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One Or More Solutions For Cutting Forces In Clay & Rock

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Goals & Targets

Problem Definition

In rock cutting the rock will fail either by brittle shear failure or by brittle tensile failure. How do these failure mechanisms depend on the UCS and the BTS values of the rock and how is the transition between those two mechanisms.

Solution

At high UCS/BTS ratios there is brittle tensile failure, at low ratios there is brittle shear failure. In between there is an area where both may occur simultaneously, resulting in the chip type of cutting process.

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Rock Cutting
Introduction

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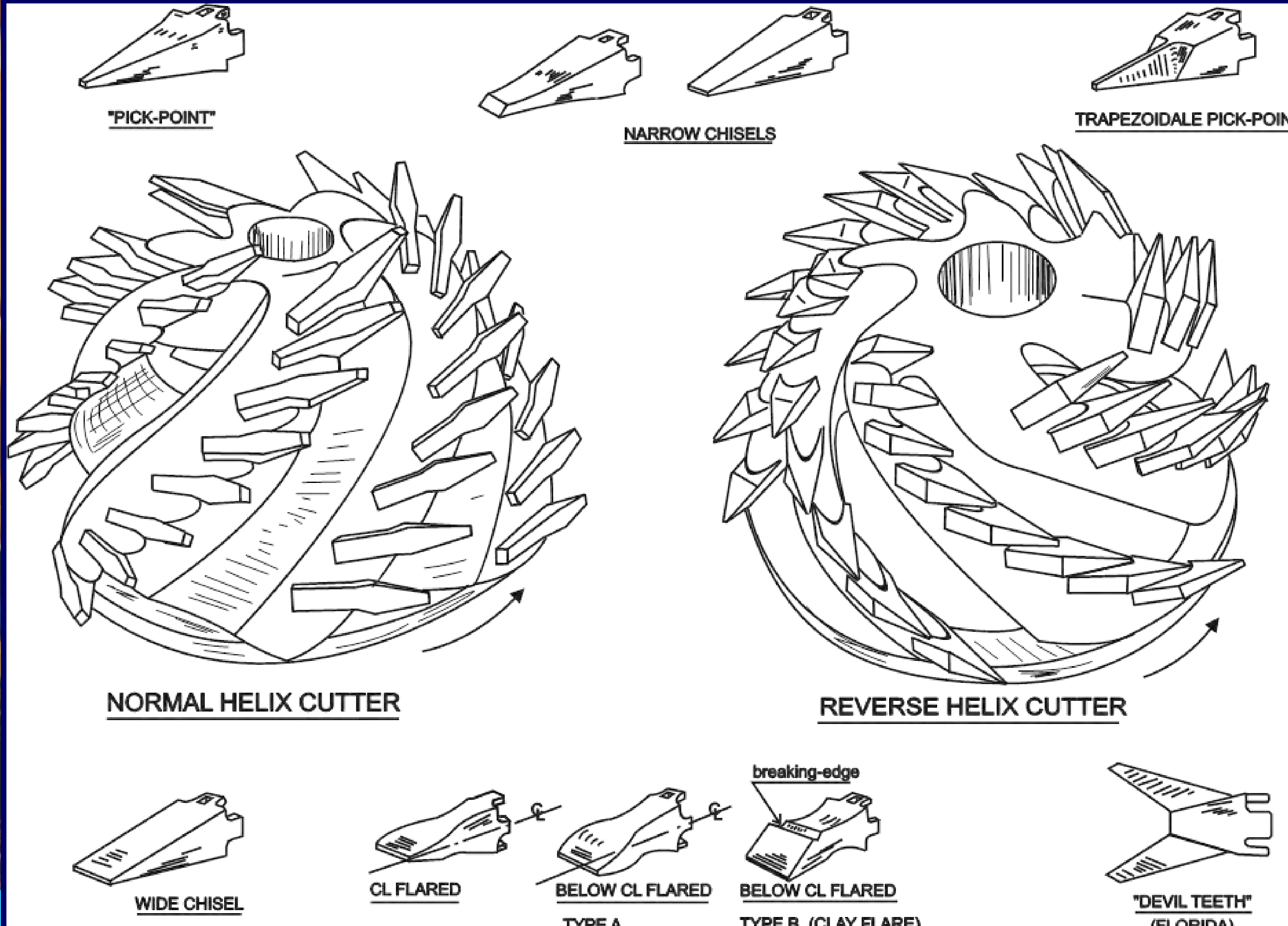
Rock Cutter Heads



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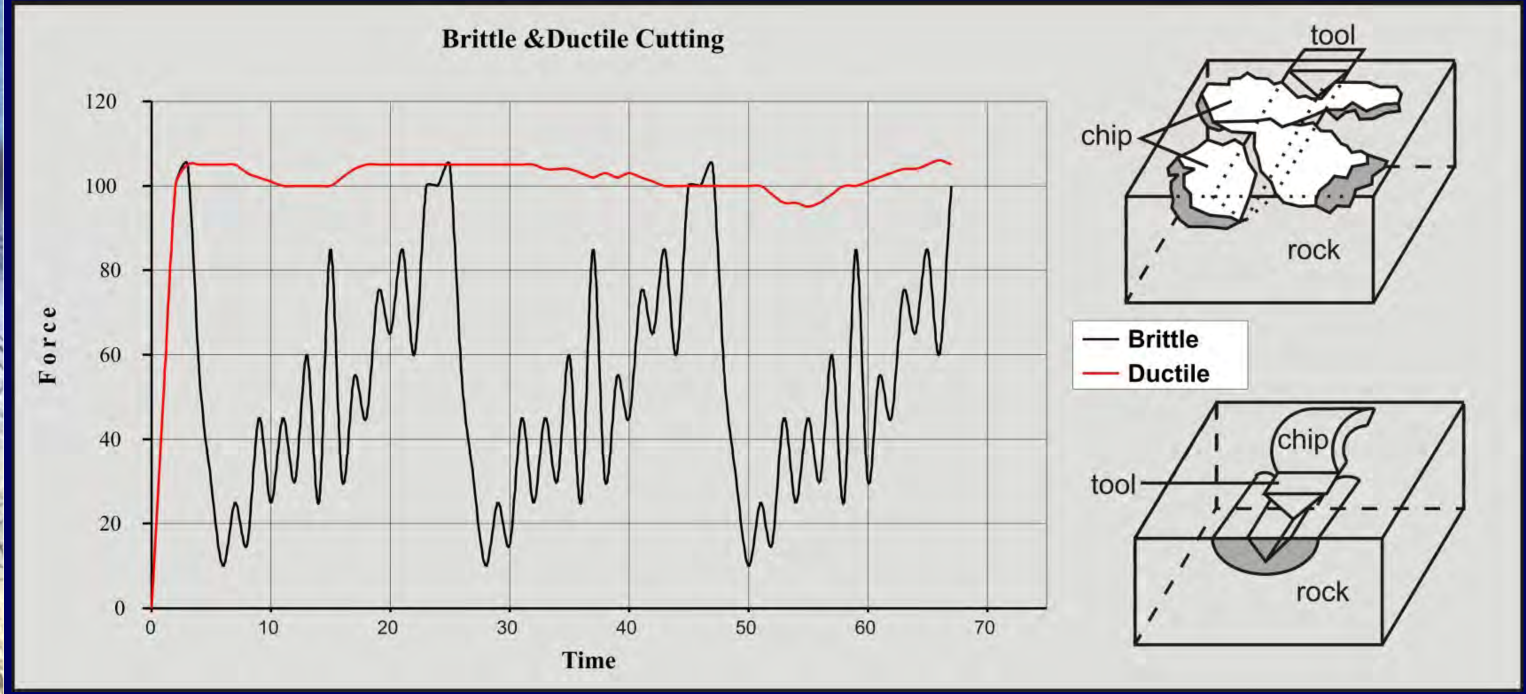
Brittle versus Ductile



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Failure Mechanisms

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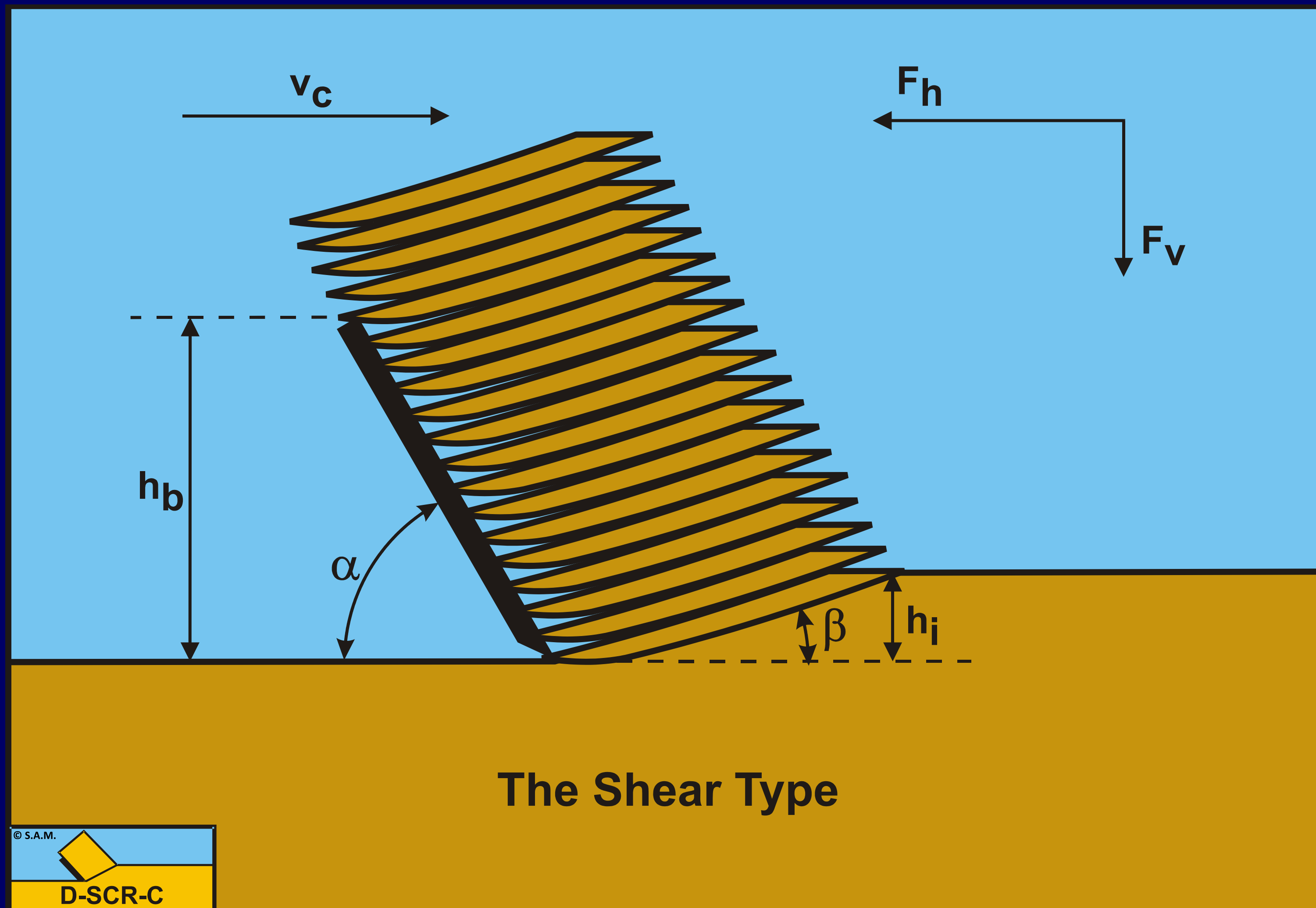
Brittle Shear Failure/Shear Type



