Studsvik RTT Analyzer A COMSOL® App to Evaluate Mechanical Properties for the Nuclear Industry

Daniel Ericsson¹, Joakim Karlsson², Martin König²

¹ Deflexional AB, Täby, Sweden
 ² Studsvik Nuclear AB, Nyköping, Sweden



Contents

- Introduction
- Using Studsvik RTT Analyzer
- Implementation in COMSOL[®]
- Conclusions



Introduction

Collaboration and background information





Collaboration

Studsvik Nuclear AB is a company in the field of nuclear technology and services

 With a history dating back over seven decades, Studsvik has established itself as a global leader in providing advanced solutions for the nuclear industry

 Deflexional is a COMSOL Certified Consultant with 25 years of experience in simulations with COMSOL Multiphysics[®]

Studsvik





Background

- Cladding is the thin-walled metal tube that forms the outer jacket of a nuclear fuel rod
- The cladding is made of Zircaloy which is an anisotropic material
- Acquiring precise material properties for the hoop direction is imperative due to the predominant internal pressure loading





Ring Tensile Tests (RTT)

- Studsvik extensively employs RTT for the evaluation of mechanical properties for cladding
- The specimen is a ring-shaped section cut from the chosen material
- It features symmetrically placed notches for stress concentration, accompanied by a dog bone-shaped center to reduce bending (Ref 1)



Ring Tensile Tests (RTT)

- The specimen is subjected to an increasing applied load
- Force and displacement are recorded
- Previously, an algorithm relied on Excel[®] to calculate yield strength, ultimate strength, and elongation, but only for specific dimensions
- This limitation required a new method and COMSOL Multiphysics[®] provides a solution through a dedicated COMSOL[®] App





The COMSOL® App

 To enhance accessibility, the application is transformed into a standalone compiled app using COMSOL Compiler™



Using Studsvik RTT Analyzer

Extract vital material data from measurements



Workflow

- Set dimensions and material data
- Import measured data for force and displacement
- Use a linear elastic study to quickly gain insights to how measurements and simulations correlates
- Perform a plasticity study
- Optionally, use optimization to obtain hardening parameters
- Extract stress-strain graphs to obtain yield strength, ultimate strength, and elongation



Modeling

- 1/8 symmetry is used to save computational time
- The mesh is automatically generated, along with element discretization options







۲ Studsvik RTT Analyzer _ \times File menu Home 🖽 Reset Windows ÷ 2 \leq \subseteq ക æ (σ) F-δ --Oreferences Geometry Mesh Import Compute Plots Table Compute Plots Table Table Dimensions Interpolations Compute Plots Force -Stress Force Export m Clear Solutions Measurements Displacement Ribbon -Data Linear Elastic Plasticity Optimization Graphs Solution Documentation Settings Preprocessing Preprocessing Material Data Linear Elastic Plasticity Optimization 🗸 🖡 Geometry ▼ # X 🙈 Update Geometry 🛕 Create Mesh **Studsvik** Tabs Ring 9.53 Outer diameter, do: mm Inner diameter, di: 8.41 mm 5 Thickness, rt: mm Width, rw: 1.98 mm 5 Waist height, rh: mm Cylinder Radius, cr: 4 mm 4.067 Width, cw: mm Height, ch: 3.02 mm 2.2 Thickness, ct: mm 0.3 Fillet, cf: mm Center Piece Diameter, bd: 8.31 mm 4.3 Width, bw: mm 1.6 Waist height, bh: mm Fillet, bf: 0.15 mm 75 • Angle, ba: Mesh Mesh size: Normal • x Z Settings Graphics deflexional 🦨

The different components in the graphical user interface

- Open the PDF file with a description of the geometry parameters by clicking the *Dimensions* button in the ribbon
- Press the Geometry button to update the graphics

					Dimensions		
٢			Studsvik RTT Analyzer				– 🗆 X
File Home							
Geometry Mesh Imp Preprocessing D	Compute Plots Table Computation and Linear Elastic	ite Plots Tab	le Interpolations Compute	Plots Table Displacemen	Stress Force Solution	Dimensio	
Preprocessing Material	Data Linear Elastic Plasticity Optimiz	atio ≡ 🎧	dimensions_drawing.	pdf × + Create	– 🗆	×	- ≢ ×
🙈 Update Geometry 🛕 Cr	eate Mesh	All tools	Edit Convert Sign	Find text or tools Q	🗄 🏟 🖶 …		
▼ Ring						_	Studsvik
Outer diameter, do: Inner diameter, di: Thickness, rt: Width, rw: Waist height, rh:	9.53 8.41 5 1.98 5	►. ₽.		do	rt rh	۲ ۳ ۳ ۳	
Radius, cr: Width, cw: Height, ch: Thickness, ct: Fillet, cf:	4 4.067 3.02 2.2 0.3			di bw ba			
▼ Center Piece			bh t				
Diameter, bd: Width, bw: Waist height, bh: Fillet, bf: Angle, ba:	8.31 4.3 1.6 0.15 75		ţ.	bd t		1	
▼ Mesh			ch			^	
Mesh size:	Normal		cn t	cr cr	cf	č B	
					Studsvik	e Q	flexional -

Create the mesh with the *Mesh* button

			Studsvik RTT Analyzer	- 0
File Home				
Geometry Mesh Preprocessing	mport surrements Data	Plasticity	TableInterpolationsOptimizationImage: Compute plots and plots a	Reset Wind Preference Clear Solut Settings
Preprocessing Materi	al Data Linear Elastic Plasticity Opt	imization 👻 🖡	Geometry × Mesh ×	
🙇 Update Geometry 🛕	Create Mesh		Q Q 𝔄 ▼ ⊕ ↓↓ ▼ ⋈ ⋈ ⋈ ⋈ ⋈ ↓	
 Ring 			St St	tudsvi
Outer diameter, do:	9.53	mm		
Inner diameter, di:	8.41	mm		1
Thickness, rt:	5	mm	ATTAX -	
Width, rw:	1.98	mm		
Waist height, rh:	5	mm		
 Cylinder 				Π
Radius, cr:	4	mm		7
Width, cw:	4.067	mm		
Height, ch:	3.02	mm		
Thickness, ct:	2.2	mm		
Fillet, cf:	0.3	mm		
 Center Piece 				
Diameter, bd:	8.31	mm		
Width, bw:	4.3	mm		
Waist height, bh:	1.6	mm		
Fillet, bf:	0.15	mm		\geq
Angle, ba:	75	0		
▼ Mesh				
Mesh size:	Normal	•		
	. 1911101			

Change the mesh size from Normal to Fine

9			Studsvik RTT Analyzer	- 0
File Home Geometry Mesh Preprocessing	mport surements Data	Plasticity	$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	Reset Window
Preprocessing Materia	al Data Linear Elastic Plasticity Opt	imization 👻 🖡	Geometry × Mesh ×	
🙉 Update Geometry 🛕	Create Mesh		Q Q ∰ ▼ ∰ ↓ ▼ ⋈ ⋈ ⋈ ⋈ ⋈ ⋈ ♂ ▼ ● ▼ 🖻 🖼 🖩 🛃 🙆 🚍	
 Ring 			S	tudsvil
Outer diameter, do:	9.53	mm		
Inner diameter, di:	8.41	mm		
Thickness, rt:	5	mm	AT HANK	
Width, rw:	1.98	mm	HTHX I	
Waist height, rh:	5	mm		
 Cylinder 				
Radius, cr:	4	mm		
Width, cw:	4.067	mm		κ
Height, ch:	3.02	mm		
Thickness, ct:	2.2	mm		
Fillet, cf:	0.3	mm		
 Center Piece 				
Diameter, bd:	8.31	mm		
Width, bw:	4.3	mm		
Waist height, bh:	1.6	mm		
Fillet, bf:	0.15	mm		
Angle, ba:	75	۰		
 Mesh 				
Mesh size:	Normal	•		
	Normal		x ²	
	Fine			
Mach				
IVIESI	コント		defl	exional

Note that the mesh is only refined in the ring

File Home				
Geometry Mesh Ir Meas	Plots Table C	ompute Plots	Interpolations Compute Plots Table Fró Force - Stress Force Export Displacement Table Table Table Table Table Table Table Table	■ Reset Windows Preferences Clear Solutions
Preprocessing	Data Linear Elastic	Plasticity	Optimization Graphs Solution Documentation	Settings
Preprocessing Materia	l Data Linear Elastic Plasticity Op	timization 👻 🖡	Geometry × Mesh ×	
🙈 Update Geometry 🛕 🤇	Create Mesh			
r Ring				tudsvik
)uter diameter, do:	9.53	mm		
nner diameter, di:	8.41	mm		E
hickness, rt:	5	mm		Ħ
Vidth, rw:	1.98	mm		
vaist height, rh:	5	mm		
r Cylinder				
adius, cr:	4	mm		$\sqrt{1}$
Vidth, cw:	4.067	mm		
leight, ch:	3.02	mm		
hickness, ct:	2.2	mm		
illet, cf:	0.3	mm		
Center Piece				
liameter, bd:	8.31	mm		4
Vidth, bw:	4.3	mm		
Vaist height, bh:	1.6	mm		
illet, bf:	0.15	mm		
ingle, ba:	75	•		
/ Mesh				
Aesh size:	Fine	•		
			x	

