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Visual Assessment of Branch Attachment Strength

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How are branches held onto stems and how strong are these branch attachments? What are the "tells" or visual suggestions of branch sustainability and potential failure? Examining branch attachments can help tree health care providers manage risk, manipulate tree structure, and better prescribe pruning to meet tree owner objectives. (Coder 2019)

In the last decade, research has consistently suggested three visual branch base components, each of differing value, for use in assessing branch attachment strength: branch / stem diameter ratios (branch ratio = BR) with an importance value of 60%; branch angle (BA) with an importance value of 25%; and included periderm or bark (IP) presence within a branch confluence with an importance value of 15%. Figure 1. Importance values are derived from the number of citations and amount of variation accounted for in branch attachment failures.

I. Branch Ratio Assessment (60% Importance Value)

One of three key visual evaluation components for branch anchorage success or failure is branch ratio (BR) or branch aspect. Branch ratio represents branch base diameter divided by stem diameter just above the branch confluence. Figure 2 provides stem and branch diameters by branch ratio. Branch ratio measures provide an estimate of how well a stem is supporting a branch. Small branch ratio branches are proportionally stronger than confluences with branch ratios closer to 1.0. Smaller branches growing from proportionally larger stems (i.e. smaller branch ratios) fail less often. (Buckley et al. 2015; Gilman 2003; Gilman 2015; Meadows & Slater 2020; Miesbauer et al. 2014a; Slater 2021; Tothill & Slater 2019; Walkden 2016). Figure 3.

Smaller Is "Better"

Smaller branch ratios show strong interconnections and intermeshing of branch and stem tissues, while large or codominant branch ratios exhibit little or no intermeshing with stem tissues. (Meadows & Slater 2021; Slater & Harbinson 2010) Rapidly growing branches with large branch ratios do not develop strong stem flange areas and do not generate effective axillary wood to hold them in-place. (Mattheck et al. 2015) The main structural difference among branch ratios is the level of interconnections and interlocking between stem and branch tissues within the stem flange area. (Meadows & Slater 2020). Figure 4.

Branch attachment failure categories are associated with branch ratios (BR). Flat surface failures have little intermeshed tissues and parallel fiber batts along the stem. *Flat surface* failures are easiest to break and represented by branch dominant / codominant branch ratios usually between 0.65 - 1.0 BR. *Embedded* *branch* failures are an intermediate form having some branch base and branch trace tissues intermeshed or interlocked with stem tissues. This failure form generates superficial splits and grooved failures down the stem usually with branch ratios between 0.50 - 0.8 BR. *Ball-in-socket* failures are represented by well intermeshed and interlocked branch and stem fibers within the branch node. This branch attachment form is most difficult to break or pull-out of a stem, and usually occurs with branch ratios between 0.10 - 0.60 BR. (Kane et al. 2008)

Codominance Issues

Branches with BR > 0.66 have weak attachments and codominant connections leading to flat and lightly embedded tissues. Codominant branches (BR >0.66) are easier to break-off compared to similar sized branches on much larger sized stems and are weakened by the lack of development of high density axillary wood in their confluence. (Gilman 2003) These attachment failures accelerate as a 0.70 branch ratio is reached and exceeded, even when wood density and associated strength are evaluated. (Kane et al. 2008)

II. Branch Angle Assessment (25% Importance Value)

The second of three key visual evaluation components for branch anchorage success or failure is branch angle (BA). Branch angle (BA) is measured as the degrees of angle between the top of a branch and its stem. There has been great debate over many years regarding the role branch angle (BA) plays, if at all, in branch attachment failure. When most lateral buds initially expand, branching angle is ~50^{o}, but load challenges and resource availability stimulate branch angle changes over time. (Sone et al. 2006)

Angle Interactions

Studies looking at branch ratio associations and periderm inclusions both associated with branch angle strength found no direct relationship. (Grabosky & Gilman 2007; Tothill & Slater 2019) Some studies examining branch angle and attachment strength could not determine branch failure variability dedicated to branch angle alone. But, the angle of branch attachment (BA) has been found to be related to attachment strength in some form. (Tothill & Slater 2019)

There are a number of suggested interactions between branch angle and attachment strength. Wider (larger) branch angles are less likely to have included periderm, and coupled with small branch ratios, are stronger than narrow branch angles. (Kane & Finn 2014; Miesbauer et al. 2014a) Horizontal branches (large angles) bend more uniformly and have stress distributed back toward larger diameter bases, where vertical branches concentrate bending at their tips with large acute bends and failures. (Miesbauer et al. 2014b) Horizontal branches (large branch angles) had double the resistance to failure of vertical branches (small branch angles). (Miesbauer et al. 2014a)

The narrower (smaller) branch angle, the weaker the attachment. (Kane 2007) Figure 5. Looking at various branch angles for the same branch ratio shows increasing strength of attachment with larger (wider) branch angles. Figure 6. As branch angle (BA) becomes smaller than 30^{o}, the risk of branch attachment failure is significantly increased. Abridging (reducing not removing) upright small branch angle branches decrease failure risks. (Miesbauer et al. 2014a)

Combo Assessment

Examining branch attachment strength as a combination of branch ratio and branch angle has value. Figure 7. Because proportional stem disruption area (surface area of stem surface dedicated to branch attachment) increases with smaller branch angles, and an associated interaction with branch ratio exists, a combined branch angle / branch ratio assessment can be made. (Walkden 2016) As branch ratio increases, branch attachment strength declines leading to a greater risk of failure. As branch angle becomes smaller, the stem disruption area from branch attachment becomes greater and of increased risk of failure. As branch angle / branch ratio values (BA / BR) exceed a calculated value of 95, branches should be abridged or removed, with abridging preferred, in order to maintain and enhance attachment strength.

