



# Numerical modelling of slip-resistant stainless steel bolted connections

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# Outline

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- Background
- Modelling of stainless steel material
- Modelling of slip-resistant connections
  - Validation of numerical models
- Parametric study
- Design rules EN 1993-1-8
- Conclusion

# Background

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- RFCS research project – Execution and reliability of slip-resistant connections for steel structures using cs and ss (SIROCO)
- Slip-resistant stainless steel connections
  - Slip factors (high slip factors can be achieved)
  - Loss of bolt preload (same level as carbon steel)
- Numerical simulation
  - Rate dependent behaviour of stainless steel (creep and relaxation)
  - Coefficient of friction for faying surface interaction

# Challenge in simulation of bolted connections

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- Finite element models are widely used to simulate bolted connections
- One of the key challenge is the friction coefficient between faying surfaces
- Particularly important for preloaded bolts
- Current study aims to provide calibrated coefficient of friction for various stainless steel surface finishes under preloaded bolts

# Modelling of stainless steel material

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- Chaboche unified model (Outukumpu)

- Plate and bolt material
  - Tensile test at various strain rate

$$\sigma = k + Q(1 - e^{-b\bar{\varepsilon}_p}) + \sum_{i=1}^3 \frac{C_i}{\gamma_i} [1 - e^{-\gamma_i \bar{\varepsilon}_p}] + D(\dot{\varepsilon}_p)^{\frac{1}{n}}$$

- Strain-hardening creep model (VTT)

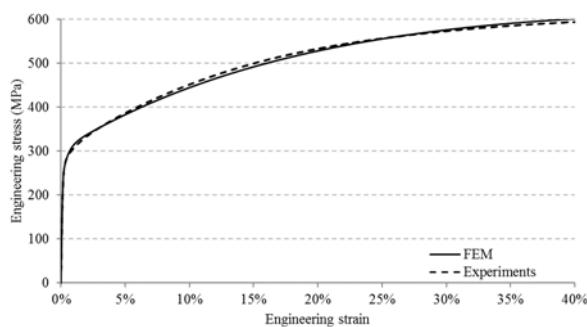
- Bolt material
  - Utilising stress relaxation test
  - Slow implementation in CREEP subroutine

$$\dot{\varepsilon}_v = c \left[ \frac{\varepsilon_v(1-b)}{c} + a^{1-b} \right]^{\frac{b}{b-1}}$$

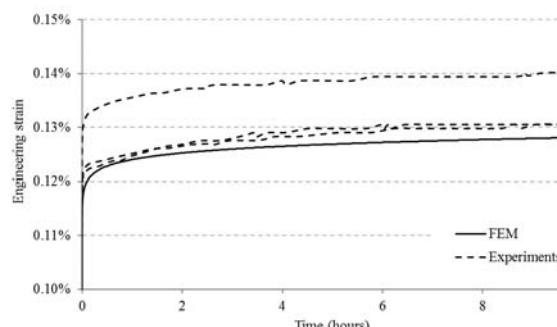
# Modelling of stainless steel material

## ■ Plate material model calibration (Chaboche)

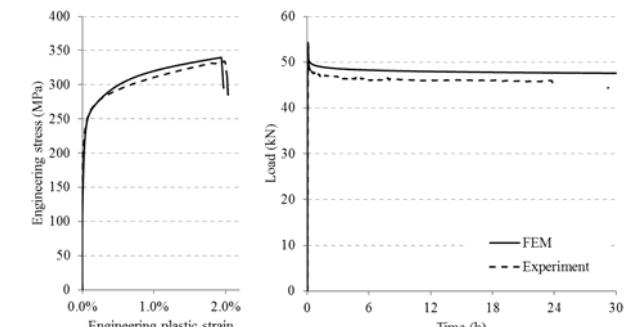
Grade	$k$ (MPa)	$D$ (MPa)	$n$	$Q$ (MPa)	$b$	$C_1$ (MPa)	$\gamma_1$	$C_2$ (MPa)	$\gamma_2$	$C_3$ (MPa)	$\gamma_3$
EN 1.4404 austenitic	73	110	15.0	380	2.5	45949	591.4	617031	6765.3	1434	2.5
EN 1.4003 ferritic	106	130	11.0	104	10.8	623733	5855.1	17430	558.6	1680	10.8
EN 1.4462 duplex	106	313	24.3	723	2.8	947349	1334.6	252038	1222.1	2971	60.0
EN 1.4162 lean duplex	109	329	30.2	649	3.5	483769	4875	102445	975.3	6766	180. 8



