

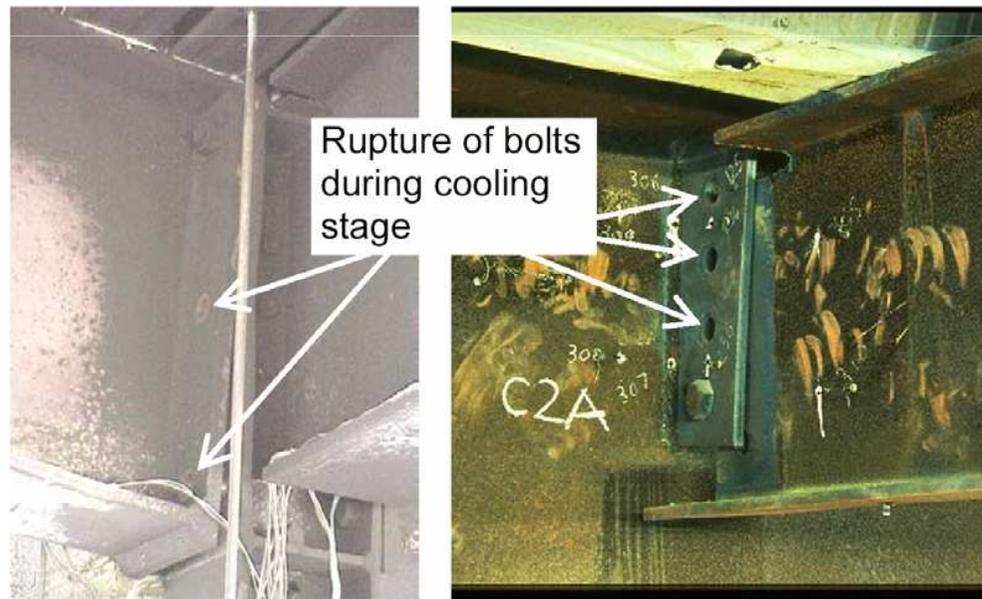
Experimental investigations and analytical models for the behavior of Grade 8.8 bolts and butt welds under heating and subsequent cooling

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Introduction

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- ❑ Cooling phase is a key issue for the resistance of connections in steel and composite structures (Cardington, Vernon,...)



Introduction

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Origins of failures in connections during cooling

- Development of tensile forces in beams and joints due to plastic deformations and axial restraints
- Limited ductility of bolts and welds components when joint resistance is not sufficient
- Loss of bolts and welds strengths not reversible → must still be investigated

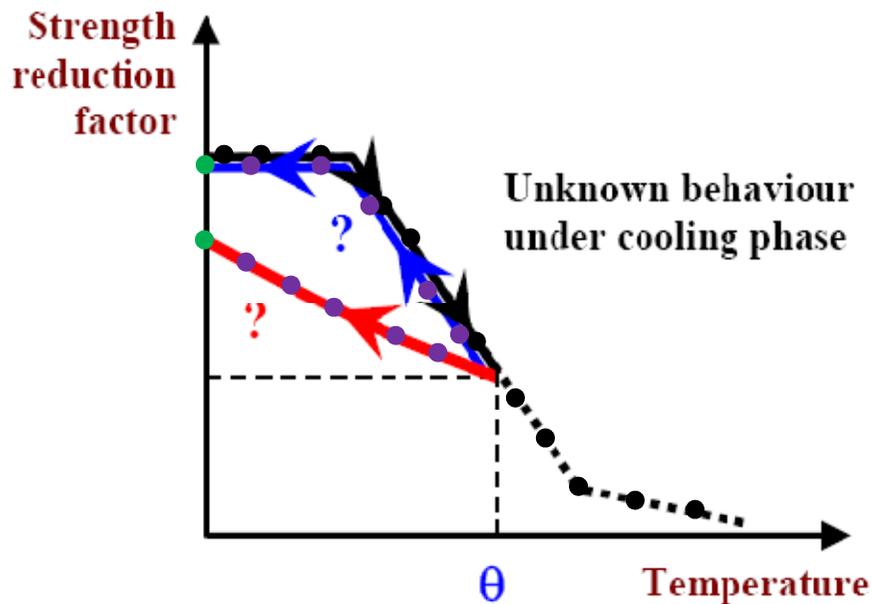
Review of previous work

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- Riaux (1980) : Tensile and shear tests on Grade 8.8 bolts after heating
- Kirby (1995) : Tensile and shear tests on Grade 8.8 bolts after heating → EN 1993-1-2
- Gonzalez (2008) : Tensile tests on Grade 10.9 bolts during heating and after cooling (residual)
- Latham (1993) : Tests on fillet and butt welds after heating → EN 1993-1-2

Introduction

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Bolts

- Heating phase : OK
- Residual : Few data
- Cooling phase : No data

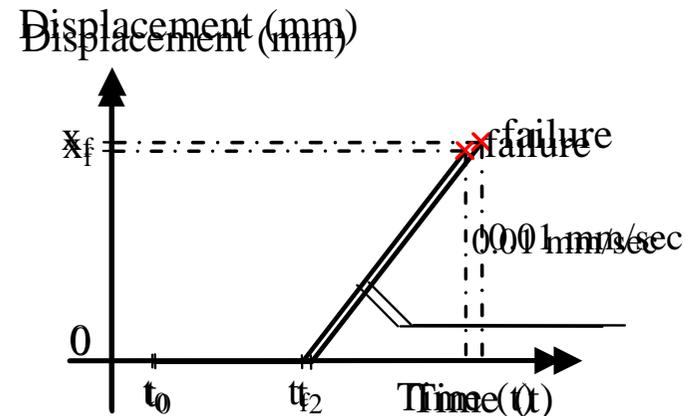
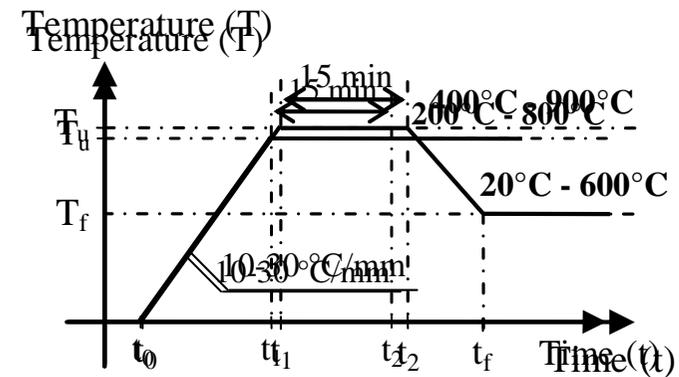
Welds