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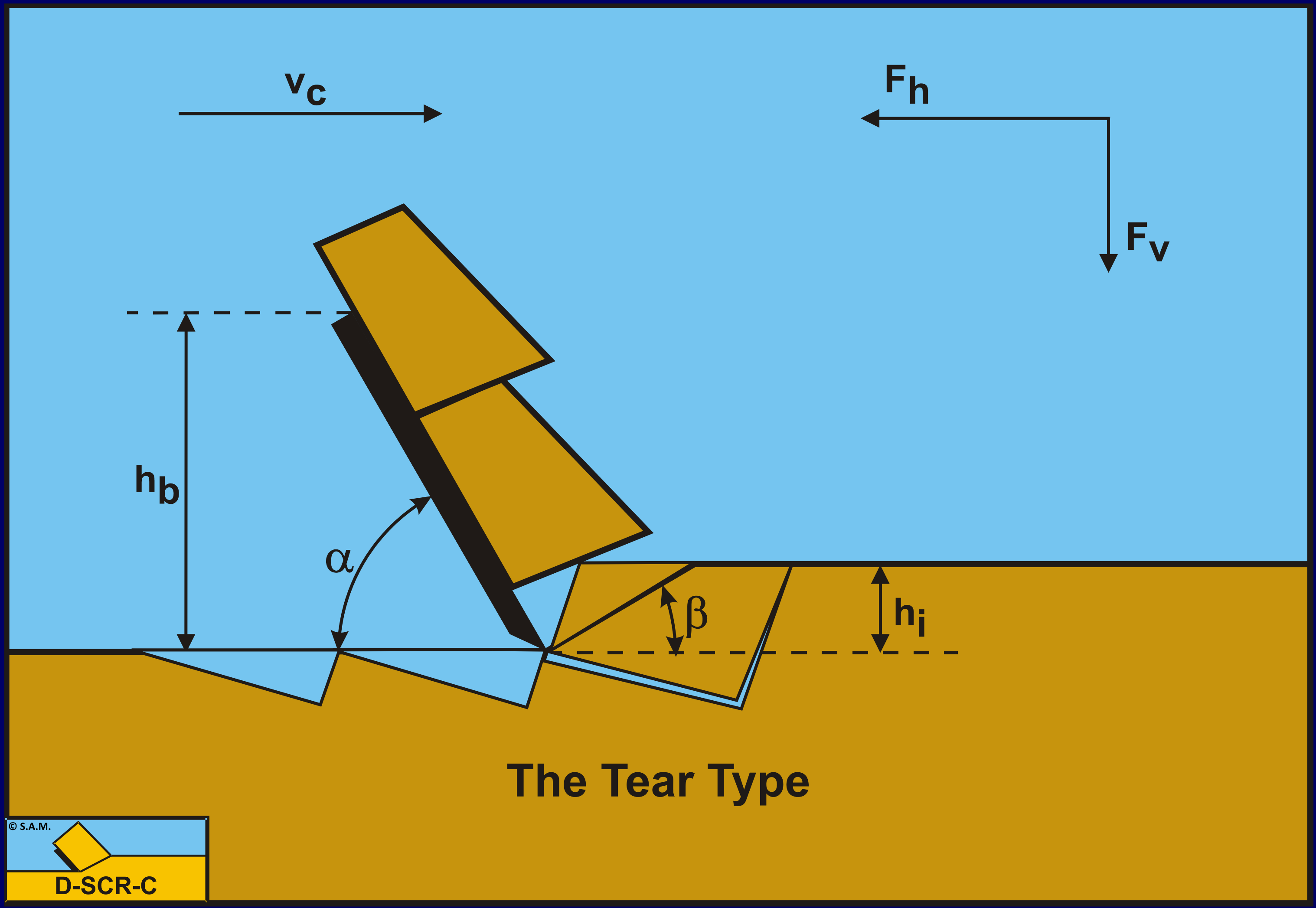
Brittle Tensile Failure/Tear Type



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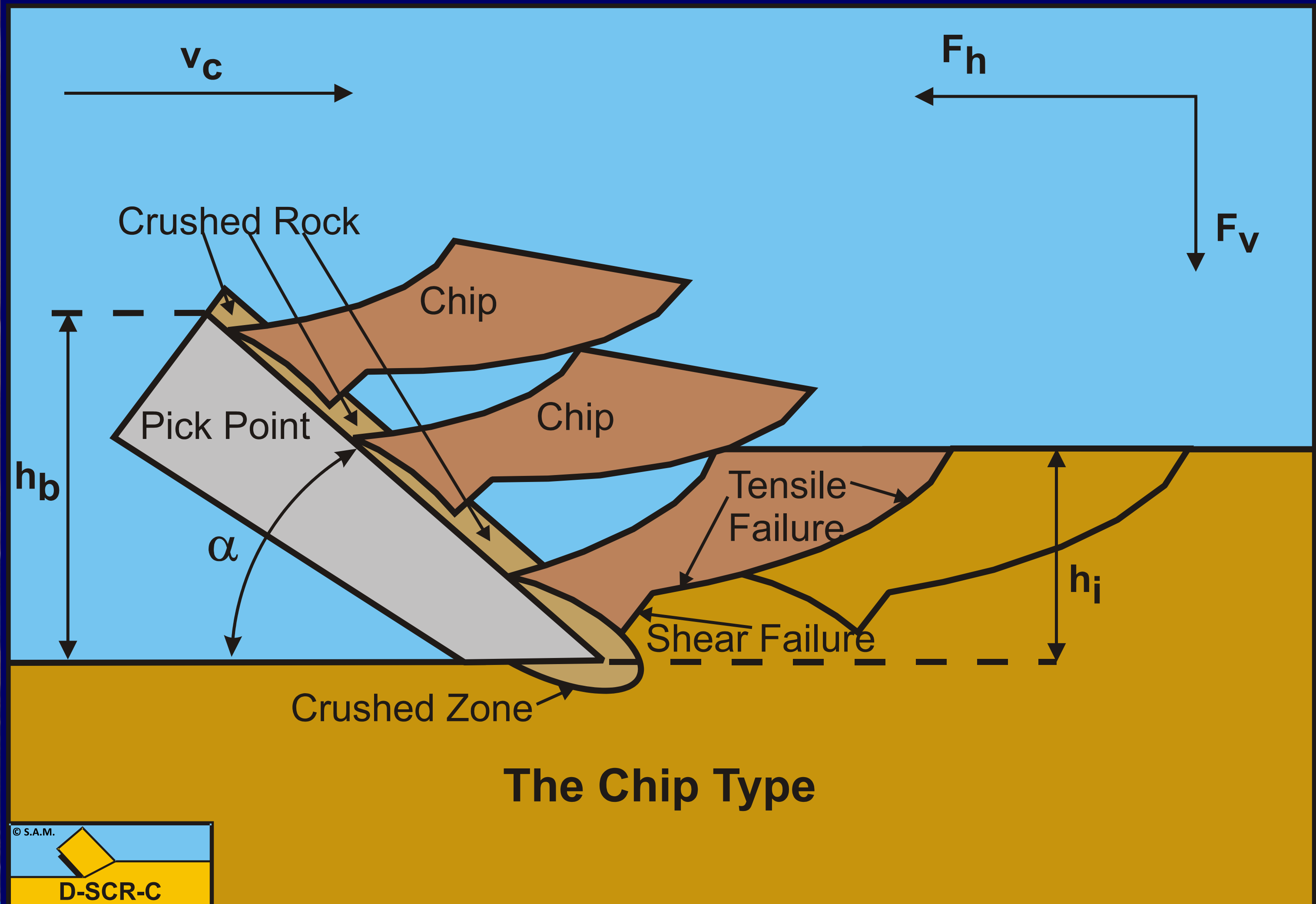
Shear & Tensile Failure/Chip Type



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Shear Failure/Shear Type
Peak Forces