Tensile test at  $\dot{\varepsilon} = 1 \times 10^{-4} s^{-1}$



Creep test at stress level 180 MPa

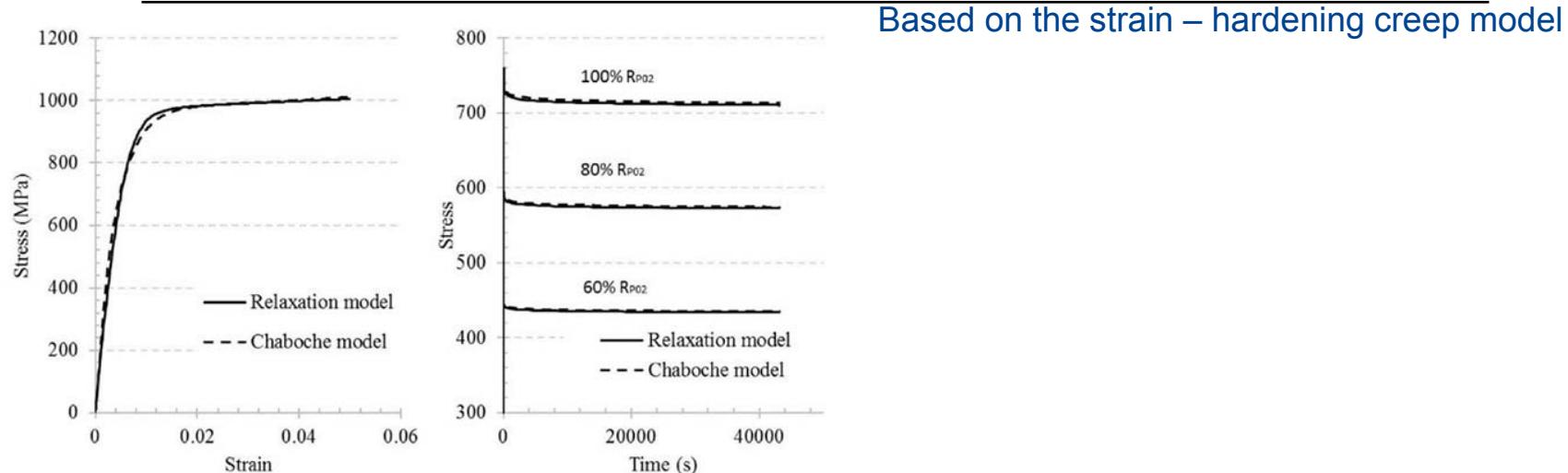


Relaxation test at strain level 2.17%

# Modelling of stainless steel material

## ■ Bolt material model calibration (Chaboche)

Grade	$k$ (MPa)	$D$ (MPa)	$n$	$Q$ (MPa)	$b$	$C_1$ (MPa)	$\gamma_1$	$C_2$ (MPa)	$\gamma_2$	$C_3$ (MPa)	$\gamma_3$
EN 1.4436 austenitic	348.0	200.0	12.0	348.0	1.0	124738.9	320.2	269288.0	2081.2	595.1	1.0
EN 1.4462 duplex	248.0	1133.0	5.13	269.7	1.0	124738.9	320.2	379288.0	2081.2	10.0	1.0
EN 1.4162 lean duplex	298.0	290.0	9.67	269.7	1.0	124738.9	320.2	379288.0	2081.2	10.0	1.0



# Modelling of slip-resistant connections

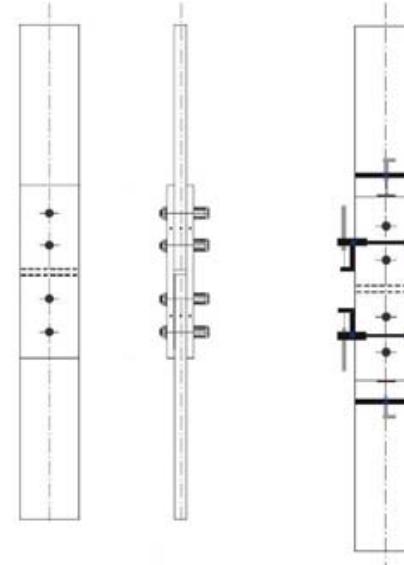
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- Bolt load relaxation test (selected test case)
  - Ferritic plate 1.4003
  - M20 austenitic bolt 1.4436
  - Clamping length = 38 mm



# Modelling of slip-resistant connections

- Slip factor tests  
(EN1090-2 Annex G)
  - Austenitic, Ferritic, Duplex and Lean Duplex plates
  - M16 stainless steel bolts (Bumax 88 and 109, austenitic)
  - Surface treatments: 1D, shot blast and grit blast

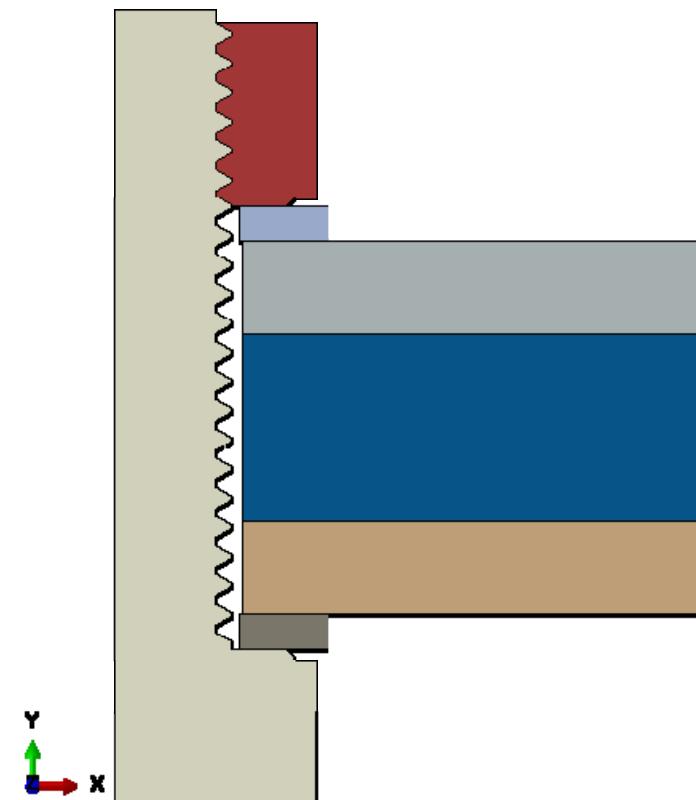


$$\mu_{i,ini} = \frac{F_{Si}}{4F_{p,C,ini}} \quad \mu_{i,act} = \frac{F_{Si}}{4F_{p,C,act}} \quad \mu_{i,nom} = \frac{F_{Si}}{4F_{p,C}}$$

