Appendix 9:Assessment of Likelihood of Damage Progression

Determining the likelihood of progression of any type of damage within the FRP deck will require judgment based on damage metrics found within the FRP composites industry. Clearly, any level of damage is not desired, but the specific issue following the discovery of damage is if the severity is significant enough to cause immediate lane closure and repair, or if action can be taken at a later time so long as public safety and the integrity of the overall deck is not impacted. As discussed in previous sections the main load-carrying member of a sandwich panel is the top facesheet which is continually subject to material stresses from direct traffic and impact loads. The top facesheet is the first structural element which will require scrutiny from any deterioration or signs of damage on the wear surface.

Probably the two most significant damage conditions for the facesheet are: 1) the separation of layers within in the facesheet, defined as a delamination, and; 2) the more severe case of full detachment a facesheet section from the underlying core, referred to as a debonded facesheet. These damage conditions may not be directly detectible and identified during routine inspections unless their size is significant enough to produce a visible bulge on the top surface, or in the case of a delamination, tap testing reveals its presence.

The presence of noncritical damage to surrounding structural elements, such as reflective cracking in the wear surface and local damage to joints, may signal the initiation of delamination, so closer examination of the underlying facesheet would be necessary. If no visible signs of physical change are apparent in the facesheet, then further examination is not needed. If a physical change or anomaly is discovered, the inspector has to determine if the conditions indicate the presence of a delamination or debond.

A methodology is proposed to measurably determine if a detected delamination will likely become worse if unattended. The procedure is based on a simplified approach taken from the damage inspection of honeycomb sandwich panels in the aircraft industry. The methodology is not intended to be a rigorous examination of failure, but is an approximate approach to determine if further degradation is likely based on measurable size of delaminations.

7.4.1 DETERMINATION OF DELAMINATION SIZE THRESHOLD

For sandwich panels or any construction with laminated sheeting, a report by the DOT/FAA[1] discusses a delamination criteria proposed by Kassapoglou that establishes a delamination threshold size at which the progressive failure of the facesheet due to local delamination buckling is likely. This threshold is the maximum delamination or debond size that can be tolerated before affecting the global behavior of the panel under local compressive forces. While this procedure was developed for continuous core type

[1] "Damage Tolerance of Composite Sandwich Structures," DOT/FAA/AR-99/91 Publication, Office of Aviation Research, Washington, D.C. 20591

honeycomb panels under compression loading, the principal can be applied to FRP deck panels subject to bending from wheel loads that impart compression forces in the facesheet.

The main laminate stresses come from wheel loads. In a delaminated or debonded section, compression stresses around its boundaries may initiate damage. The delaminated area acts like a separate plate section which may buckle if the total compression stresses applied to its boundaries are large enough. Figure 7.4-1 illustrates a typical delamination within a panel span. The buckling stress is dependent on size of the area and the threshold stress for buckling decreases for larger areas. Thus if the working stress resulting from wheel load, P, or any other source reaches or exceeds the buckling stress, the delamination may occur and can continue to grow progressively under repeated loads.

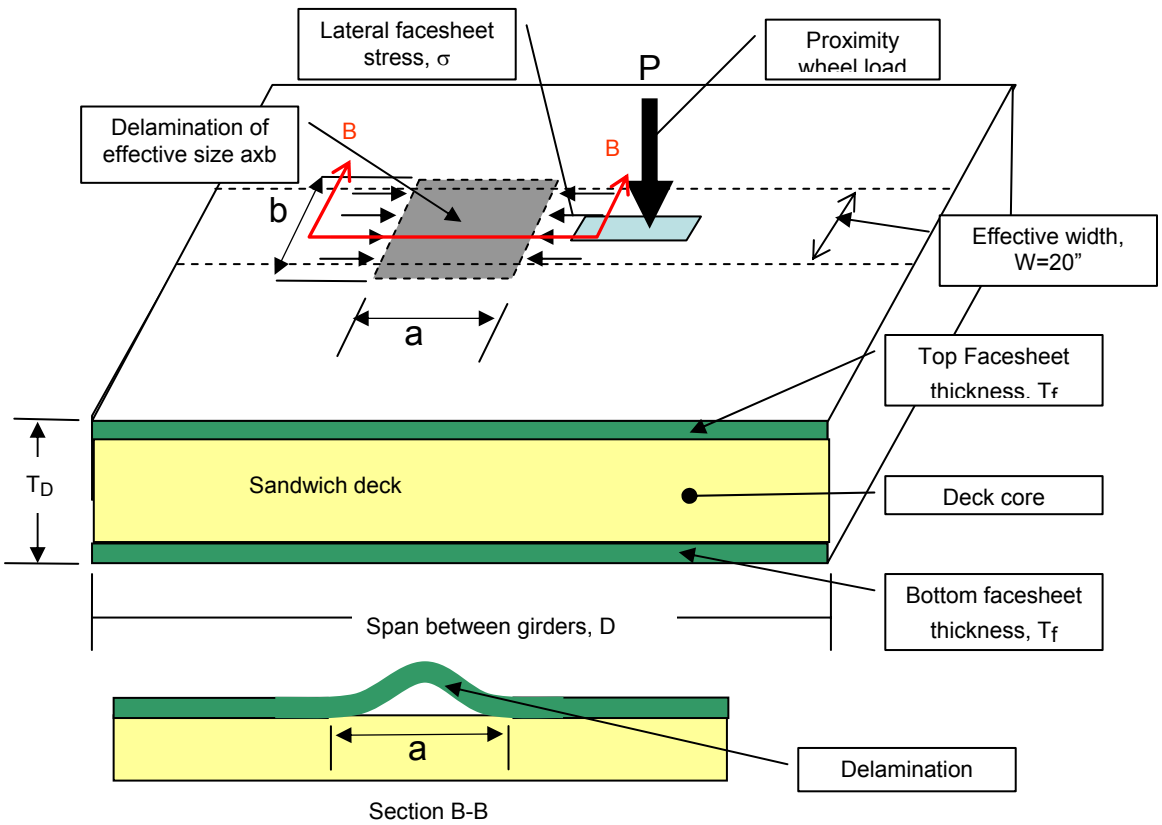


Figure 7.4-1. Schematic of a Local Delamination.