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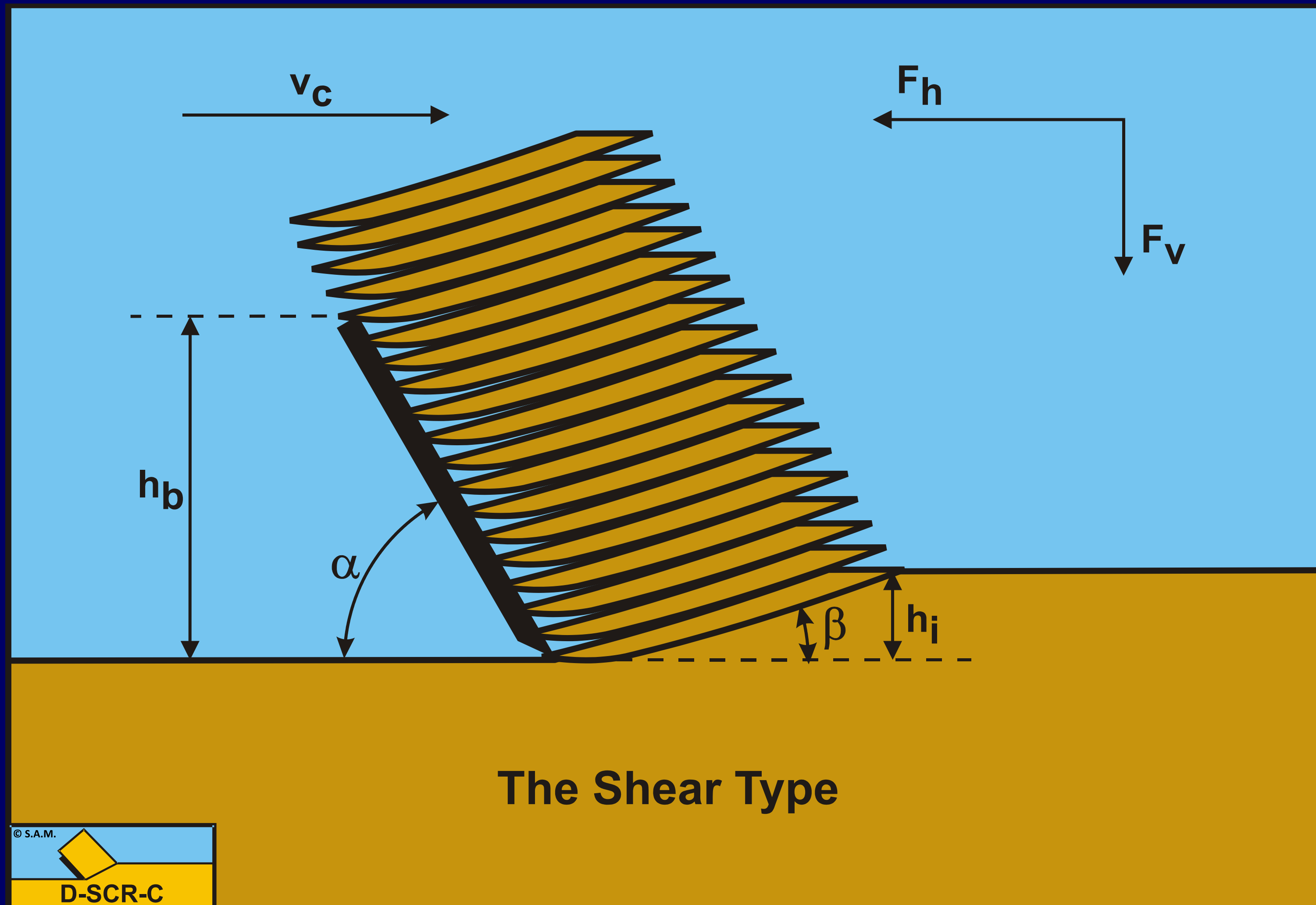
Brittle Shear Failure/Shear Type



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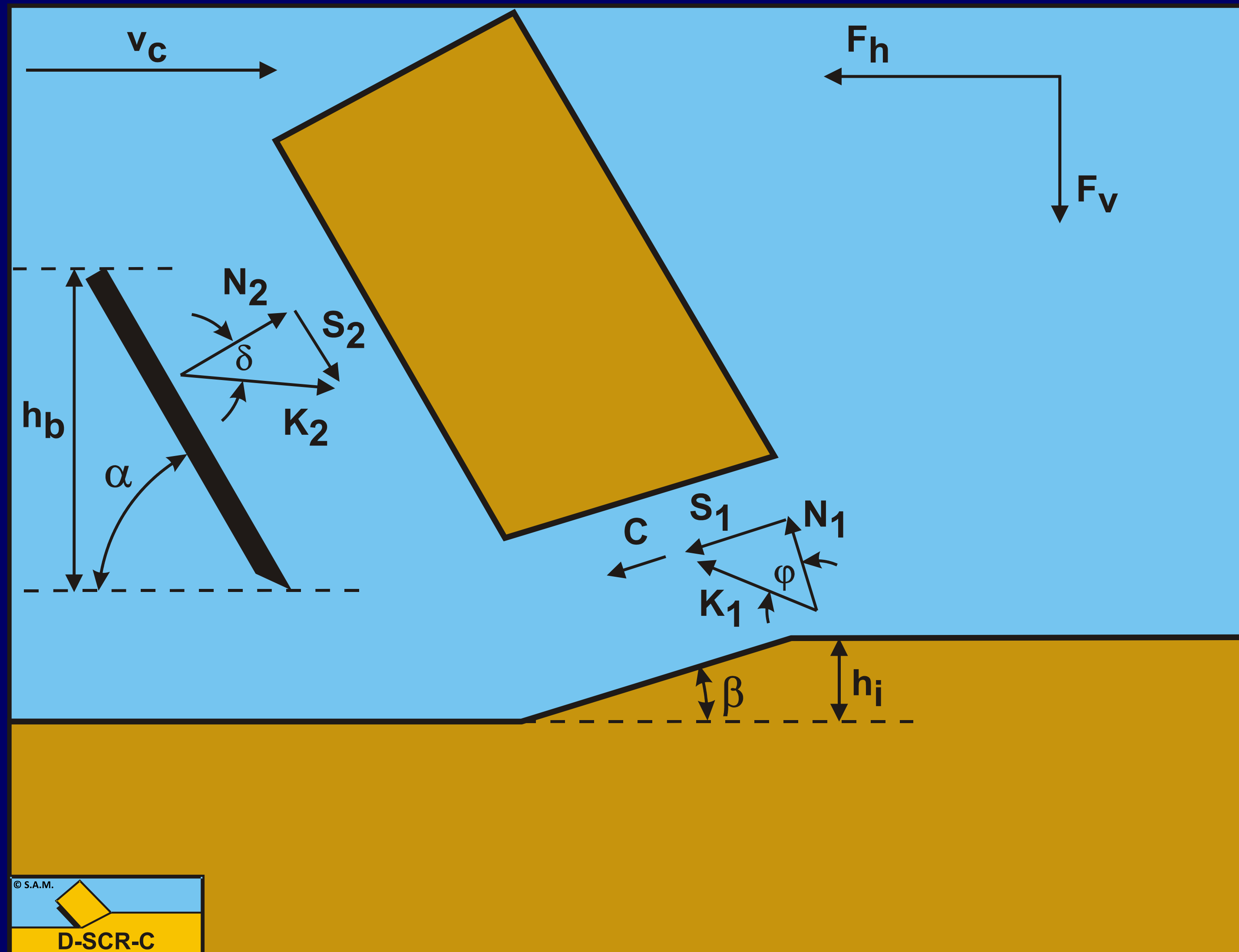
Forces on the Layer Cut



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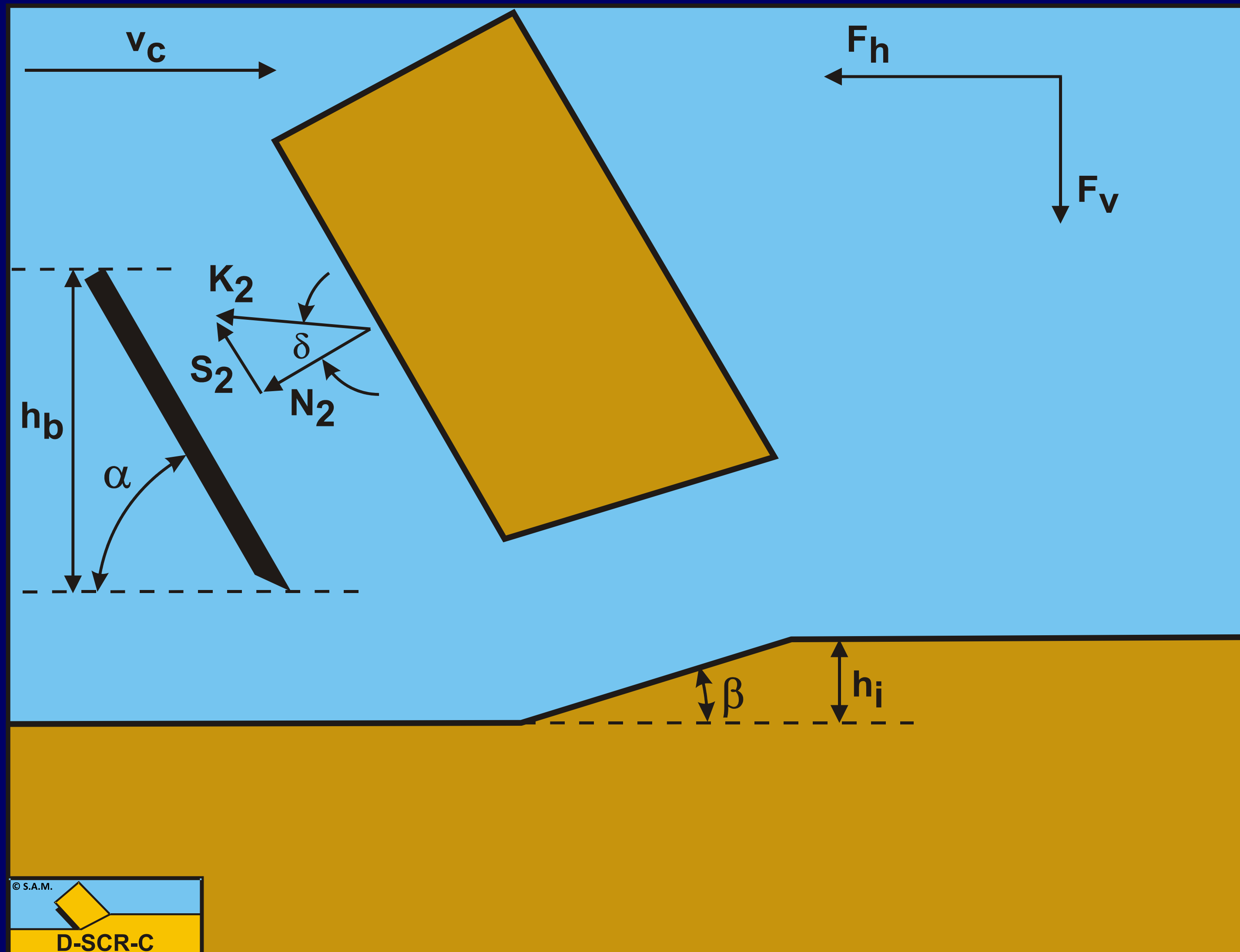
Forces on the Blade



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Resulting Cutting Forces

$$c = \frac{UCS}{2} \cdot \left(\frac{1 - \sin(\varphi)}{\cos(\varphi)} \right)$$

$$C = \frac{c \cdot h_i \cdot w}{\sin(\beta)}$$

$$\beta = \frac{\pi}{2} - \frac{\alpha + \delta + \varphi}{2}$$

$$F_h = \frac{2 \cdot c \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \sin(\alpha + \delta)}{1 + \cos(\alpha + \delta + \varphi)} = \lambda_{HF} \cdot c \cdot h_i \cdot w$$

$$F_v = \frac{2 \cdot c \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \cos(\alpha + \delta)}{1 + \cos(\alpha + \delta + \varphi)} = \lambda_{VF} \cdot c \cdot h_i \cdot w$$

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Stresses on the Shear Plane

$$c = \frac{UCS}{2} \cdot \left(\frac{1 - \sin(\varphi)}{\cos(\varphi)} \right)$$

$$N_1 = \frac{C \cdot \sin(\frac{\alpha + \delta - \varphi}{2})}{\cos(\frac{\alpha + \delta + \varphi}{2})} \cdot \cos(\varphi)$$

$$\sigma_1 = \frac{c \cdot \sin(\frac{\alpha + \delta - \varphi}{2})}{\cos(\frac{\alpha + \delta + \varphi}{2})} \cdot \cos(\varphi)$$

$$\tau_1 = c + \sigma_1 \cdot \tan(\varphi)$$

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Failure Criteria

The Mohr Circle

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Failure Criteria

The Mohr circle can never cross or touch one of the failure criteria. These criteria are:

- The shear failure criterion.
- The tensile failure criterion.