# Modelling of slip-resistant connections

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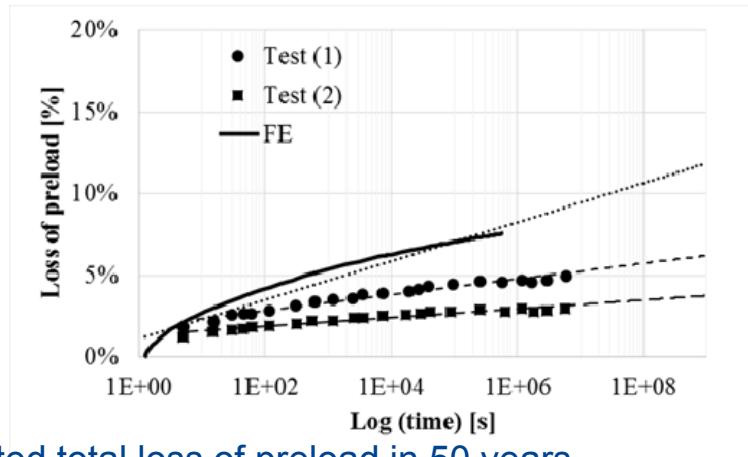
- 2D axisymmetric model
  - Bolt preload relaxation
  - Plate: Ferritic 1.4003
  - Bolt: M20, Austenitic 1.4436
  - Chaboche model for both plate and bolt material
  - Two step analysis:  
preloading + relaxation
  - UAMP for preloading



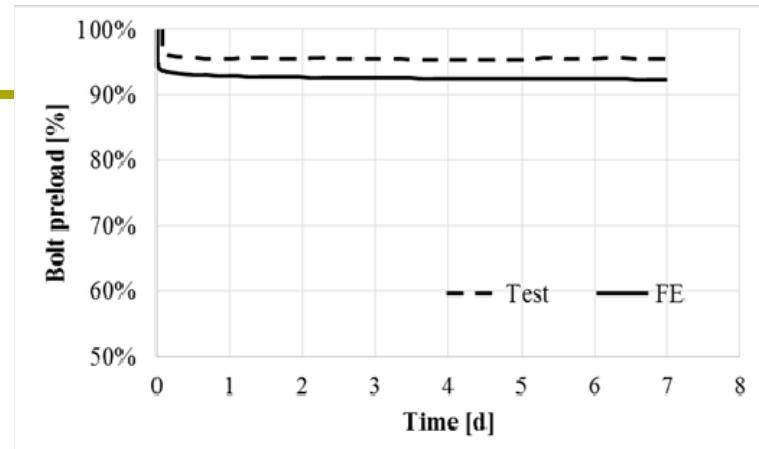
# Modelling of slip-resistant connections

## ■ Validation

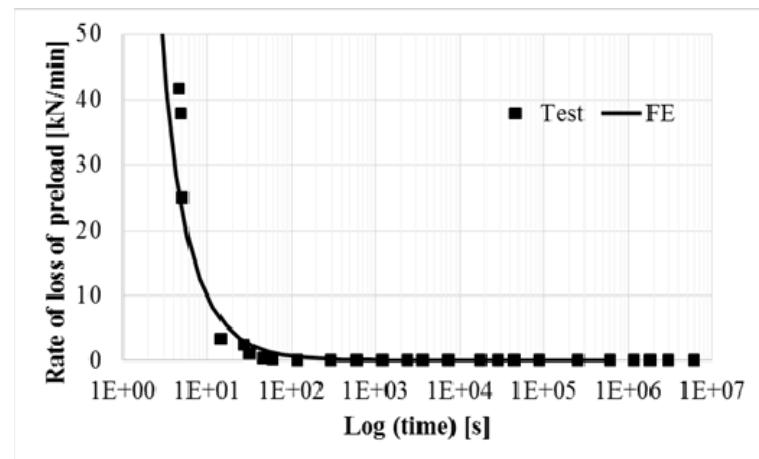
- Loss of preload is in good agreement in short to medium term
- Numerical model is more conservative in longer term