Functional Codominance

Another view of branch angle and its interaction with branch ratio provides a further attachment strength assessment. For any given branch ratio, a branch angle value is reached where the stem disruption area of branch attachment approaches an equivalent attachment strength level of a codominant branch. For example, a branch ratio of a 1.0 branch is codominant (branch dominant) at any branch angle, whether a wide 90^{o} or a narrow 20^{o}. A branch ratio of 0.5 approaches codominance attachment strength levels at <30^{o} branch angle. Branch ratio (BR) and branch angle (BA) can be used together as a guide for abridging or removing functionally codominant branches. Figure 8.

III. Included Bark Assessment (15% Importance Value)

A third visual branch attachment strength component which is commonly cited is included periderm (IP = included periderm or bark). Periderm inclusions are a seam of periderm enveloped within a confluence and disrupts axillary wood formation and tissue interconnections. (Meadows & Slater 2020) A branch base or stem flange crack or rimple on top of a confluence suggests a branch is not well integrated into a stem and may have included periderm. (Mattheck et al. 2015)

Inclusion Values

There have been conflicting values determined for periderm inclusions on branch attachment strength, ranging from large impact to no impact. One study suggested strength of branch attachments was not related directly to periderm inclusions unless inclusions were of large proportions. (Kane et al. 2008) Included periderm reduced confluence strength especially within codominant attachments. (Kane & Clouston 2008).

Narrow or thin periderm included confluences failed at 76% of the load for normal (no included periderm) branch confluences, and only at 54% of the load for a normal branch when wide periderm inclusions are present. (Meadows & Slater 2020; Slater 2021; Tothill & Slater 2019) Included periderm was detrimental to attachment strength and tended to be found with small branch attachment angles (<25^{o} BA), large branch ratios (>0.7 BR), and V-shaped confluences. (Kane 2007; Kane 2014; Kane et al. 2008; Kane & Finn 2014; Mattheck et al. 2015)

Examining Attachments

One simple means for assessing included periderm is by estimating extent of the inward folded rimple, crease, or valley of periderm captured within a stem flange. Estimating the percent of stem flange circumference showing included periderm can help determine potential branch attachment problems. Figure 9. The greater the stem flange circumference disrupted by included periderm (IP), the weaker the branch attachment will be.

The first step of this assessment is to estimate stem flange circumference around a branch base. A second step estimates how much a stem flange shows external evidence of included periderm on top of its confluence which disrupts the axil area. Estimates can be made in degrees for the total area, or more easily by percent of circumference disrupted. Figure 10. When assessing included periderm, small stem flange circumference disruptions should be noted, but are rarely a structural issue. As included periderm openings to the outside approaches 100^{o} or 28% of the stem flange circumference involved, the branch base progressively becomes more structurally compromised.

Branch Attachment Strength Recommendations

A list of key findings and derived best practices for tree health care providers regarding branch attachments include:

1. Visual assessments should concentrate on branch ratio (60%), branch angle (25%) and periderm inclusion (15%) signs for branch attachment strength;
2. Protect and defend axillary wood areas on top of a stem/branch confluence from friction heat, abrasion and injury; (Coder 2019)
3. Monitor for the presence of fractures or cracks within the axillary wood of confluences, especially after large storms; (Coder 2021d; Walkden 2016)
4. The stem flange area should be carefully conserved and never cut or injured, regardless of its visible length outward along a branch; (Coder 2021a; Dujesiefken & Liese 2015)
5. Abridge (shorten with proper reduction) rather than remove branches with large and codominant branch ratios (BR >0.66) in order to attain and maintain strong tree control of branches; (Coder 2021a; Dahle & Grabosky 2010; Dujesiefken & Liese 2015)
6. Abridge (reduce) upright growing branches strongly, and attempt to develop larger branch angles -- branches in lower crown areas will require more abridging to generate the same branch ratio change as in upper branches; (Gilman 2015; Miesbauer et al. 2014a) and,
7. Assess branch attachment strength and keep branch ratios below 0.66, branch angles greater than 30^{o}, and included periderm less than 100^{o} or less than 28% of stem flange confluence circumference.

Conclusions

In summary, a tree health care provider must effectively assess, protect, and treat (abridge, reduce, remove) branches as needed to conserve and defend the entire tree while minimizing failure risks. (Coder 2021b; Coder 2021c; Coder 2021e) Figure 11. Tree health care providers must also work to maintain structurally sound and biologically efficient branches. Branch attachment strength assessment is key to low risk, tree-sustaining management. Build expectations of branch attachment success and failure for both more effective care and greater appreciation among tree owners and the public.

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Citation:

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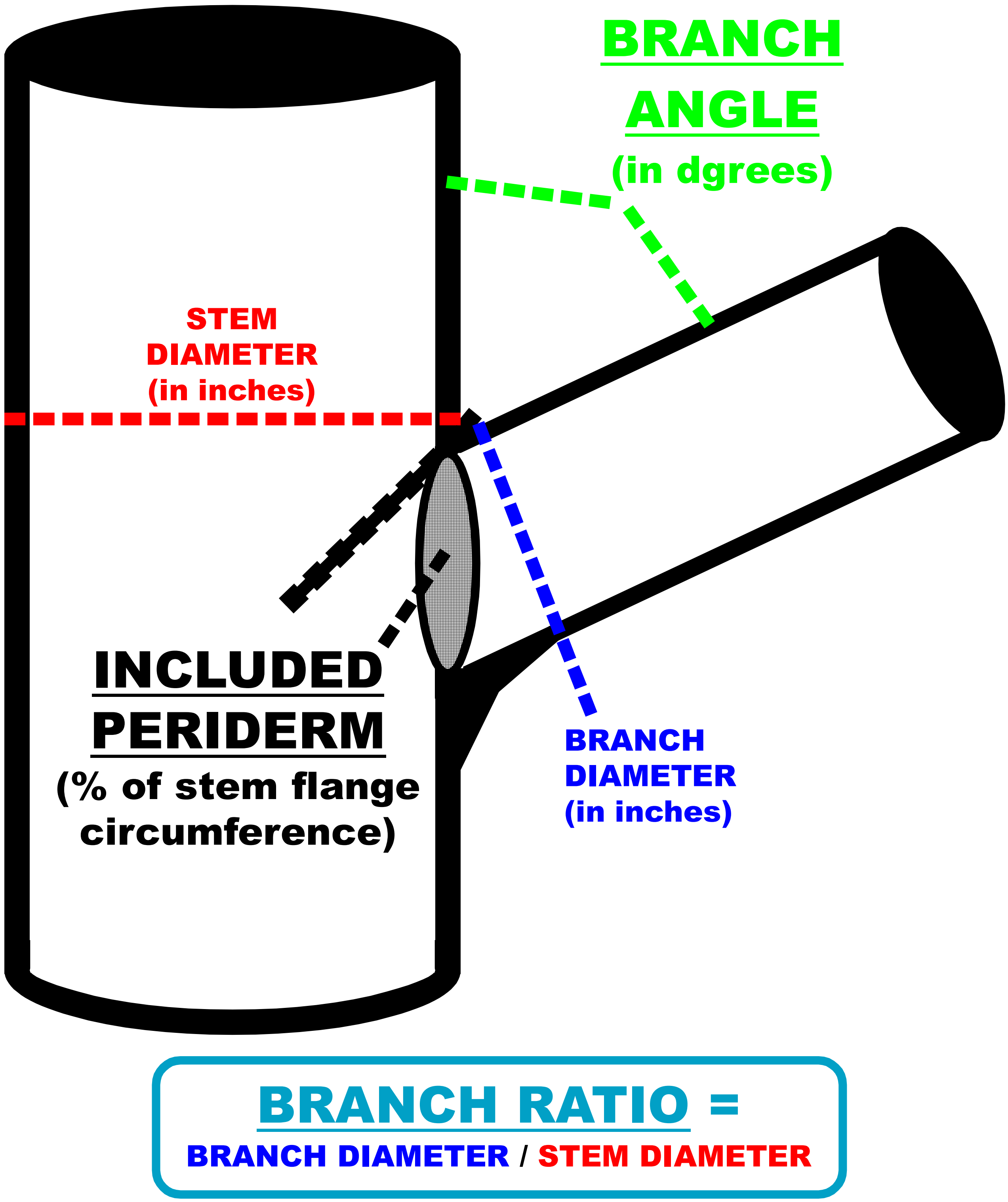

Figure 1: Visual branch measures used in estimating branch attachment strength and resistance to failure.
(In this example: branch ratio = BR = 0.5; branch angle = BA = 65°; included periderm percent = IP = 0%)

BRANCH DIAMETERS

BRANCH RATIO	STEM DIAMETER (INCHES) 5"	10"	15"	20"	25"	30"	35"	40"	50"
0.1	.5"	1	1.5	2	2.5	3	3.5	4	5
0.2	1	2	3	4	5	6	7	8	10
0.3	1.5	3	4.5	6	7.5	9	11	12	15
0.33	1.7	3.3	5.0	6.6	8.3	10	12	13	17
0.4	2	4	6	8	10	12	14	16	20
0.5	2.5	5	7.5	$\boxed{10}$	13	15	18	20	25
0.6	3	6	9	12	15	18	21	24	30
0.66	3.3	6.6	10	13	17	20	23	26	33
0.7	3.5	7	11	14	18	21	25	28	35
0.8	4	8	12	16	20	24	28	32	40
0.9	4.5	9	14	18	23	27	32	36	45
1.0	5	10	15	20	25	30	35	40	50

Figure 2: List of branch diameters in inches for a given branch ratio across selected stem diameters in inches.
(For example, branch diameter for a branch ratio of 0.5 on a 20 inch diameter stem = 10 inches)