If the Mohr circle touches or crosses one of the failure criteria, failure will occur.

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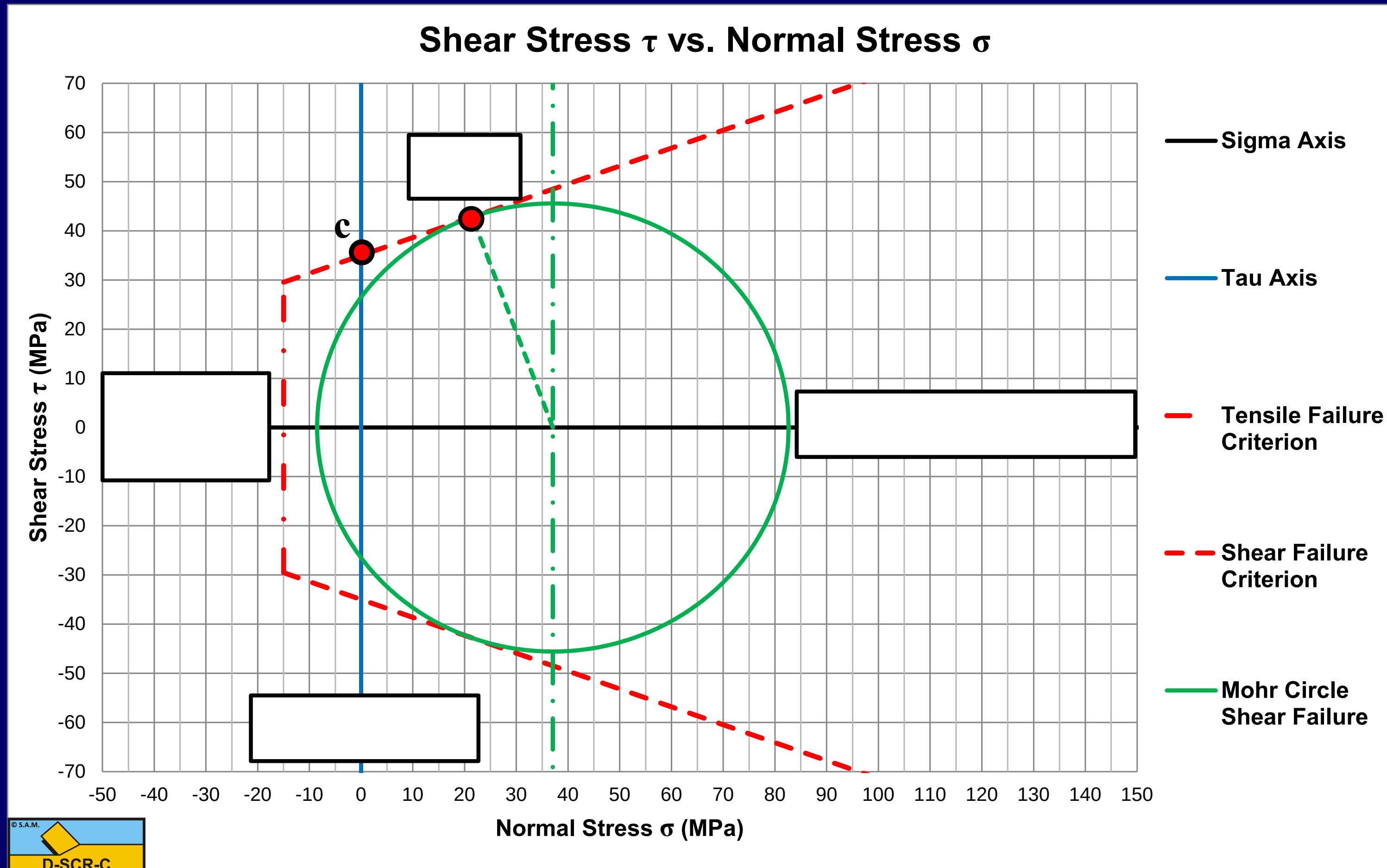
The Mohr Circle, BTS=-15 MPa



UCS=100 MPa, BTS=-15 MPa, α=60º, φ=20º, h_i=0.1 m & w=0.1 m

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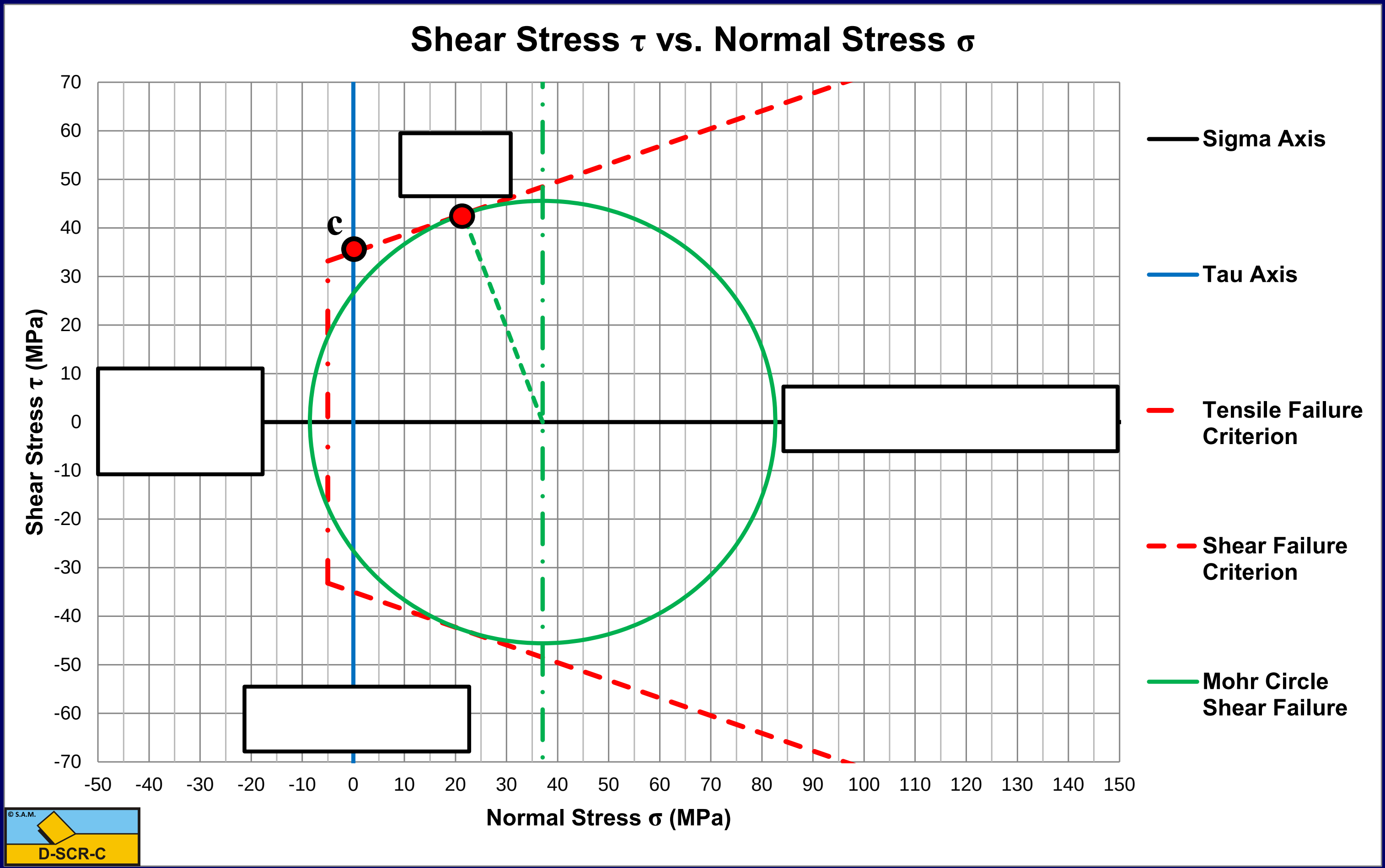
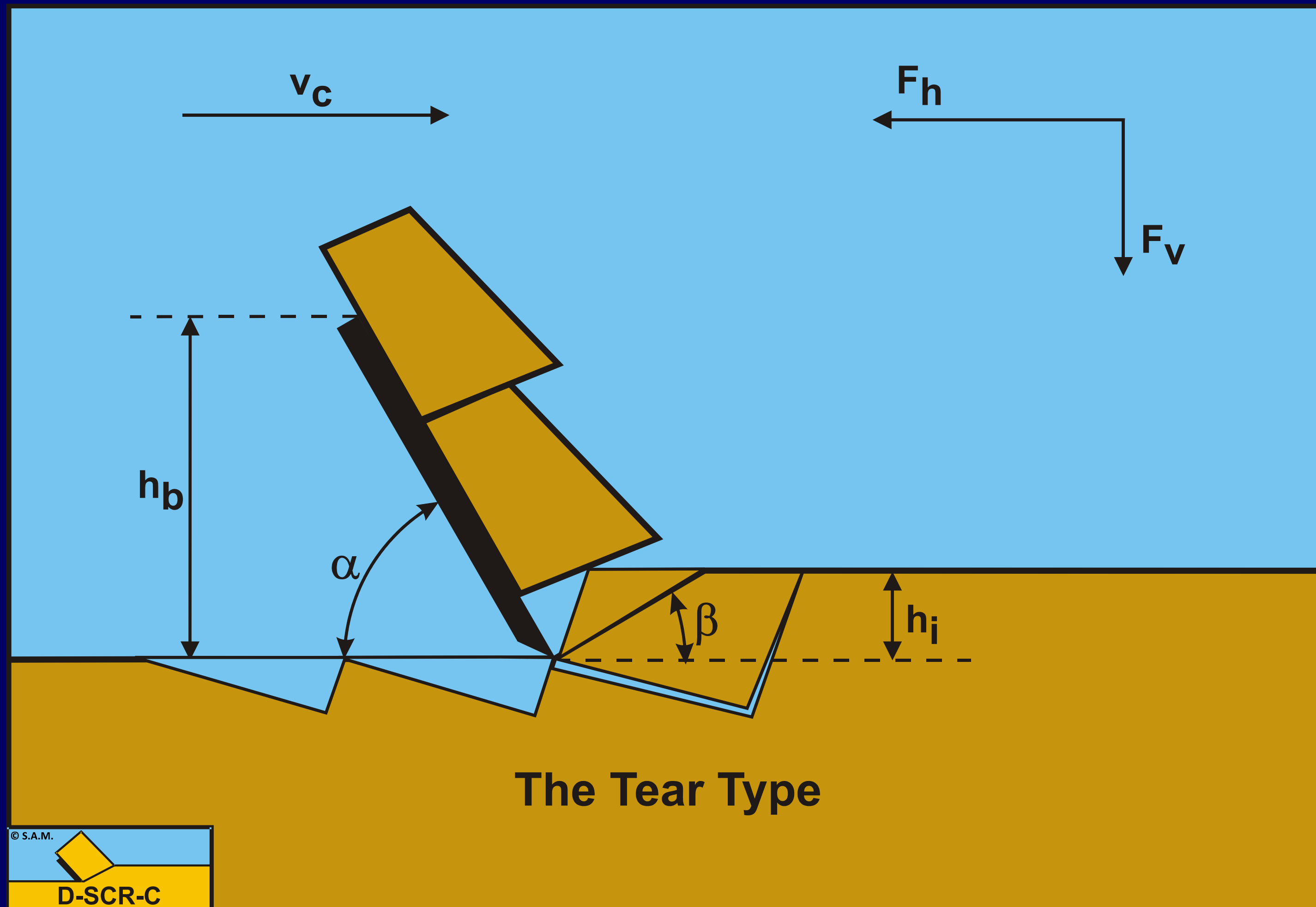
Tensile Failure/Tear Type
Peak Forces