Switch back to Normal mesh for faster calculations

			Studsvik RTT Analyzer	- 0
File Home				
Geometry Mesh Preprocessing	Data	pompute Plots Plasticity	Table Interpolations Compute Plots Table Optimization Optimization Graphs Force - Displacement	Reset Windo Preferences Clear Solution Settings
Preprocessing Materia	al Data Linear Elastic Plasticity Opt	timization 👻 🖡	Geometry × Mesh ×	
🙈 Update Geometry 🛕	Create Mesh		Q Q ∰ ▼ ∰ ↓ ▼ ½ ½ № ½ № (♂ ▼ < ▼) □ □ □ □ □ □ □ -	
 Ring 			S	tudsvil
Outer diameter, do:	9.53	mm		\geq
nner diameter, di:	8.41	mm		
Thickness, rt:	5	mm	H H H H H H H H H H H H H H H H H H H	
Width, rw:	1.98	mm		
Waist height, rh:	5	mm		1
 Cylinder 				
Radius, cr:	4	mm		\mathcal{T}
Width, cw:	4.067	mm		× I
Height, ch:	3.02	mm		
Thickness, ct:	2.2	mm		
Fillet, cf:	0.3	mm		
 Center Piece 				
Diameter, bd:	8.31	mm		
Width, bw:	4.3	mm		
Waist height, bh:	1.6	mm		
Fillet, bf:	0.15	mm		
Angle, ba:	75	•		
 Mesh 				
	Normal	•		
Mesh size				



Benchmark Test of an Aluminum Alloy

- Tests are normally performed for Zircalloys
 The test temperature is high
- In this benchmark an aluminum alloy is tested in room temperature



- Open the *Material* tab
- Enter material data
- Thermal expansion parameters are of huge importance when the test is performed in high temperatures
- Friction can be included

			Studsvik RTT Analyzer	- 0
File Home	Compute Plots Table Con	npute Plots	ble Interpolations Compute Plots Table Force - Stress Force Export Dimensions	Reset Window
Preprocessing Data	ents - Linear Elastic	Plasticity	• Displacement • • • Optimization Graphs Solution Documentation	Settings
Preprocessing Material D	ata Linear Elastic Plasticity Optir	nization 👻 🖡	Geometry × Mesh ×	
r Ring			९, ९, छ, • 団 । ↓ • थ थ थ थ थ। ♂ • । ● • ७ ७ ७ ७ ₪ ⊍ । ◙ ⊖	
oisson's ratio:	0.33			itudsvil
Density:	2810	kg/m³		
Thermal expansion coefficient:	бе-б	1/K		
 Cylinder 				
/oung's modulus:	205	GPa		
Poisson's ratio:	0.33			
)ensity:	8117	kg/m³		
Thermal expansion coefficient:	1.8e-5	1/K		
 Center Piece 				× I
/oung's modulus:	205	GPa		
Poisson's ratio:	0.33			
Density:	8117	kg/m³		
Thermal expansion coefficient:	1.8e-5	1/K		
 Thermal Properties 				
Reference temperature:	25	°C		
lest temperature:	25	°C		\leq
 Friction 				
✓ Include friction				
riction coefficient:	0.125			



Import measured force and displacement

 Press Import Measurements to import force and displacement
 Cylin Young's Poisson' Density: Thermal
 Young's Young's

	I		I			
3			Studsvik RTT Analyzer			– o ×
File Home						
Geometry Mesh	ort ments	Compute Plots Table	e Interpolations Compute Plots Table	$\begin{array}{c c} & & & \\ \hline F-\delta & & \\ Force - & \\ Displacement & \\ \hline \end{array} \begin{array}{c} & & \\ \hline \\ F \\ \hline \end{array} \begin{array}{c} \\ F \\ $	Export Dimensions	■ Reset Windows
Preprocessing Dat	a Imports and plots measured data.	Plasticity	Optimization	Graphs	Solution Documentation	Settings
Preprocessing Material	Data Linear Elastic Plasticity C	ptimization 👻 🖡 🛛 Ge	ometry $ imes$ Mesh $ imes$			-
▼ Ring		•	, Q, ⊕, ▼ ⊕ ↓ ▼ ½½ ½½ №2	C • 🗣 🖻 🖻 🗐		
Poisson's ratio:	0.33				St	tudsvik
Density:	2810	kg/m³				
Thermal expansion coefficient:	бе-б	1/K				
▼ Cylinder				HH		ŧ
Young's modulus:	205	GPa				
Poisson's ratio:	0.33					-
Density:	8117	kg/m³			XXHTT	
Thermal expansion coefficient:	1.8e-5	1/K			KXALT \	
 Center Piece 					JAAX M	
Young's modulus:	205	GPa			XXX	
Poisson's ratio:	0.33				X I	
Density:	8117	kg/m³			1×1	
Thermal expansion coefficient:	1.8e-5	1/K			+111	
 Thermal Properties 						
Reference temperature:	25	°C		THXT	HTI	
Test temperature:	25	°C		+		
 Friction 						
✓ Include friction				HHXX /		
Friction coefficient:	0.125		у 111111111	THY		
				THL		
		X				



Paste data from Excel[®] or import files

)		Studsvik RTT A	nalyzer	- 0
File Home				
Geometry Mesh Preprocessing Data	tents Compute Plots Table Comput	e Plots Table Interpolations C	© □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	port Dimensions Documentation Documentation
Preprocessing Material D	Data Linear Elastic Plasticity Optimiza	tion 👻 🖡 Geometry 👋 Mesh	×	
▼ Ring		@.Q.@.▼ ⊕ \	- • • • • • • • • • • • • • • • • • • •	0
Poisson's ratio:	0.33			🕳 Studsvik
Density:	2810	📳 Import Measurements	×	
Thormal expansion coefficients	50 6	Displacement (mm)	Force (N)	
merma expansion coernelent.	06-0	0.033	171 12	
▼ Cylinder		0.036	180.37	
Young's modulus:	205	0.038	189.47	
Poisson's ratio	0.33	0.040	200.48	
Density	0117	0.043	211.96	2 THIT
Density:	10.5	0.044	222.13	XXTHHYY
Inermal expansion coefficient:	1.8e-5	0.046	234.99	KATEN
 Center Piece 		0.049	248.42	
Value ale manadulus:	205	0.051	259.55	\times \times \times \times
Young's modulus:	205	0.053	271.82	
Poisson's ratio:	0.33	0.056	285.16	\sim / \sim \sim
Density:	8117	0.058	296.13	X
Thermal expansion coefficient:	1.8e-5	0.059	306.06	
 Thermal Properties 		0.062	318.27	
mermannoperaes		0.064	330.09	+ TTI
Reference temperature:	25	0.067	341.06	
Test temperature:	25	0.069	352.31	
 Friction 		0.072	364.87	
		0.074	3/3.83	
Include friction		0.070	400.70	
Friction coefficient:	0.125	0.075	400.75	
		0.083	423.10	
		0.086	436.53	
		0.088	449.21	
		0.091	460.41	
		↑↓+≒≅∖k≂	· · · · · · · · · · · · · · · · · · ·	
			OK Cancel	

A force and displacement graph is automatically plotted

)			Studsvik RTT Analyzer	- 0
File Home				
Geometry Mesh Import Preprocessing Data	ents	Compute Plots	Interpolations Compute Plots Table Optimization Graphs	F) F) <t< th=""></t<>
Preprocessing Material D	ata Linear Elastic Plasticity		netry × Eorce-Displacement × Mesh ×	
Ring				
Poisson's ratio	0.33			Studsvil
Density:	2810	ka/m³	Force (N) and L	Study VI
Thermal expansion coefficient:	бе-б	1/K	1200 -	
 Cylinder 			1100	
Young's modulus:	205	GPa	1000	
oisson's ratio:	0.33		1000 -	
Density:	8117	kg/m³	900 -	
Thermal expansion coefficient:	1.8e-5	1/K	800	
 Center Piece 			700	
Young's modulus:	205	GPa	600	
Poisson's ratio:	0.33			
Density:	8117	kg/m³	500 -	
Thermal expansion coefficient:	1.8e-5	1/K	400 -	
 Thermal Properties 			300	
Reference temperature:	25	°C	200 -	
lest temperature:	25	°C	100	······ Imported measurement
 Friction 				
✓ Include friction			0 0.1 0.2 0.3 Displace	0.4 0.5 0.6 0.7 ement (mm)
	0.125		ulations Measurements	
			Linear elastic Imported measurements	
			Plasticity Compensated measurements	
			Plasticity optimization Interpolated data points	

