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The effect of the geometric imperfections on the rotational capacity of steel beams at elevated temperatures

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Description of the problem

- The global plastic analysis of steel structures requires that at the plastic hinge locations, the cross sections of the members which contain the plastic hinge should have rotational capacity greater than the required at the plastic hinge position

- According to Eurocode 3, this problem is handled through the classification of the cross sections

- Sufficient rotation capacity may be assumed at the plastic hinge if the cross section of the member is of Class1

- In the case of the fire design of steel structures, the classification of the cross sections is conducted in the same way as in room temperature, except that a factor of 0.85 is used for the calculation of i.e. it is:

$$\varepsilon = 0.85\left[235/f_y\right]^{0.5}$$

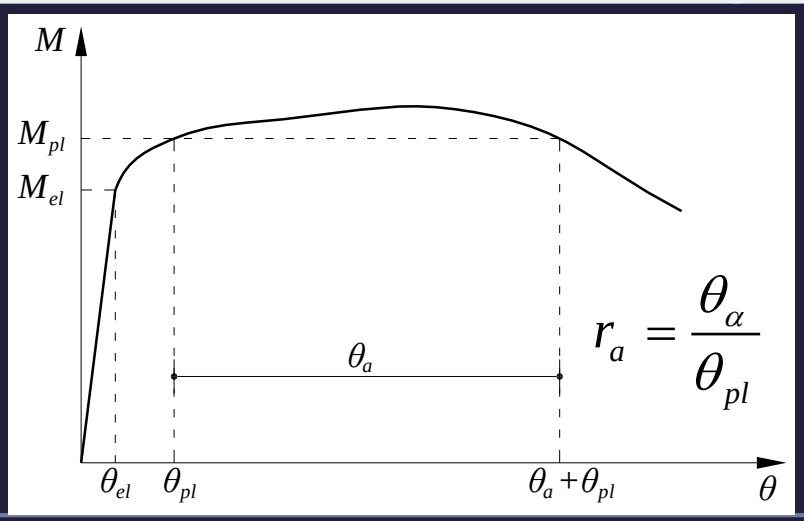
where f_y is the yield strength at 20ºC.

Description of the problem

But:

- **This consideration does not take into account several factors that affect the rotational capacity of steel members under fire conditions, as the lack of the strain hardening in the stress-strain relationship after the temperature of 400ºC, the effect of the initial imperfections etc.**
- **These parameters may lead to a premature occurrence of local or lateral torsional buckling in the plastic range, therefore limiting the available rotational capacity.**

Definition of the rotational capacity

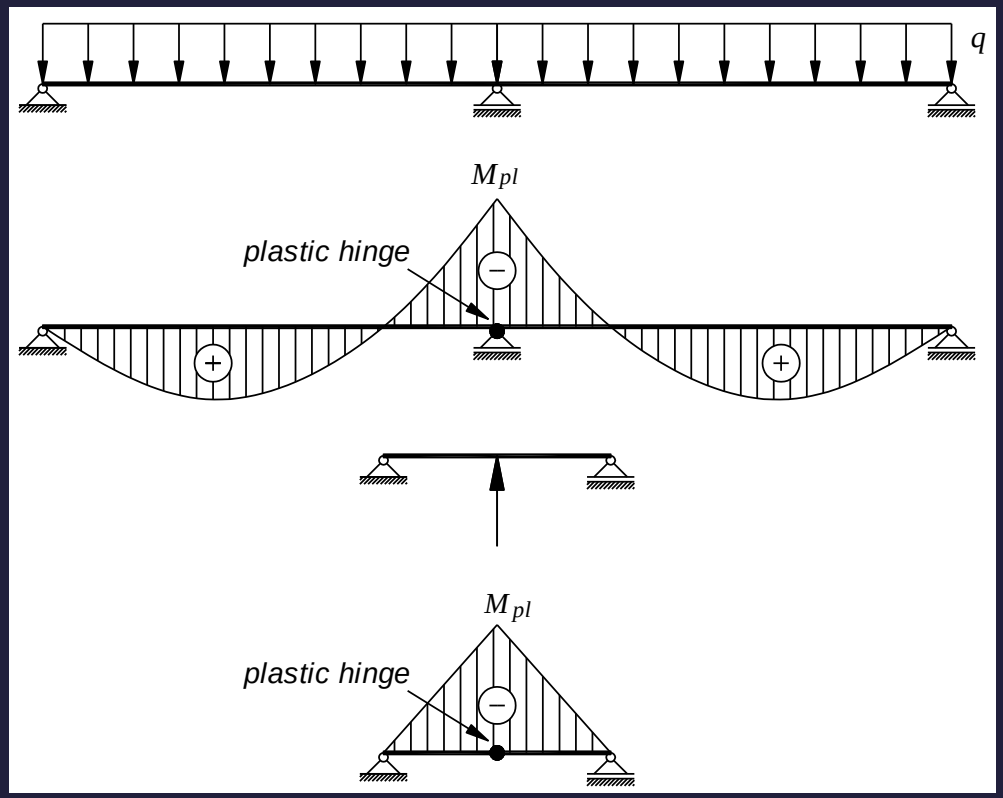


$$r_a = \frac{\theta_\alpha}{\theta_{pl}}$$

- ✓ θ_α *is* the range of the rotation over which the plastic moment resistance of the cross section is retained
- ✓ θ_{pl} corresponds to the plastic moment resistance of the cross section defined as $M_{pl,T} = f_{y,T} w_{pl}$

Description of the problem

The structural system that is considered at this study is a two span continuous steel I-beam under uniform loading