The Mohr Circle, BTS=-5 MPa



UCS=100 MPa, BTS=-5 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

Brittle Tensile Failure/Tear Type



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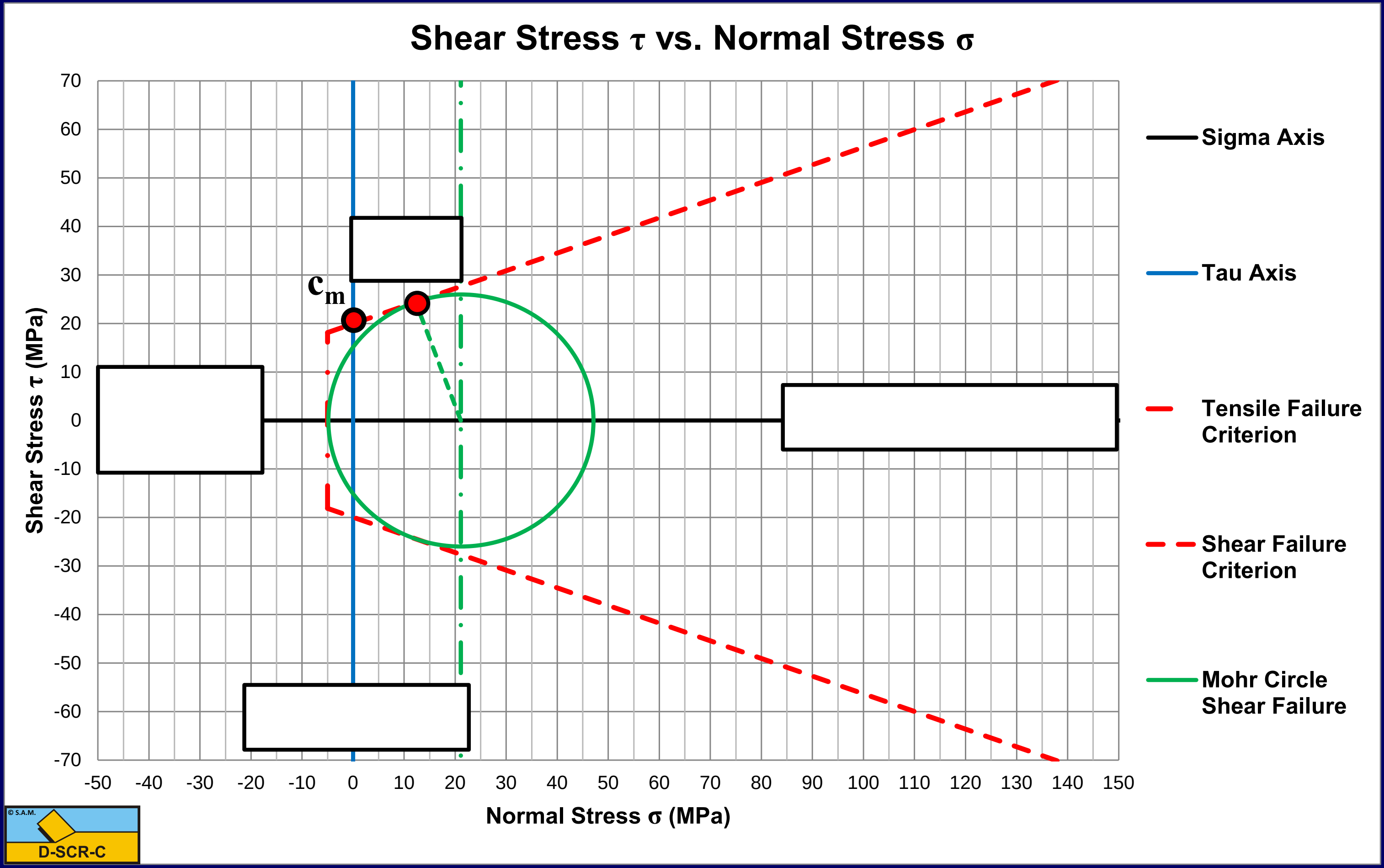
The Reduced Mohr Circle

The Mohr circle can never cross or touch one of the failure criteria. So if it crosses the tensile strength criterion, tensile failure will occur.

This can be modeled by defining a mobilized shear strength (cohesion) that creates a Mohr circle just touching the tensile strength criterion, based on the tensile strength.

This mobilized cohesion however also results in a different shear angle β.

The Reduced Mohr Circle, BTS=-5 MPa



UCS=57 MPa, BTS=-5 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

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Mobilized Shear Strength

$$F_h = \frac{2 \cdot c_m \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \sin(\alpha+\delta)}{\cos(\pi/4) + \cos(\alpha+\delta+\varphi)} = \lambda_{HT} \cdot \sigma_T \cdot h_i \cdot w$$

$$F_v = \frac{2 \cdot c_m \cdot h_i \cdot w \cdot \cos(\varphi) \cdot \cos(\alpha+\delta)}{\cos(\pi/4) + \cos(\alpha+\delta+\varphi)} = \lambda_{VT} \cdot \sigma_T \cdot h_i \cdot w$$

$$c_m = \frac{\sigma_T}{\left(\dfrac{\sin\left(\dfrac{\alpha+\delta-\varphi-\pi/4}{2}\right)}{\cos\left(\dfrac{\alpha+\delta+\varphi-\pi/4}{2}\right)} - 1 \right) \cdot \left(\dfrac{1-\sin(\varphi)}{\cos(\varphi)} \right)}$$

$$\beta = \frac{\pi}{2} - \frac{\pi/4+\alpha+\delta+\varphi}{2}$$

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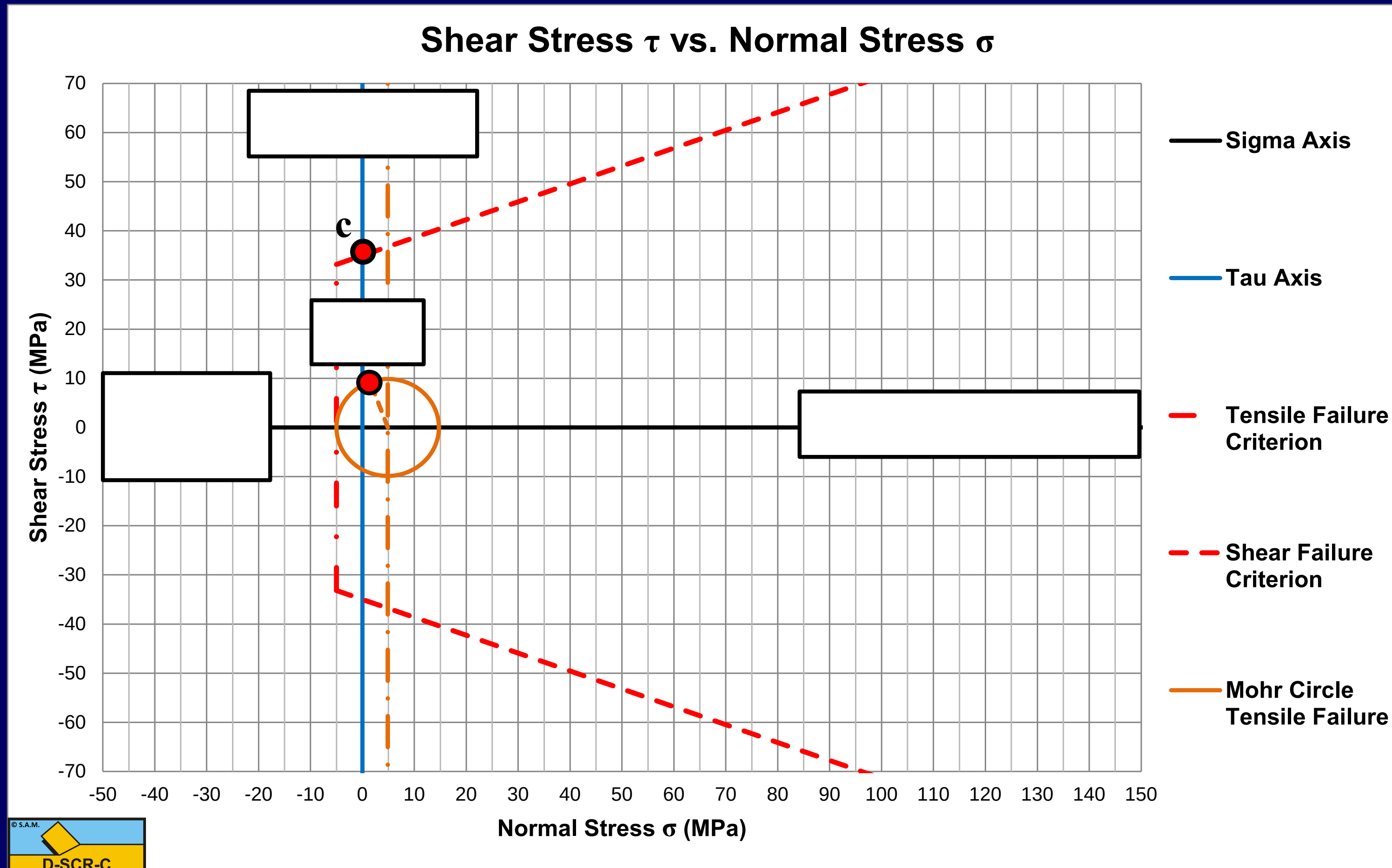
The Reduced Mohr Circle, BTS=-5 MPa



