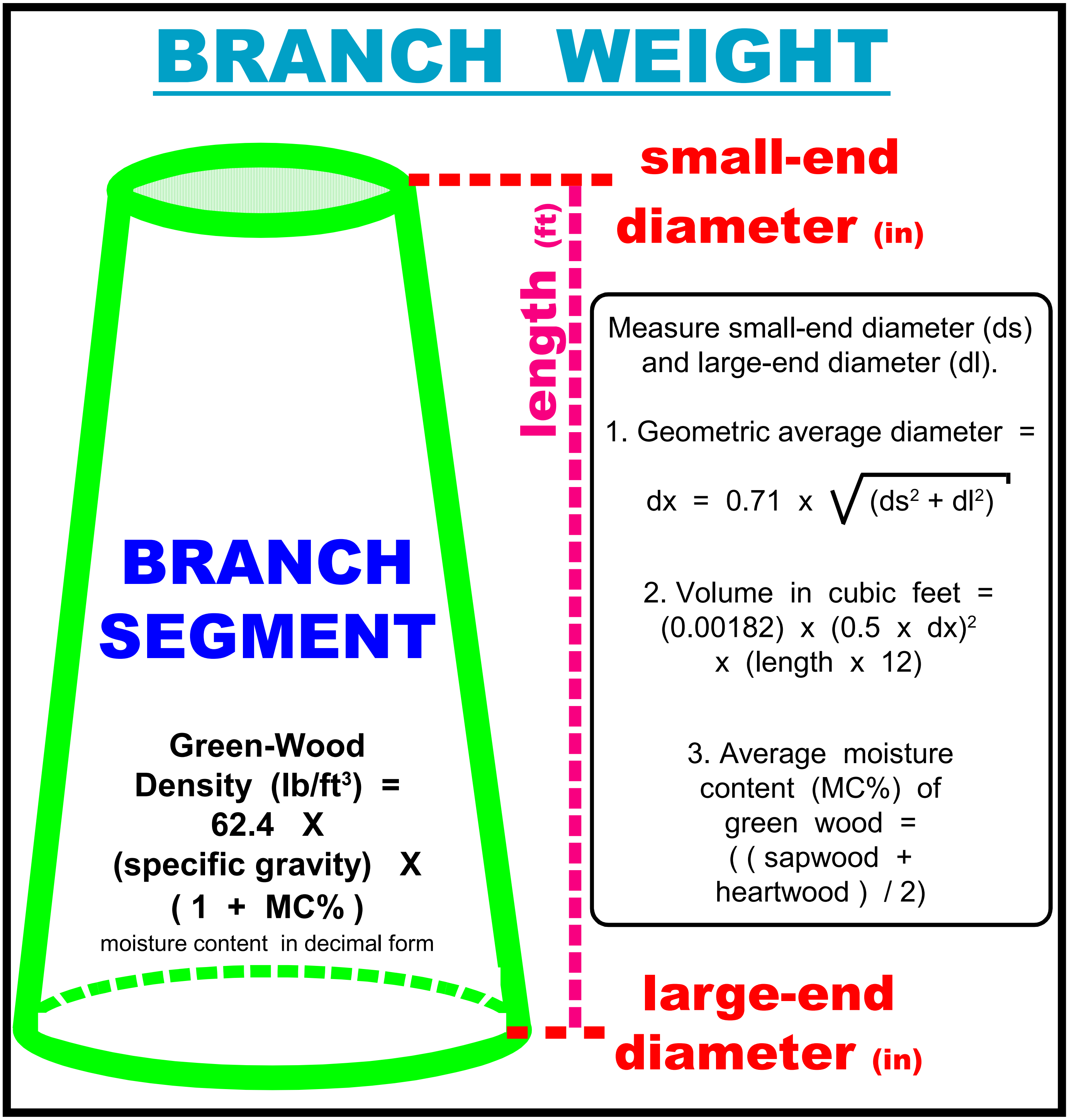

Figure 3: Estimating weight of branch in pounds depends upon its green wood density. Branch length, diameter, moisture content, and species dependent specific gravity are components. (Coder 2021a)