Projected total loss of preload in 50 years



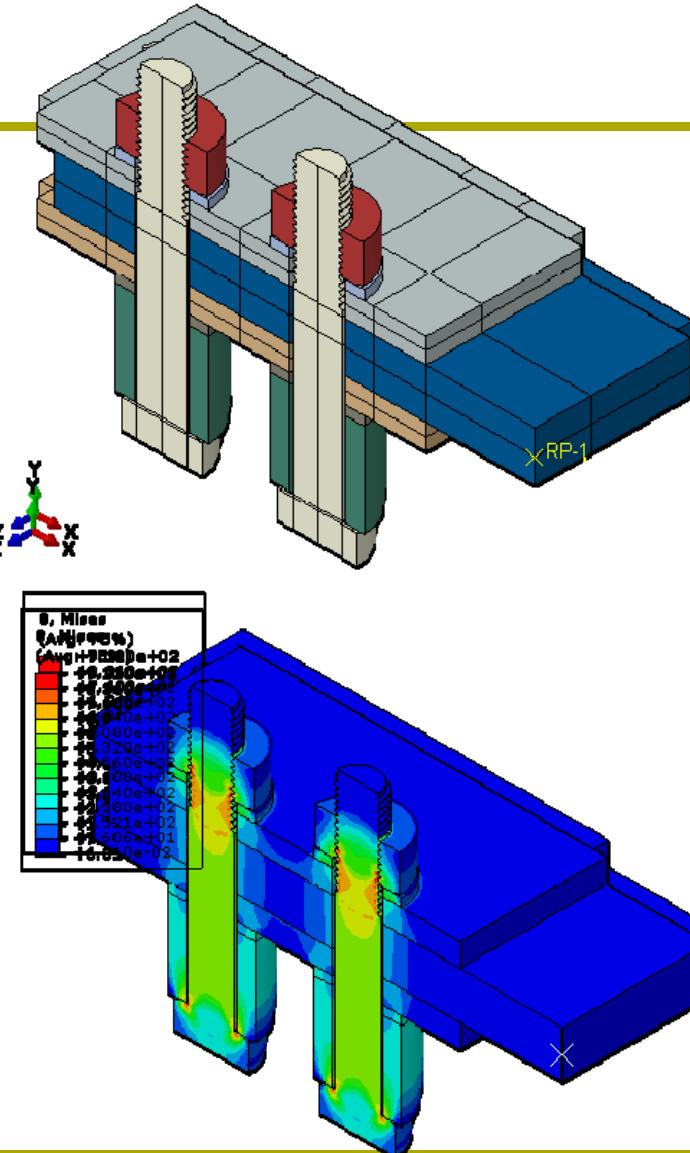
Loss of preload in 7 days



Rate of loss of preload in 7 days

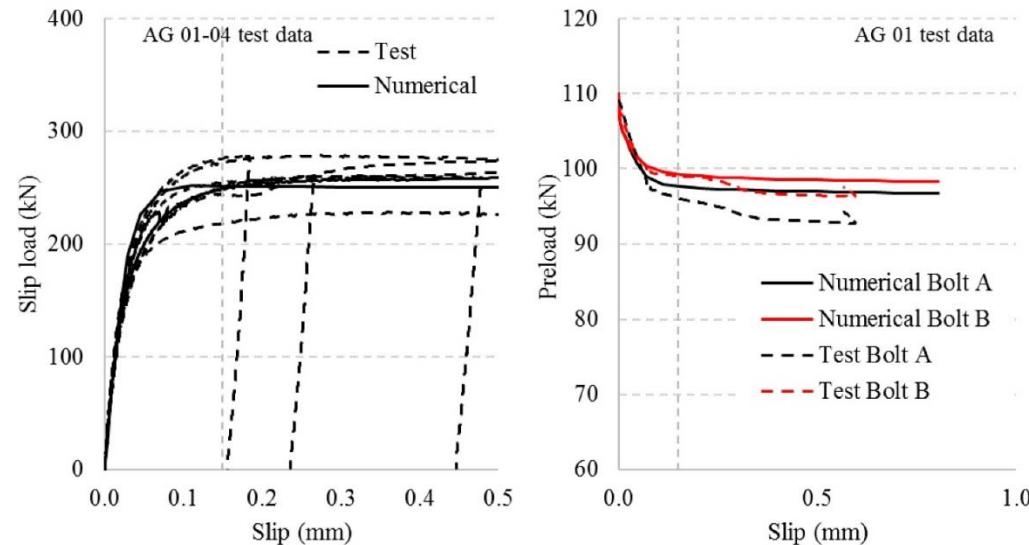
# Modelling of slip-resistant connections

- 3D slip-resistant connection model (M16)
  - Double symmetry
  - Preload (UAMP) + slip displacement
  - Chaboche model for both plate and bolt material
  - Load cell and washer assumed elastic
  - Static coefficient of friction  $\mu_s$  to be calibrated



# Modelling of slip-resistant connections

- Calibration
  - Example: slip resistant connection made of grit blasted austenitic plates with Bumax 109 M16 austenitic bolt ( $f_{y,0.2} = 823 \text{ MPa}$ ,  $f_u = 966 \text{ MPa}$ )
  - $\mu_s = 0.64$