UCS=100 MPa, BTS=-5 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

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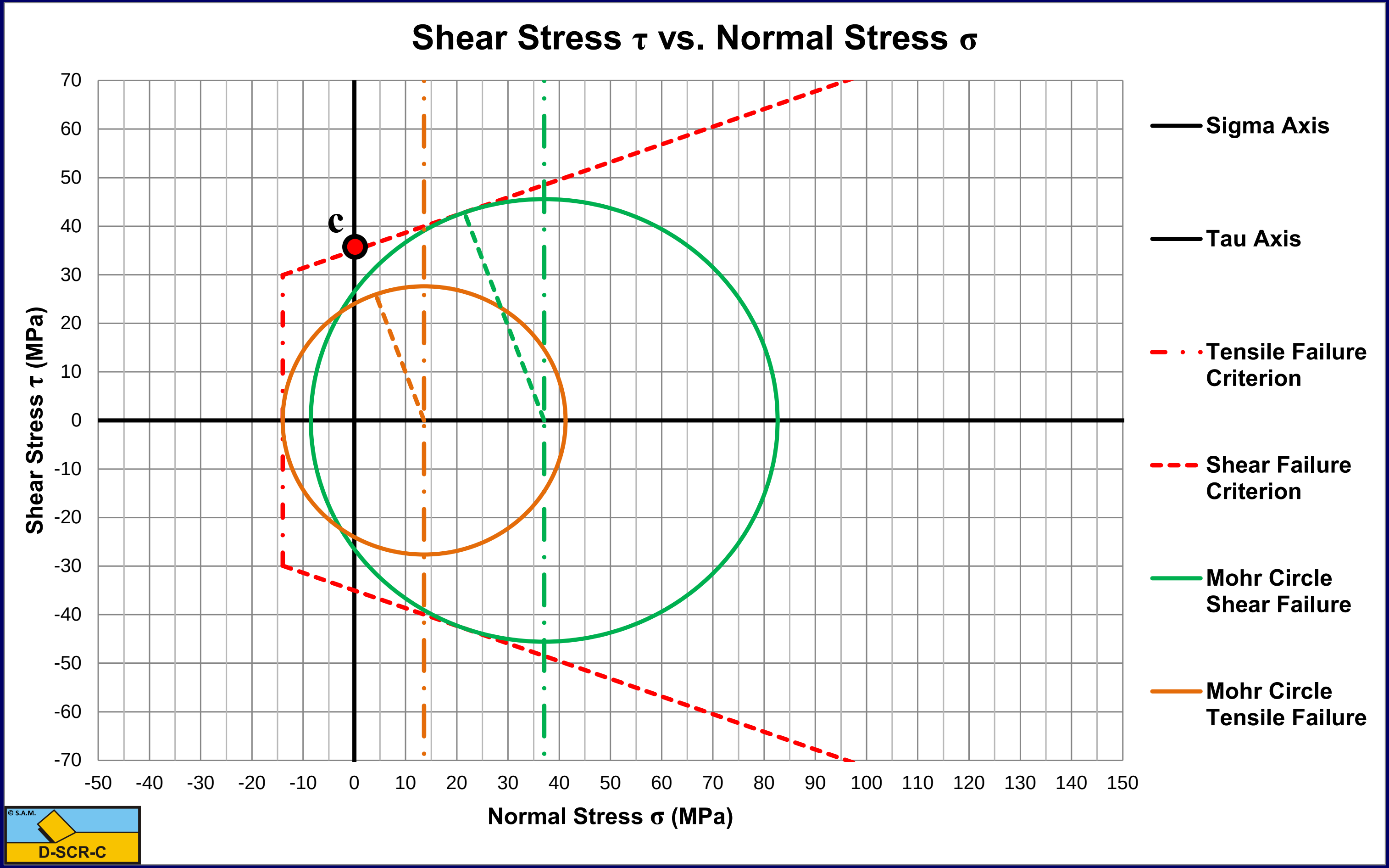
Two Solutions?

The Mohr Circles, BTS=-14 MPa



UCS=100 MPa, BTS=-14 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

Two Limits

The Chip Type

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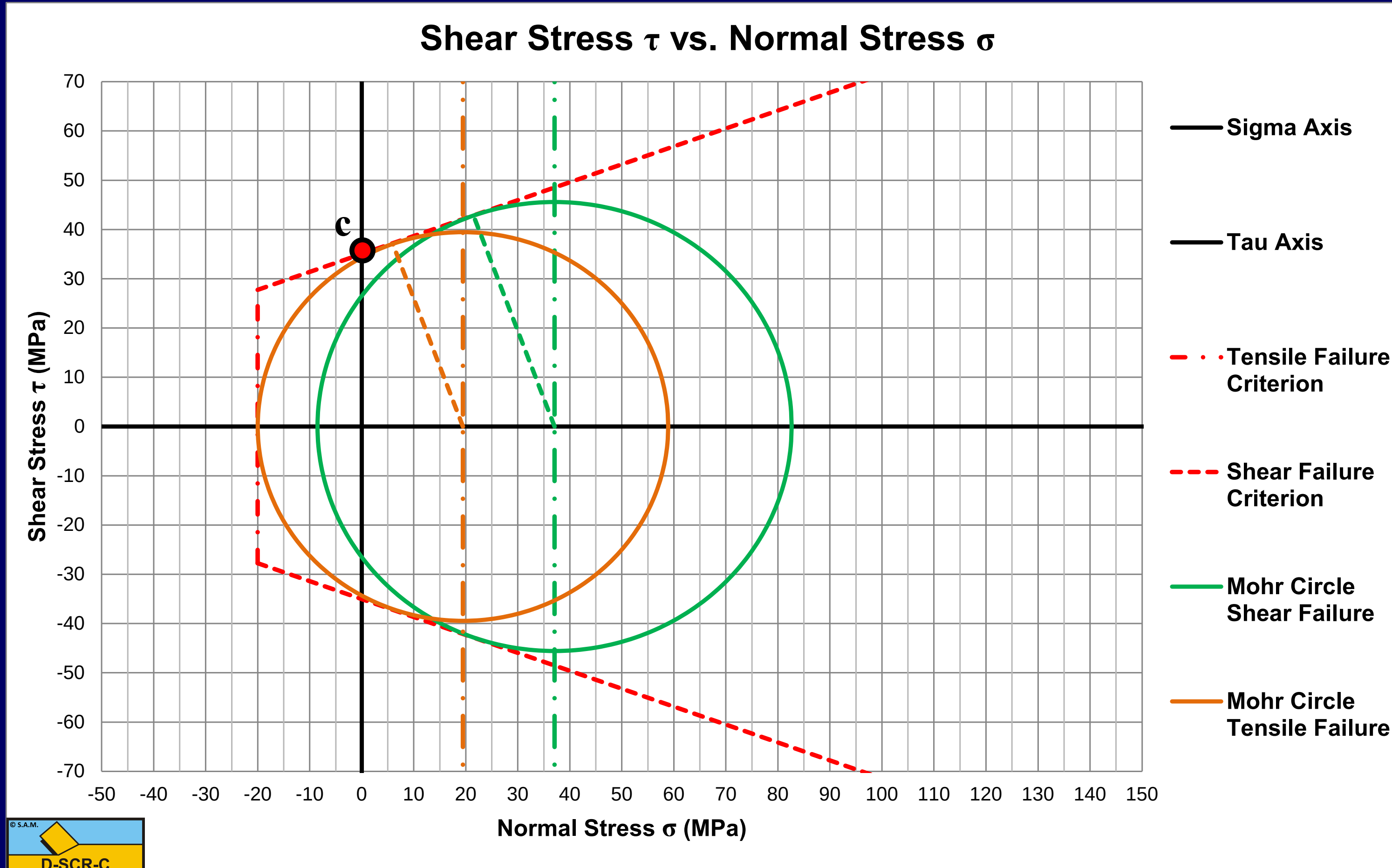
The Mohr Circles, Lower Limit