The delamination shown is analogous to a free-standing clamped plate buckling under compression forces generated by wheel loads, thus the limit buckling stress can be derived from classic plate theory. From Young[2], the buckling formula for a clamped rectangular plate of dimension a x b (see Figure 7.1-4) subject to in-plane loads is expressed as

[2] Young, Warren C., "Formulas for Stress and Strain," McGraw-Hill, 6th edition, 1989

$$\sigma = KK(\mathrm{x})\frac{E}{1-\nu^2}\left(\frac{T_f}{b}\right)^2 \qquad 7.4\text{-}1a$$

where:

σ = buckling stress in units of force/area

$KK(\mathrm{x}) = 3.6e^{-0.6\mathrm{x}} + 5.73$ (exponential curve fit of data presented in Reference 3).

E = effective Young's modulus of the face sheet

v = Poisson's ratio

T_f = facesheet thickness

b = width of the delamination

a = length of the delamination

x = rectangular aspect ratio, a/b, of the delamination

The Young's modulus and Poisson's ratio of the facesheet are values that can be obtained from the engineering specifications of the deck. The direct application of this equation, however, is limited by the measurements an inspector must make. In practice the exact size and shape of the delamination will not be readily obvious, and in this form the equation has little practical application to inspection.

For inspection, we are interested in establishing a conservative threshold stress that can be compared with arbitrary delamination shapes, therefore it is more practical to recast this equation into a usable formula based on a measurable size. It is difficult enough for inspectors to find facesheet delaminations or debonds, but once found, determining the dimensions of the defect would be very approximate. In order to simplify the inspection task, it is reasonable to suggest a widest width measurement be measured for the entire delamination. This would assume that the affected area is a square, so therefore, a = b in equation 7.4-1a. Accordingly, x =1.0 and,

KK(x) = 7.7

Therefore,

$$\sigma = KK(x)\frac{E}{1-\nu^2}\left(\frac{t}{b}\right)^2 \Rightarrow 7.7\frac{E}{1-\nu^2}\left(\frac{t}{d}\right)^2 \qquad 7.4\text{-}1b$$

where d = maximum measurable diameter of the delamination.

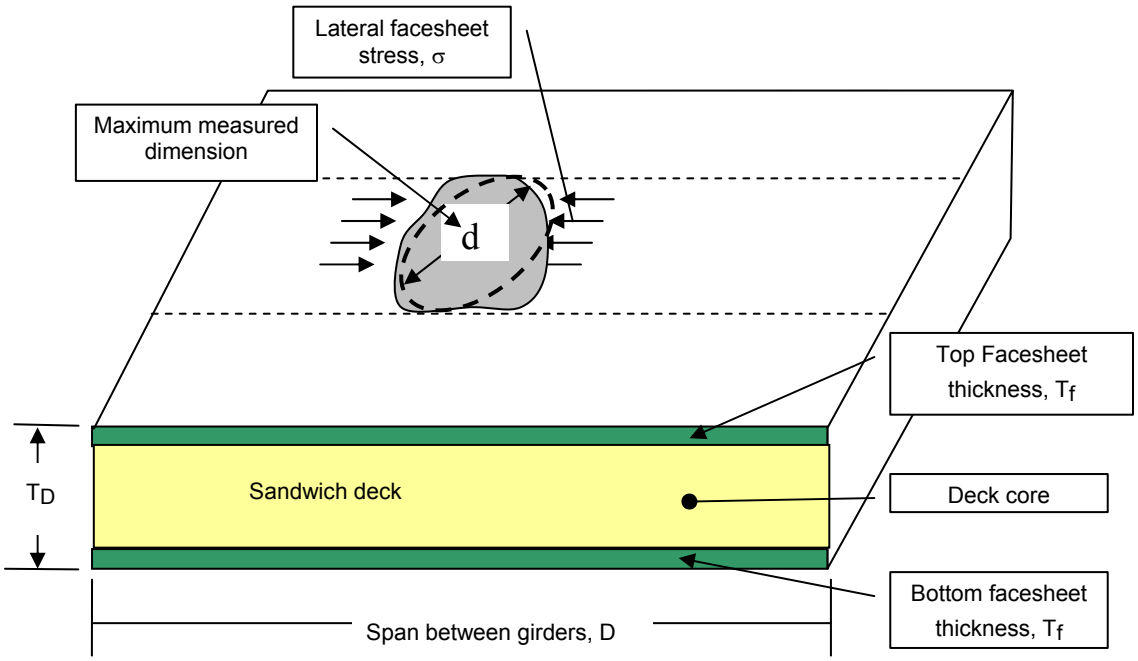


Figure 7.4-2. Schematic of a Local Delamination with an Arbitrary Shape.

Note that this is a simplified formula to determine delamination threshold sizes for purpose of inspection and is not a rigorous prediction of catastrophic failure; it is intentionally conservative so as to provide a safe lower bound estimate for inspection.

Additional assumptions for use of this formula are:

- The facesheet has nearly equal stiffness in the longitudinal and transverse directions. If the facesheets are known to be orthotropic, the effective modulus can be approximated by

  $$E = \sqrt{E_L \cdot E_T}$$

  E_L=Longitudinal modulus

  E_T=Transverse modulus

- Compression stress at the mid-span drives failure

Application to general delamination sizes

A plot of the buckling stress versus delamination size is shown in Figure 7.4-3.