# Modelling of slip-resistant connections

## ■ Calibration of all available test data

Test ID	Steel grade	Surface finish	Preload [kN]	$\mu_{\text{ini,mean}}$		$\mu_{\text{act,mean}}$		$\mu_{\text{nom,mean}}$		ABAQUS	$\mu_s$
				Test	ABAQUS	Test	ABAQUS	Test	ABAQUS		
A_1D		1D		0.21	0.20	0.21	0.21	0.20	0.20	0.21	
A_SB	1.4404	SB		0.29	0.29	0.30	0.30	0.29	0.29	0.3	
A_GB		GB	M16	0.56	0.56	0.60	0.60	0.56	0.56	0.6	
F_GB	1.4003	GB	Bumax 88 $F_p,c = 88$	0.64	0.64	0.69	0.69	0.65	0.65	0.71	
D_GB	1.4462	GB		0.60	0.59	0.63	0.62	0.60	0.60	0.62	
LD_GB	1.4162	GB		0.51	0.51	0.53	0.53	0.51	0.51	0.54	
A1D		1D		0.20	0.19	0.20	0.20	0.19	0.19	0.2	
AS	1.4404	SB	M16	0.33	0.32	0.34	0.34	0.32	0.32	0.34	
AG		GB	Bumax 109	0.58	0.57	0.65	0.64	0.57	0.57	0.64	
FG	1.4003	GB	$F_p,c =$	0.70	0.68	0.75	0.77	0.68	0.68	0.77	
DG	1.4462	GB	110	0.66	0.66	0.69	0.70	0.66	0.66	0.68	
LG	1.4162	GB		0.63	0.63	0.65	0.68	0.63	0.63	0.705	

Note:

- (1) The clamping length  $\Sigma t = 74$  mm for M16 Bumax 88 bolts and  $\Sigma t = 77$  mm for M16 Bumax 109 bolts, the clamping length to bolt diameter ratio are therefore  $\Sigma t/d = 4.6$  and 4.8 respectively.
- (2) SB: short blasted, GB: grit blasted
- (3)  $\mu_s$ : calibrated static coefficients of friction used in ABAQUS for the faying surface between plates, a friction coefficient of 0.5 is assumed for all other surfaces in contact

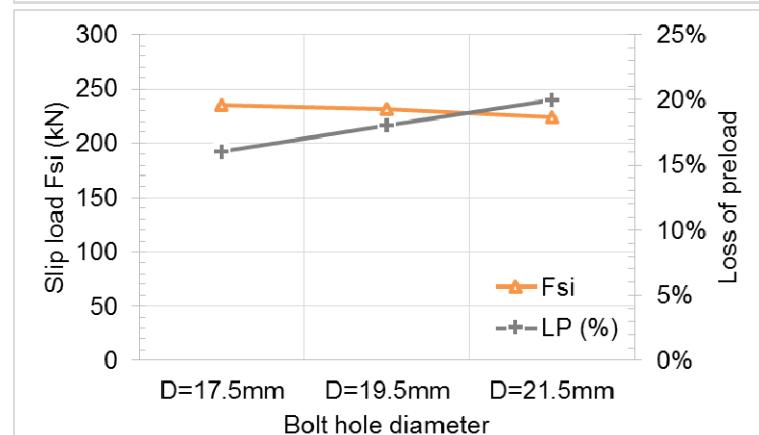
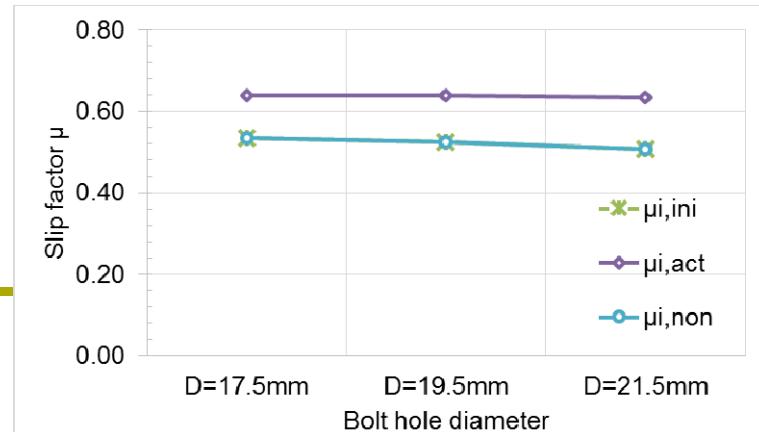
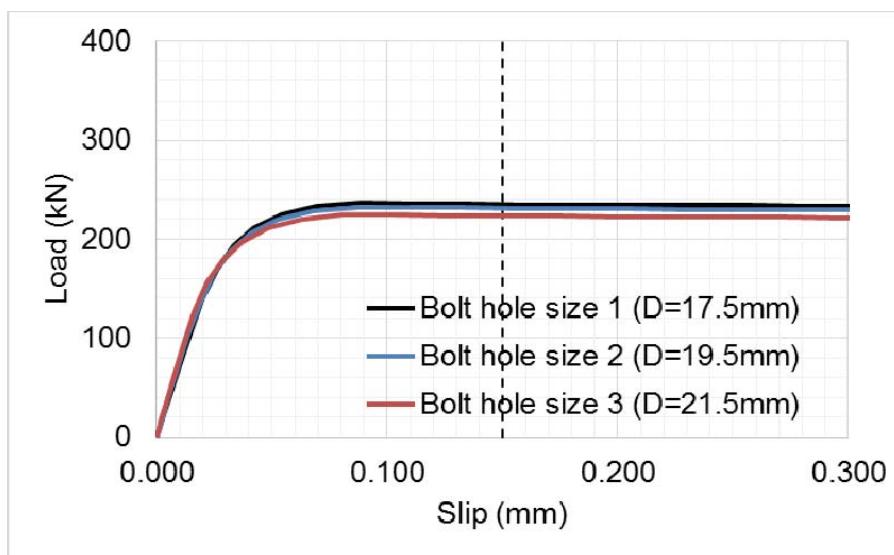
# Parametric study