- Heating phase : OK
- Residual : No data
- Cooling phase : No data

Test Methodology for this project (CSM)

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- Room temperature tests
- Steady-state tests at elevated temperatures (a)
- Steady-state tests performed at various T_f after temperature has reached T_u (b)



Test Methodology (CSM)

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Schedule of tests performed on Grade 8.8 bolts

Tensile tests

| Heating | | Cooling | | |
|------------------|----------|------------|------------|----------|
| $T_u = T_f$ [°C] | n. tests | T_u [°C] | T_f [°C] | n. tests |
| 20 | 2 | 400 | 200 | 2 |
| 200 | 1 | | 100 | 1 |
| 400 | 1 | | 20 | 1 |
| 600 | 1 | 600 | 400 | 1 |
| 800 | 1 | | 300 | 1 |
| | | | 200 | 2 |
| | | | 100 | 1 |
| | | 800 | 20 | 1 |
| | | | 600 | 1 |
| | | | 400 | 1 |
| | | | 300 | 1 |
| | | | 200 | 2 |
| | | | 100 | 1 |
| | | 20 | 1 | |
| | | 900 | 20 | 1 |

Shear tests

| Heating | | Cooling | | |
|------------------|----------|------------|------------|----------|
| $T_u = T_f$ [°C] | n. tests | T_u [°C] | T_f [°C] | n. tests |
| 20 | 2 | 600 | 400 | 1 |
| 200 | 1 | | 300 | 1 |
| 400 | 1 | | 200 | 2 |
| 600 | 1 | | 100 | 1 |
| 800 | 1 | | 20 | 1 |
| | | 800 | 600 | 1 |
| | | | 400 | 1 |
| | | | 300 | 1 |
| | | | 200 | 2 |
| | | | 100 | 1 |
| | | 900 | 20 | 1 |

Test Methodology (CSM)

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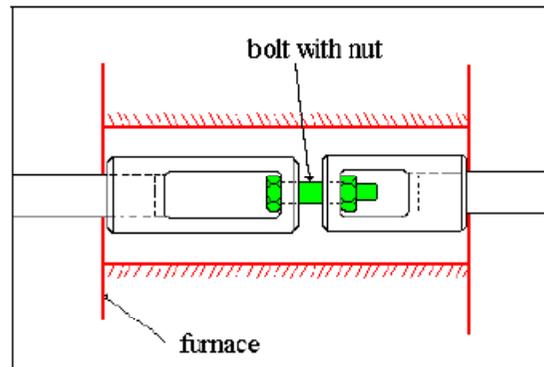
Schedule of tests performed on welds

| Heating | | Cooling | | |
|------------------|----------|------------|------------|----------|
| $T_u = T_f$ [°C] | n. tests | T_u [°C] | T_f [°C] | n. tests |
| 20 | 1 | 400 | 200 | 1 |
| 200 | 1 | | 100 | 1 |
| 400 | 1 | | 20 | 1 |
| 600 | 1 | 600 | 400 | - |
| 800 | 1 | | 200 | - |
| | | | 20 | 1 |
| | | 800 | 600 | 1 |
| | | | 400 | 1 |
| | | | 200 | 1 |
| | | 900 | 20 | 1 |
| | | | 400 | 1 |
| | | | 200 | 1 |
| | | | 20 | 1 |

Test set-up : Bolts in Tension (CSM)

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- M12x50mm bolts (limited loading capacity)
- Clamps made of NIMONIC 115 alloy (heat resistant)