UCS=100 MPa, BTS=-20 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

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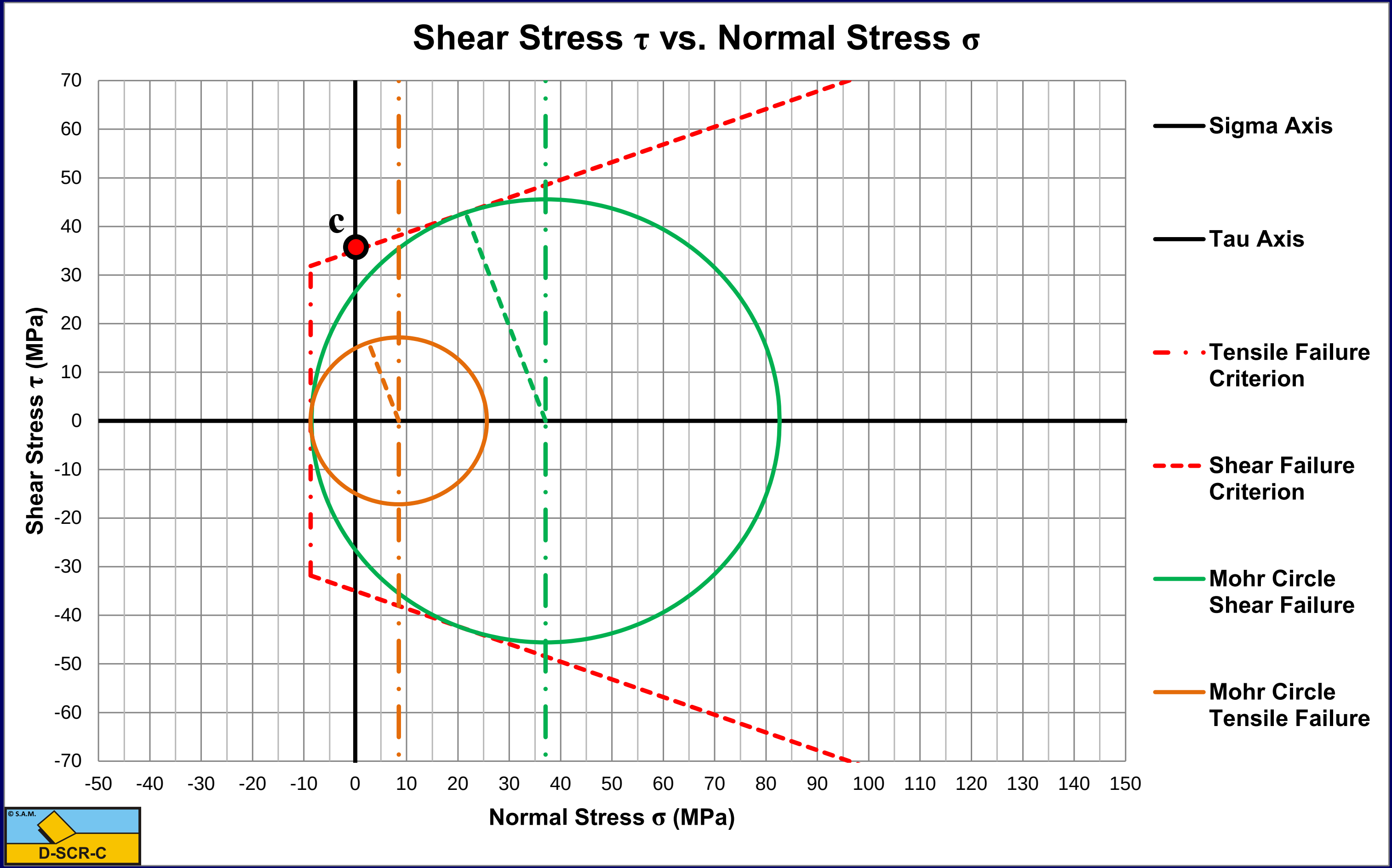
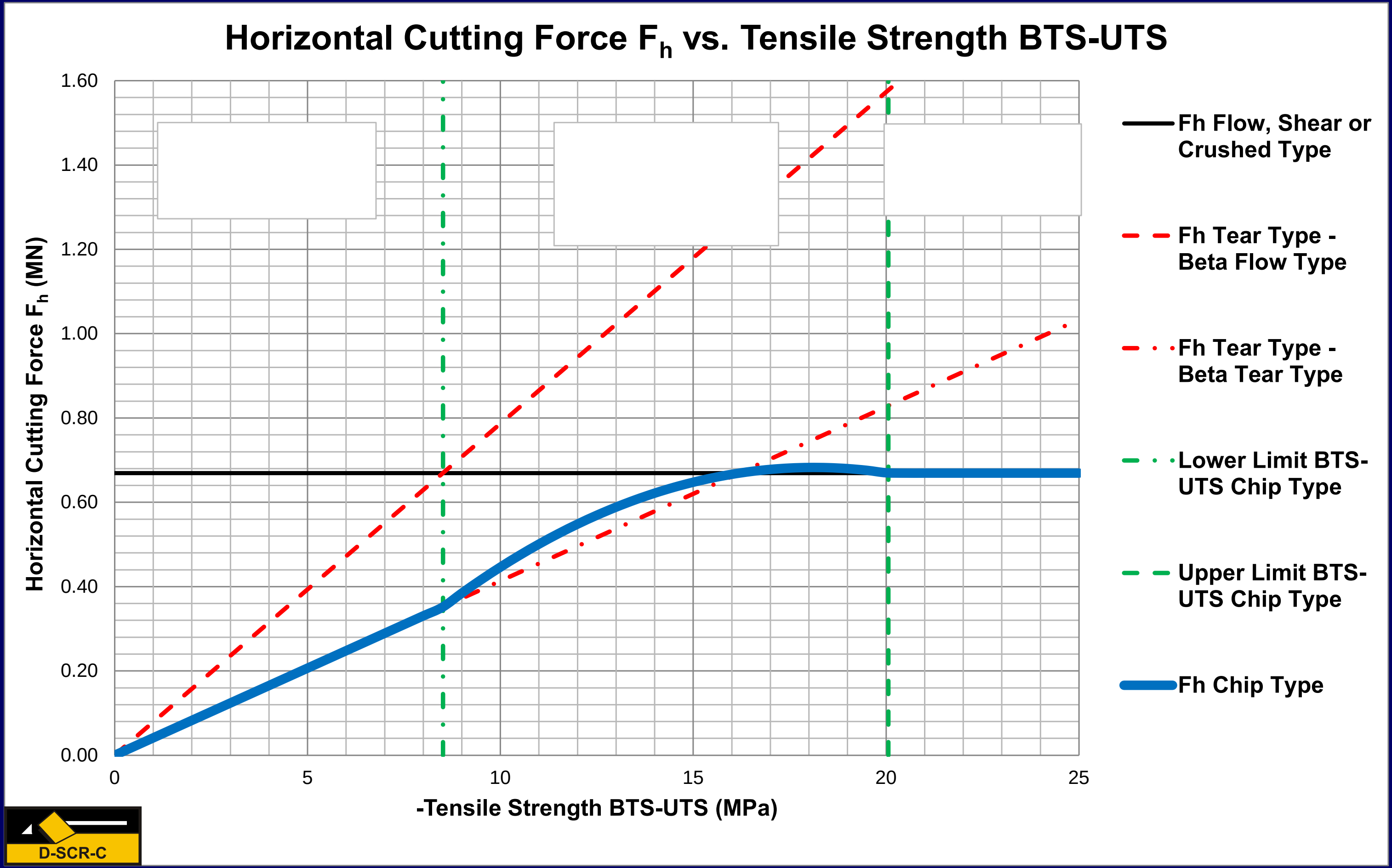
The Mohr Circles, Upper Limit



UCS=100 MPa, BTS=-8.7 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

The Horizontal Cutting Force



UCS=100 MPa, α=60º, φ=20º ,

h_i=0.1 m & w=0.1 m

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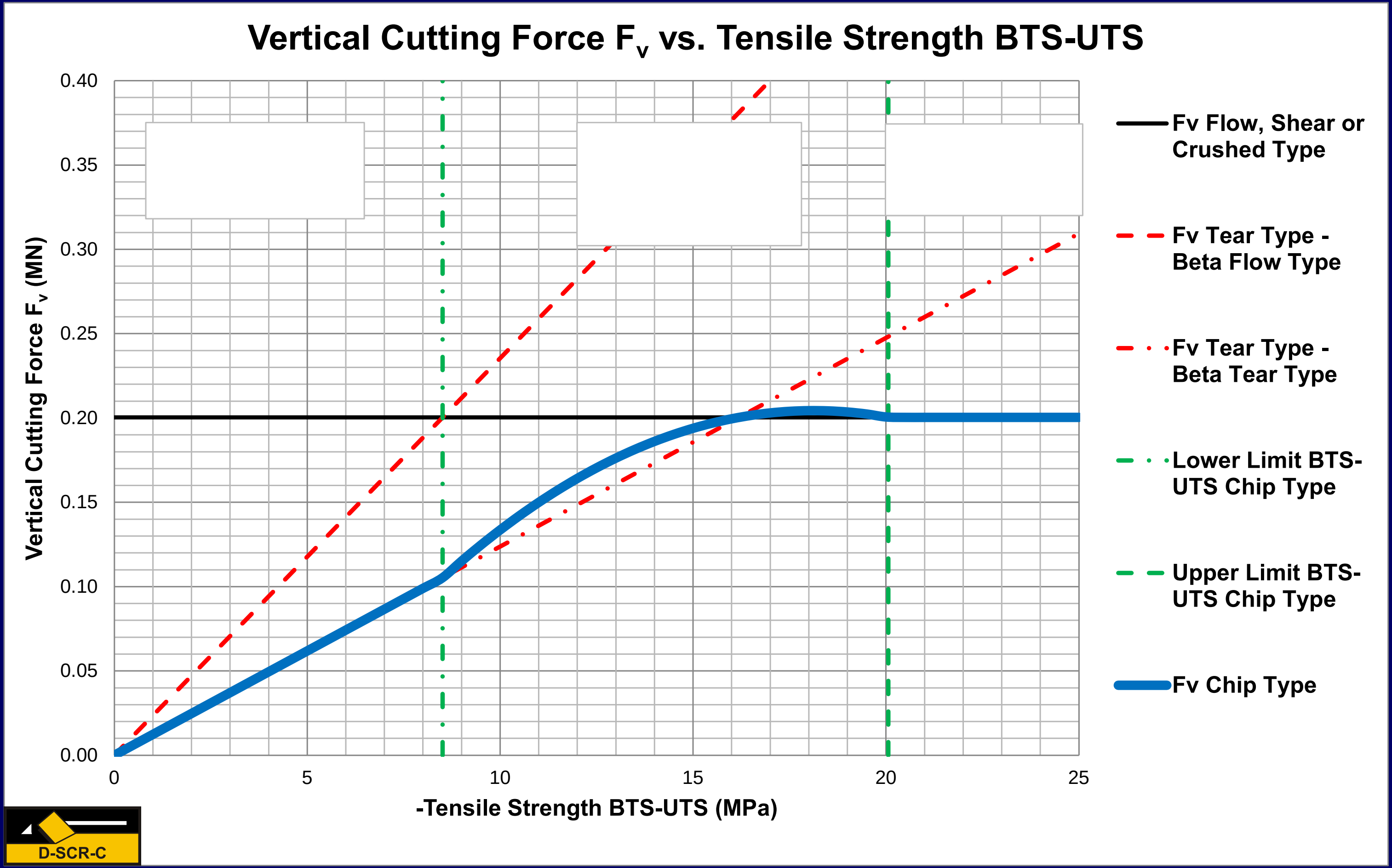
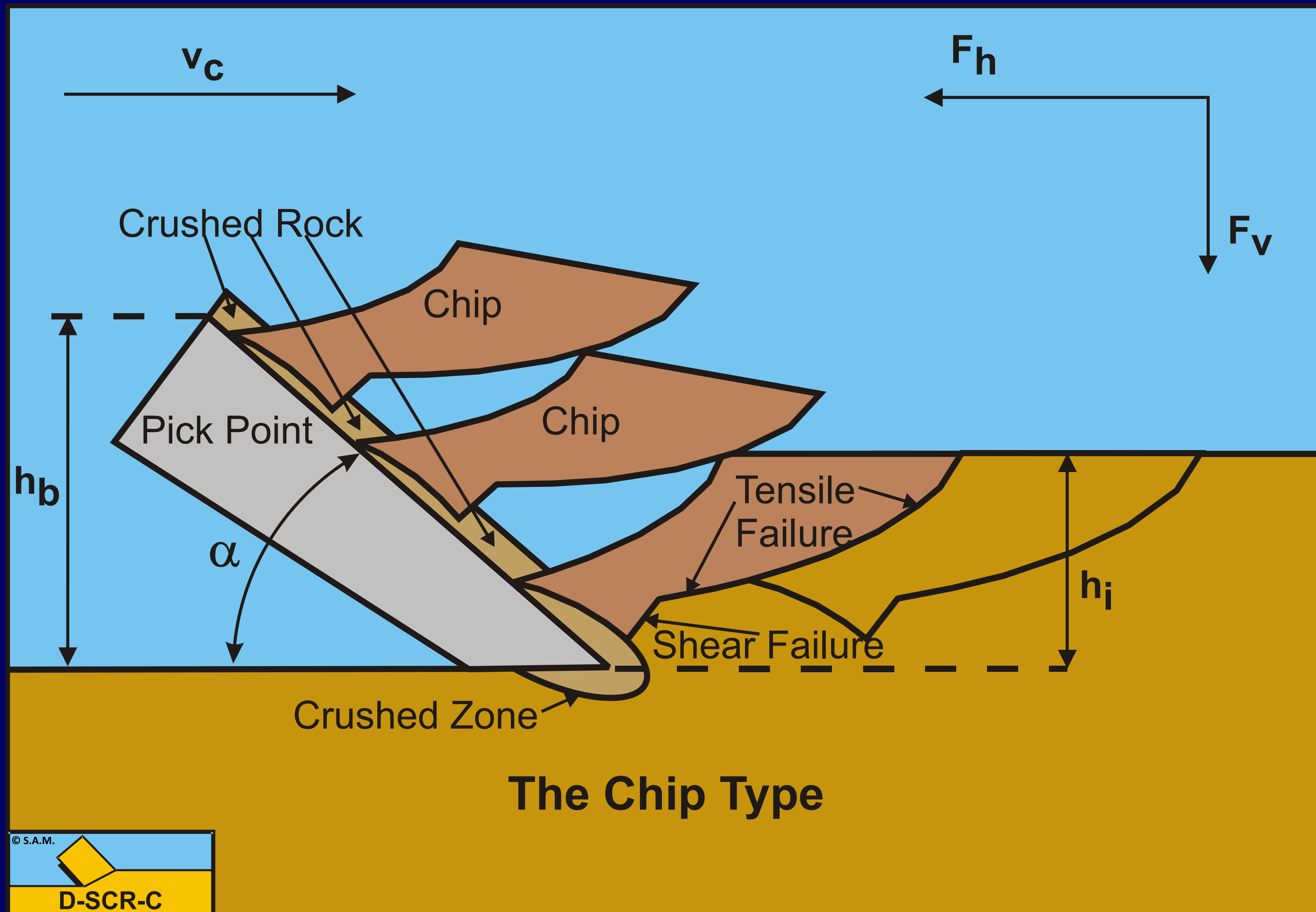
The Vertical Cutting Force