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- In progress
  - Grit blasted austenitic plates with Bumax 109 bolts
  - Hole diameter
  - Preload level:  $0.9F_{p,C}^*$ ,  $F_{p,C}^*$ , and  $F_{p,C}$
- $$F_{p,C} = 0.7f_{ub}A_s$$
- $$F_{p,C}^* = 0.7f_yA_s$$
- Plate thickness
  - Bolt size

# Parametric study

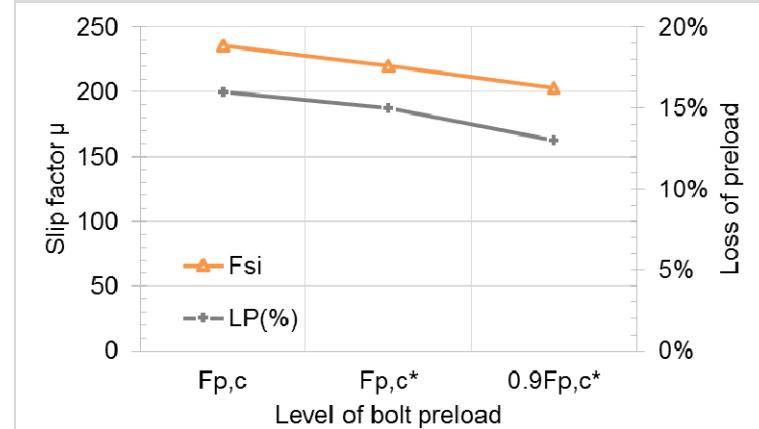
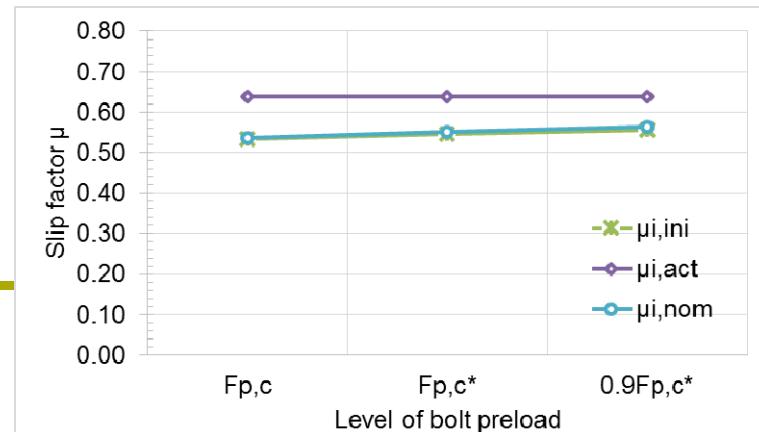
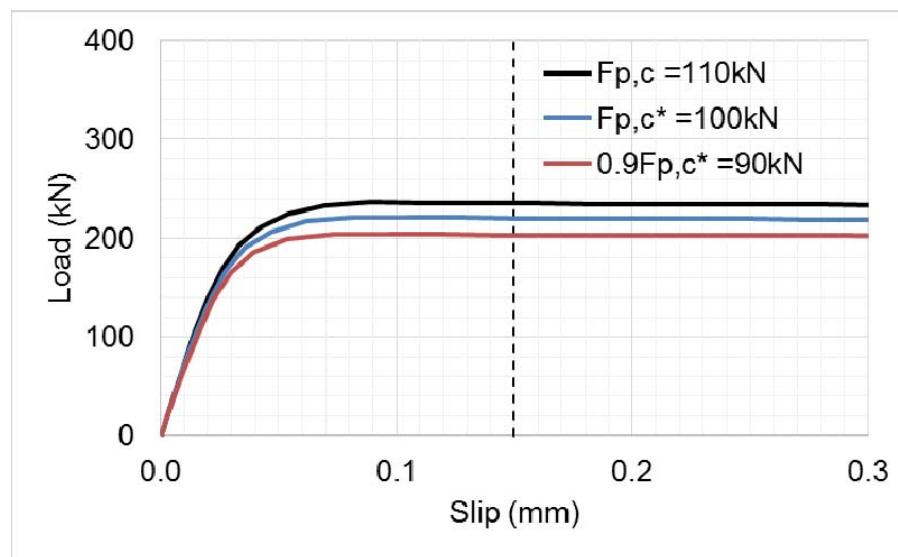
## ■ Bolt hole size



	Hole diameter		
	17.5mm	19.5mm	21.5mm
$F_{si}$ (kN)	235	231	224
$\mu_{i,ini}$	0.53	0.52	0.51
$\mu_{i,act}$	0.64	0.64	0.63
$\mu_{i,nom}$	0.54	0.53	0.51
LP(%)=	16%	18%	20%

# Parametric study

- Preload level



	Preload level		
	110 kN	100 kN	90 kN
$F_{si}$ (kN)	235	220	203
$\mu_i,ini$	0.53	0.55	0.56
$\mu_i,act$	0.64	0.64	0.64
$\mu_i,nom$	0.54	0.55	0.56
$LP(\%)=$	16%	15%	13%