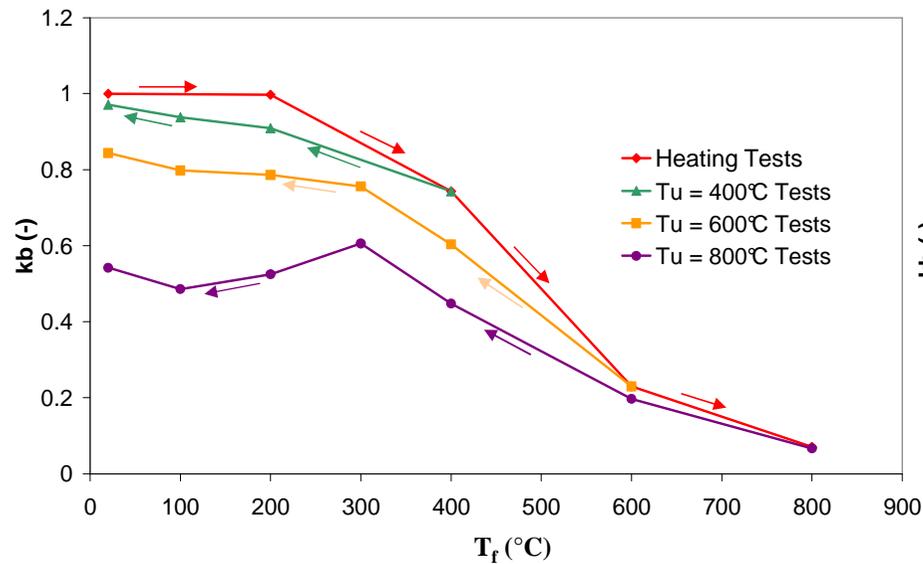


Treatment of test results

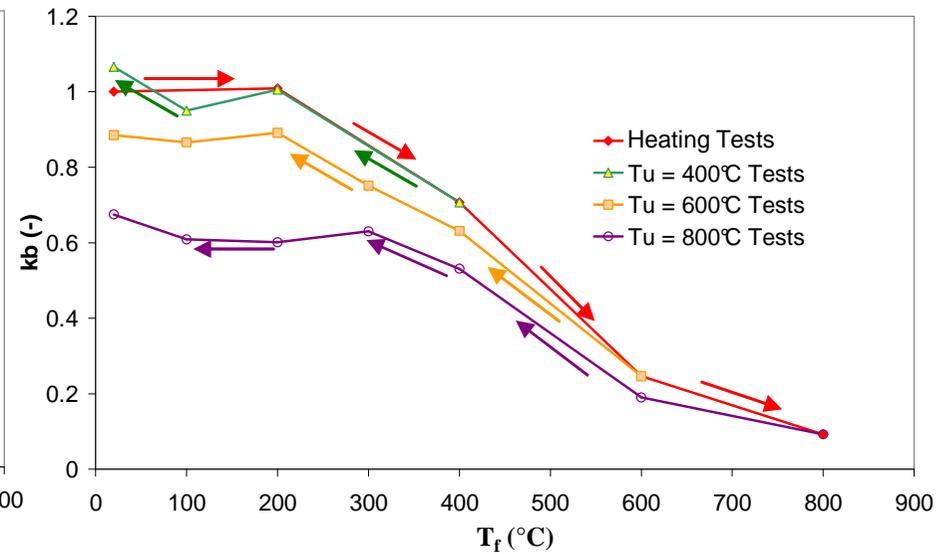
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Experimental values of reduction factor for bolt strength k_b

Tensile tests



Shear tests



Treatment of test results

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Model for bolt strength f_{ub} during cooling

EN 1993-1-2

$$f_{ub}(T_f, T_u) = k_b(T_f) \cdot k_{nr,b}(T_f; T_u) \cdot f_{ub,20^\circ C}$$

$$k_{nr,b} = 1$$

for $T_u \leq 500^\circ C$

$$k_{nr,b}(T_f; T_u) = \min\left(1; 1 - \frac{0.4}{300}(T_u - \max(T_f; 500^\circ C))\right)$$

for $500^\circ C \leq T_u \leq 800^\circ C$

T_f : Failure temperature

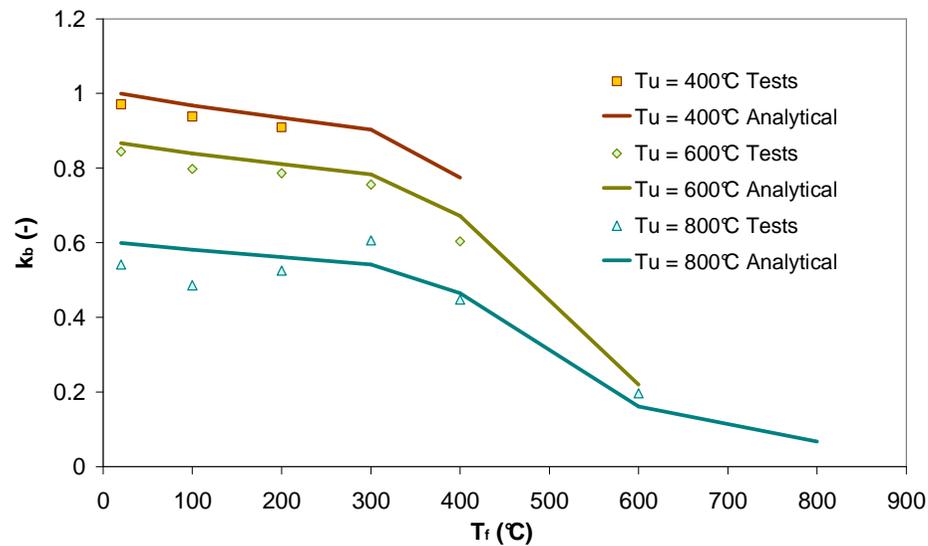
T_u : Upper temperature (at the end of heating phase)

Treatment of test results

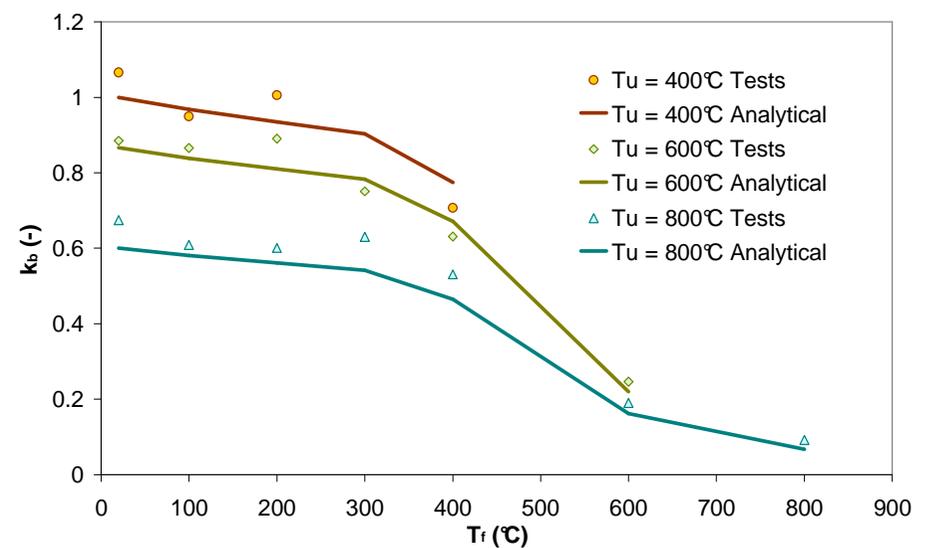
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Reduction factor for bolt strength k_b : Tests vs Model