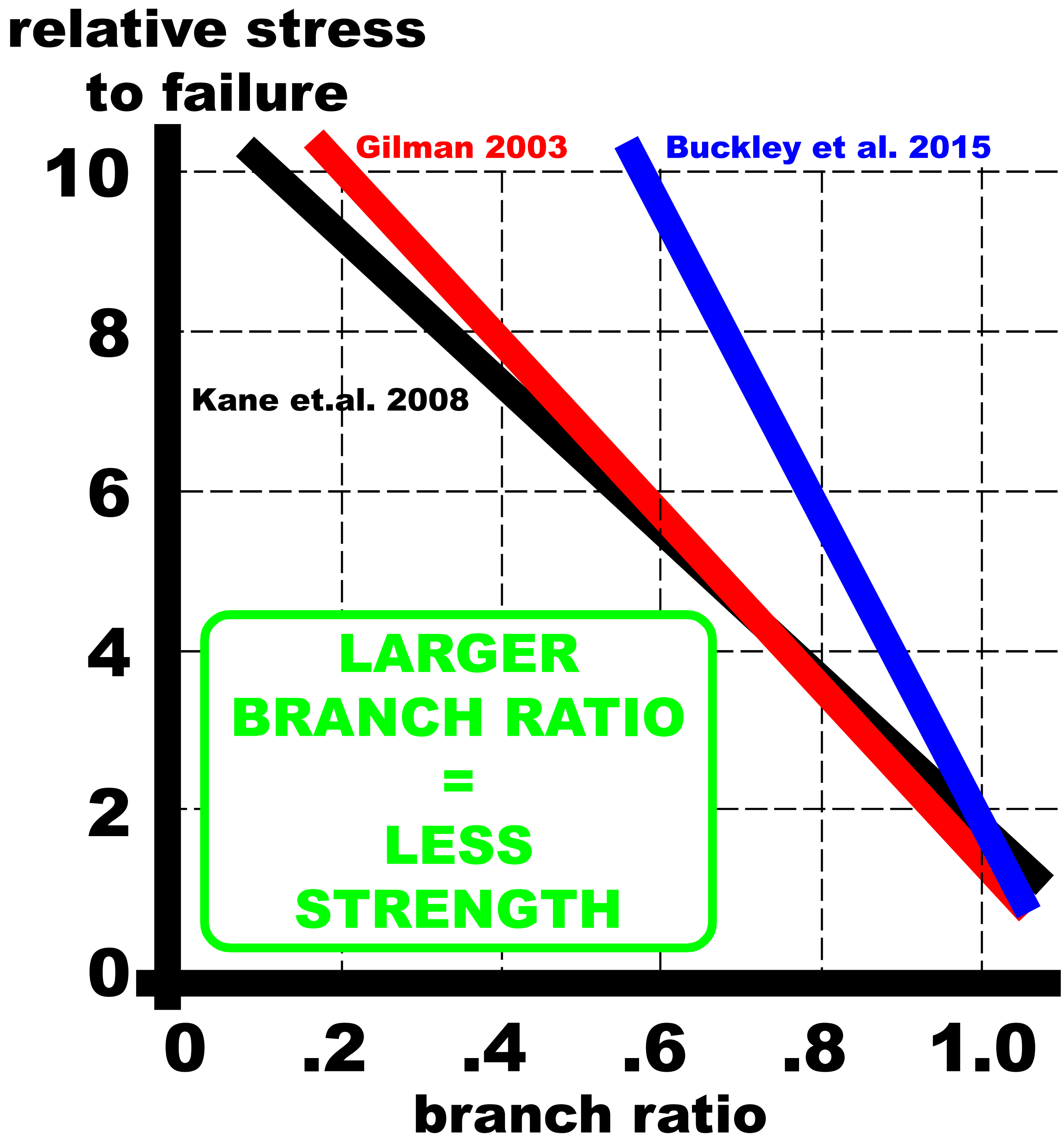

Figure 3: Relative force for failure of a branch based upon its branch ratio (branch diameter / stem diameter).
(Buckley et al. 2015; Gilman 2003; Kane et.al. 2008)