Linear Elastic Analysis

- Young's Modulus is known
- Begin with a linear elastic study to obtain results fast
- Compare the results with the measured data



Click on the Linear Elastic tab

	– Linea	ir Elastic se	settings	
			Studsvik RTT Analyzer	- 0
File Home				
Geometry Mesh Preprocessing Data	Compute Plots Tab	le Compute Plots	Table Table Optimization Table Optimization Table Table Table Optimization Table T	Reset Windo
Preprocessing Material	Data Linear Elastic Plasticit	ty Optimization 👻 🖡	Geometry × Force-Displacement × Mesh ×	
 Compute Linear Elastic 			(@, Q, @, ▼ (⊞) Ⅲ ﷺ 🔲 🙋 🚍	
 Young's Modulus 			Force (N) and Displacement (mm)	tudsvi
′oung's modulus:	72000	MPa		T T
Study Settings			1200	
)isplacement, stepsize:	0.01	mm	1100	
)isplacement, stop:	0.25	mm	1000	
 Discretization 			900	
lement discretization:	Linear	•		
			· · · · · · · · · · · · · · · · · · ·	
			500 -	
			400 -	
			300	
			200	
			100 Importe	d measurement
			Displacement (mm)	0.
			Simulations	
			Linear elastic Imported measurements	
			Plasticity ontimization Internolated data noints	

Switch to Quadratic elements

				Studsvik RT	T Analyzer					- 0	×
File Home											
Geometry Mesh Imp Measur	ort ements	Compute Plots	Table	Interpolations	Compute Plots	F-δ Force - Displacement	Stress Force	Export	Dimensions	Reset Windo Operation of the set	ons
Preprocessing Da	ta Linear Elastic	Plasticity			Optimization	0	Graphs	Solution [Ocumentation	Settings	
Preprocessing Material	Data Linear Elastic Plasticity	Optimization 👻 🖡	Geo	metry × For	ce-Displacement $ imes$	$_{\rm Mesh} \times$					-
= Compute Linear Elastic			€	ର୍ 👧 🕶 🏚	🎹 🗮 🔲 🗖 🤅	•					
▼ Young's Modulus						Force (N)	and Displacen	nent (mm)	St	tudsvi	k
Young's modulus:	72000	MPa					-1	1	-		
 Study Settings 				1200							•••
Displacement, stepsize:	0.01	mm		1100							
Displacement, stop:	0.25	mm		1000		and the second sec					
 Discretization 				900							
Element discretization:	Linear	-		800		/					
	Linear		_	800	1	*					
	Quadratic serendipity		e N	700 -	1						
	Qubic serendipity		orc	600	/						
			L.	500	le de la companya de						
				500 -	1						
				400 -	- /						
				300	/						
				500	1.1						
				200 -	1			_			
				100	••••				····· Imported	measurement	s
				100							_
				0	0.1	0.2 D	0.3 0.3 (isplacement (n).4 0 nm)	.5 0	.6 0.7	
			Sim	ulations	Measurem	ents					
				Linear elastic	✓ Import	ed measurements					
				Plasticity	Compe	ensated measurements	s				

Compute —

- Enter Young's modulus which is a well-known parameter for most materials
- In the Study Settings section, enter the displacement step size and stop
- Press any of the *Compute* buttons to start the simulation

				Studsvik RTT Analyzer	- 0
File Home					
Geometry Mesh Preprocessing	Dort rements Compute Plots Table Compute ata Linear Elastic Compute Compute Compute	ompute Plots Plasticity	Table	e Interpolations Compute Plots Table Optimization Graphs Force - Stress Force Stress Stress Solution Documentation	Reset Window Preferences Clear Solution Settings
Preprocessing Material	Data Linear Elastic Plasticity Op	timization 👻 🖡	Geo	eometry × Force-Displacement × Mesh ×	
= Compute Linear Elastic			æ	k Q @ ▼ ፼ !!!! ≡ □] ⊠ =	
 Young's Modulus 				Force (N) and Displacement (mm)	Studsvil
Young's modulus:	72000	MPa			
 Study Settings 				1200 -	
Displacement, stepsize:	0.01	mm		1100	
Displacement, stop:	0.25	mm		1000	
 Discretization 				900	
Element discretization:	Quadratic serendipity	•		800 -	
			(Z	700	
			Force	600 -	
			-	500	
				400	
				300 -	
				200 -	
				100 Impor	ted measurements
					i i
				0 0.1 0.2 0.3 0.4 0.5 Displacement (mm)	0.6 0.7
			Sim	Measurements	
				Linear elastic Vince Imported measurements Plasticity Compensated measurements	

 The simulation and the imported measurements don't match due to test rig deformations





- Click on the Data tab
- In the Compensated Data section, enter a slope correction and a shift to fit the compensated measurements with the linear elastic study

	 Data sett 	ings	
			Studsvik RTT Analyzer – D X
File Home			
Geometry Mesh Preprocessing Data	Compute Plots Table Linear Elastic	Compute Plots Plasticity	TableInterpolationsImage: Compute Plots TableImage: Compute Plots
Preprocessing Material Data	Linear Elastic Plasticity O	ptimization 👻 🖡	Geometry × Force-Displacement × Mesh ×
➔ Import F-0 Plot Force/Displacement	ent		@, Q, @, ▼ ፼ !!!! 篇 🔲 @ 🖨
 Compensated Data 			Force (N) and Displacement (mm) Studsvik
ilope for data correction: 12)isplacement shift: 0.	12	N/mm	Simulations Measurements Plasticity Pla



Plasticity

- Depending on the tested material, the use of different hardening models are required
- Studsvik RTT Analyzer supports several hardening models and it's possible to define user-defined functions
- Since the test performed in this presentation is an aluminum alloy, the *Ludwik* hardening model is used

 Compute Plasticity Young's Modulus Plasticity Plasticity model: Large plastic strains Isotropic hardening model: Ludwik Perfectly plastic Linear Mpa MPa Interpolation Function Bilinear softening Plot Minimum plastic strains : Power Law softening Lognormal softening Plot Hardening Study Settings Discretization 	Preprocessing	Material	Data	Linear Elastic	Plasticity	Optimiza	tion 🔻
 Young's Modulus Plasticity Plasticity model: Large plastic strains Isotropic hardening model: Ludwik Perfectly plastic Linear Mys0 Ludwik Interpolation Function Bilinear softening Plot Minimum plastic strains : Maximum plastic strains : Study Settings Discretization 	= Compute Plas	ticity					
 Plasticity Plasticity model: Large plastic strains Isotropic hardening model: Ludwik Perfectly plastic Linear MPa MPa MPa MPa Plot Plot Minimum plastic strains : Maximum plastic strains : Study Settings Discretization 	Young's Mode	ulus					
Plasticity model: Large plastic strains Isotropic hardening model: Ludwik Equation: Linear Perfectly plastic Linear Arge plastic strains Perfectly plastic Linear MPa MPa MPa NPa Plot Plot Bilinear softening Power Law softening Power Law softening Lognormal softening Lognormal softening Plot Study Settings Study Settings Discretization	 Plasticity 						
Isotropic hardening model: Equation: σ_{ys0} k n Plot Minimum plastic strains : Maximum plastic strains : Study Settings Ludwik Interpolation Function Bilinear softening Power Law softening Lognormal softening Plot Hardening Discretization Ludwik Perfectly plastic Linear MPa	Plasticity model:			Large plastic stra	ains	•	
Equation: Perfectly plastic MPa σ_{ys0} Ludwik MPa k Interpolation MPa n Function MPa Plot Bilinear softening 1 Minimum plastic strains : Exponential softening 1 Maximum plastic strains : Power Law softening 1 ✓ Plot Hardening 1 ✓ Study Settings 5	lsotropic hardenin	ig model:	ſ	Ludwik		•	
σys0 Linear MPa k Interpolation MPa n Function Bilinear softening Plot Bilinear softening 1 Minimum plastic strains : Power Law softening 1 Maximum plastic strains : Lognormal softening 1 V Plot Hardening 1 Discretization Study Settings 1	Equation:			Perfectly plastic			
Ludwik MPa k Interpolation MPa n Function MPa Plot Bilinear softening 1 Minimum plastic strains : Power Law softening 1 Maximum plastic strains : Lognormal softening 1 V Flot Hardening 1 V Study Settings V	σ			Linear			140
k Interpolation MPa n Function MPa Plot Bilinear softening 1 Minimum plastic strains : Power Law softening 1 Maximum plastic strains : Lognormal softening 1 V Plot Hardening 1 Study Settings Discretization 1	0 ys0			Ludwik			MPa
n Function Plot Bilinear softening Minimum plastic strains : Exponential softening Maximum plastic strains : Power Law softening Lognormal softening 1 C Plot Hardening Study Settings Discretization	k			Interpolation			MPa
Plot Exponential softening 1 Minimum plastic strains : Power Law softening 1 Maximum plastic strains : Lognormal softening 1 ✓ Plot Hardening 1 ✓ Study Settings 5 ✓ Discretization 1	n			Function			
Minimum plastic strains : Dower Law softening 1 Maximum plastic strains : Lognormal softening 1 C Plot Hardening 1 Study Settings Discretization 1	Plot			Bilinear softening	ning		
Maximum plastic strains : Lognormal softening 1	Minimum plastic strains :			Power Law soften	ning		1
 Plot Hardening Study Settings Discretization 	Maximum plasti	c strains :		Lognormal softer	nina		1
 Study Settings Discretization 			I	Plot Hardening	a		
 Discretization 	Study Setting			<u> </u>	2		
Discretization	s study setting.	,					
	Discretization						