Tensile tests



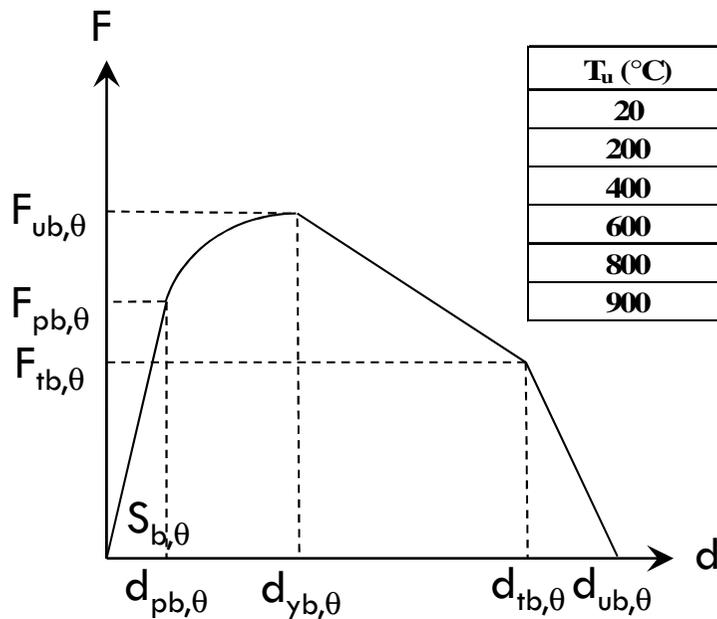
Shear tests



Treatment of test results

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Force-displacement model for bolts in tension



| T_u (°C) | $k_{pb,\theta}$ |
|------------|-----------------|
| 20 | 0.9 |
| 200 | 0.8 |
| 400 | 0.75 |
| 600 | 0.75 |
| 800 | 0.6 |
| 900 | 0.6 |

$$S_{b,T_u,T_f} = 0.8 EA_s / L_b \quad (EC3)$$

$$F_{ub,T_u,T_f} = k_{nr,T_u,T_f} k_{b,T_f} f_{ub,20^\circ C} A_s$$

$$F_{pb,T_u,T_f} = k_{pb,T_u} F_{ub,T_u,T_f}$$

$$F_{tb,T_u,T_f} = \min(500 \text{ MPa} * A_s ; F_{ub,T_u,T_f})$$

$$d_{pb,T_u,T_f} = F_{pb,T_u,T_f} / S_{b,T_u,T_f}$$

$$d_{yb,T_u,T_f} = 1 \text{ mm}$$

$$d_{tb,T_u,T_f} = 5 \text{ mm}$$

$$d_{ub,T_u,T_f} \in [7.5 ; 12.5] \text{ mm}$$

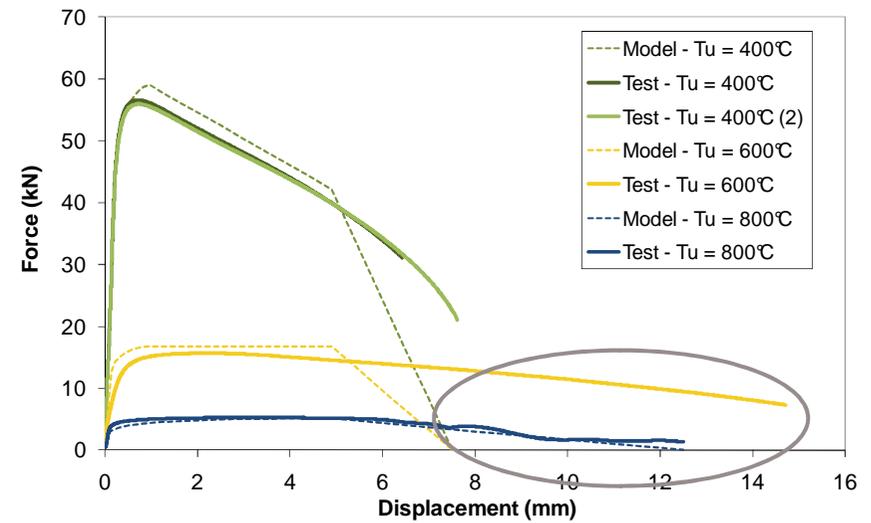
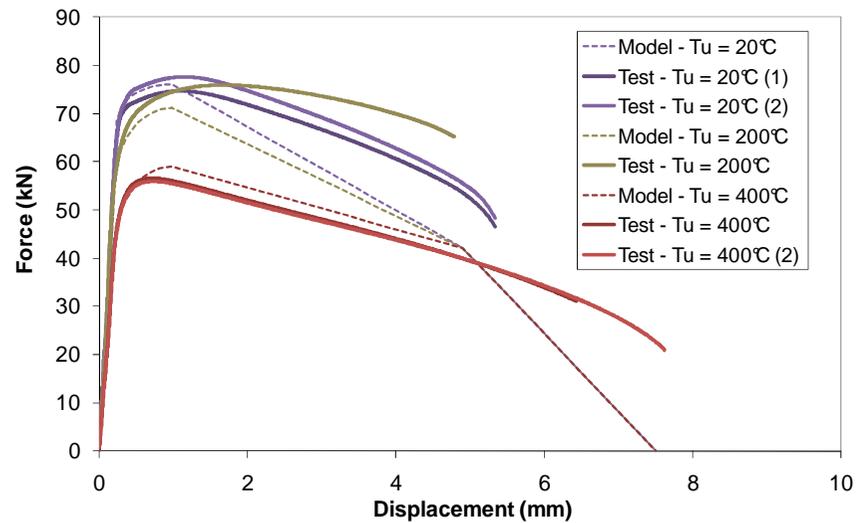
| T_u (°C) | $d_{ub,\theta}$ (mm) |
|---|----------------------|
| $T_u \leq 600^\circ C$ | 7.5 |
| $600^\circ C \leq T_u \leq 800^\circ C$ | lin. interpol. |
| $T_u \geq 800^\circ C$ | 12.5 |

