The **Strength Reduction Factors of Bolts** in relation to both **Temperature** and **Strain Rate**

Diana Duma

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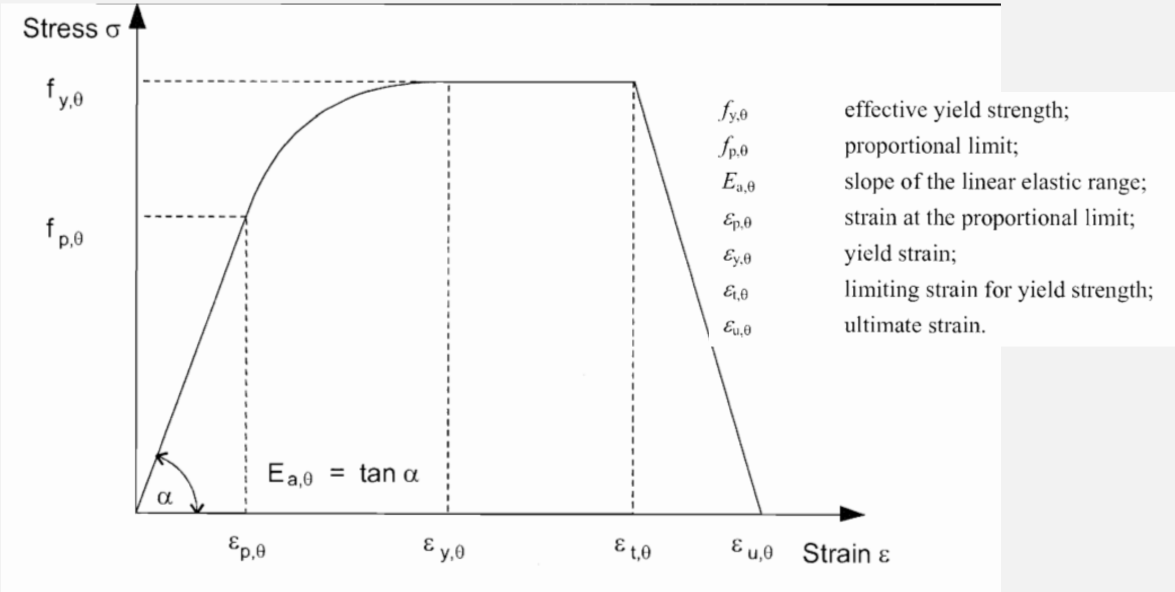
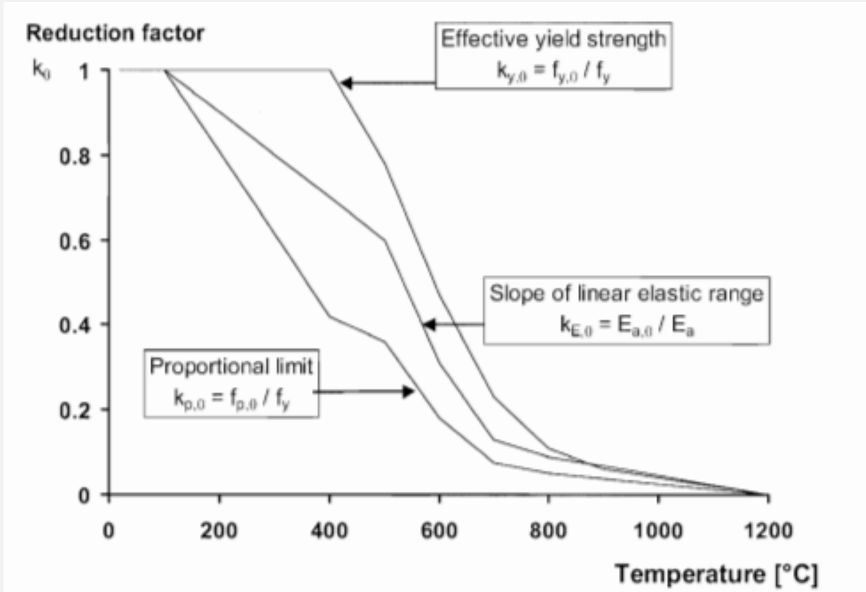
CURRENT APPROACH

- Strength reduction factors for steel according to EN 1993-1-2

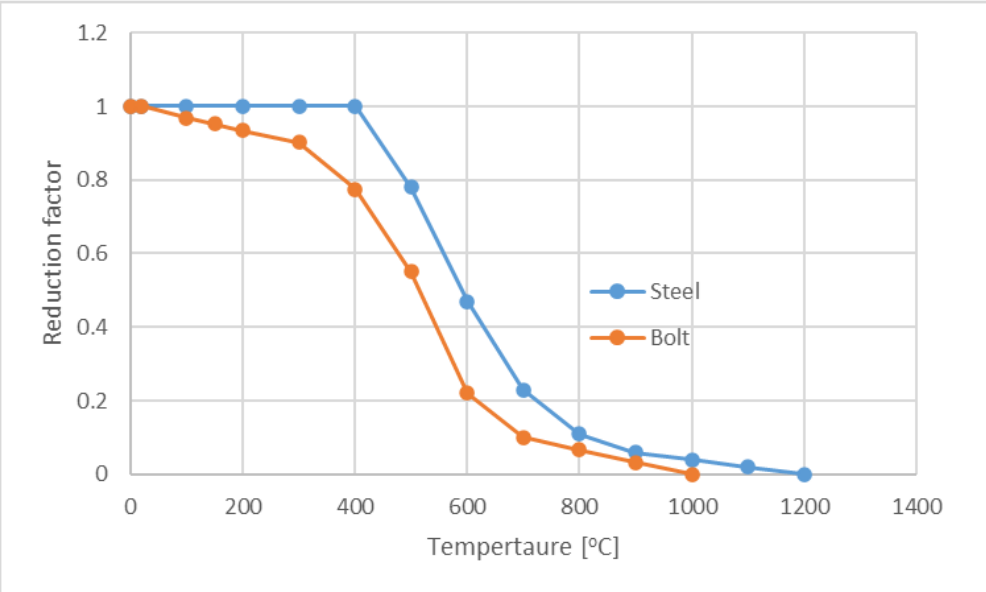




Reduction factors for the stress-strain relationship of carbon steel at elevated temperatures

CURRENT APPROACH

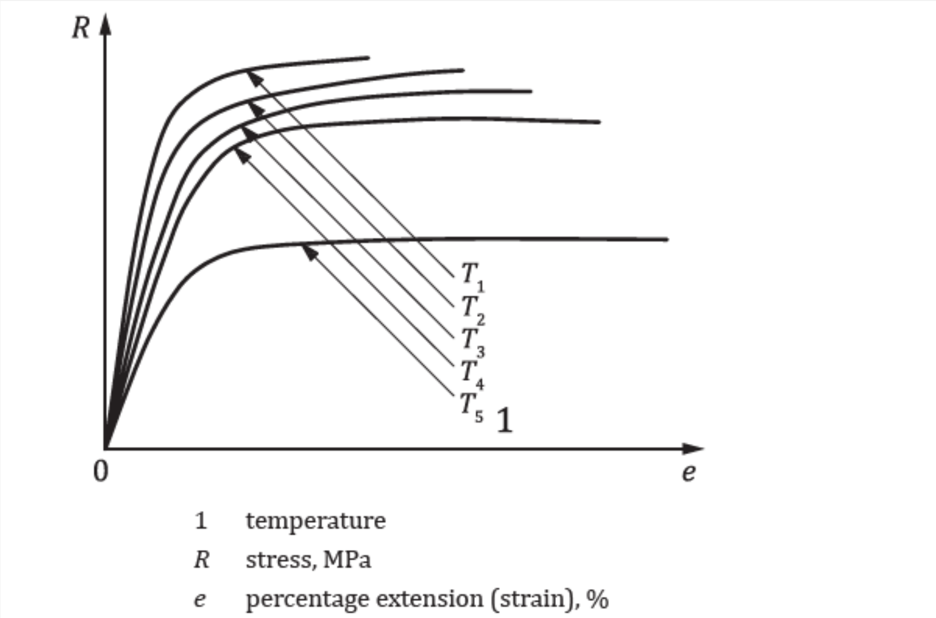
- Strength reduction factors for steel vs bolts according to EN 1993-1-2:



Temperature θ_a [ºC]	Reduction factor for yield strength $k_{y,\theta} = f_{y,\theta} / f_y$	Reduction factors for bolts $k_{b,2} = f_{u,\theta} / f_{u,b}$ (tension and shear)
20	1	1
100	1	0,968
150	-	0,952
200	1	0,935
300	1	0,903
400	1	0,775
500	0,78	0,550
600	0,47	0,220
700	0,23	0,100
800	0,11	0,067
900	0,06	0,033
1000	0,04	0