CUBIC FEET VOLUME IN BRANCH SEGMENT

diameter (inches)	circumference (inches)	branch length (feet) 1	2	3	4	5	6	7	8	9	10	11	12	13
2	6.3	0.02	0.04	0.07	0.09	0.11	0.13	0.15	0.17	0.2	0.2	0.2	0.3	0.3
3	9.4	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.4	0.5	0.5	0.6	0.6
4	13	0.1	0.2	0.3	0.35	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.1
5	16	0.1	0.3	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.6	1.8
6	19	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6
7	22	0.3	0.5	0.8	1.1	1.3	1.6	1.9	2.1	2.4	2.7	2.9	3.2	3.5
8	25	0.4	0.7	1.1	1.4	1.8	2.1	2.4	2.8	3.1	3.5	3.8	4.2	4.5
9	28	0.4	0.9	1.3	1.8	2.2	2.7	3.1	3.5	4.0	4.4	5	5	6
10	31	0.6	1.1	1.6	2.2	2.7	3.3	3.8	4.4	5.0	6	6	7	7
11	35	0.7	1.3	2.0	2.6	3.3	4.0	4.6	5	6	7	7	8	9
12	38	0.8	1.6	2.	3.	3.9	5	6	6	7	8	9	9	10
13	41	0.9	1.8	2.8	3.7	4.6	6	7	7	8	9	10	11	12
14	44	1.1	2	3	4	5	6	8	9	10	11	12	13	14
15	47	1.2	2.5	3.7	5	6	7	9	10	11	12	14	15	16
16	50	1.4	3	4	6	7	8	10	11	13	14	15	17	18
17	53	1.6	3	5	6	8	10	11	13	14	16	17	19	21
18	57	1.8	4	5	7	9	11	12	14	16	18	20	21	23
19	60	2.0	4	6	8	10	12	14	16	18	20	22	24	26
20	63	2.2	4	7	9	11	13	15	18	20	22	24	26	28
21	66	2.4	5	7	10	12	14	17	19	22	24	27	29	31
22	69	2.6	5	8	11	13.	16	19	21	24	26	29	32	34
23	72	2.9	6	9	12	14	17	20	23	26	29	32	35	38
24	75	3.1	6	9	13	16	19	22	25	28	31	35	38	41
25	79	3.4	7	10	14	17	21	24	27	31	34	38	41	44

Figure 4: Number of cubic feet in a non-tapered branch segement with a given diameter or circumference (in inches), for lengths between 1 and 13 feet.
Note table values are rounded approximations. (Coder 2021a)