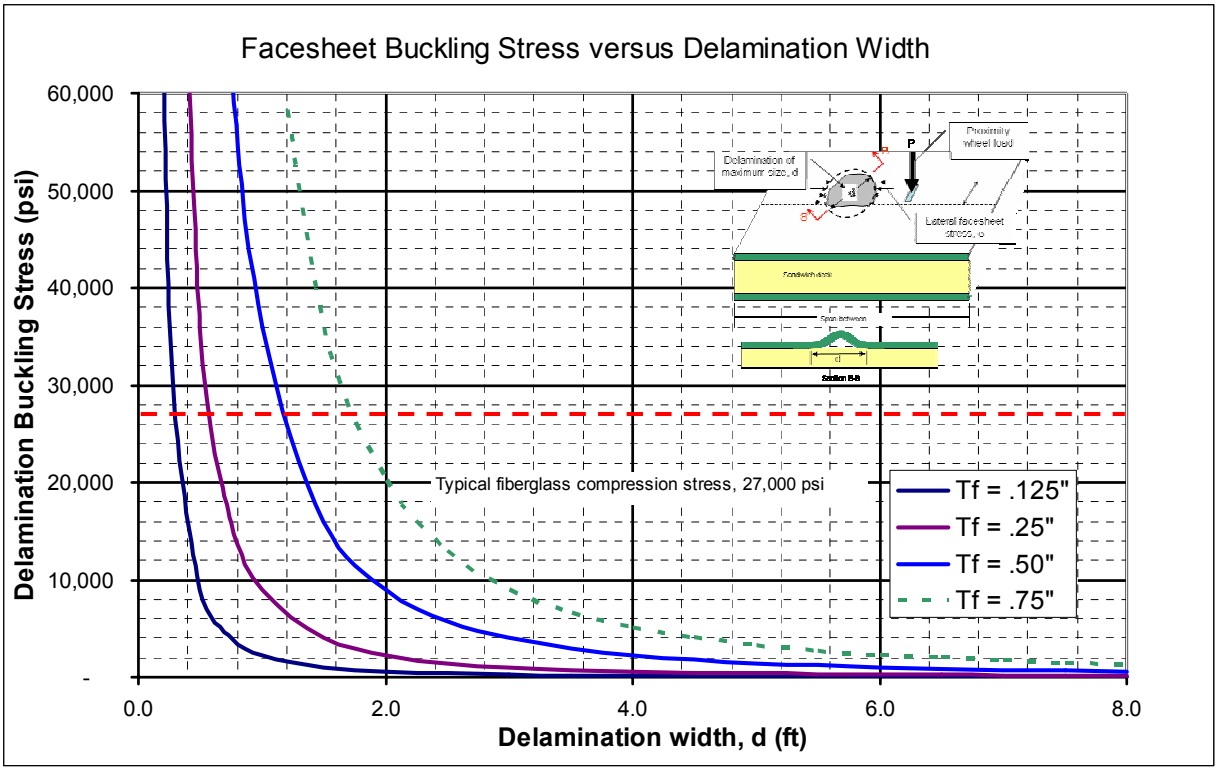


Figure 7.4-3. Facesheet Critical Stress versus Delamination Size.

Note the unit of **d** is in feet. Figure 7.4-3 essentially shows the drop in buckling stress capacity of the facesheet versus measured size of a delamination, for the range of thicknesses of the top facesheet in FRP panels. The cut-off stress is the material failure stress of the laminate itself. Typically, the compression strength of a facesheet made with quasi-isotropic lay-up (equal stiffness in the longitudinal and transverse directions) range between 27,000 to 34,000 psi. The 27,000 psi level is shown here which denotes the stress level at which material failure, as opposed to panel buckling, will occur.

As shown in Figure 7.4-3 a delamination may extend to over a foot in width before theoretically failing. Accordingly, the panel will still be able to sustain repeated traffic loads as long the imparted stresses remain below the indicated buckling stresses.

Establishing Residual Load Capacity

How does one use the above relationship to determine residual load capacity of the FRP deck before repairs are made? Conservatively, using simple beam theory to determine the relationship between a wheel load and the fiber stresses due to simple bending of a strip of deck, a critical load, P, to critical stress, σ, to, delamination size, a, can be established.

Assuming a worst case moment condition based on simply supported beam equilibrium, shown in Figure 7.4-4, the normal facesheet stress is:

Moment, M, and facesheet force, F

$$M := \frac{P \cdot D}{4} \qquad F := \frac{M}{TD} \qquad 7.4\text{-}2$$

where:

P = Wheel load at center span

M = bending moment due to center load, P

D = Span between girders

T_d = Sandwich deck thickness

F = Force resultant on facesheets

W = Effective compression load width, assume to be 20” (about 2 x tire foot print)

T_f = Facesheet thickness

The working stress in the facesheet, therefore, due to P is:

$$\sigma_W := \frac{F}{W \cdot T_f} \qquad 7.4\text{-}3$$

Back substituting the above equation 7.4-3 into the moment equation 7.4-2 gives:

$$P := 4 \cdot \frac{\sigma_W \cdot T_f \cdot TD \cdot W}{D} \qquad 7.4\text{-}4$$

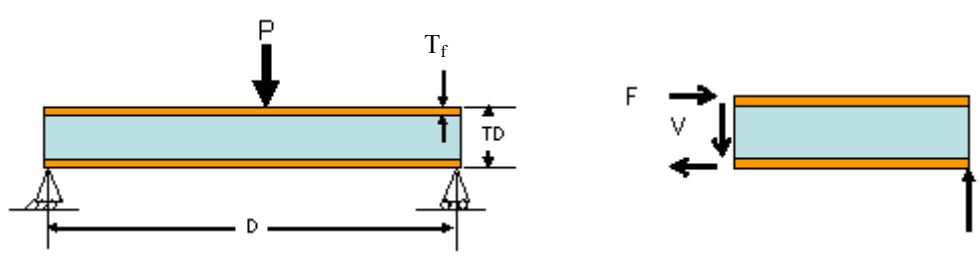


Figure 7.4-4. Free Body Diagram for Simple Sandwich Beam.

While not entirely correct, the free body diagram ignores concentrated vertical core stiffness that may exist in webs.

The relationship in equation 7.4-4 can now be used to determine critical load capacity of the deck to existing delamination size in conjunction with equation 7.4-1. Note that the wheel load is now a function of deck geometry and girder spacing.

7.5 CHARTS FOR ASSESSMENT RATINGS OF FRP DECKS

This section contains working charts for two deck depths, 8 in. and 5 in. deep section for girder spacing from 2 ft to 10 ft. Instruction for using the charts is given in Figure 7.5-1.