Treatment of test results

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Force-displacement model for bolts in tension

Heating ($T_u = T_f$)



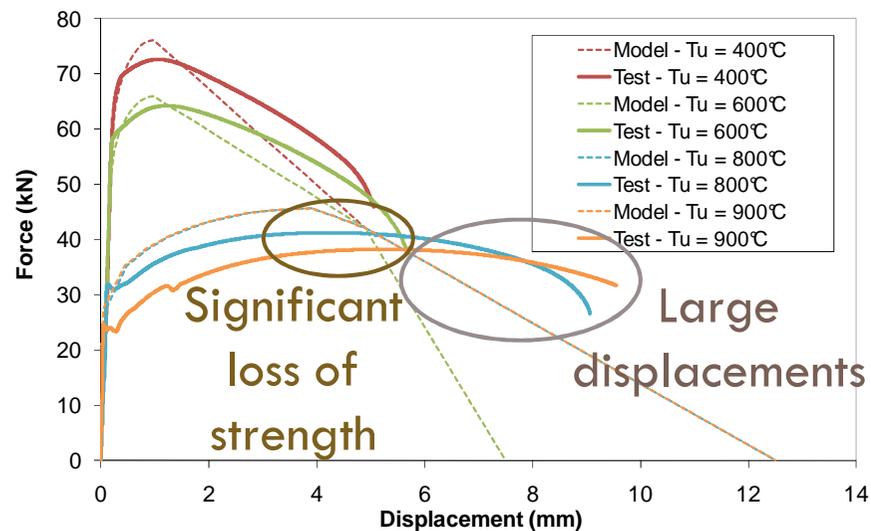
Large displacements

Treatment of test results

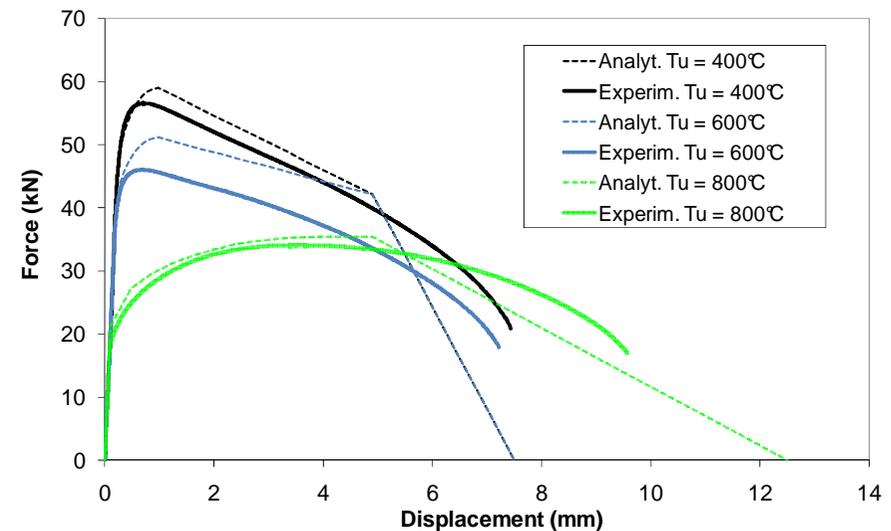
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Force-displacement model for bolts in tension

Residual ($T_f = 20^\circ\text{C}$)



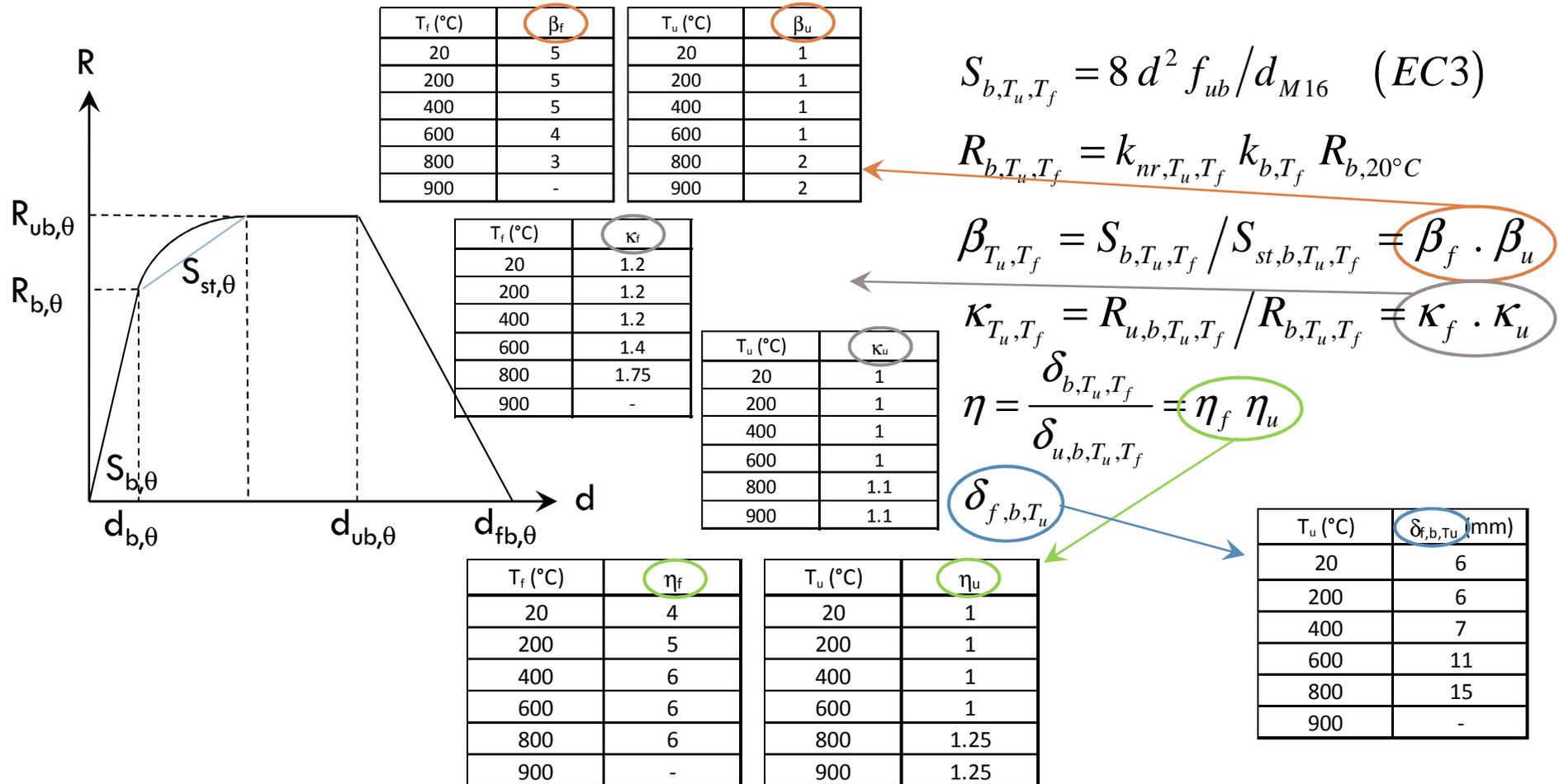
Cooling ($T_f = 400^\circ\text{C}$)