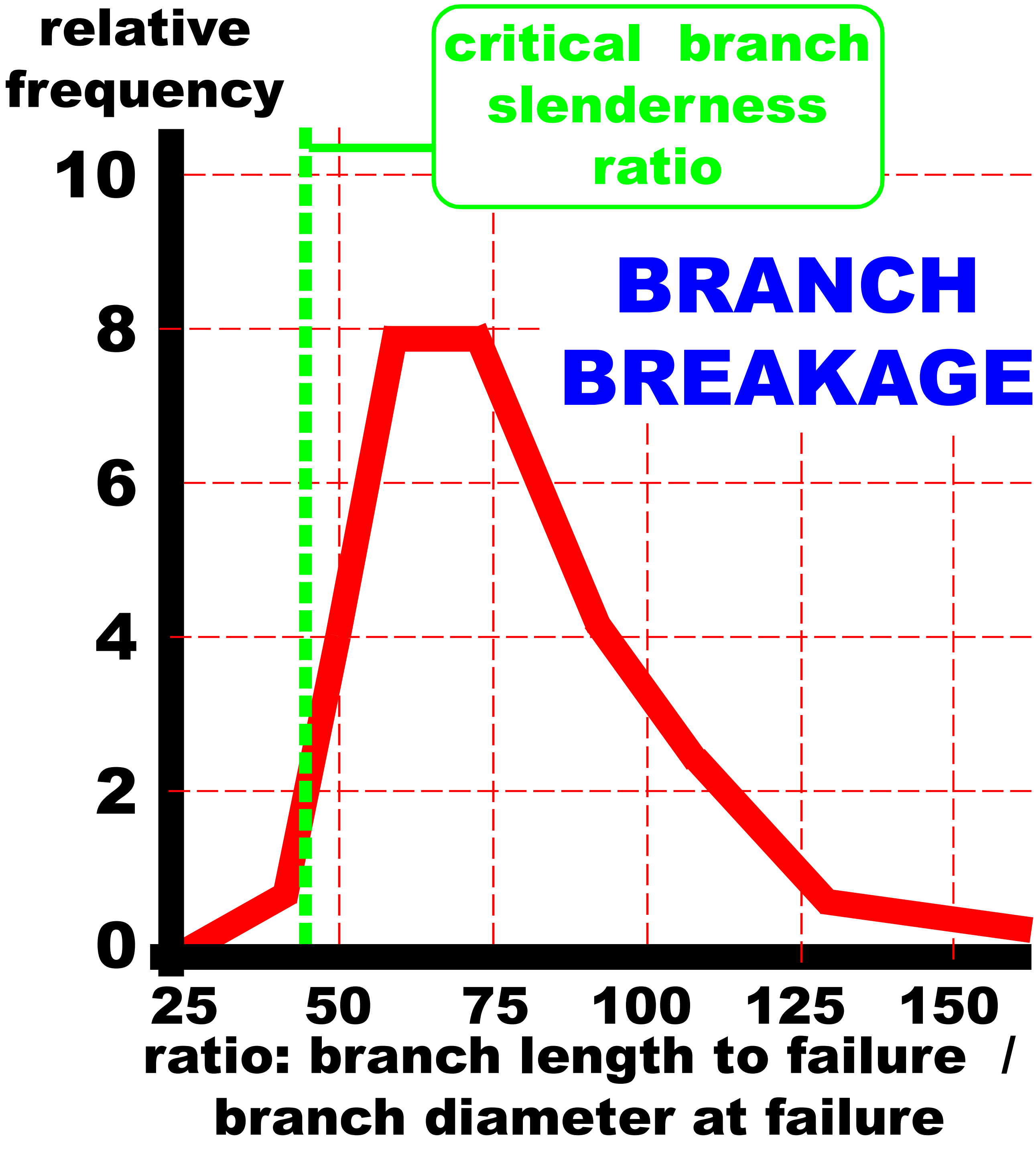

Figure 5: Branch slenderness ratio (branch length from tip back to failure point, divided by branch diameter at failure point), and associated failure levels.
(derived from Mattheck et.al. 2015)