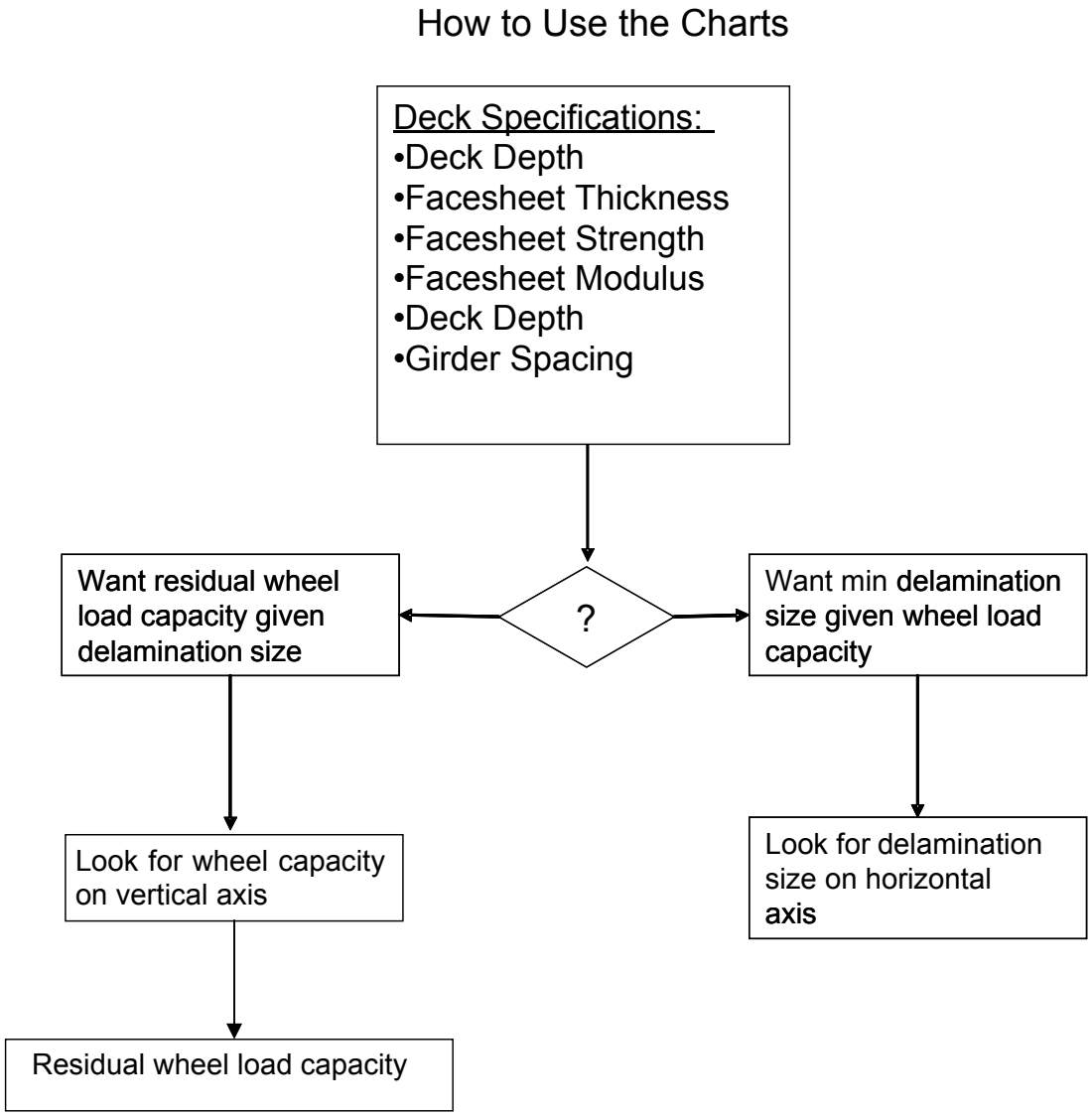


Figure 7.5-1 Diagram for using load capacity charts of FRP deck with delaminations

Notes on use and limitations:

1. Charts apply to fiberglass composite decks spanning between girders in girder/stringer type bridge superstructure

2. Reference load capacity is AASHTO HS-20 and HS-25

3. Facesheet reference modulus of elasticity is 2.4x 10^6 psi which is a typical stiffness value for structural fiberglass laminates. For other values a correction factor to the wheel load capacity, P can be applied as follows:

Correction for different modulus: $P = P(chart) * \frac{E(actual)}{E(reference)}$