CURRENT APPROACH

- Determining the strength reduction factors for bolts according to ISO 6892-2



Stress-strain curves at a given strain rate and different temperatures

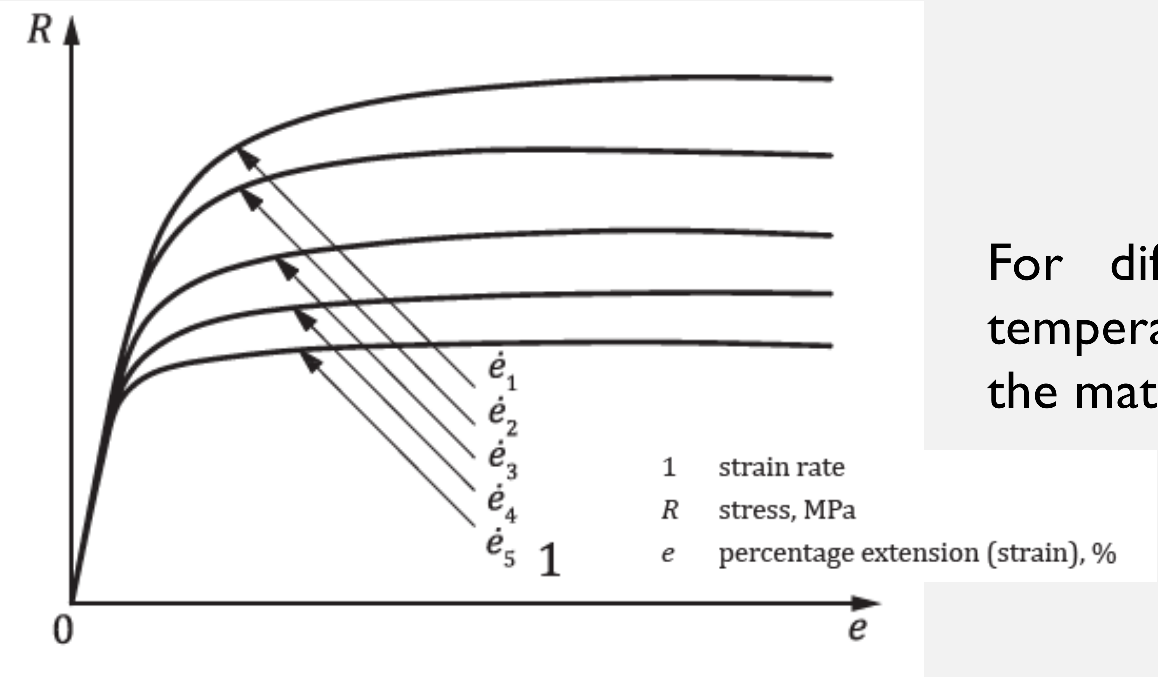
$$k_b = \frac{f_{u,\theta}}{f_{u,b}}$$

= the ratio between ultimate tensile strength at elevated temperature, $f_{u,\theta}$, and ultimate tensile strength at normal temperature, f_{ub}

For a given strain rate and different temperatures, there are large differences in the material response (T1 < T2 < T3 < T4 < T5).

CURRENT APPROACH

- Determining the strength reduction factors for bolts according to ISO 6892-2



Stress-strain curves at 850 °C and different strain rates

$$k_b = \frac{f_{u,\theta}}{f_{u,b}}$$

= the ratio between ultimate tensile strength at elevated temperature, $f_{u,\theta}$, and ultimate tensile strength at normal temperature, f_{ub}

For different strain rates at elevated temperature, there are large differences in the material response: $\dot{e}_1 > \dot{e}_2 > \dot{e}_3 > \dot{e}_4 > \dot{e}_5$.

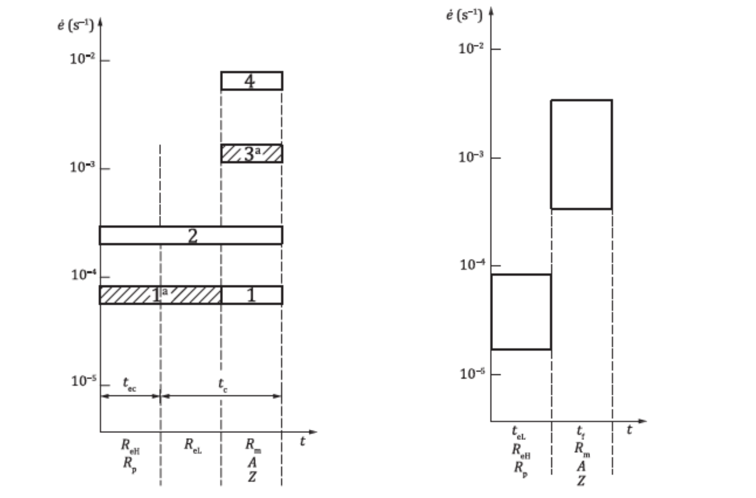
WHICH IS THE PROPER STRAIN RATE VALUE?

❑ISO 6892-2: two methods of testing are described:

- The first, Method A, is based on strain rates (including crosshead separation rate) with narrow tolerances (±20 %)
- and the second, Method B, is based on conventional strain rate ranges and tolerances.

Method A : recommended e=0.0014 s^{-1} +/-20%

Method B: 0.000 33 s^{-1} and 0.003 3 s^{-1}



a) Method A

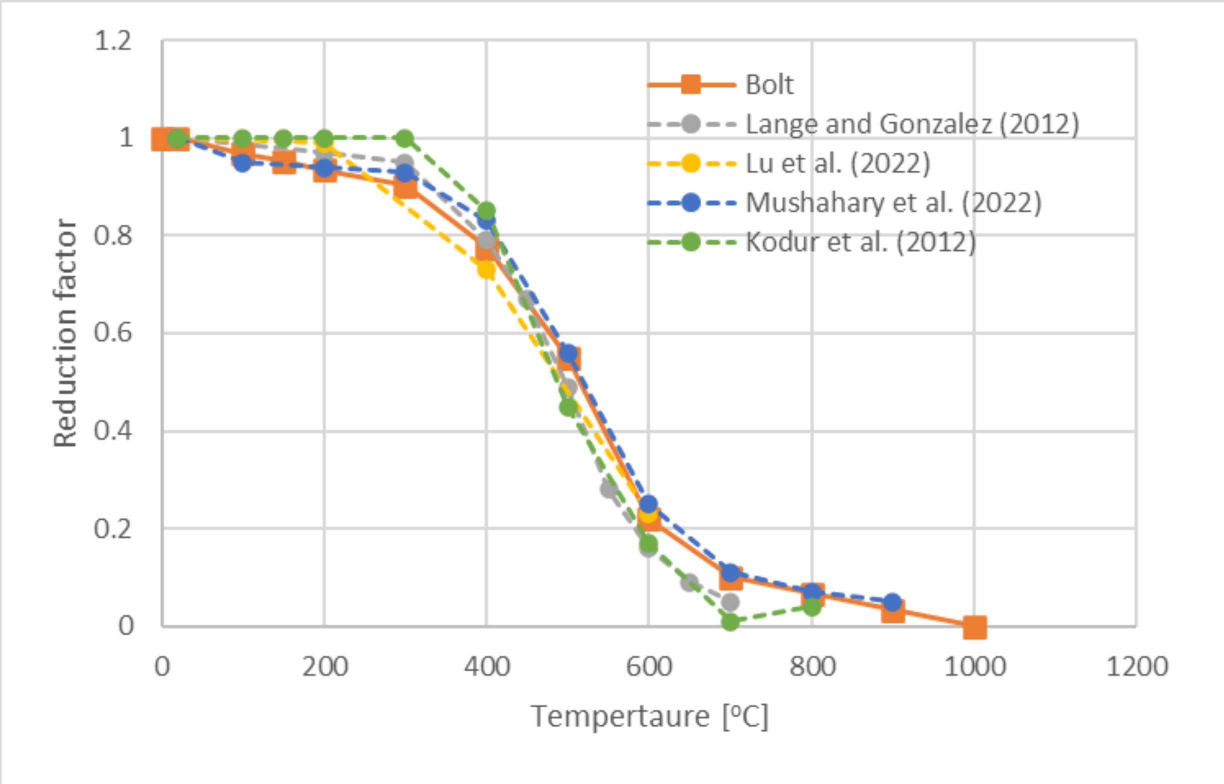
b) Method B

Key

$\dot{e}$	strain rate
t	time progress of the tensile test
t_c	crosshead control time
t_{ec}	extensometer control time or crosshead control time
t_{el}	time range (elastic behaviour) for determination of the parameters listed (see ISO 6892-1 for designations)
t_f	time range (usually up to fracture) for determination of the parameters listed (see ISO 6892-1 for designations)
1	Range 1: $\dot{e}$ = 0,000 07 s^{-1} (0,004 2 min^{-1}) with a relative tolerance of ±20 %
2	Range 2: $\dot{e}$ = 0,000 25 s^{-1} (0,015 min^{-1}) with a relative tolerance of ±20 %
3	Range 3: $\dot{e}$ = 0,001 4 s^{-1} (0,084 min^{-1}) with a relative tolerance of ±20 %
4	Range 4: $\dot{e}$ = 0,006 7 s^{-1} (0,4 min^{-1}) with a relative tolerance of ±20 %
a	Recommended.