Treatment of test results

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Force-displacement model for bolts in shear

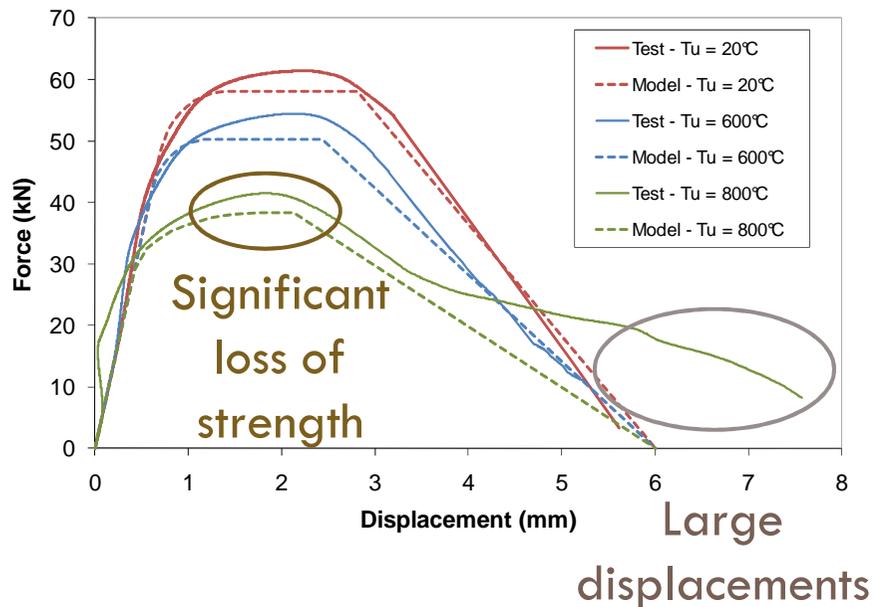


Treatment of test results

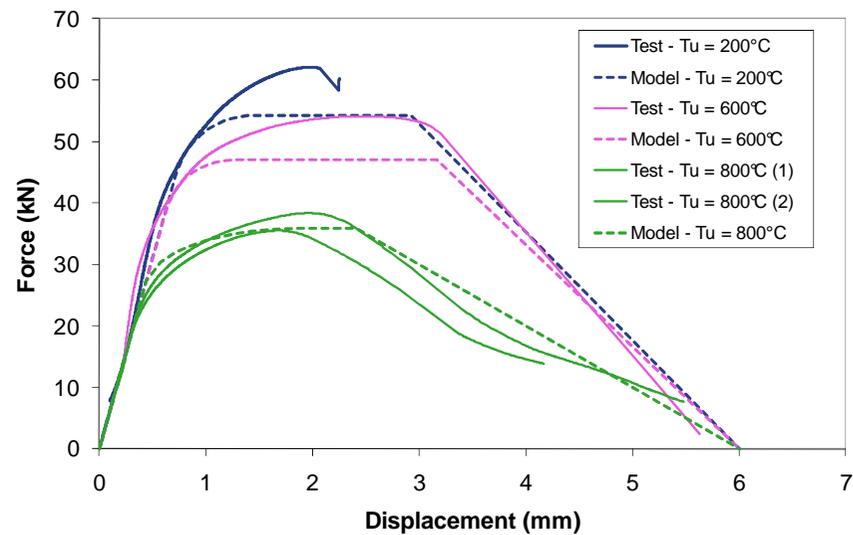
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Force-displacement model for bolts in shear

Cooling ($T_f = 20^\circ\text{C}$)



Cooling ($T_f = 200^\circ\text{C}$)