BRANCH RATIO

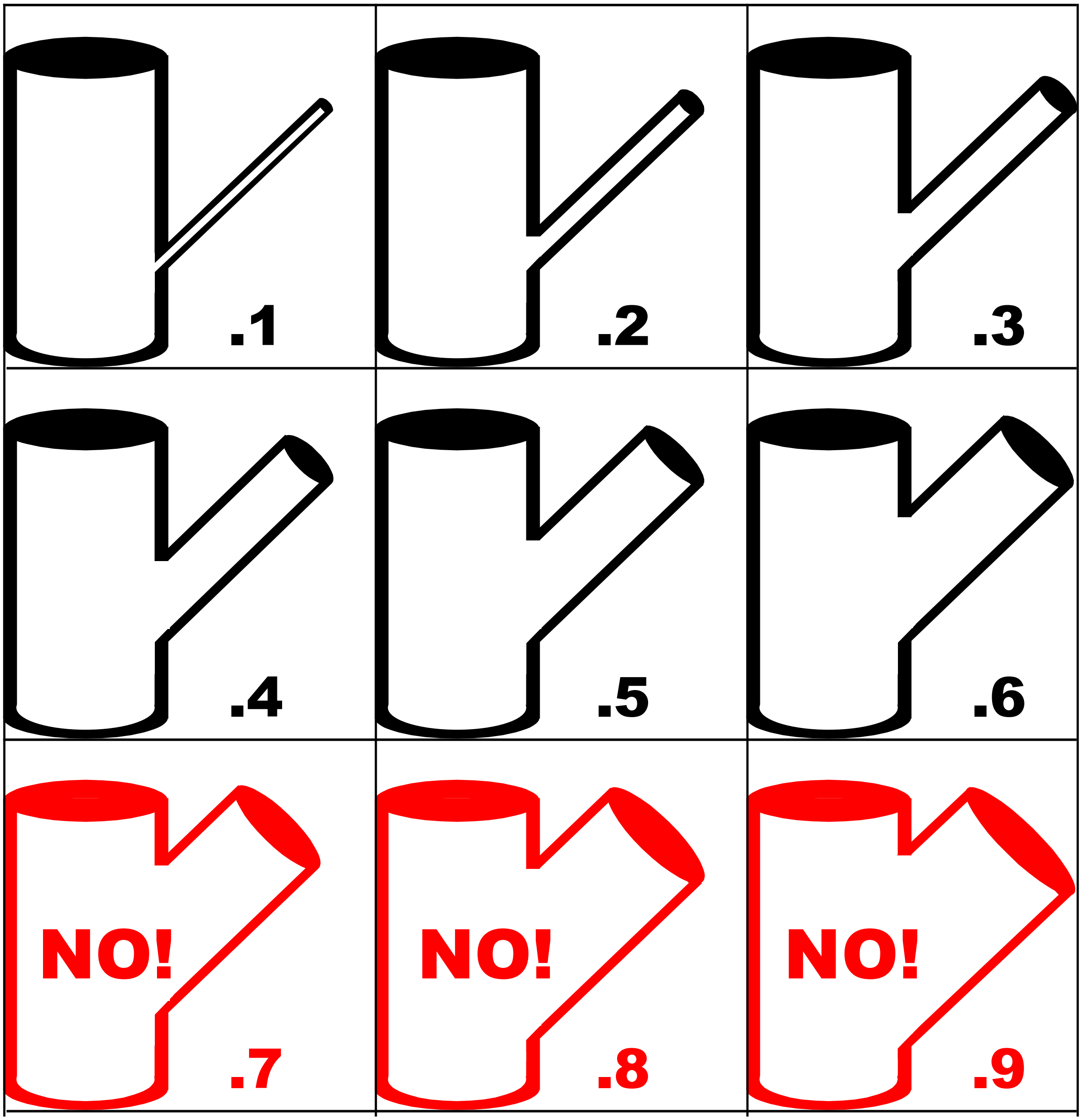

Figure 4: Examples of branch ratios (branch diameter / stem diameter) ranging from 0.1 to 0.9, all with the same branch angle of 45°.
(Note: Branch attachment strength significantly declines above BR = 0.66)

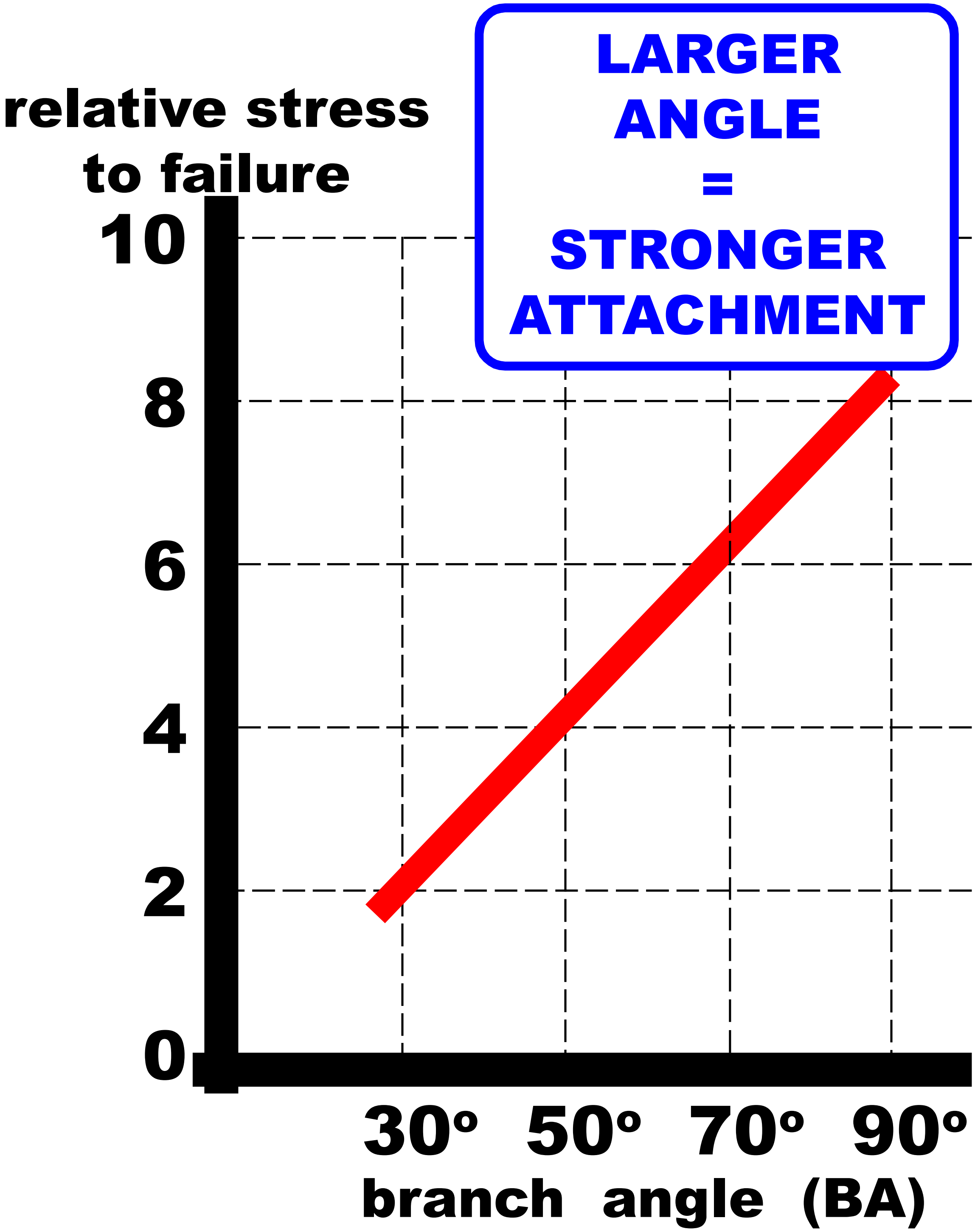

Figure 5: Relative attachment strength over a range of branch angles (BA). (Kane 2007)