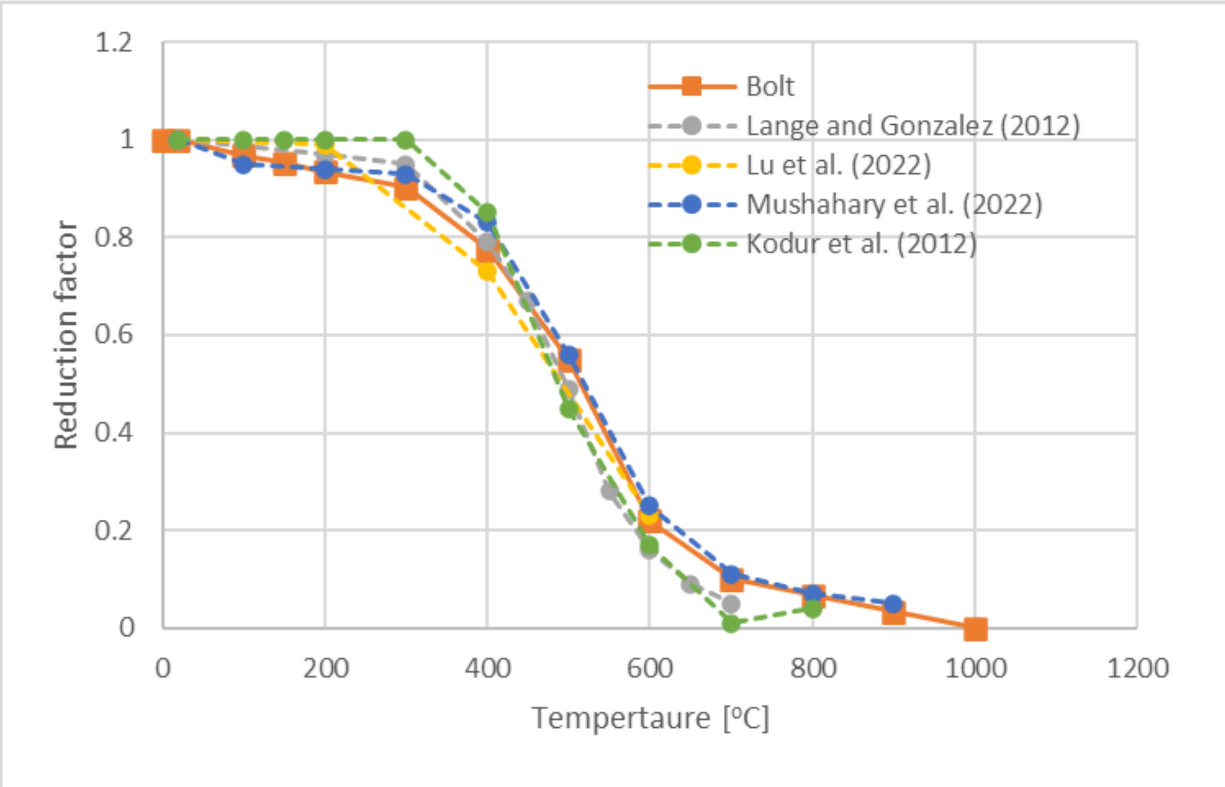
Figure 1 — Illustration of strain rates to be used during the tensile test, if R_{eH}, R_{eL}, R_p, R_m, A and Z are determined

INFLUENCE OF THE STRAIN RATE VALUE INDUCED IN A BOLT OVER ITS BEHAVIOUR



Although no specific research was published so far to quantify the influence of strain rate, this aspect is clearly observed by others (Bull et al., 2015; Both et al., 2021) and is also mentioned in ISO 6892-2 (2011).

LITERATURE REVIEW



The reduction factors from EN 1993-1-2 are developed following Kirby's experimental research realized in 1995. (Kirby, 1995) - **0.000033 s^{-1}**

Lange and Gonzalez (2012) – **0.00042 s^{-1}**

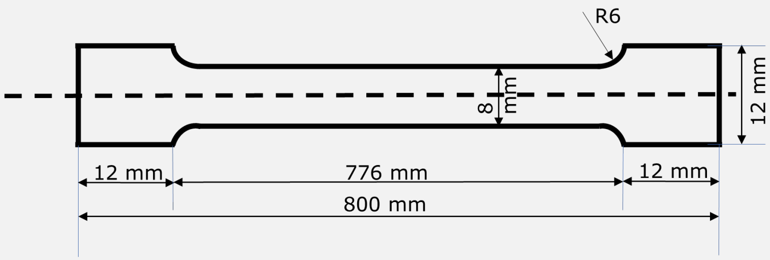
Lu et al (2022) – **0.005 mm/ s^{-1}**

Mushahary et al. (2022) – **0.0083 mm/ s^{-1}**

Kodur et al. (2012) – **150 kN/min**

TEST PROGRAM

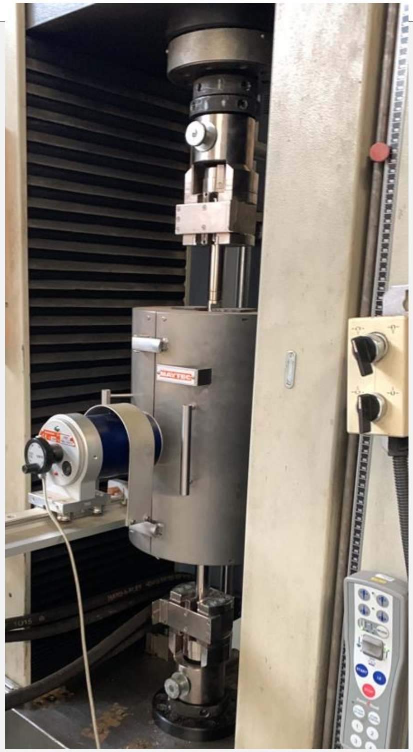
- Tensile tests on material acc. ISO 6892-2,
- on machined specimens,
- from M12 grade 10.9 bolts (EN 14399-4)



Total configurations		Tested configuration								
		20 [°C]	150 [°C]	300 [°C]	400 [°C]	500 [°C]	542 [°C]	600 [°C]	700 [°C]	800 [°C]
S1	**0.000033 [s^{-1}]**	√	√	√	√	√	√	√	√	√
S2	**0.00033 [s^{-1}]**	√	√	√	√	√	0	√	√	√
S3	**0.002 [s^{-1}]**	√	0	√	√	√	0	√	√	0
S4	**0.0033 [s^{-1}]**	√	√	√	√	√	√	√	√	√
S5	**0.008 [s^{-1}]**	√	0	√	√	√	0	√	√	0
S6	**0.01 [s^{-1}]**	√	0	√	√	√	0	√	√	0
S7	**0.02 [s^{-1}]**	√	√	√	√	√	√	√	√	√
S8	**0.04 [s^{-1}]**	√	0	√	√	√	0	√	√	0
S9	**0.06 [s^{-1}]**	√	0	√	√	√	0	√	√	√

EXPERIMENTAL SET-UP

Instron universal testing machine of 250 kN



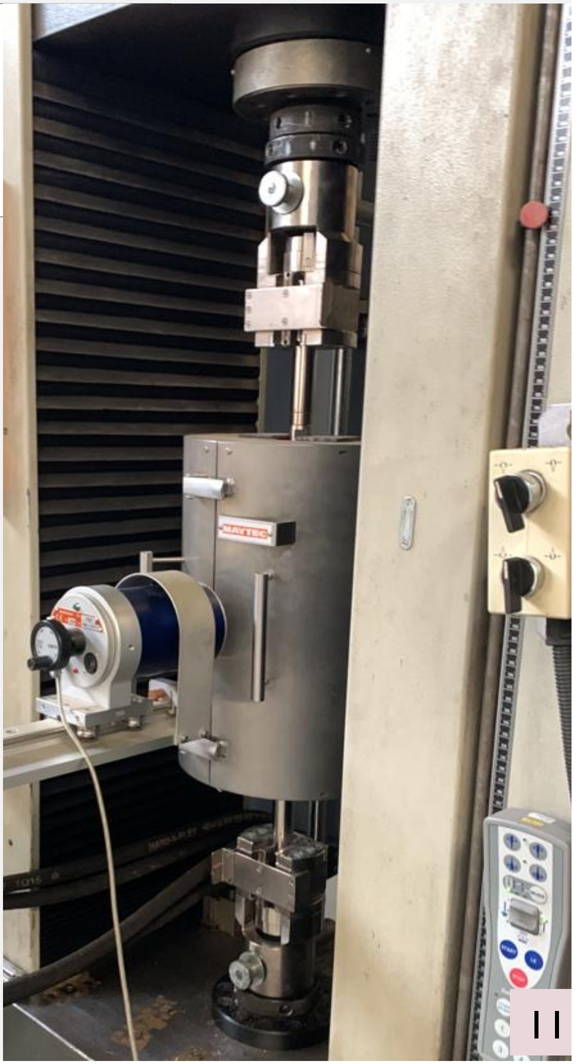
Extensometer – MAYTEC PMA-12/V7-1, HT-Extensometer up to 1500 °C

Furnace – MAYTEC HTO-08/01, Round Furnace up to 1000 °C

TEST PROCEDURE

- The tests were conducted following ISO 6892-2 (2011) standard.
- The specimen was firstly secured at top end of the machine's crosshead.
- The testing protocol comprises of heating the specimen at a rate of 10 K/min until the desired testing temperature is reached,
- followed by a 10-minute holding period at this temperature (referred to as the soaking period).
- The specimen was secured at bottom end of the machine's crosshead.
- During the test, the top part of the specimen moved along the vertical axis while the bottom part remained stationary.

TEST PROCEDURE



- The sensor arms permit the establishment of the initial gauge length. They are made from ceramics, with a knife-edge shape at the edge, to ensure optimal contact with the specimen. These arms are inserted into the furnace through a slot to make contact with the heated sample. L_0 = 40 mm
- The strain rate control is based on the machine's displacement, reported to the calibrated length of the sample. The strain rate was kept constant until the end of the test, marked by the failure of the specimen, in order to determine the tensile strength R_m.
- The recorded data are treated in MATLAB.