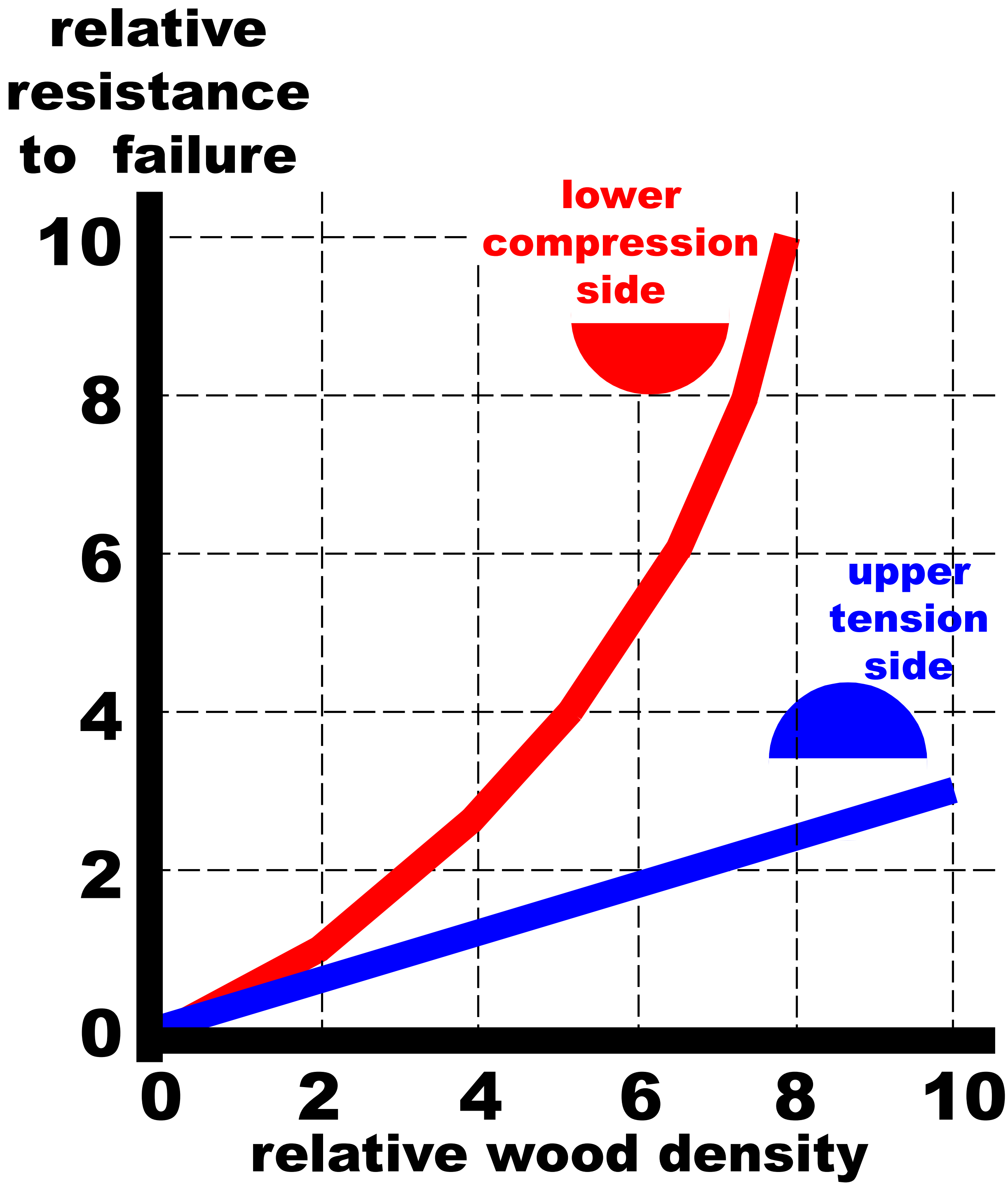

Figure 6: Difference between branch top half (tension side) and bottom half (compression side), and the changing relative resistance to fracture with increasing species wood density. (after James et.al. 2017)

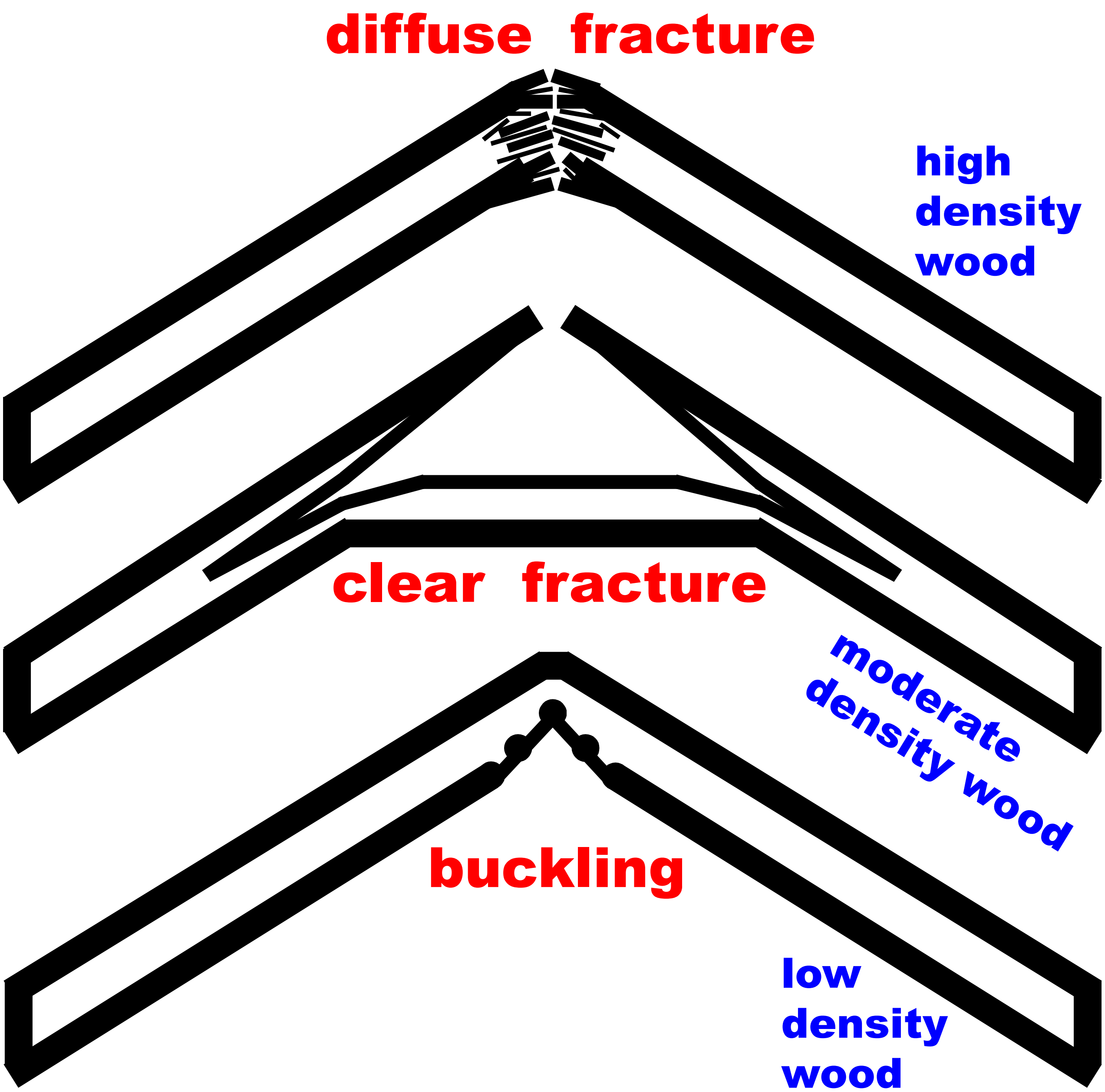

Figure 7: Three typical failures in tree branches: diffuse and clear fractures initiated from a tension break on the top surface, and buckling from compression crushing on the bottom surface. (van Casteren et.al. 2012)