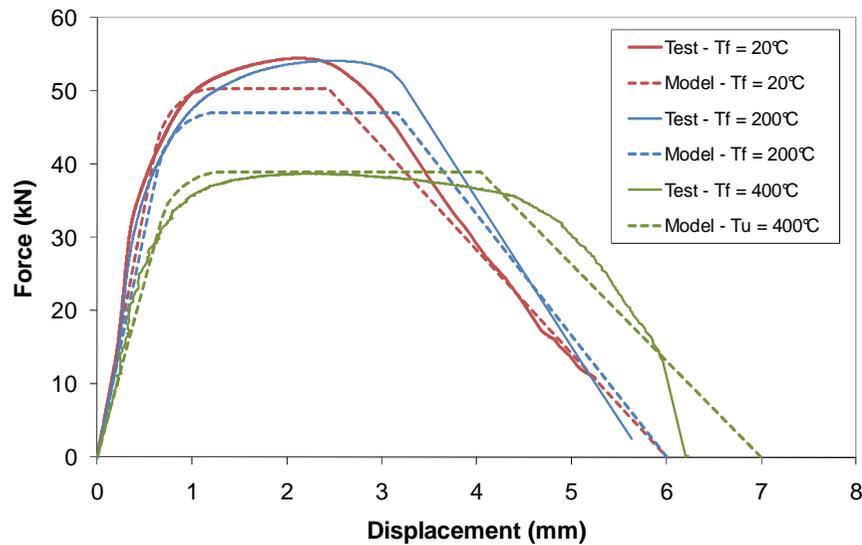


Treatment of test results

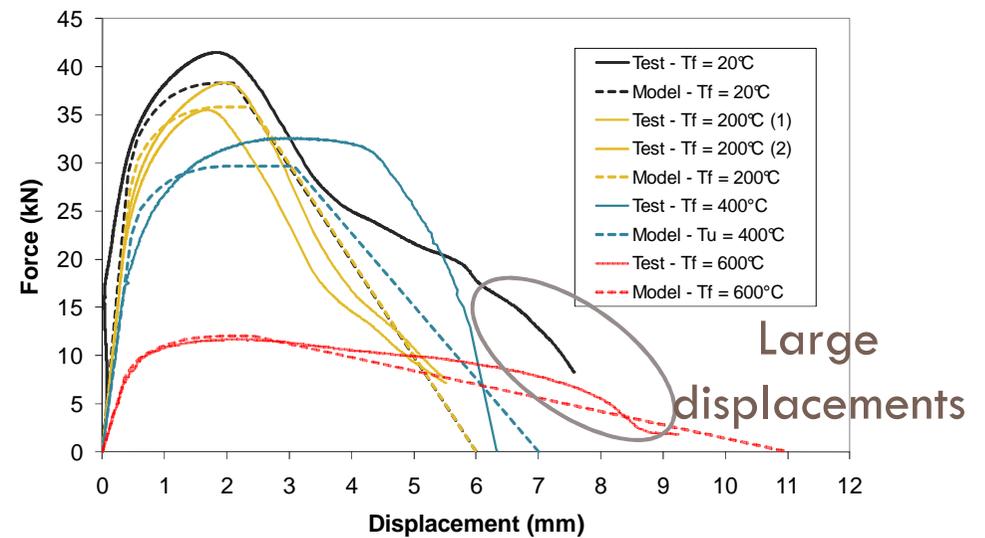
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Analytical model for bolts in shear

Cooling ($T_u = 600^\circ\text{C}$)



Cooling ($T_u = 800^\circ\text{C}$)



Test set-up : Welds in Shear (CSM)

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- Butt welded specimens loaded in tension
- Clamps made of NIMONIC 115 alloy (heat resistant)

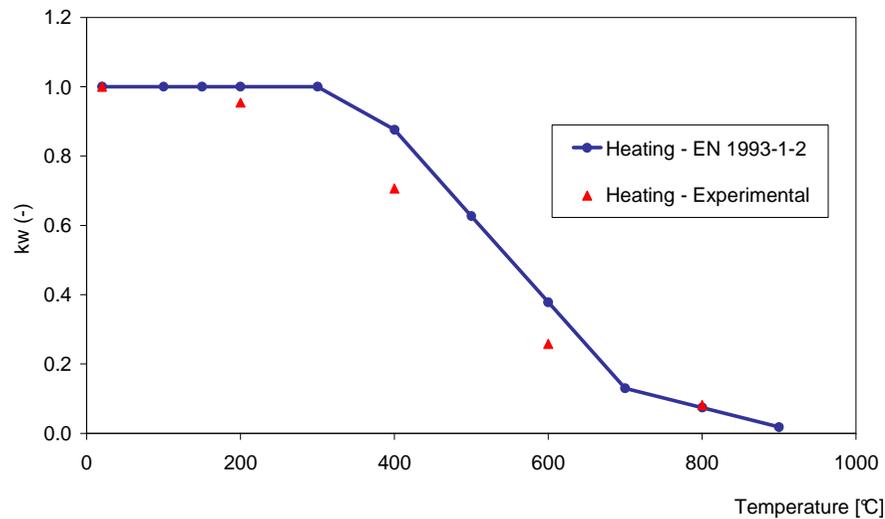


Treatment of test results

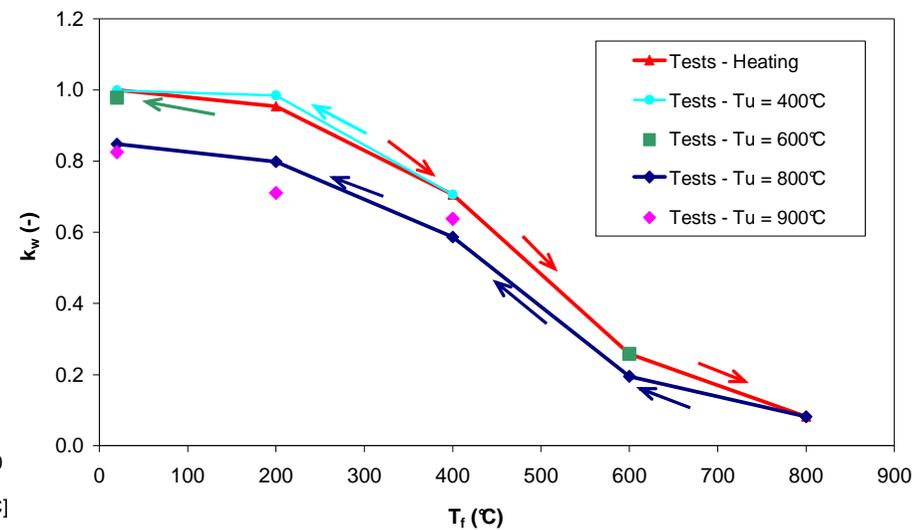
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Experimental values of reduction factor for weld strength k_w