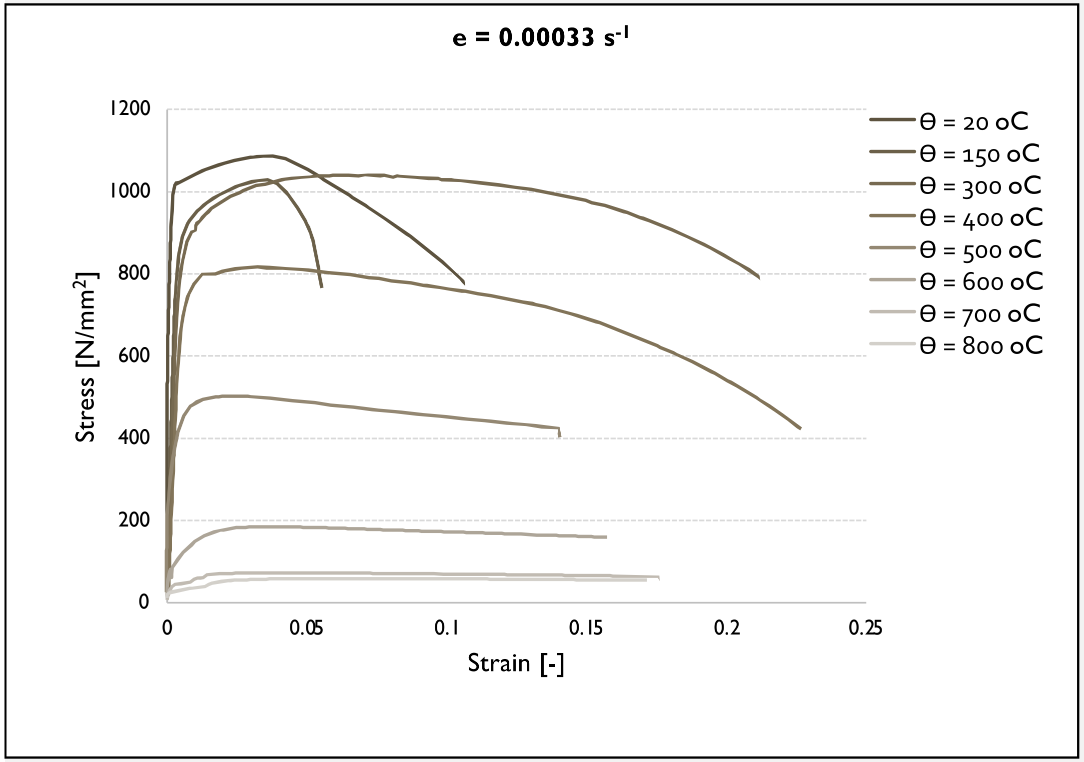
RESULTS

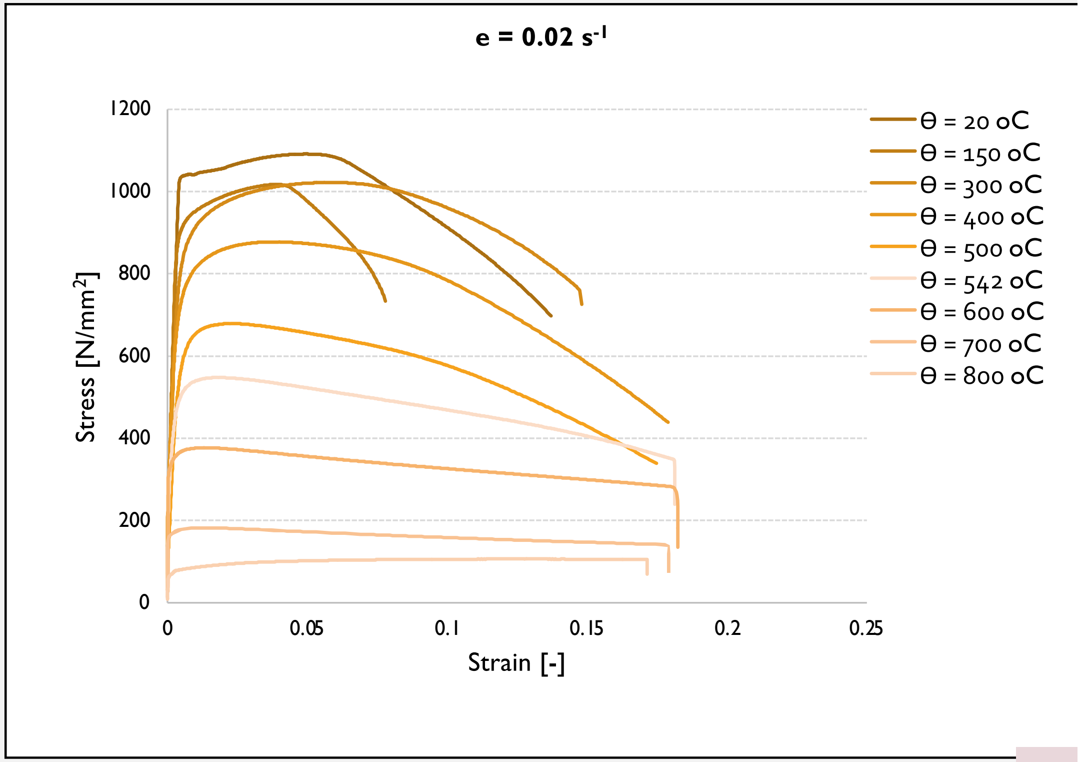
- The stress-strain curves were recorded, and the results treated in MATLAB