- Click the *Plasticity* tab
- Set Young's Modulus or use the same as in the linear elastic study
- Select isotropic hardening model and the hardening parameters
- Define the steps for the simulation in the Study Settings section

			Studsvik RTT Ar	nalyzer		- 0
File Home Import Import Geometry Mesh Import Preprocessing Material D = Compute Plasticity Voung's Modulus Import Import Import Preprocessing Material D = Compute Plasticity Voung's Modulus Import O O Young's modulus: Plasticity Plasticity	ents Compute Plots Linear Elastic Plasticity Optim	Plasticity ization • •	Table Interpolations Co Interpolations Co Op Geometry × Force-I • Q • Q 1300 • I 1200 • I 1100 • I	Image: Second state Image: Second state Image: Second state Image: Second state </th <th>The second se</th> <th>Dimensions Dumentation Dimensions</th>	The second se	Dimensions Dumentation Dimensions
sotropic hardening model: Equation: σ _{ys0} k n -Plot Minimum plastic strains : Maximum plastic strains :	Large plastic strains Ludwik $\sigma_{ys} = \sigma_{ys0} + k \varepsilon_{pe}^{n}$ 387 425 0.17 0 2 \checkmark Plot Hardening	 MPa MPa 1 1 	1000 - 900 - 800 - Ž 700 - 500 - 400 - 300 -			
 Study Settings Step type: Displacement, start: Displacement, stepsize: 	Start/Step/Stop 0 0.02	▼ mm mm		0.1 0.2 0.3 Dia	0.4 0.5	mported measurements Compensated measurements 0.6 0.7
Displacement, stop: Discretization	0.74	mm	Simulations C Linear elastic Plasticity	Measurements Imported measurements Imported measurements Imported measurements		

 Press the *Plot Hardening* button to visualize the selected hardening function

3			Studsvik RTT Analyzer	– 🗆 ×
File Home				
Geometry Mesh Preprocessing Data	tents Compute Linear Elastic	Compute Plots Ta Plasticity	e Interpolations Compute Plots Table Optimization Graphs	Export Solution Documentation
Preprocessing Material D	ata Linear Elastic Plasticity	Optimization 👻 🖡	$cometry imes \ Hardening \ Function imes \ Force-Displacement \ imes \ Mesh$	×
= Compute Plasticity			. Q @ ▼ ፼ !!!! @ 🖨	
 Young's Modulus 			Hardening Function	(MPa) Studsvik
From linear elastic study	User-defined		-	
Young's modulus:	72000	MPa		
 Plasticity 			450 -	
Plasticity model:	Large plastic strains	•	400 -	
lsotropic hardening model:	Ludwik	•		
Equation:	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \varepsilon_{\rm pe}^n$		350 -	
$\sigma_{\rm ys0}$	387	MPa		
k	425	MPa	300 -	
n Plot	0.17		250	
Minimum plastic strains :	0	1	250	
Maximum plastic strains :	2	1	200 -	
	C Plot Hardening			
 Study Settings 			150 -	
Step type:	Start/Step/Stop	•	100	
Displacement, start:	0	mm	100 -	
Displacement, stepsize:	0.02	mm	50 -	
Displacement, stop:	0.74	mm		
 Discretization 			o –	
Element discretization:	Linear	•	0 0.5 1 Plastic Strain (1.5 2

Enter new hardening parameters and plot the hardening function

				tudsvik RTT Analyzer		- 0
File Home						
Geometry Mesh Preprocessing Data	nts Compute Plots Table Co Linear Elastic	mpute Plots	Table In	erpolations Compute Plots Table	Force - Stress Force Displacement - Graphs	Export Solution Documentation Settings
Preprocessing Material Da	ta Linear Elastic Plasticity Opti	imization 👻 🖡	Geometr	× Hardening Function × Fo	rce-Displacement ×	
 Compute Plasticity 			€.Q.	R - 🔁 🎹 🔚 🗖 🖨		
▼ Young's Modulus					Hardening Function (MF	Studsvik
From linear elastic study Voung's modulus:	User-defined 72000	MPa	4	0		
 Plasticity 			4	00-		
Plasticity model:	Large plastic strains	•				
lsotropic hardening model:	Ludwik	•	3	50 -		
Equation:	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^n$					
$\sigma_{ m ys0}$	350	MPa	3	00-		
k	400	MPa	ר (Pa			
n Diat	0.15		2 ctio	50 -		
Minimum plastic strains :	0	1	Fun			
Maximum plastic strains :	2	1	liui 2	00 -		
	C Plot Hardening		Harde			
 Study Settings 			1	.0 -		
Step type:	Start/Step/Stop	•	1	0 -		
Displacement, start:	0	mm				
Displacement, stepsize:	0.02	mm		io -		
Displacement, stop:	0.74	mm				
 Discretization 				o		
Element discretization:	Linear	•		0 0.5	1 Plastic Strain (1)	1.5

- Change the *Element* discretization to Quadratic serendipity for better accuracy
- Press Compute Plasticity

)			Studsvik RTT Analyzer – 🗆
File Home			
Geometry Mesh Preprocessing Data	t compute Plots Table Com Linear Elastic	Plots Plasticity	Table Interpolations Compute Plots Table F-δ Stress Force - Displacement Export Dimensions Dimensions Clear Solution Optimization Optimization Graphs Solution Documentation Settings
Preprocessing Material D	ata Linear Elastic Plasticity Optim	nization 👻 🖡	Geometry × Hardening Function × Force-Displacement ×
= Compute Plasticity			(
 Young's Modulus 			Force (N) and Displacement (mm)
From linear elastic study	User-defined		
Young's modulus:	72000	MPa	
 Plasticity 			
Plasticity model:	Large plastic strains	•	
otropic hardening model:	Ludwik	•	1000 -
quation:	$\sigma_{\rm ys}{=}\sigma_{\rm ys0}{+}k\varepsilon_{\rm pe}^n$		900
$\sigma_{\rm ys0}$	350	MPa	800 -
k	400	MPa	2 700
Plot	0.15		600 - <u> </u>
Minimum plastic strains :	0	1	500 -
Maximum plastic strains :	2	1	400 -
	C Plot Hardening		300 -
 Study Settings 			200 -
tep type:	Start/Step/Stop	•	100 - Compensated measurements
)isplacement, start:	0	mm	
)isplacement, stepsize:	0.02	mm	0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 Displacement (mm)
Displacement, stop:	0.74	mm	Simulations
 Discretization 			✓ Linear elastic Imported measurements
Element discretization:	Quadratic serendipity	•	Plasticity Compensated measurements

 The result is not satisfactory, and the user can try with new parameters to fit the plasticity results to the compensated measurements

)				Studsvik RTT Analy	zer				- 0
File Home									
Geometry Mesh Preprocessing Data	ents	Compute Plots	Table	Interpolations Comp	pute Plots Tabl	e Force - Displacement Gray	Stress Force	Export Solution	Reset Wind ♀ Preferences ♀ Clear Soluti Settings
Preprocessing Material D	ata Linear Elastic Plasticity	Optimization 👻 🖡	Geome	try 👋 Hardening	g Function $ imes$	Force-Displacement	×		
 Compute Plasticity 			e e	🙊 🕶 💷 🖩	I 🖸 🖨				
 Young's Modulus 						Force (N) ar	nd Displacemen	t (mm) 🛛 🖇	tudsvi
From linear elastic study Young's modulus:	User-defined	MPa	1	300 -		ም	1		
 Plasticity 			1	200 -		4			
Plasticity model:	Large plastic strains	•	1	100 -		1000	0.0000		
lsotropic hardening model:	Ludwik	•	1	000 -					
Equation:	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^n$			900 -					
$\sigma_{\rm ys0}$	350	MPa	_	800 -					
k	400	MPa	e (N	700 -		5			
n - Plot	0.15		Ford	600 -	ľ				
Minimum plastic strains :	0	1		500 -					
Maximum plastic strains :	2	1		400 -	ľ				
	C Plot Hardening			300 -					
 Study Settings 				200-				Linear elastic	2
Step type:	Start/Step/Stop	-		100 -				Compensate	d measuremen
Displacement, start:	0	mm		0	0.1 0	2 0.2	0.4	0.5 0.6	0.7
Displacement, stepsize:	0.02	mm		0	0.1 0	.∠ 0.3 Disp	0.4 lacement (mm)	0.5 0.6	0.7
Displacement, stop:	0.74	mm	Simula	tions	Measurement	s			
 Discretization 			🖌 Lin	ear elastic	Imported	measurements			
Element discretization:	Quadratic serendipity	•	✓ Pla	sticity	Compensa	ated measurements			