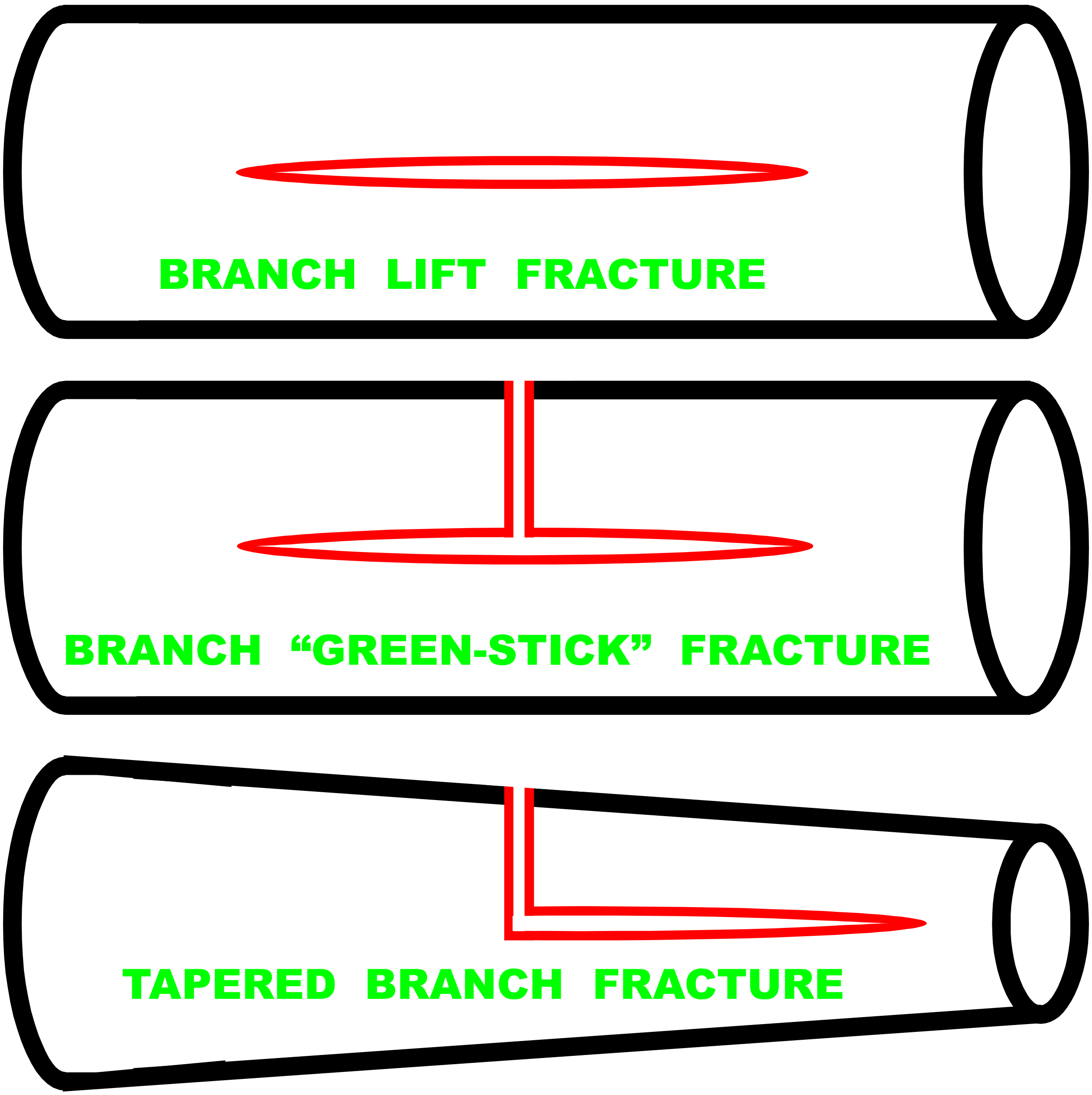

Figure 8: Failure patterns from bending in tree branches.
(after Ennos & van Casteren 2010)