- The tensile strength was obtained for each configuration

- Each configuration repeated between 2 and 4 times

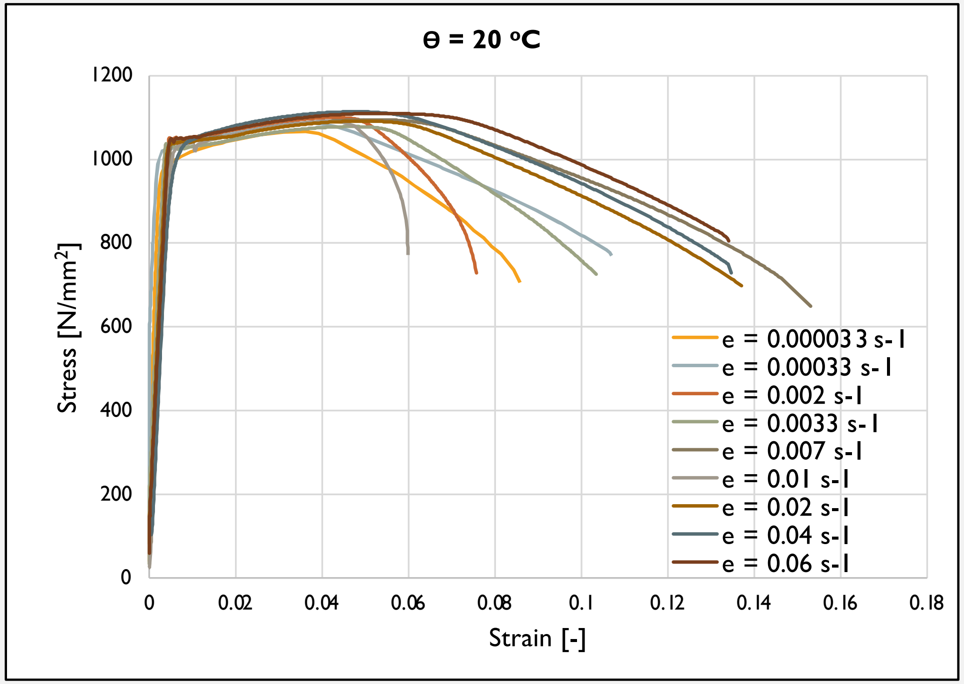
RESULTS - TEMPERATURE

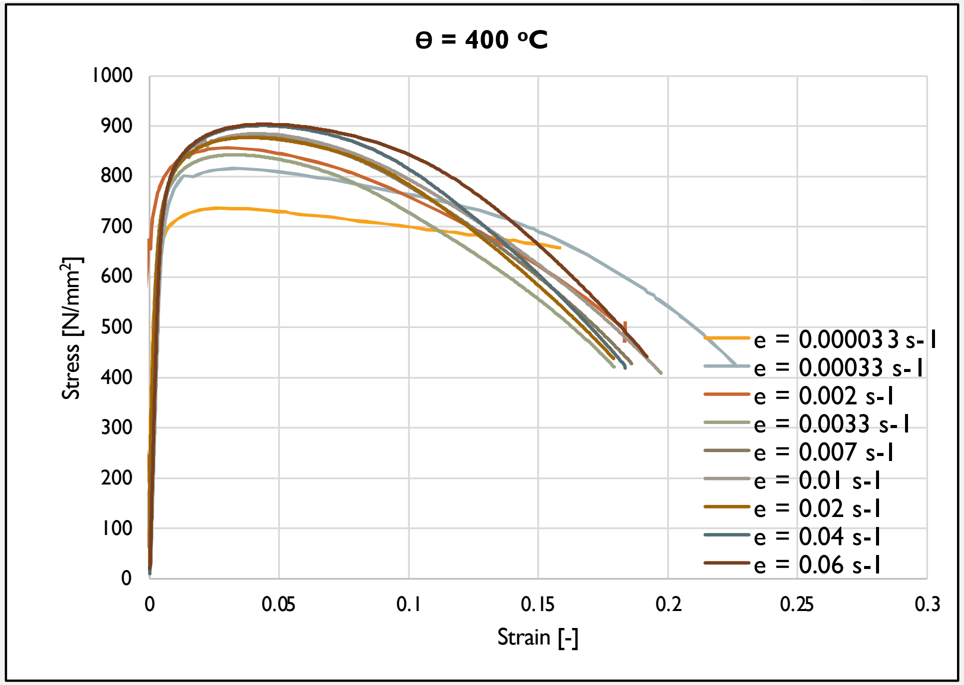




RESULTS - STRAIN RATE

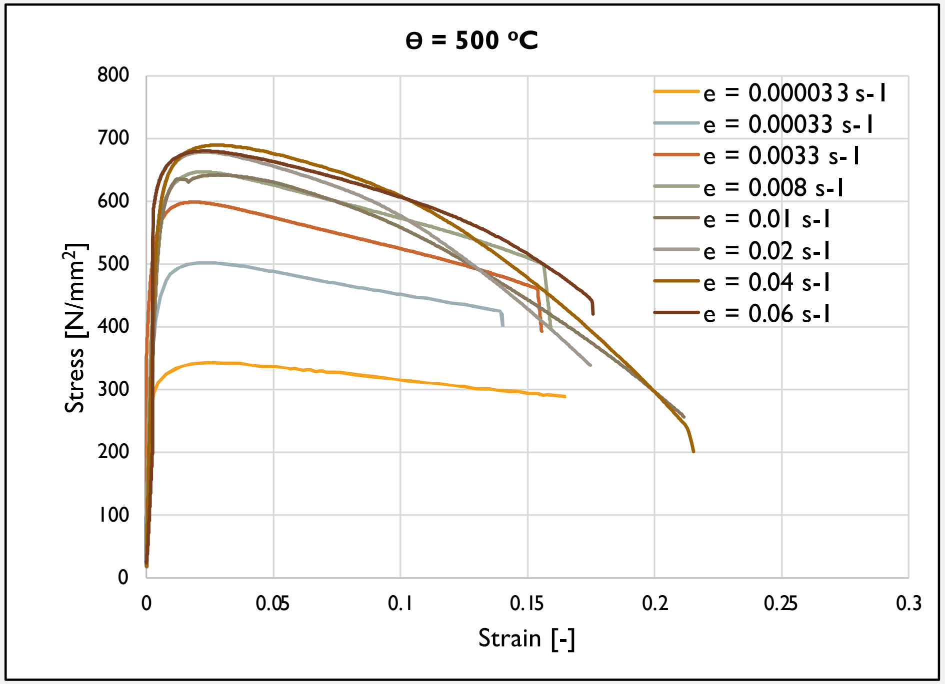
Temperature [°C]	20	150	300	400	500	600	700	800
Variation [%]	**1.35**	2.03	2.76	**6.15**	20.0	34.8	40.8	42.2

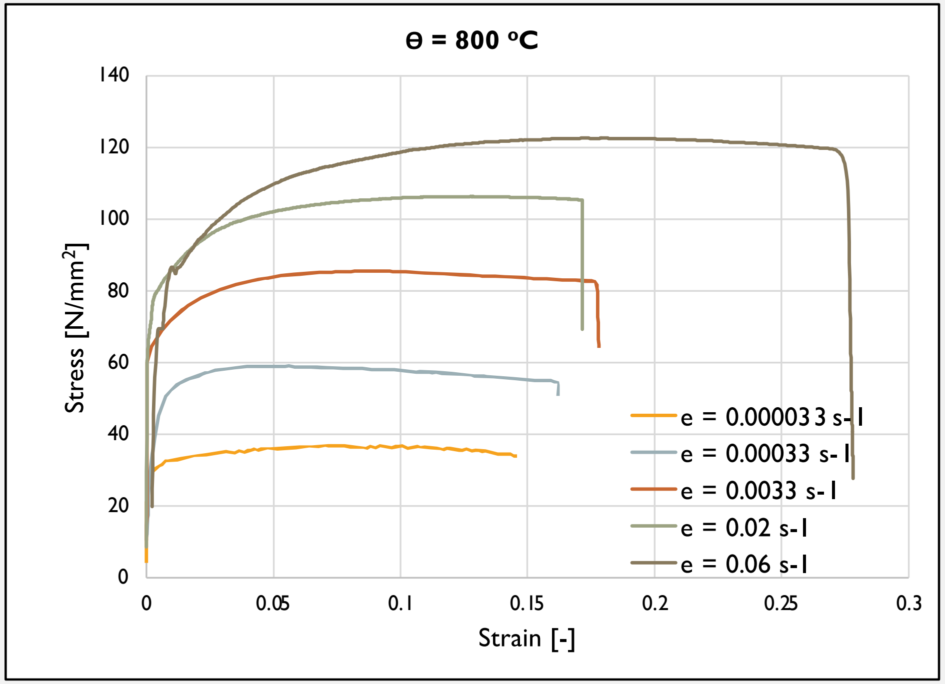




RESULTS - STRAIN RATE

Temperatura [ºC]	20	150	300	400	500	600	700	800
Variation [%]	1.35	2.03	2.76	6.15	**20.0**	34.8	40.8	**42.2**





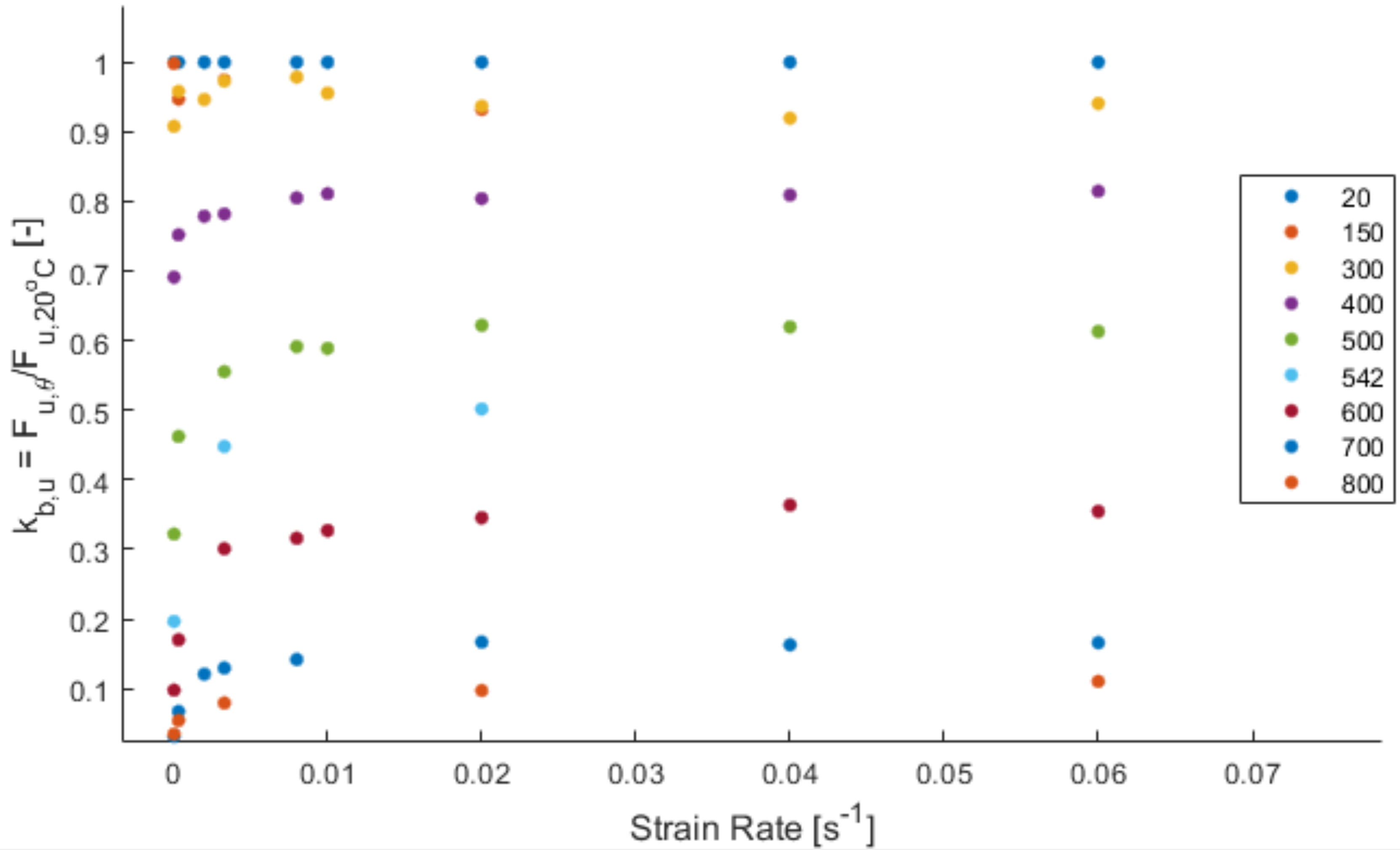
REDUCTION COEFFICIENTS

Proposed formulation for new reduction factor, $\mathbf{k_{b,u,new}}$:

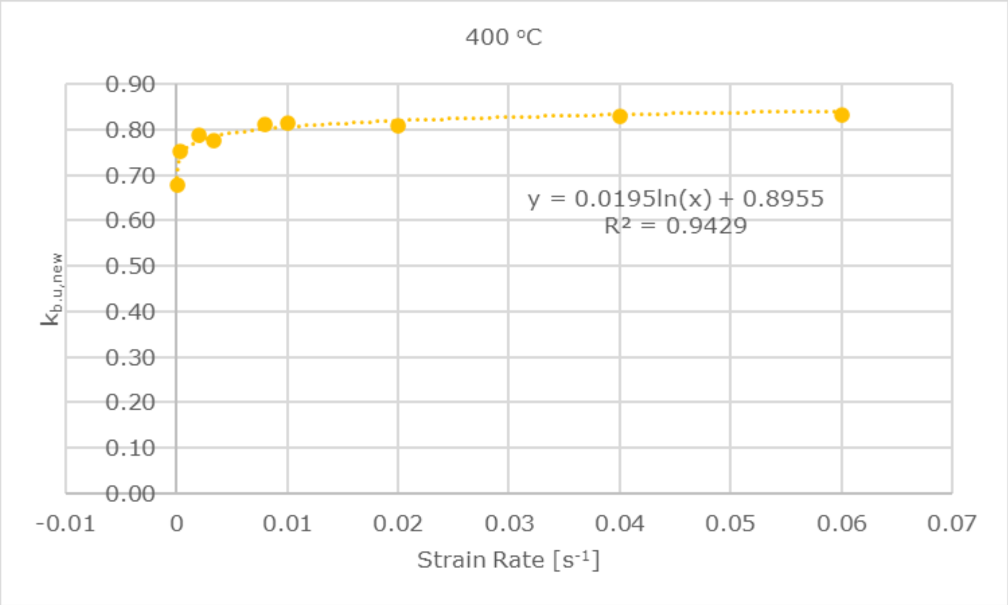
- The tensile strength reduction factor, $\mathbf{k_{b,u,new}}$, is defined as the ratio between the tensile strength at elevated temperature under a certain strain rate, $\mathbf{f_{u,\theta,\dot{e}}}$, and the tensile strength at normal temperature, under a strain rate of 0.00033 s^{-1}, $\mathbf{f_{u,20}}$.