BRANCH ANGLE

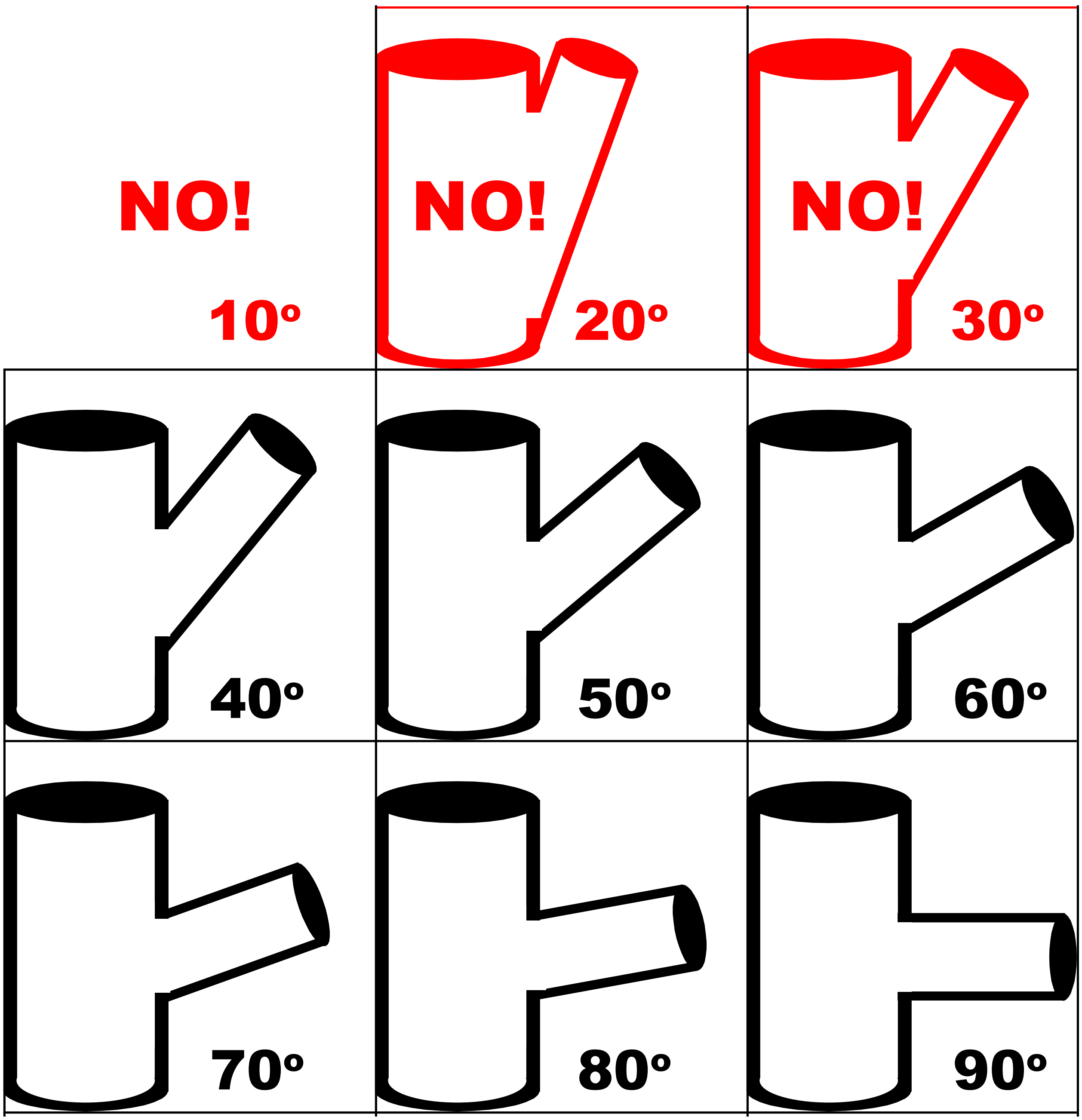

Figure 6: Examples of branch angles ranging from 10° to 90°, all with the same branch ratio. (BR = 0.5)
(Note: Branch attachment strength declines as BA < 30°.)

BRANCH ANGLE / BRANCH RATIO

BRANCH ANGLE	BRANCH RATIO 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
90°	900	450	300	225	180	150	129	113	100	90
80°	800	400	267	200	160	133	114	100	89	80
70°	700	350	233	175	140	117	100	88	78	70
60°	600	300	200	150	120	100	86	75	67	60
50°	500	250	167	125	100	83	71	63	56	50
40°	400	200	133	100	80	67	57	50	44	40
30°	300	150	100	75	60	50	43	38	33	30
20°	200	100	67	50	40	33	29	25	22	20
10°	100	50	33	25	20	17	14	13	11	10

proportionally large branches

small branch angles

Figure 7: Branch attachment strength based upon branch angle (BA) in degrees divided by branch ratio (BR). Branches with BA / BR values less than 95 should be abridged or removed. (derived from Walkden 2016)