Optimization

- The app provides optimization routines utilizing the Optimization Module
- Using the BOBYQA method, the hardening parameters are automatically fitted to the measured data
- The user can easily select which parameters that should be optimized

 Plasticity 								
Plasticity model:		Large plastic strains 🔹						
lsotropic hardening mode	:	Ludwik		-				
Equation:		$\sigma_{\rm ys}{=}\sigma_{\rm ys0}{+}i$	k€ ⁿ pe					
 Plasticity Parameters 								
\checkmark Optimize $\sigma_{\rm ys0}$								
Initial value (MPa)	Scale (M	Pa)	Lower bound (MPa)	Upper bound (MPa)				
387	387		300	450				
✓ Optimize k								
Initial value (MPa)	Scale (M	Pa)	Lower bound (MPa)	Upper bound (MPa)				
400	400		300	500				
Ontimize n								
• Optimize II								
 Initial value (MPa) 	Scale (M	Pa)	Lower bound (MPa)	Upper bound (MPa)				
 Initial value (MPa) 0.1 	Scale (MI 0.1	Pa)	Lower bound (MPa) 0.05	Upper bound (MPa) 0.25				
 Initial value (MPa) 0.1 Plot Hardening Initial 	Scale (MI 0.1 Values	Pa)	Lower bound (MPa) 0.05	Upper bound (MPa) 0.25				
 Optimize In Initial value (MPa) 0.1 Plot Hardening Initial Optimization Settings 	Scale (MI 0.1 Values	Pa)	Lower bound (MPa) 0.05	Upper bound (MPa) 0.25				
 Initial value (MPa) 0.1 Plot Hardening Initial Optimization Settings Optimality tolerance: 	Scale (MI 0.1 Values	Pa) 0.01	Lower bound (MPa) 0.05	Upper bound (MPa) 0.25				



Click the Optimization tab

	— Op	timization settings
0		Studsvik RTT Analyzer – 🗆
File Home		
Geometry Mesh Import Measurements Data	Compute Plots	Table Interpolations Compute Plots Table Optimization Op
Preprocessing Material Data Linear Elastic Plasticity	Optimization 🛃 🖡	Geometry × Hardening Function × Force-Displacement × Mesh ×
Create Interpolation Data Points = Compute Optimization	^	@, Q, :9, ▼ ⊕ Ш ≡ 🔲 🙍 🖨
 Interpolation Data Points 		Force (N) and Displacement (mm)
Displacement start: 0.14	mm	
Displacement step size: 0.01	mm	1200 -
Displacement end: 0.3	mm	1100 -
▼ Young's Modulus		1000
From linear elastic study		
Young's modulus: 72000	MPa	900
▼ Plasticity		800 -
Plasticity model:	•	
Isotropic hardening model:	•	600
Equation: $\sigma_{\rm vs} = \sigma_{\rm vs0} + k \epsilon_{\rm pe}^n$		500
Disticity Parameters		400 -
		300
Optimize Syso		200
Initial value (MP. Scale (MPa) Lower bound (MPa Upper 387 387 300 450	bound (MPa	100 - Plasticity -
		Compensated measurements
Initial value (MP Scale (MPa) Lower bound (MPa Upper 400 300 500	bound (MPa	0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 Displacement (mm)
✓ Optimize n		Simulations Measurements
Initial value (MP Scale (MPa) Lower bound (MPa Upper 0.1 0.05 0.25	bound (MPa	Linear elastic Imported measurements Imported measurements Compensated measurements Plasticity optimization Interpolated data points

- In the Interpolation Data Points section, enter start, step size and stop
- This data will create points following the *Compensated measured* graph
- The optimization will use these interpolation points as "targets"
- Press Create Interpolation Data Points

	Studsvik RTT Analyzer – 🗆 🗙
File Home	
Geometry Mesh Preprocessing Data	ity Optimization Compute Plots Table Optimization Graphs Compute Stress Force - Displacement Stress Force - Displacement Stress
Preprocessing Material Data Linear Elastic Plasticity Optimization	Geometry × Hardening Function × Force-Displacement × Mesh × Image: Mesh × Imag
Create Interpolation Data Points = Compute Optimization	
 Interpolation Data Points 	Force (N) and Displacement (mm)
Displacement start:0.14mmDisplacement step size:0.02mmDisplacement end:0.74mm	
▼ Young's Modulus	1000
From linear elastic study User-defined Young's modulus: 72000 MPa	900
 Plasticity 	300
Plasticity model:Large plastic strainsIsotropic hardening model:LudwikEquation: $\sigma_{ys} = \sigma_{ys0} + k \epsilon_{pe}^{n}$	2 /00 - 2 600 - 500 -
 Plasticity Parameters 	400 -
\checkmark Optimize σ_{ys0}	300 -
Initial value (MP Scale (MPa) Lower bound (MPa Upper bound (MPa 387 387 300 450 ✓ Optimize k	200 100 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Initial value (MP Scale (MPa) Lower bound (MPa Upper bound (MPa 400 400 300 500	0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 Displacement (mm)
✓ Optimize n ▶ Initial value (MP. Scale (MPa) Lower bound (MPa Upper bound (MPa 0.1 0.05 0.25	Linear elastic Imported measurements Imported measurements Compensated measurements Plasticity optimization Interpolated data points

- The interpolation data points (green) follow the compensated measurements with the step size set in the *Interpolation Data* section
- Note that the first point is located at a displacement of 0.14 mm since this is the first to fit the measurements and the linear elastic simulation

	Studsvik RTT Analyzer ×
File Home	
Geometry Mesh Preprocessing Data	ty Optimization Compute Plots Table Optimization Graphs Compute Plots Table Clear Solution
Preprocessing Material Data Linear Elastic Plasticity Optimization	Geometry × Hardening Function × Force-Displacement × Mesh ×
Create Interpolation Data Points = Compute Optimization	@ Q @ ▼ 🕀 🛄 🇮 🔲 @ 🖨
 Interpolation Data Points 	Force (N) and Displacement (mm) Studsvik
Displacement start: 0.14 mm	
Displacement step size: 0.02 mm	1200
Displacement end: 0.74 mm	1100
▼ Young's Modulus	
From linear elastic study O User-defined	
Young's modulus: 72000 MPa	900 -
 Plasticity 	800
Plasticity model:	
Isotropic hardening model:	500-
Equation: $O_{ys} = O_{ys0} + \kappa \epsilon_{pe}$	400
 Plasticity Parameters 	
\checkmark Optimize σ_{ys0}	
Initial value (MP: Scale (MPa) Lower bound (MPa Upper bound (MPa	200 - Plasticity -
387 387 300 450	100 - 100 - Interpolated data points
✓ Optimize k	
Initial value (MP. Scale (MPa) Lower bound (MPa Upper bound (MPa	0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
400 400 300 500	Displacement (mm)
✓ Optimize n	Simulations Measurements
Initial value (MP- Scale (MPa) Lower bound (MPa Upper bound (MPa	✓ Plasticity ✓ Compensated measurements
0.1 0.1 0.05 0.25	Plasticity optimization Interpolated data points

- In the *Plasticity Parameters* section, check the hardening parameters that should be optimized
- Provide initial values, scales, and lower and upper bounds
- In the Optimization Settings section, a tolerance and the maximum number of evaluations can be set
- Press the *Compute* button in the *Optimization* section of the ribbon