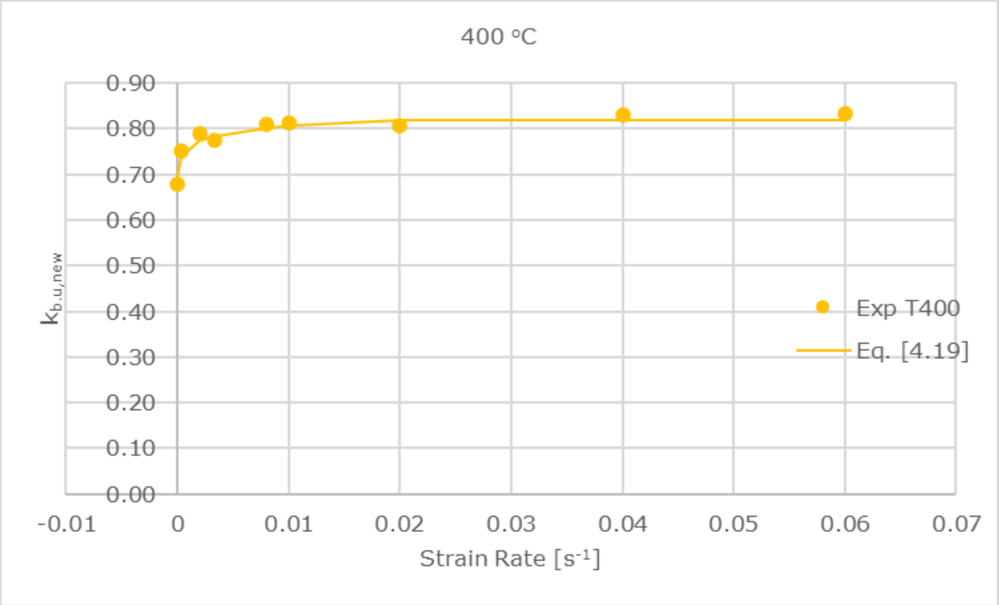
$$\mathbf{k_{b,u,\,new} = f_{u,\theta,\dot{e}} \,/\, f_{u,20}}$$

- The value of the fixed tensile strength, $\mathbf{f_{u,20}}$, was chosen as it offers close results of $\mathbf{k_{b,u}}$, no matter the strain rate applied. One can easily find this value, by the technical sheet of a grade 10.9 bolt.


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$k_{b,u} = F_{u,\theta}/F_{u,20°C}$ [-]
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Strain Rate [s^{-1}]
20
150
300
400
500
542
600
700
800

REDUCTION COEFFICIENTS

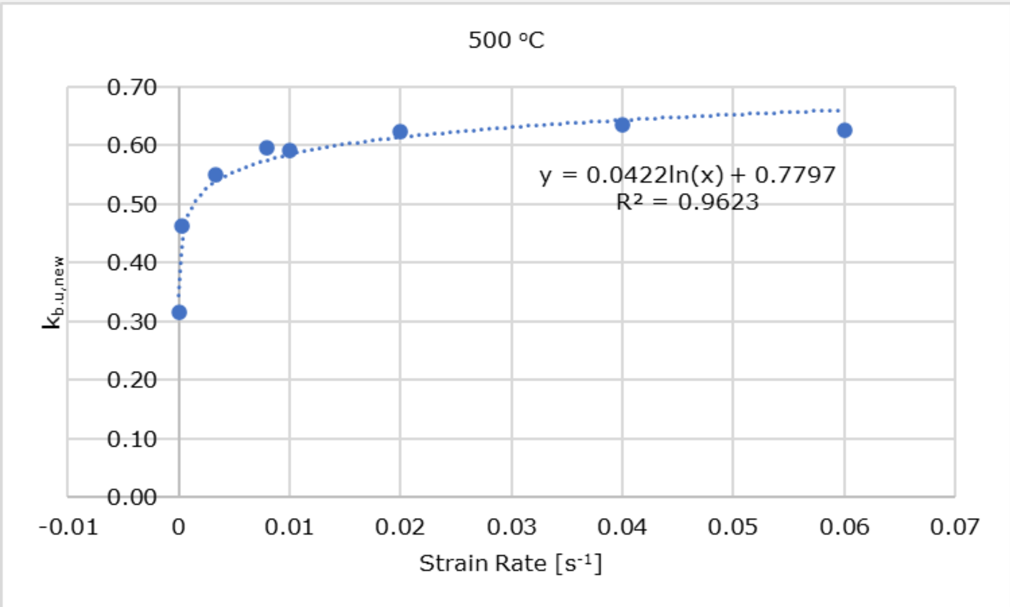


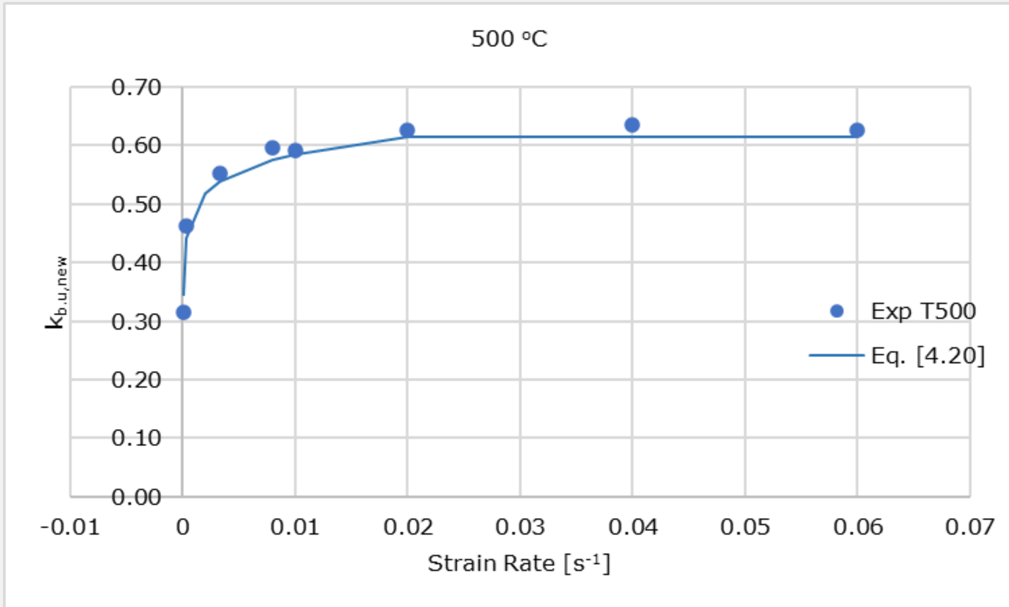


For θ = 400 °C: $k_{b,u,new} = 0.0195 \ln(\dot{e}) + 0.8955$, for $0.000033\ s^{-1} \leq \dot{e} < 0.02$
and $k_{b,u,new} = 0.819$, for $\dot{e} \geq 0.02$ [4.19]

Where $\dot{e}$ = strain rate [s^{-1}].