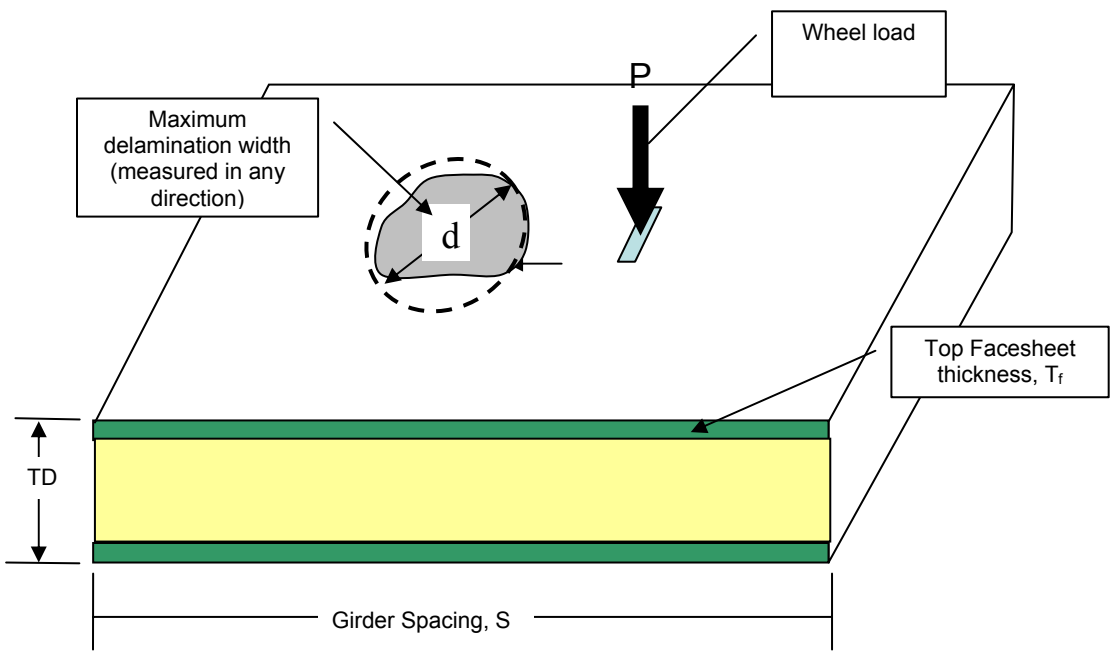


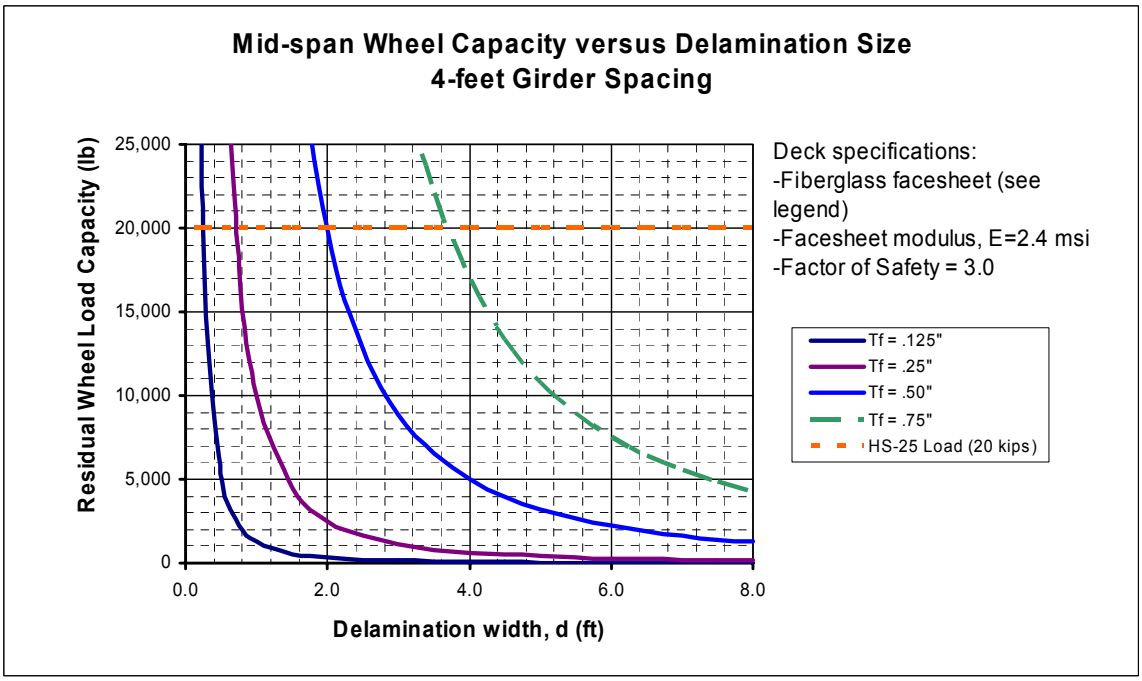
Figure 7.5-2 Deck parameters for delamination charts

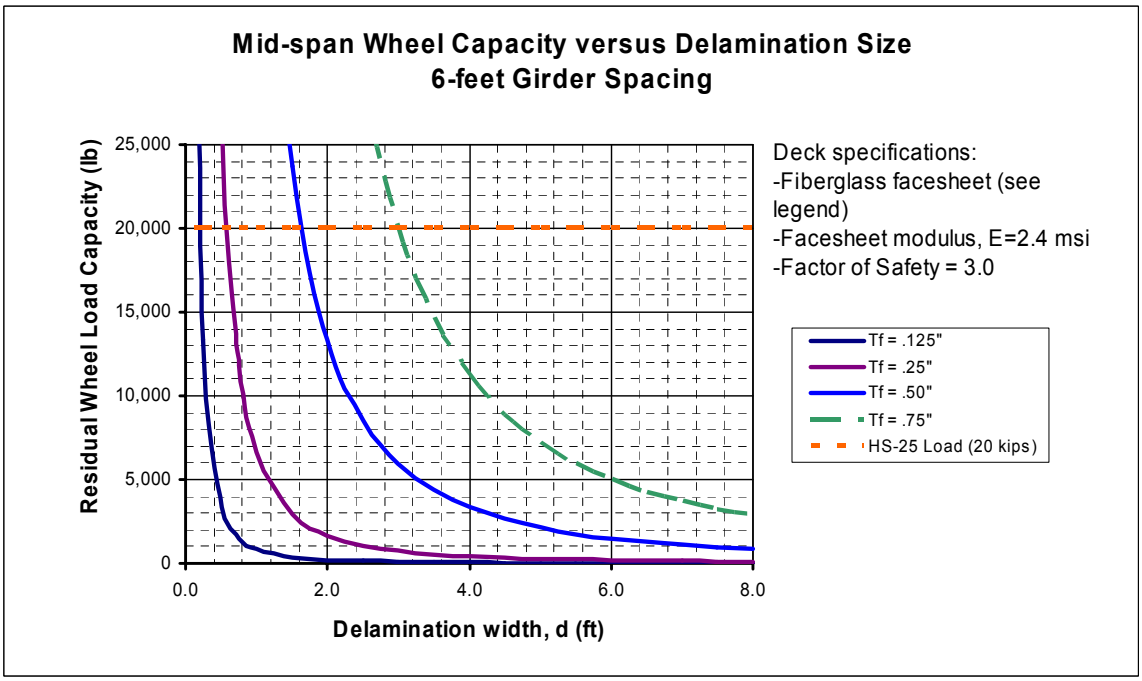
Consideration of Safety Factors in Residual Capacity