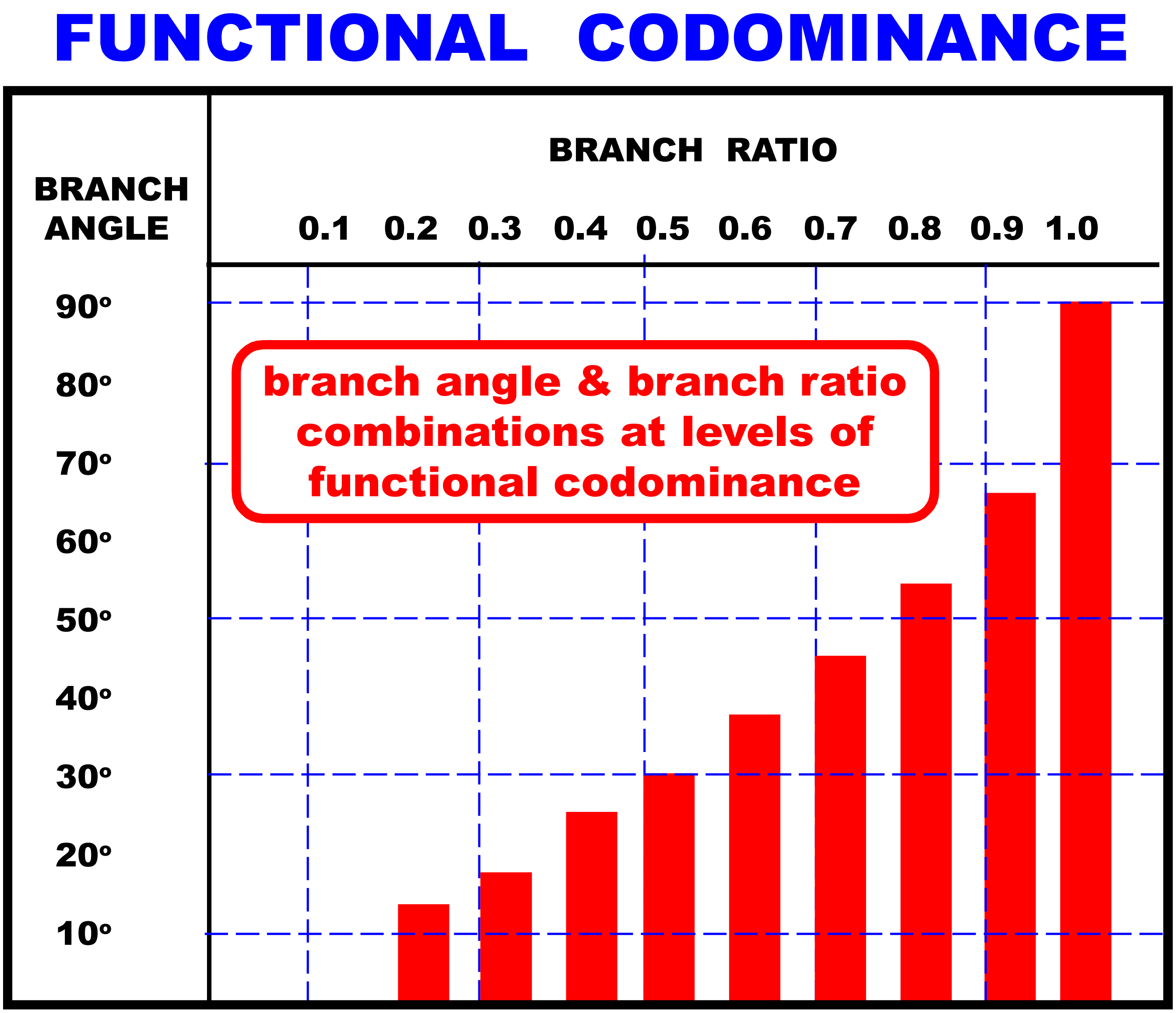

Figure 8: Branch attachment interactions between branch angle (BA) and branch ratio (BR) values where functional codominance (branch dominance) is reached or exceeded.
Branches with attributes in red should be abridged or removed, with abridging preferred. (derived partially from Walkden 2016)

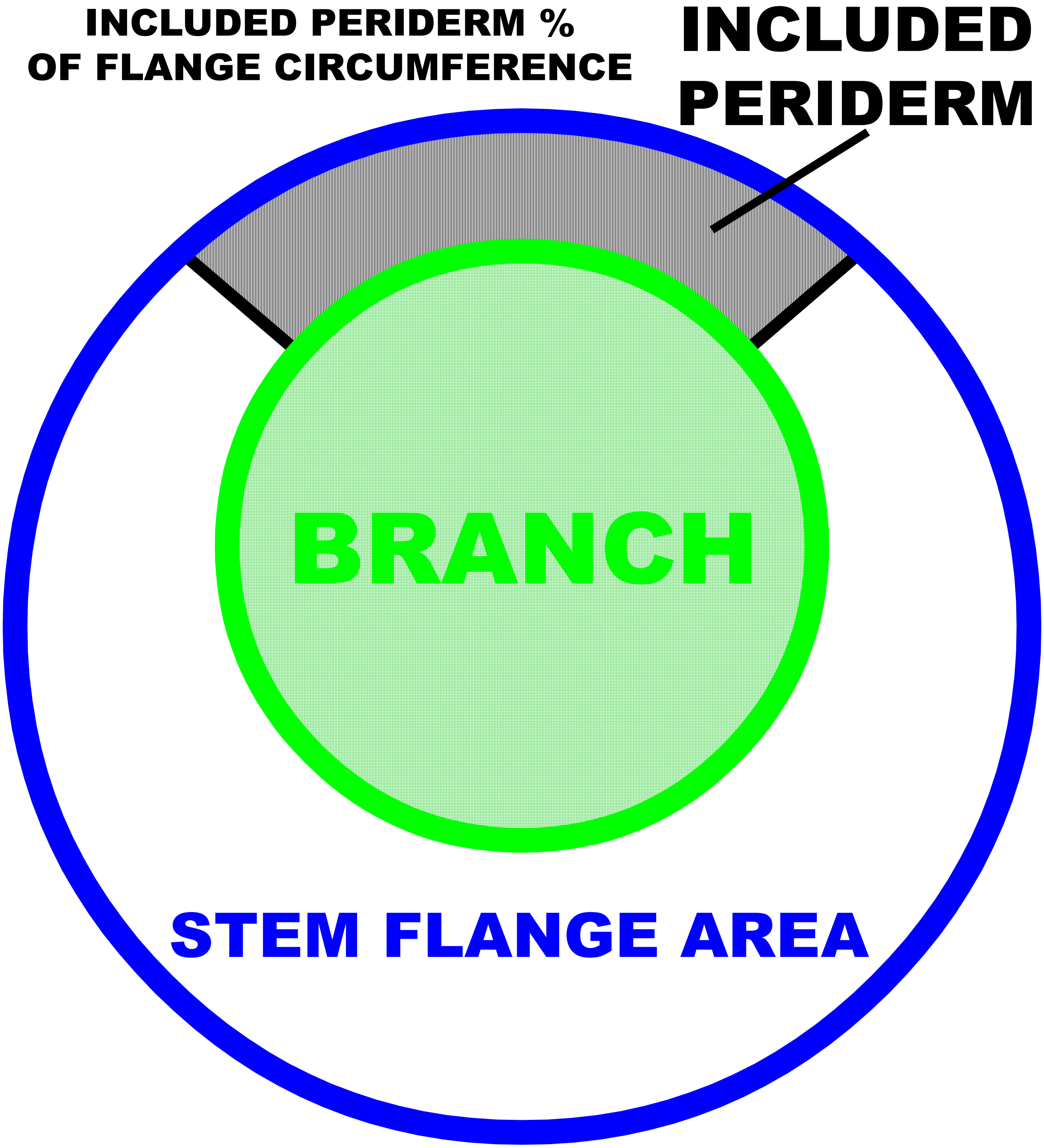

Figure 9: Included periderm (IP) within a stem flange. The percent of flange circumference with included periderm is an estimate of branch attachment weakness.
(In this case: IP = 100^{o} or 28% included periderm)