REDUCTION COEFFICIENTS

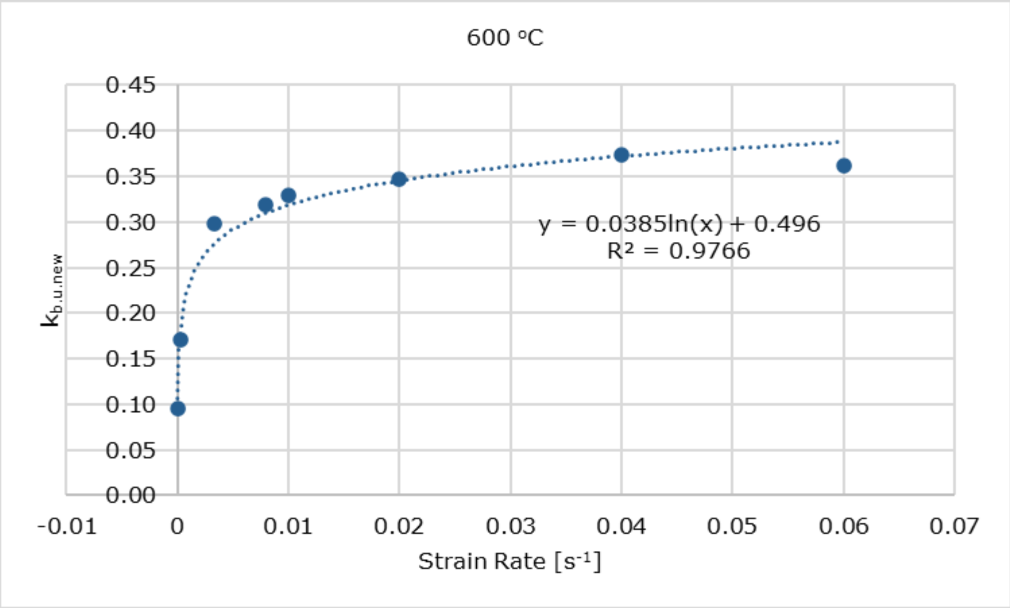


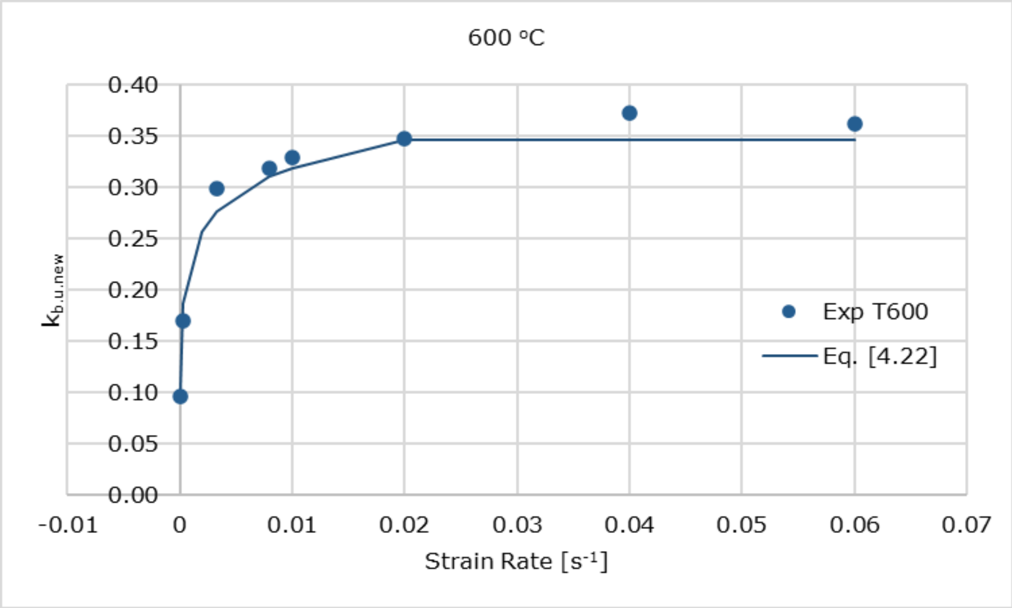


For θ = 500 ºC $k_{b,u,new} = 0.0422 \ln(\dot{e}) + 0.7797$, for $0.000033\ s^{-1} \le \dot{e} < 0.02$
and $k_{b,u,new} = 0.615$, for $\dot{e} \ge 0.02$ [4.20]

Where $\dot{e}$ = strain rate [s^{-1}].

REDUCTION COEFFICIENTS

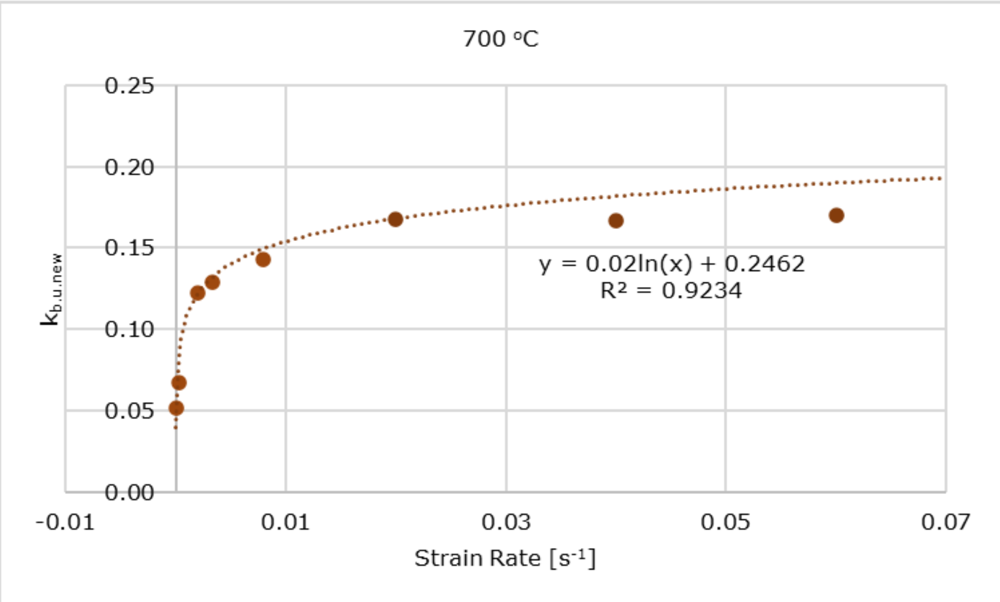


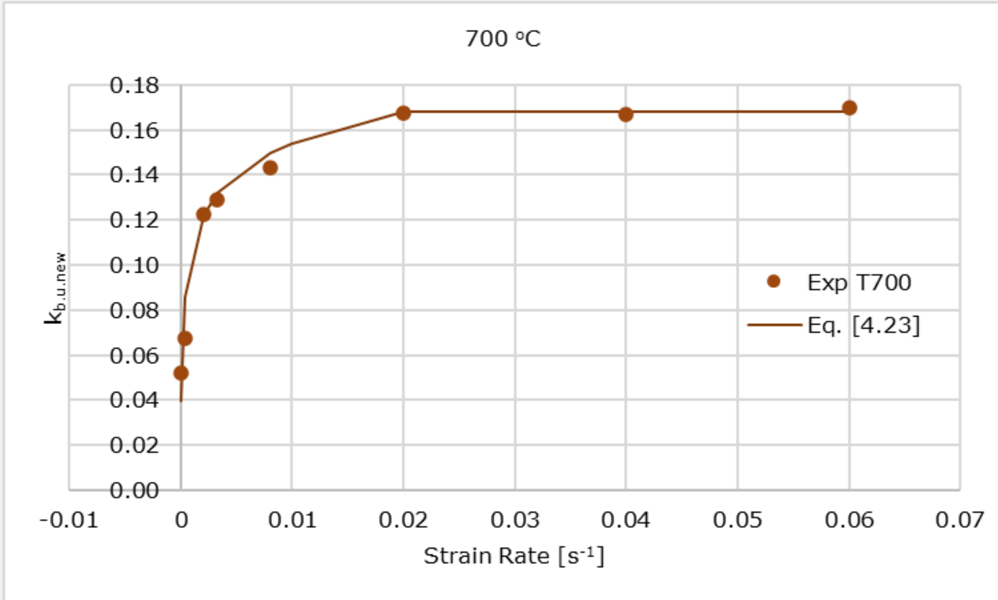


For θ = 600 ºC $k_{b,u,new} = 0.0385 \ln(\dot{e}) + 0.496$, for $0.000033\ s^{-1} \leq \dot{e} < 0.02$
and $k_{b,u,new} = 0.345$, for $\dot{e} \geq 0.02$ [4.22]

Where $\dot{e}$ = strain rate [s^{-1}].