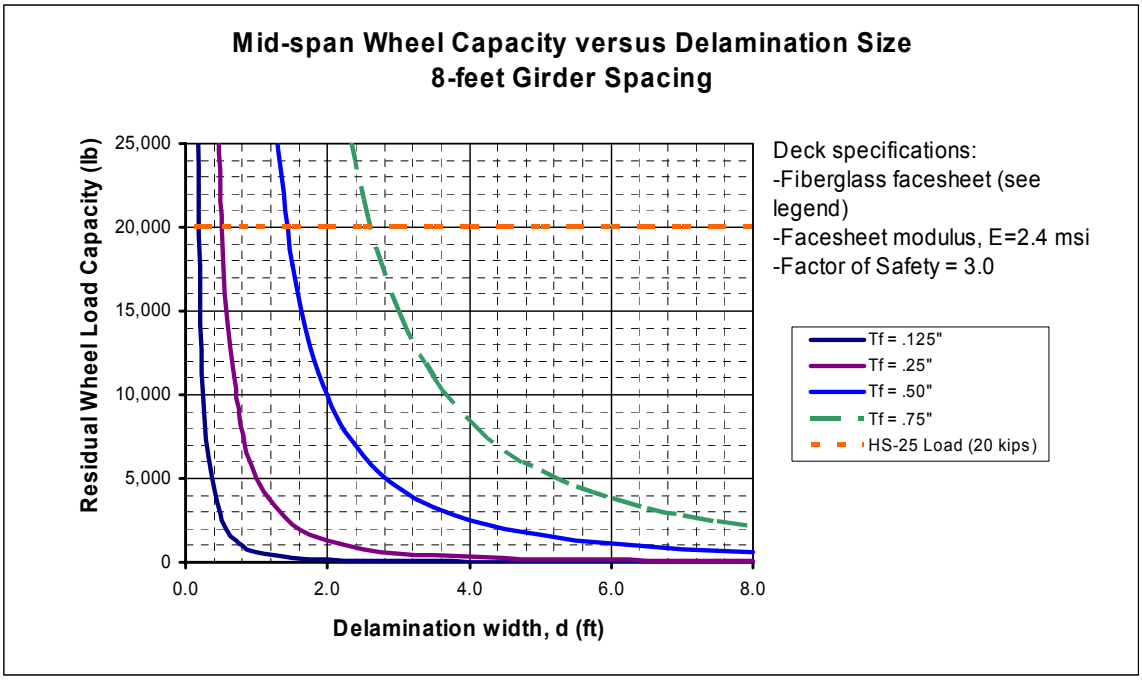
Unlike bridge decks built with conventional materials, there is no standard safety factor applicable to FRP deck construction. Most past projects have specified independent safety factors of 3.0 or more of design loads. In view of this, the developers of this manual decided to present the assessment data with an assumed safety factor = 3.0. In determining the residual capacity of decks using these charts, therefore, a safety factor can be applied by dividing the residual wheel capacity as determined from the charts and or formula by a preferred Safety Factor,

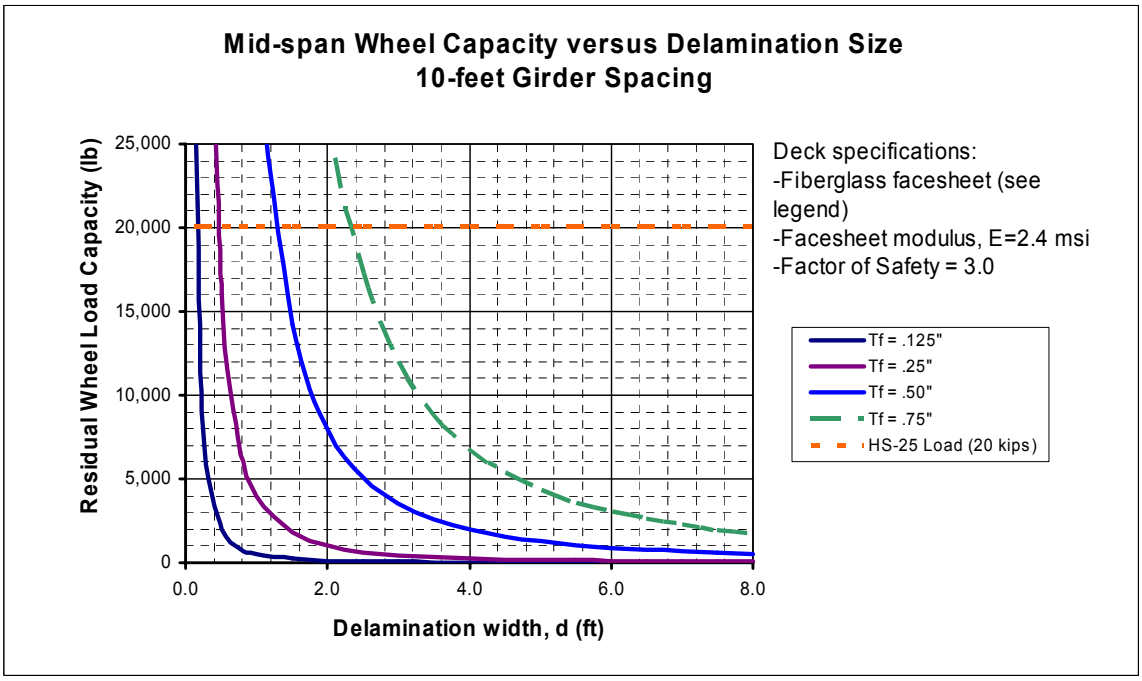
$$Working\ Capacity = \frac{Wheel\ Load\ Capacity}{SafetyFactor}$$