Į.					Studsvik RTT Ar	alyzer				- 0	כ
File Home											
Geometry Mesh Preprocessing	Import Measurements Data	Compute Plots Linear Elastic	Table Compute Plots Plasticit	; Table I	nterpolations Co	Computes the opt	Table F-δ Table Force Displacent timized plasticity pa	Stress Force	Export Solution Doc	imensions Clear Sol Clear Sol Setting	/indov nces olutior
Preprocessing M	aterial Data	Linear Elastic Plasti	icity Optimization	Geometry	× Hardenir	ig Function $ imes$	Force-Displacem	ent $ imes$ Mesh $ imes$			• 1
Plasticity model:		Large plastic strains	•	@ Q (2 - 🔁 📖	🗮 🔲 🖆 🖨	Eorce (N)	and Displacement	(mm)	Studsvil	k
lsotropic hardening m	odel:	Ludwik	•				Force (N)	and Displacement	. (11111)	Staasvii	
Equation:	0	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^n$									_
 Plasticity Paramet 	ters			120	0					00000000	•
✓ Optimize σ _{vs0}				110	0		00				
Initial value (MP)	Scale (MPa)	Lower bound (MPa	Upper bound (MPa	100	o –						
387	387	300	450	90	o -						
✔ Optimize k				80	0						
► Initial value (MP)	Scale (MPa)	Lower bound (MPa	Upper bound (MPa	- 70	0						
400	400	300	500	e N			/				
✔ Optimize n				Ford	0-						
► Initial value (MD	Scale (MDa)	Lower bound (MPa	Upper bound (MPa	50	0	ľ					_
0.1	0.1	0.05	0.25	40	0						
Plot Hardening In	itial Values			30	o -						
	•			20	0					ity	
 Optimization Sett 	ings			10					—— Comp	ensated measurements	:s
Optimality tolerance:	(0.01				000			Interp	olated data points	
Maximum number of	evaluations:	1000			0 0000						
 Discretization 					0	0.1 0	0.2 0.3 Di	0.4 splacement (mm)	0.5	0.6 0.7	
Element discretization		Quadratic serendipity	•	Simulatio	ns	Measuremen	nts				
 Optimization Res 	ults			Linea	elastic	Imported	d measurements	_			
				✓ Plasti	ity	Compen	sated measuremen	5			

- The *Plasticity optimization* curve follows the measurement
- The calculated hardening parameters are presented in the Optimization Results section
- The optimized results can be copied to the plasticity study for further analysis

	Studsvik RTT Analyzer —	
File Home		
Geometry Mesh Import Measurements Preprocessing Data Linear Elastic	Interpolations Ompute Plots Table Interpolations Ompute Plots Table Fr-δ Force - Stress Force Export Dimensions Dimensions Optimization Plasticity Optimization Optimization Graphs Solution Documentation Set	t Windows erences r Solutions ttings
Preproc Material Data Linear E Plasticity Optimi •	Geometry × Force-Displacement ×	~ #
Equation: $\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^{\prime\prime} \label{eq:static}$	Q Q ⊕ ▼ ⊕ = □ □ ⊕	
 Plasticity Parameters 	Force (N) and Displacement (mm) Stud	svik
\checkmark Optimize σ_{ys0}		
Initial value (Iv Scale (MPa) Lower bound (M Upper bound (M 387 387 300 450		<u>~~~</u>
✓ Optimize k	1100-	- 0 0
Initial value (Iv Scale (MPa) Lower bound (M Upper bound (M 400 400 300 500		
✓ Optimize n	800 -	
Initial value (lv Scale (MPa) Lower bound (M Upper bound (M 0.1 0.1 0.05 0.25		
Plot Hardening Initial Values Optimization Settings	500 -	
Optimality tolerance: 0.01 Maximum number of evaluations: 1000	400 - 300 - 200 - Linear elastic → Plasticity	
 Discretization 	100 - Plasticity optimization	romonto -
Element discretization: Quadratic serendipity 🔹		ements
 Optimization Results 	0 0.1 0.2 0.3 0.4 0.5 0.6 Displacement (mm)	0.7
$\sigma_{ys0} = 414.7 \text{ MPa}$ k = 405.6 MPa n = 0.1857 Copy Results to Plasticity	Simulations Measurements Imported measurements Imported measurements	

3D solution plots are available from the *Plots* menu in the ribbon

9		Studsvik	RTT Analyzer		– 🗆 X
File Home					
Geometry Mesh Preprocessing Data	ts Compute Plots Table Comp Linear Elastic	ute Plots Table Plasticity	ons Compute Plots Optimizatic δ Displacement	Stress Force Export aphs Solution Do	Dimensions Clear Solutions
Preproc Material Data L	inear E Plasticity Optimi 💌	Geometry × Force-Disp	placement × σ_v von Mises Stress		•
Equation:	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^{\prime\prime}$	● Q ; ●	🕜 Hoop Stress		
 Plasticity Parameters 			E Total Strain)isplacement (mm)	Studsvik
\checkmark Optimize σ_{vs0}			ε _p Plastic Strain		
Initial value (N Scale (MPa)	Lower bound (M Upper bound (M	1300 -	٣		
387 387	300 450	1200 -	- P	AAAAAAAA	
\checkmark Optimize k		1100 -	Ø 1000	000000000	0000000000
Initial value (N Scale (MPa)	Lower bound (M Upper bound (M	1000 -	p p a b		
400 400	300 500	900 -			
🖌 Optimize n		800	T T		
Initial value (IV Scale (MPa)	Lower bound (M Upper bound (M	2 700	X IIII		
0.1 0.1	0.05 0.25	001	1		
Plot Hardening Initial Values		<u>ද</u> 600			
 Optimization Settings 		400	9		
Optimality tolerance:	0.01	400 -			
Maximum number of evaluations:	1000	300 -			Inear elastic
 Discretization 		200 -		- <u></u>	lasticity optimization
Element discretization	Quadratic serendinity	100 -		(Compensated measurements
Element discretization.	Quadratic sciencipity	0			
 Optimization Results 		0	0.1 0.2 0.3 Displa	0.4 0.5 icement (mm)	0.6 0.7
$\sigma_{\rm ys0}$ = 414.7 MPa		Simulations	Measurements		
k = 405.6 MPa		✓ Linear elastic	Imported measurements		
n = 0.1857		✓ Plasticity	Compensated measurements		
Copy Results to Plasticity		Plasticity optimization	Interpolated data points		

The initial displacement is zero

٩			Studsvik RTT Analyzer		– 🗆 X
File Home					
Geometry Mesh Preprocessing Data	ts Compute Plots Table Compute	Plots Plots Plasticity	Interpolations Compute Plots Table	F-δ Force - Stress Force Displacement	Dimensions Dimensions Object Dimensions Dimensions Object Dimensions Settings
Preproc Material Data L	inear E Plasticity Optimi 💌 🖡	Geometry $ imes$	Displacement - Optimization × Force	e-Displacement 🗵	- 1
Equation:	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^{\prime\prime}$	€ € ⊕ •	🔁 🎝 🔻 🔯 VZ 🖾 🖬 🕑 🕶	- 🖻 🖩 🔽 📘 🗖 🗧	
 Plasticity Parameters 		disp(1)=0		Displacement (mm)	Studsvik
\checkmark Optimize $\sigma_{\rm ys0}$					
Initial value (IV Scale (MPa) 387 387	Lower bound (M 300 450				
✓ Optimize k					
Initial value (N Scale (MPa) 400 400	Lower bound (M Upper bound (M 300 500				
✓ Optimize n					
Initial value (№ Scale (MPa)	Lower bound (M Upper bound (M				
0.1 0.1	0.05 0.25				
Plot Hardening Initial Values					0
 Optimization Settings 					
Optimality tolerance:	0.01				
Maximum number of evaluations:	1000				
 Discretization 					
Element discretization:	Quadratic serendipity 🔹	v			
 Optimization Results 		z			
$\sigma_{ys0} = 414.7 \text{ MPa}$ k = 405.6 MPa		x			
n = 0.1857	×	Displacement	•		



 Use the combo-box below the graphics to change the solution step

9					Studsvik RTT	Analyzer					- 0	×
File Home												
Geometry Mesh	Import Measurement Data	ts Compute Plo	ots Table Compu	te Plots Table	Interpolations	Compute Plots	Table Force Displace	Stress For Graphs	ce Export	Dimensions	Reset Wir Preference Clear Solu Setting	idows es utions
Preproc Mat	terial Data Li	near E Dlasticit	v Ontimi v I	Geometry X	Displacement	- Optimization X	Force-Displace	ment X				
Equation:		$\sigma_{\rm ys} = \sigma_{\rm ys0} + k\epsilon_{\rm f}$							7			
 Plasticity Para 	meters			dian(22) E				ment (mm)		S	tudev	ik
\checkmark Optimize σ_{v}	50			uisp(33)=5	E-4		Displace	nent (mm)		5	luusv	
Initial value (N 387	Scale (MPa) 387	Lower bound (M 300	Upper bound (M 450									0.25
✓ Optimize k												0.2
Initial value (N 400	Scale (MPa) 400	Lower bound (M 300	Upper bound (M 500									0.2
✔ Optimize n	1		1									
Initial value (N 0.1	Scale (MPa) 0.1	Lower bound (M 0.05	Upper bound (M 0.25									0.15
Plot Hardenin	g Initial Values Settings											
Optimality toleran Maximum numbe	ce: r of evaluations:	0.01										0.1
 Discretization 												0.05
Element discretizat	tion:	Quadratic serence	lipity 🔻									
 Optimization I 	Results			z								
$\sigma_{ys0} = 414.7 \text{ M}$ k = 405.6 M	1Pa 1Pa			x								0
= 0.1857	to Plasticity		~	Displacement -	•							
Cha	ange th	ne soluti	on step									