REDUCTION COEFFICIENTS

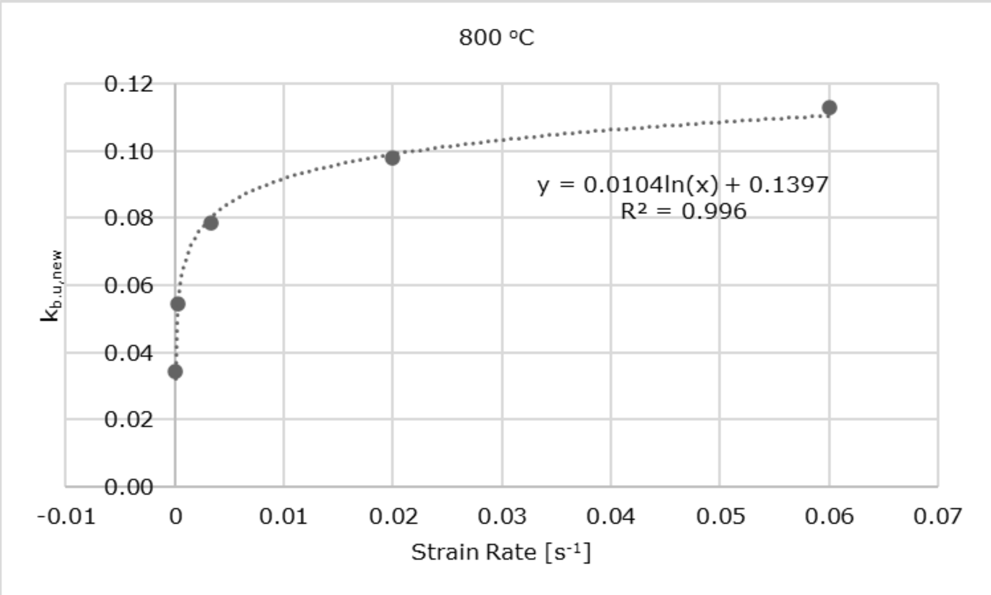


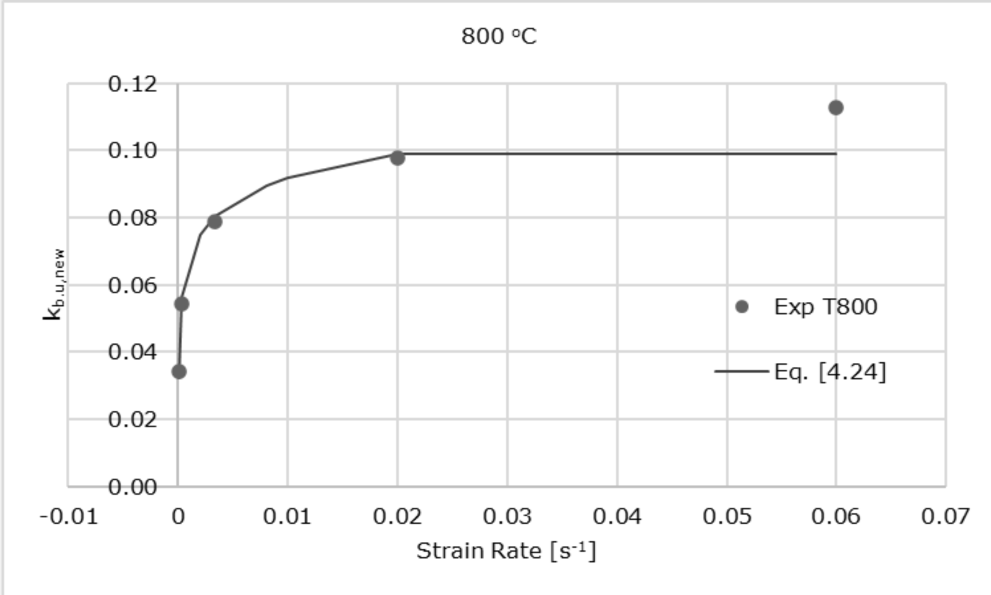


For θ = 700 ºC $k_{b,u,new} = 0.02\ \ln(\dot{e}) + 0.2462$, for $0.000033\ s^{-1} \le \dot{e} < 0.02$
and $k_{b,u,new} = 0.166$, for $\dot{e} \ge 0.02$ [4.23]

Where $\dot{e}$ = strain rate [s^{-1}].

REDUCTION COEFFICIENTS



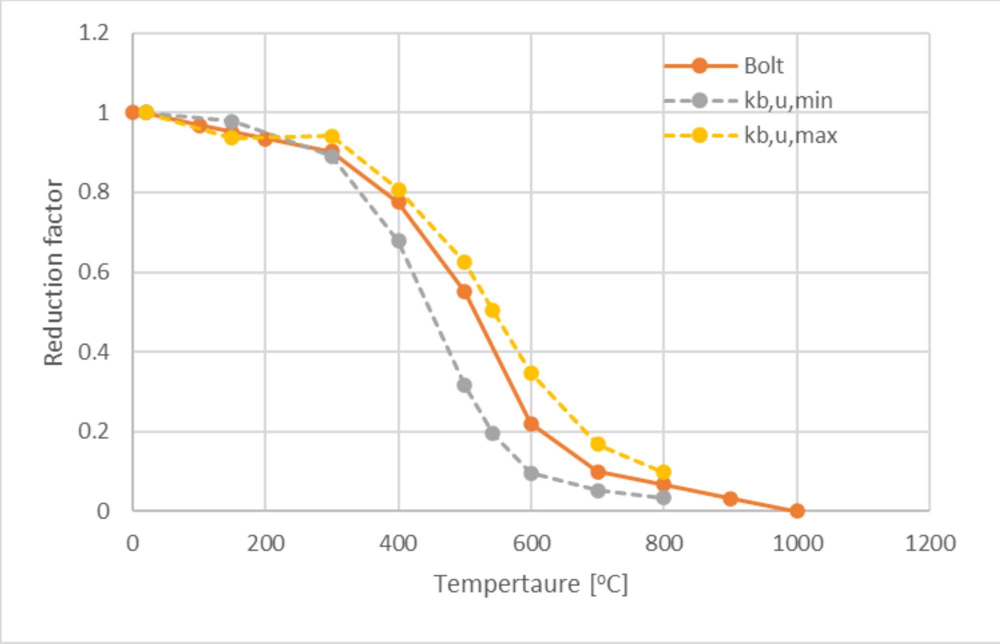


For θ = 800 °C $k_{b,u,new} = 0.0104 \ln(\dot{e}) + 0.1397$, for $0.000033\ s^{-1} \leq \dot{e} < 0.02$
and $k_{b,u,new} = 0.099$, for $\dot{e} \geq 0.02$ [4.23]

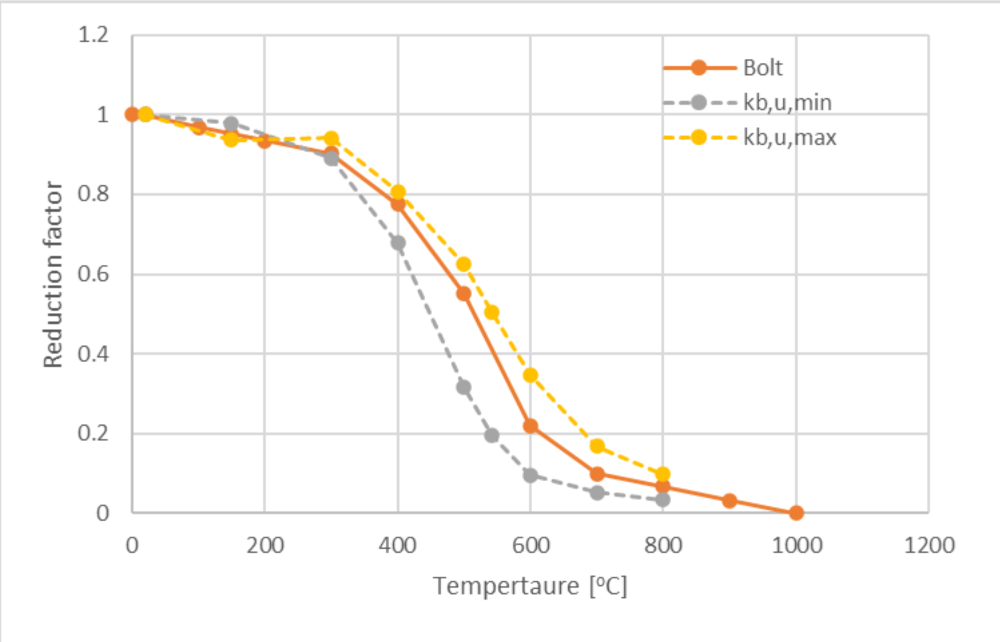
Where $\dot{e}$ = strain rate [s^{-1}].

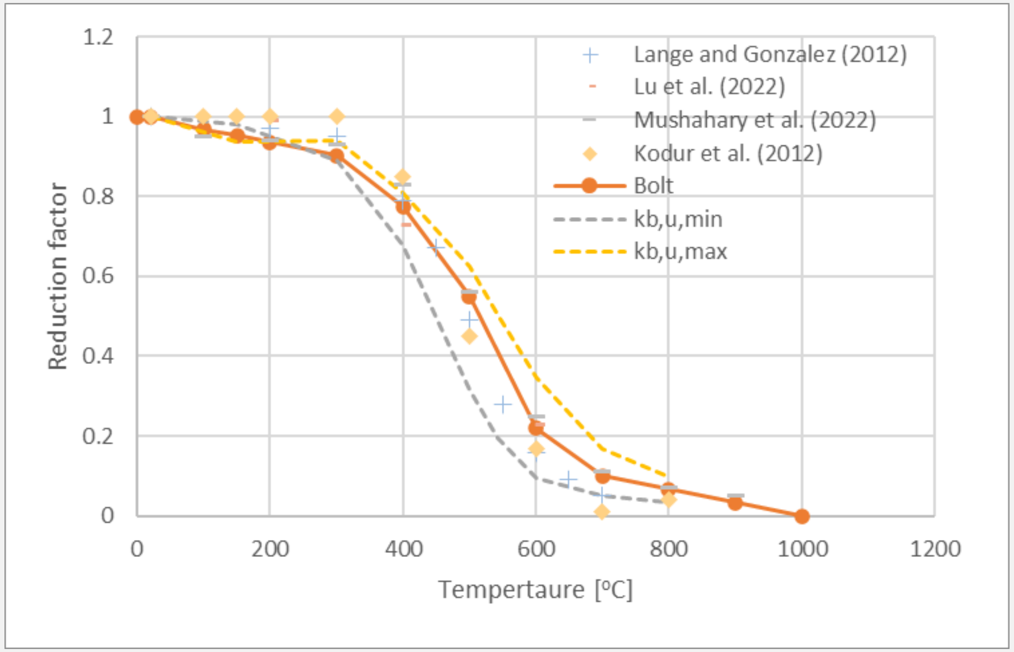
PROPOSED REDUCTION COEFFICIENTS

T [ºC]	$k_{b,u,min}$ 0.000033 [s^{-1}]	$k_{b,u,max}$ 0.02 [s^{-1}]	$k_{b,ec3}$
20	1	1	1
100			0.968
150	0.979	0.936	0.952
200			0.935
300	0.891	0.941	0.903
400	0.678	0.808	0.775
500	0.316	0.625	0.55
542	0.195	0.504	
600	0.096	0.347	0.22
700	0.052	0.168	0.1
800	0.034	0.098	0.067
900			0.033



PROPOSED REDUCTION COEFFICIENTS





CONCLUSION

- The aim of this research was to understand the behaviour of high strength bolts for steel structures, in particular grade 10.9 bolts in fire conditions, under different strain rates.
- Experimental study on mechanical properties of high strength bolts at elevated temperatures, concluded with new reduction factors for bolt strength, depending on the strain rate
- Further research can expand the method's scope, including :
  - validating the new coefficients for various bolt grades.
  - investigating the impact of thread stripping on bolt assembly failure.
  - enhancing the knowledge in the field of numerical simulations of connections under different loading conditions.

Diana Duma

BRE

Thank you for your attention!

Questions?