# Parametric study

- Plate thickness
  - i.e. bolt length

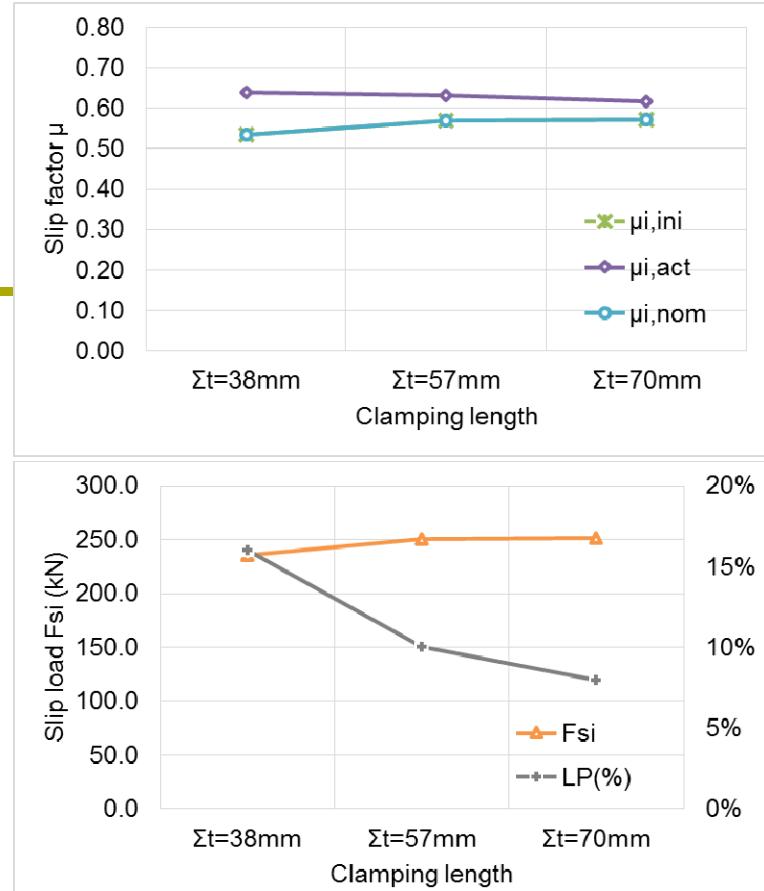
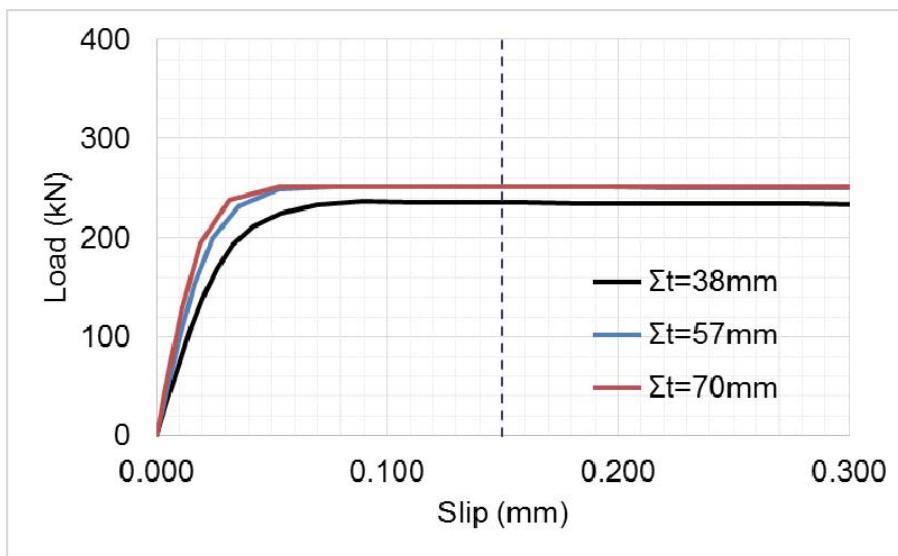
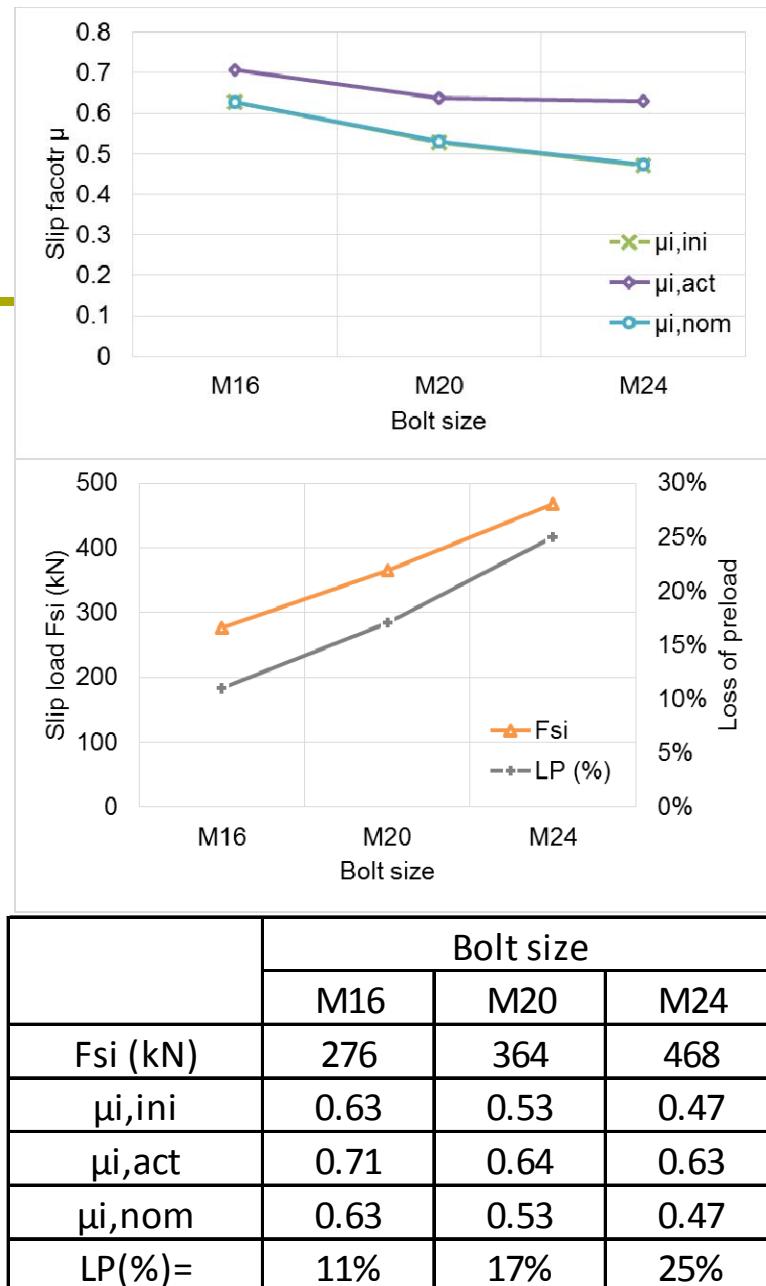
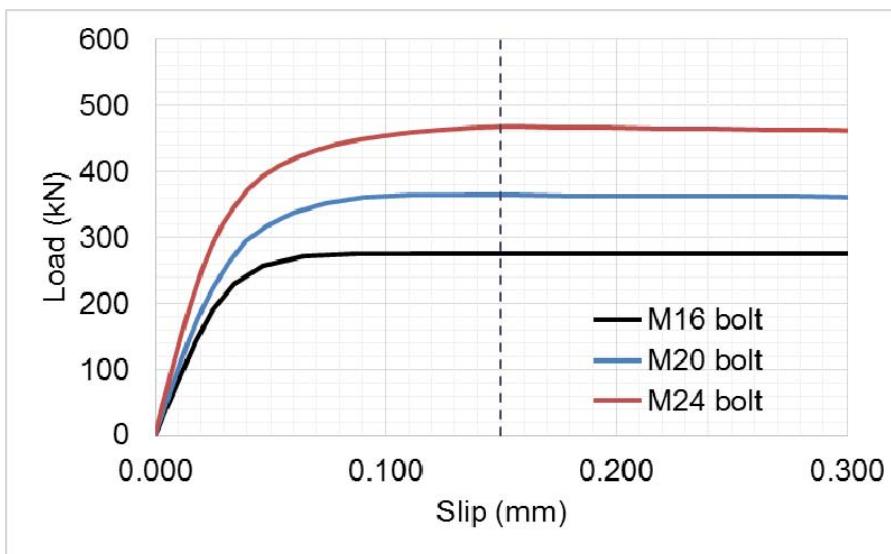