Visualize the last step

	Studsvik RTT Analyzer	– 🗆 ×
File Home		
Geometry Mesh Import Preprocessing Data Linear Elastic	Plots Table Optimization Optimization Graphs Sol	cport Dimensions Dimensions
Preproc Material Data Linear E Plasticity Optimi	Geometry × Displacement - Optimization × Force-Displacement ×	• 1
Equation: $\sigma_{ys} = \sigma_{ys0} + k\epsilon_{pe}^{\prime\prime}$		
 Plasticity Parameters 	disp(46)=7.4E-4 Displacement (mm)	Studsvik
\checkmark Optimize $\sigma_{ m ys0}$		
Initial value (IVScale (MPa)Lower bound (MUpper bound (M387387300450		0.35
✓ Optimize k		
Initial value (N Scale (MPa) Lower bound (M Upper bound (M 400 400 300 500		0.3
✓ Optimize n		0.25
Initial value (Iv Scale (MPa) Lower bound (M Upper bound (M		
0.1 0.1 0.05 0.25		• • 0.2
Plot Hardening Initial Values		
Optimization Settings		- 0.15
Optimality tolerance: 0.01		
		0.1
Discretization		
Element discretization: Quadratic serendipity 🔻	у	0.05
 Optimization Results 	3	
$\sigma_{ys0} = 414.7 \text{MPa}$	X	0
n = 0.1857	Displacement	
Copy Results to Plasticity	· 7.4E-4 ▼ ▶	
· · · · · · · · · · · · · · · · · · ·		



 The von Mises Stress at the last step

0	Studsvik RTT Analyzer	– 🗆 X
File Home		
Import Geometry Mesh Import Measurements Import Compute Import Plots Import Table Import Compute Import Plots Import Table Import Compute Preprocessing Data Linear Elastic	Plots Table Interpolations Compute Plots Table Optimization Optimization Optimization Optimization	Reset Windows
Preproc Material Data Linear E Plasticity Optimi 🗸	Geometry × von Mises Stress - Optimization × Displacement - Optimization × Force-Displacement ×	- +
Equation: $\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^{\prime\prime}$		
 Plasticity Parameters 	disp(46)=7.4E-4 von Mises Stress (MPa)	tudsvik
\checkmark Optimize $\sigma_{\rm ys0}$		▲ 900
Initial value (Iv 387 Scale (MPa) 387 Lower bound (M 300 Upper bound (M 450 Optimize k Initial value (Iv 400 Scale (MPa) 400 Lower bound (M 400 Upper bound (M 500 Optimize n Initial value (Iv 0.05 Scale (MPa) 0.1 Lower bound (M 0.1 Upper bound (M 0.25 Plot Hardening Initial Values Voptimization Settings Initial value (Iv 0.01 Initial value (Iv 0.1 Initial values Optimization Settings Initial value (Iv 0.01 Initial value (Iv 0.01 Initial values Optimality tolerance: 0.01 Initial value Initial value Indextrement discretization Initial value Initial value Initial value Optimization Results Onther the value Initial value Initial value		 900 800 700 600 500 400 300 200 100 0
$\sigma_{ys0} = 414.7 \text{ MPa}$ k = 405.6 MPa n = 0.1857	Displacement 1 7.4E-4	▼ 0



The Hoop Stress at the last step

8		Studsvik F	RTT Analyzer	– 🗆 ×
File Home				
Geometry Mesh Preprocessing Data	ts Compute Plots Table Con Linear Elastic	Plots Plots Plasticity	Image: Second state in the s	Export Colution Documentation Settings
Preproc Material Data L	inear E Plasticity Optimi	F I Geometry × Hoop Stres	is - Opti × von Mises Stress × Displacement - Opt	$ imes$ Force-Displacement $ imes$
Equation:	$\sigma_{\rm ys}{=}\sigma_{\rm ys0}{+}k\epsilon_{\rm pe}^{\prime\prime}$	^ @ Q @ ▼ ⊕ ↓ ▼	xy yz xz 🙀 🔿 🗸 🔷 🕶 🖼 🖬 🖬 🗐 🚔	
 Plasticity Parameters 		disp(46)=7.4E-4	Hoop Stress (MPa)	Studsvik
☑ Optimize σ_{ys0}				▲ 719
Initial value (№ Scale (MPa) 387 387	Lower bound (M Upper bound (M 300 450			×10 ³
✓ Optimize k				0.6
 Initial value (IV Scale (MPa) 400 400 	Lower bound (M Upper bound (M 300 500			• • 0.4
✔ Optimize n				0.2
Initial value (Iv Scale (MPa) 0.1 0.1 0.1 0.1	Lower bound (M 0.05 0.25			o
				0.2
Optimality tolerance: Maximum number of evaluations:	0.01			0.4
 Discretization 				
Element discretization:	Quadratic serendipity 🔹	v		-0.8
 Optimization Results 		z		-1
σ _{ys0} = 414.7 MPa k = 405.6 MPa		x		▼ -1.01×10 ³
n = 0.1857		Displacement T.4E-4	Þ	



The Hoop Strain at the last step

•			Studsvik RTT Analyzer		– 🗆 X
File Home					
Geometry Mesh Preprocessing Data	ts Compute Plots Table Co Linear Elastic	Plasticity	Interpolations Compute Plots Table	F-δ Force - Displacement Graphs	Dimensions Documentation Settings Reset Windows
Preproc Material Data L	inear E Plasticity Optimi	🗕 🖡 🛛 Geometry 🗡	Hoop Strain × Hoop Stress >	von Mises Stre × Displacement -	× Force-Displace ×
Equation:	$\sigma_{\rm ys} = \sigma_{\rm ys0} + k \epsilon_{\rm pe}^{\prime\prime}$				
 Plasticity Parameters 		disp(46)=7	.4E-4	Hoop Strain (1)	Studsvik
✓ Optimize σ_{ys0}					▲ 0.223
Initial value (Iv Scale (MPa) 387 387	Lower bound (M Upper bound (M 300 450	1			
\checkmark Optimize k					0.2
Initial value (Iv Scale (MPa) 400 400	Lower bound (M Upper bound (M 300 500	1			
✓ Optimize n					0.15
Initial value (Iv Scale (MPa) 0.1 0.1 0.1 O.1	Lower bound (M Upper bound (M 0.05 0.25	1			
					0.1
Optimization Settings Optimality tolerance: Maximum number of evaluations:	0.01				0.05
 Discretization 					
Element discretization:	Quadratic serendipity 🔻	v			
 Optimization Results 		z			ľ
σ _{ys0} = 414.7 MPa k = 405.6 MPa		x			▼ -0.0148
n = 0.1857		Displacement	4 •		



The *Plastic Strain* at the last step

9		Studsvik R	T Analyzer		– 🗆 X
File Home					
Geometry Mesh Import Measurements C	Compute Plots Table Compute	Plots Table Interpolation	s Compute Plots Table	Force - Displacement	Dimensions
Preprocessing Data	Linear Elastic PI	asticity	Optimization	Graphs Solution	Documentation Settings
Preproc Material Data Linear E	E Plasticity Optimi 🝷 🖡	Geometry × Plastic St 2	Strain × Hoop Str.	$ imes$ Hoop Str $ imes$ von Mise $ imes$	Displace × Force-Dis × 🗸
Equation: $\sigma_{ys} =$	$=\sigma_{ys0} + k\epsilon_{pe}^{"}$	@ Q @ ▼ 🕀 🗸 1	xy tyz txz 🕅 🛛 🔿 🔻 🛛 🛋	- 🖿 🔳 🔽 📄	
 Plasticity Parameters 		disp(46)=7.4E-4	Equivalent	Plastic Strain, solid.epe (1)	Studsvik
\checkmark Optimize $\sigma_{\rm ys0}$					▲ 0.176
Initial value (IVScale (MPa)Low387387300	ver bound (M Upper bound (M 450				
✓ Optimize k					•• 0.16
Initial value (N Scale (MPa) Low 400 400 300	ver bound (M Upper bound (M 500				• • 0.14
✓ Optimize n	<u>.</u>				0.12
Initial value (IV Scale (MPa) Low 0.1 0.1 0.05	ver bound (M 0.25				0.1
C Plot Hardening Initial Values					0.08
 Optimization Settings 					0.08
Optimality tolerance: 0.01 Maximum number of evaluations: 1000					0.06
 Discretization 					0.04
Element discretization: Qua	adratic serendipity 🔻	v			0.02
 Optimization Results 		z			o
$\sigma_{y = 0} = 414.7 \text{ MPa}$ k = 405.6 MPa		x			▼ 0
n = 0.1857		Displacement Image: 10 state 7.4E-4	▶		