No Cooling



Heating + Cooling



Treatment of test results

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Analytical values of reduction factor for bolt strength k_w

EN 1993-1-2

$$f_{uw}(T_f, T_u) = k_w(T_f) \cdot k_{nr,w}(T_f; T_u) \cdot f_{uw,20^\circ C}$$

$$k_{nr,w} = 1 \quad \text{for } T_u \leq 600^\circ C$$
$$k_{nr,w} = 1 - \frac{0.2}{200} (T_u - \max(T_f; 600^\circ C)) \quad \text{for } 600^\circ C \leq T_u \leq 800^\circ C$$
$$k_{nr,w} = 1 - \frac{0.2}{200} (800^\circ C - \max(T_f; 600^\circ C)) \quad \text{for } 800^\circ C \leq T_u \leq 900^\circ C$$

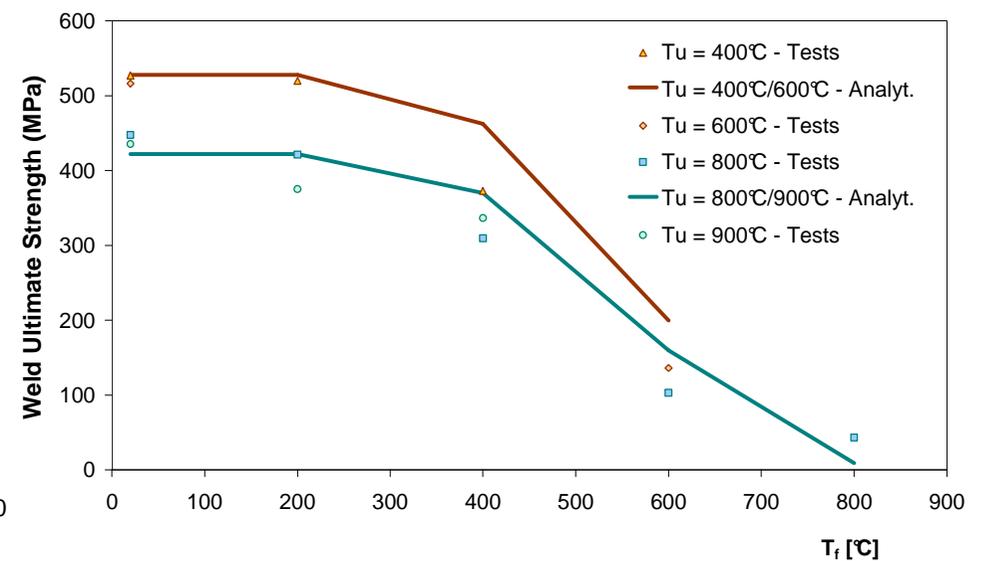
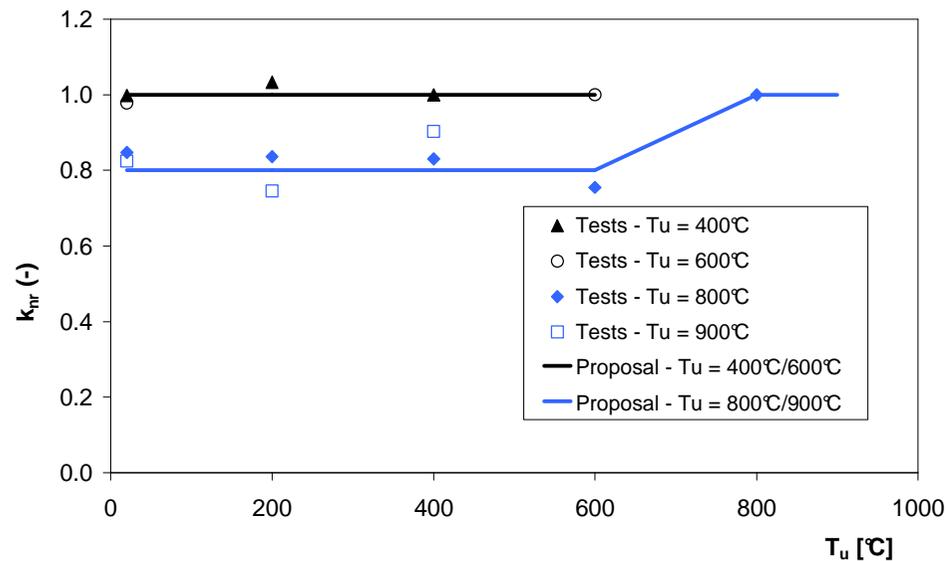
T_f : Failure temperature

T_u : Upper temperature (at the end of heating phase)

Treatment of test results

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Analytical values of weld strength k_w during cooling



Conclusions

- The influence of heating-cooling cycles on bolts and welds strength is significant ($k_{nr,b,min} = 0.6$; $k_{nr,w,min} = 0.8$)
- Ductility of bolts is increased when submitted to a heating-cooling cycle where T_u (at the end of the heating phase) exceeds 500°C .
- Material laws, including a descending branch, have been proposed for bolts in tension and bolts in shear. These can be applied to component-based models aimed at predicting the behaviour of steel connections under natural fire.

Acknowledgements

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Thank you for your attention !