	Plate thickness		
	38mm	57mm	70mm
F <sub>si</sub> (kN)	235.3	251.0	251.4
μ <sub>ini</sub>	0.53	0.57	0.57
μ <sub>act</sub>	0.64	0.63	0.62
μ <sub>nom</sub>	0.54	0.57	0.57
LP(%)	16%	10%	8%

# Parametric study

## Bolt size

- Fixed clamping length = 46 mm
- Fixed bolt distance = 60 mm



# Design rules EN 1993-1-8

Carbon steel	Stainless steel
$F_{p,C} = 0,7 f_{ub} A_s$	$F_{p,C} = x f_{ub} A_s$ where $x \leq 0,7$
$F_{S,Rd} = \frac{k_s n \mu}{\gamma_{M3}} F_{p,C}$  $\mu$ is given in Table 3.7 $\gamma_{M3}$ is 1.25 (and $\gamma_{M3,ser}=1,1$ )	$F_{S,Rd} = \frac{k_s n \mu}{\gamma_{M3}} F_{p,C}$  $\mu$ $\gamma_{M3}$ , $\gamma_{M3,ser}$

# Conclusion

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- Numerical models were calibrated against relaxation tests and slip factor tests in the current study
- Loss of bolt load and slip behaviour of the numerical models were compared favourably to test results
- Static coefficient of friction in FE model for commonly used stainless steel plates of various surface finishes were determined
- The validated numerical model can be used/extended to predict behaviour of slip-resistant stainless steel connections in more complicated service conditions
- Design rules for slip-resistant stainless steel bolted connections will be proposed based on test and numerical results



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