 Numerical values are available by clicking the *Table* button in the ribbon





-12 e	-1 e-3 0.00								T Analyzer	
disp	disp (mm)	Initial yield stress, Ludwik hardening (MPa)	k, Ludwik hardening (MPa)	n, Ludwik hardening	Force (N)	Engineering stress (MPa)	Engineering stress without friction (MPa)	True		
.0000	0.0000	414.68	405.63	0.18567	0.0000	0.0000	0.0000	0.000		
.0000E-5	0.020000	414.68	405.63	0.18567	5.9617	2.6883	3.0724	2.688		o 🔍 🕴
.0000E-5	0.040000	414.68	405.63	0.18567	11.981	5.4025	6.1743	5.402		
.0000E-5	0.060000	414.68	405.63	0.18567	18.049	8.1389	9.3016	8.139	Compute Pl	ots lable For
.0000E-5	0.080000	414.68	405.63	0.18567	24.216	10.920	12.480	10.92	Ontimization	Opens a tabl
.0000E-4	0.10000	414.68	405.63	0.18567	32.342	14.584	16.668	14.58	Optimization	-
.2000E-4	0.12000	414.68	405.63	0.18567	71.998	32.467	37.105	32.48	Strain -	× Hoop Str., ×
.4000E-4	0.14000	414.68	405.63	0.18567	155.66	70.195	80.222	70.25		noop oum
.6000E-4	0.16000	414.68	405.63	0.18567	318.11	143.45	163.94	143.6	ky tyz txz 📷	0
.8000E-4	0.18000	414.68	405.63	0.18567	520.73	234.82	268.36	235.3		
.0000E-4	0.20000	414.68	405.63	0.18567	714.14	322.03	368.04	323.0		Equivalent Plasti
.0000E-4	0.20000	414.68	405.63	0.18567	714.14	322.03	368.04	323.0		
.2000E-4	0.22000	414.68	405.63	0.18567	886.53	399.77	456.88	401.4		
2000E-4	0.22000	414.68	405.63	0.18567	886.53	399.77	456.88	401.4		
.4000E-4	0.24000	414.68	405.63	0.18567	1015.5	457.94	523.36	460.3		
.4000E-4	0.24000	414.68	405.63	0.18567	1015.5	457.94	523.36	460.3		
.6000E-4	0.26000	414.68	405.63	0.18567	1084.8	489.16	559.04	493.1		
.8000E-4	0.28000	414.68	405.63	0.18567	1123.1	506.46	578.82	512.6		
.0000E-4	0.30000	414.68	405.63	0.18567	1148.6	517.94	591.93	526.7		
.2000E-4	0.32000	414.68	405.63	0.18567	1167.2	526.35	601.54	537.9		
.4000E-4	0.34000	414.68	405.63	0.18567	1181.7	532.87	608.99	547.3		
.6000E-4	0.36000	414.68	405.63	0.18567	1193.3	538.09	614.96	555. ć		
.8000E-4	0.38000	414.68	405.63	0.18567	1202.8	542.37	619.85	563.1		
.0000E-4	0.40000	414.68	405.63	0.18567	1210.6	545.91	623.90	570.0		
.0000E-4	0.40000	414.68	405.63	0.18567	1210.6	545.91	623.90	570.0		
.2000E-4	0.42000	414.68	405.63	0.18567	1217.1	548.86	627.27	576.4		
2000E-4	0.42000	414.68	405.63	0.18567	1217.1	548.86	627.27	576.4		
4000E-4	0.44000	414.68	405.63	0.18567	1222.6	551.32	630.08	582.4		
4000E-4	0.44000	414.68	405.63	0.18567	1222.6	551.32	630.08	582.4		r
.6000E-4	0.46000	414.68	405.63	0.18567	1227.1	553.36	632.41	588.2		
8000E-4	0.48000	414.68	405.63	0.18567	1230.9	555.05	634.34	593.6		
.8000E-4	0.48000	414.68	405.63	0.18567	1230.9	555.05	634.34	593.6		
.0000E-4	0.50000	414.68	405.63	0.18567	1233.9	556.42	635.91	598.9		
2000E-4	0.52000	414.68	405.63	0.18567	1236.4	557.52	637.17	604.0		
4000E-4	0.54000	414.68	405.63	0.18567	1238.2	558.37	638.14	609.0		
6000E-4	0.56000	414.68	405.63	0.18567	1239.6	558.99	638.84	613.9		
8000F-4	0.58000	414.68	405.63	0.18567	1240.5	559.40	639.31	618.7		
0000E-4	0.60000	414.68	405.63	0.18567	1241.0	559.62	639.57	623.4		
2000E-4	0.62000	414.68	405.63	0.18567	1241.1	559.66	639.62	628.0		
2000E-4	0.62000	414.68	405.63	0.18567	1241.1	559.66	639.62	628.0		
4000E-4	0.64000	414.68	405.63	0.18567	1240.8	559.54	639.47	632.6		
6000E-4	0.66000	414.68	405.63	0 18567	1240.2	559.25	639.14	637.2		
8000E-4	0.00000	414.68	405.63	0 18567	1230.2	558.80	638.63	641.9		
0000E-4	0.00000	414.60	405.05	0.10507	1227.0	550.00	627.05	646.2		
2000E-4	0.70000	414.60	405.05	0.10507	1226.2	557 47	627.11	650.0		
2000E-4	0.72000	414.00	405.05	0.10007	1230.3	556.60	037.11 C2C 12	030.5		



Engineering Strain in Gauges

For historical reasons, the engineering strain is calculated in two gauges with different length



Gauge #1

Gauge #2



 To visualize the stress and strain graphs, click the Stress menu in the Graphs section in the ribbon





 The Engineering Stress versus the Engineering Strain in Gauge #1 is visualized





 The Engineering Stress versus the Engineering Strain in Gauge #2 is visualized





Export results data directly to Excel[®] for further analysis

3		Studsvik RTT Analyzer	– 🗆 ×
File Home			
Geometry Mesh Preprocessing Data	mpute Plots Table Compute Linear Elastic P	Interpolations Compute Plots Table Interpolations Compute Plots Table Sticity Optimization Graphs	Reset Windows Preferences Clear Solutions Settings
Preproc Material Data Linear E	. Plasticity Optimi 🝷 🖡	Geometry × Stress-Strain G2 × Stress-Strain G1 ×	Linear Elastic 🗸 👻
Equation: $\sigma_{ys} = c$	$\sigma_{ys0} + k \epsilon_{pe}^{"}$	 Optimizatio Optimizatio 	n
 Plasticity Parameters 		Engineering Stress (MPa) and Engineering Strain in Gauge #2 (%	Studsvik
\checkmark Optimize $\sigma_{\rm ys0}$		700 FT	
Initial value (Iv Scale (MPa) Lower 387 387 387 300	bound (M Upper bound (M 450		<u></u>
✓ Optimize k			
Initial value (Iv Scale (MPa) Lower 400 400 300	bound (M 500	550 - 500 - 1	
Initial value (Iv Scale (MPa) Lower 0.1 0.1 0.05	bound (M Upper bound (M 0.25	400	
Plot Hardening Initial Values		300	
 Optimization Settings 		Ê 250 - 1	
Optimality tolerance: 0.01 Maximum number of evaluations: 1000			
 Discretization 			
Element discretization: Quad	Iratic serendipity 🔻		Plasticity
 Optimization Results 			 Plasticity optimization
$\sigma_{ys0} = 414.7 \text{ MPa}$ k = 405.6 MPa n = 0.1857		0 1 2 3 4 5 Engineering strain in gauge #2 (%)	6 7
E Copy Results to Plasticity		Ə Import Stress/Strain Graph	

Results to Customers

- The data can now be extracted, and the customer will receive the requested material data
 - yield strength
 - ultimate strength
 - elongation



Implementation in COMSOL®

The used products to create the app



Used Products in the Model

COMSOL Multiphysics[®] and the following add-on products

- Structural Mechanics Module
 - Non-linear Structural Materials Module or Geomechanics Module
- Optimization Module
- Design Module or CAD Import Module



Used Products to Create the Application

- The app was built with Application Builder
- By utilizing Java[®] programming code, many model setup tasks are simplified, demonstrating how a complex simulation can be made accessible to a wider audience
- To enhance accessibility, the application is transformed into a standalone compiled app using COMSOL Compiler[™]



Conclusion

Ring tensile tests enter a new dimension with new dimensions



Summary

- Ring tensile tests are employed to evaluate the mechanical properties of fuel cladding materials
- New technology allows for the import of measured data into a COMSOL[®] App to extract vital material information
- Simulated results are compared with the measured forcedisplacement diagram, and upon reaching satisfactory agreement, the stress-strain curve is obtained
- This new Finite Element Method-based approach enables testing with varying dimensions, offering the potential to reduce result uncertainties



References

1. 1. S. Arsene, and J. Bai, A New Approach to Measuring Transverse Properties of Structural Tubing by a Ring Test, Journal of Testing and Evaluation, 1996.



deflexional.com