UCS=100 MPa, α=60º, φ=20º ,
h_i=0.1 m & w=0.1 m

Shear & Tensile Failure/Chip Type



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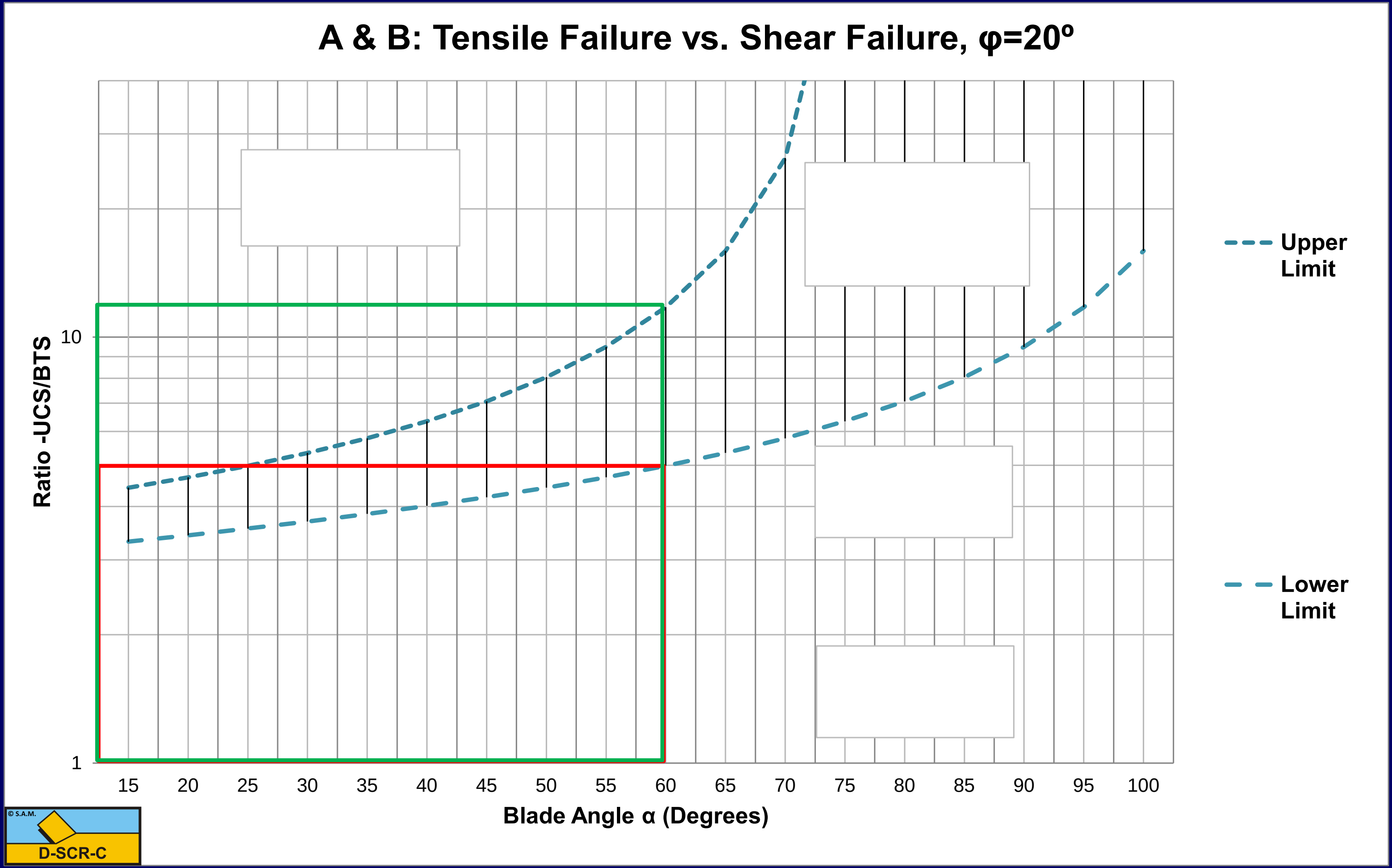
Lower & Upper Limits



UCS=100 MPa, BTS=-20 MPa, α=60º, φ=20º

Conclusions

- Below the UCS/BTS lower limit there is always shear failure.
- Above the UCS/BTS upper limit there is always tensile failure.
- Between the two limits there is most probably a combination of both failure mechanisms as is present in the Chip Type.

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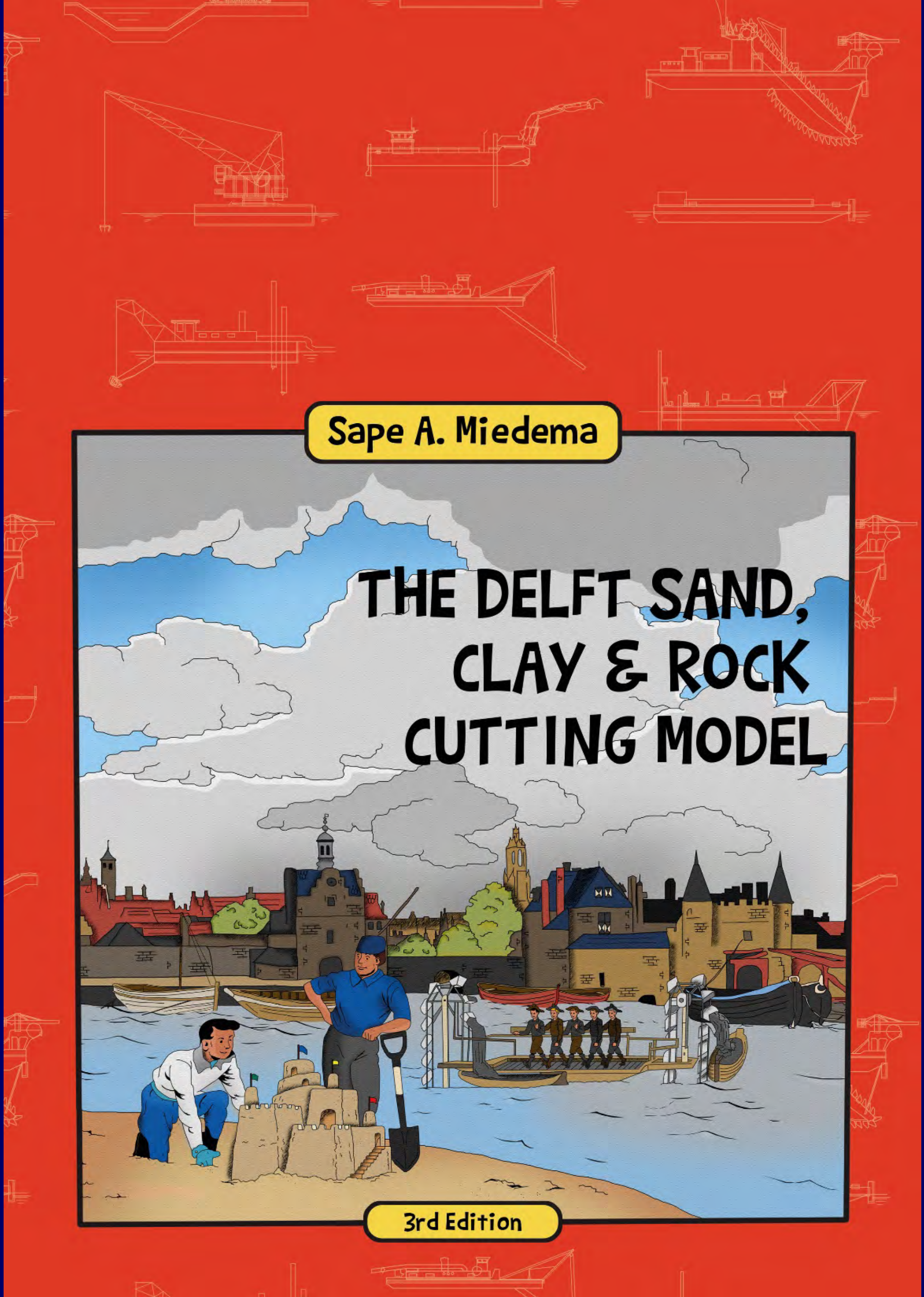

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Questions?