RESIDUAL CAPACITY FOR 8" FRP DECKS

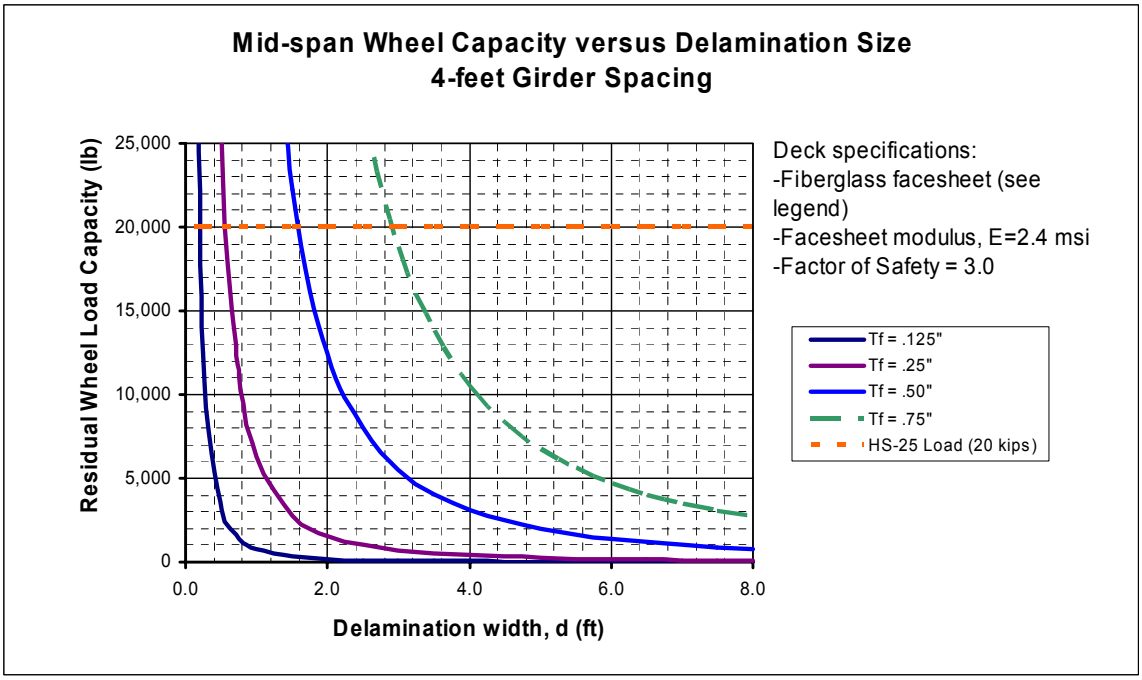


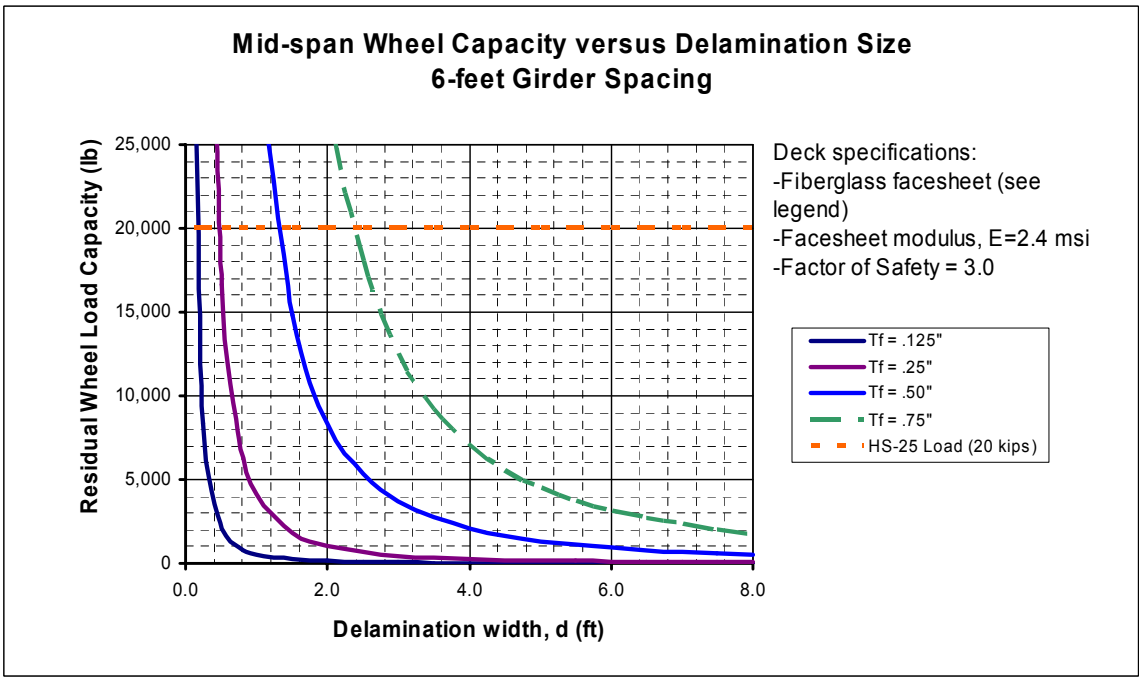


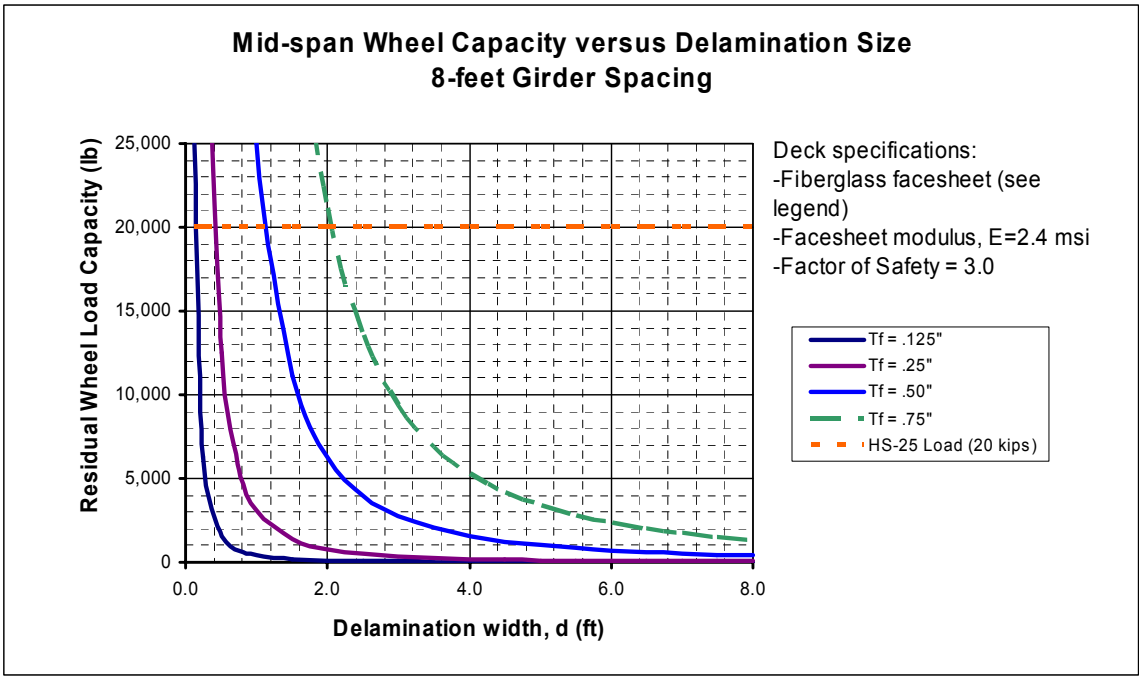

Mid-span Wheel Capacity versus Delamination Size
8-feet Girder Spacing
Residual Wheel Load Capacity (lb)
25,000
20,000
15,000
10,000
5,000
0
0.0
2.0
4.0
6.0
8.0
Delamination width, d (ft)
Deck specifications:
-Fiberglass facesheet (see legend)
-Facesheet modulus, E=2.4 msi
-Factor of Safety = 3.0
Tf = .125"
Tf = .25"
Tf = .50"
Tf = .75"
HS-25 Load (20 kips)

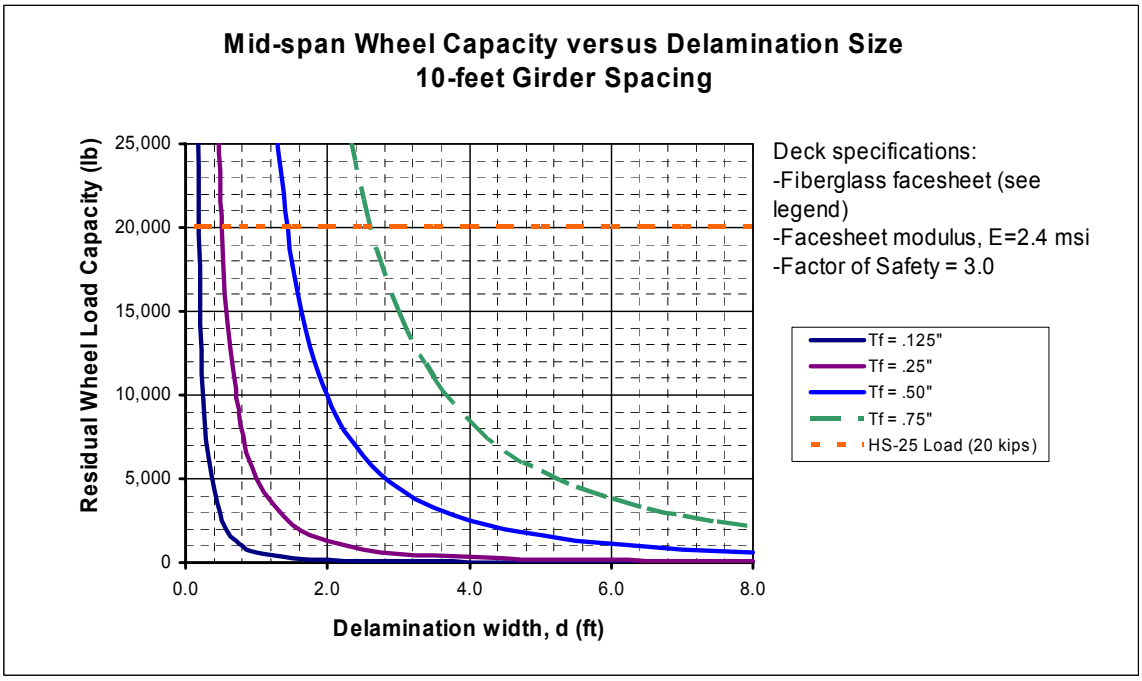

Mid-span Wheel Capacity versus Delamination Size
10-feet Girder Spacing
Residual Wheel Load Capacity (lb)
25,000
20,000
15,000
10,000
5,000
0
0.0
2.0
4.0
6.0
8.0
Delamination width, d (ft)
Deck specifications:
-Fiberglass facesheet (see legend)
-Facesheet modulus, E=2.4 msi
-Factor of Safety = 3.0
Tf = .125"
Tf = .25"
Tf = .50"
Tf = .75"
HS-25 Load (20 kips)

RESIDUAL CAPACITY FOR 5" FRP DECKS






Mid-span Wheel Capacity versus Delamination Size
8-feet Girder Spacing
Residual Wheel Load Capacity (lb)
25,000
20,000
15,000
10,000
5,000
0
0.0
2.0
4.0
6.0
8.0
Delamination width, d (ft)
Deck specifications:
-Fiberglass facesheet (see legend)
-Facesheet modulus, E=2.4 msi
-Factor of Safety = 3.0
Tf = .125"
Tf = .25"
Tf = .50"
Tf = .75"
HS-25 Load (20 kips)


Mid-span Wheel Capacity versus Delamination Size
10-feet Girder Spacing
Residual Wheel Load Capacity (lb)
25,000
20,000
15,000
10,000
5,000
0
0.0
2.0
4.0
6.0
8.0
Delamination width, d (ft)
Deck specifications:
-Fiberglass facesheet (see legend)
-Facesheet modulus, E=2.4 msi
-Factor of Safety = 3.0
Tf = .125"
Tf = .25"
Tf = .50"
Tf = .75"
HS-25 Load (20 kips)