INCLUDED PERIDERM

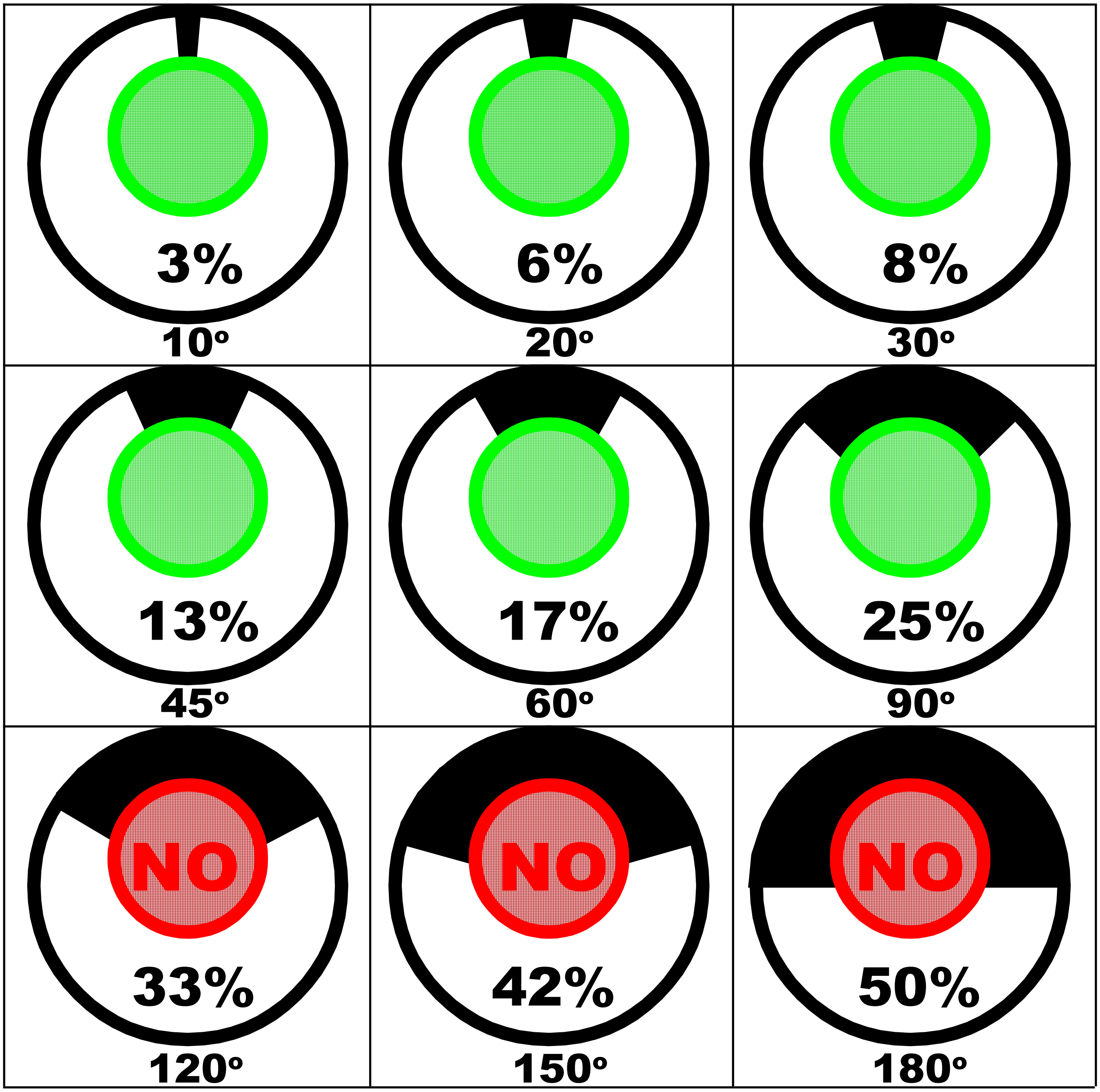

Figure 10: Assessing percent or degrees of stem flange circumference occupied by included periderm (IP).
Shaded center is branch base, thick circle around branch is circumference of stem flange, and black solid shaded area at top is included periderm. Included periderm >28% or >100° of stem flange circumference represents progressively greater branch attachment problems and failure risks.

BRANCH ATTACHMENT TREE HEALTH CARE

assess:

- **BRANCH RATIO (BR)**
- **BRANCH ANGLE (BA)**
- **INCLUDED PERIDERM (IP)**

protect:

- **AXILLARY WOOD**
- **STEM FLANGE**
- **BRANCH TRACE AREA**

abridge / reduce / remove:

- **CODOMINANT BRANCHES**
  - **>0.66 BR**
- **UPRIGHT BRANCHES <30° BA**
- **INCLUDED PERIDERM > 28% IP**

Figure 11: Check-list of tree health care management practices to gauge and maintain structurally sound branch attachments.