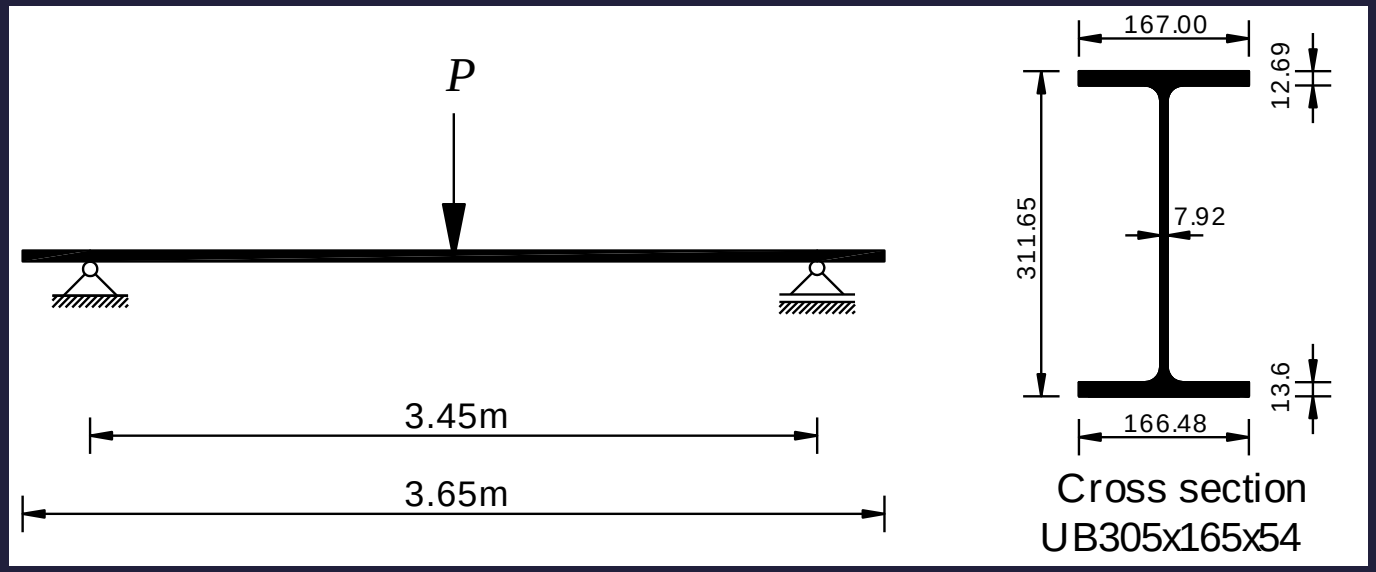
Notice:

The structural system that is used in this study is referred to a typical beam specimen of the published experimental study by R.B. Dharma and K.H. Tan. All the geometrical dimensions and the material properties are considered according to this study.

In order to <u>simplify</u> the problem a simply supported beam is considered which is loaded at the mid-span.

Objective of the study

The problem that is handled in this study is the evaluation of the rotational capacity of a simply supported steel I-beam under fire conditions.

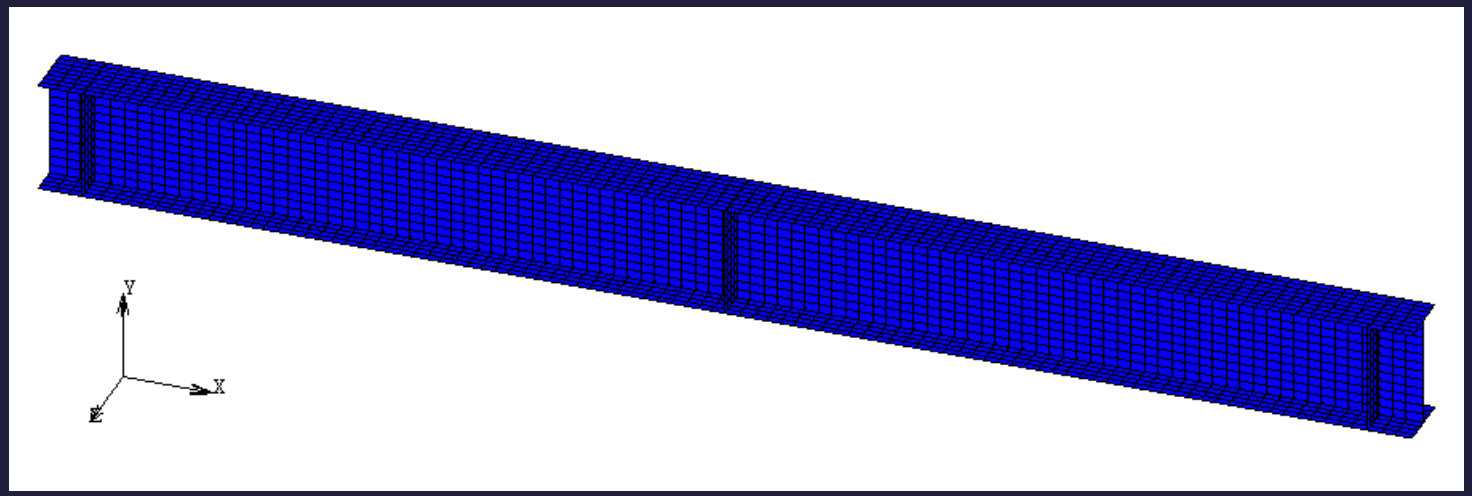


Specifically:

- moment-rotation curves are obtained, for different temperatures, under the consideration that the temperature of the beam is uniform and constant.
- various analyses are conducted taking into account different amplitudes of the initial geometrical imperfections.

The numerical model

The three-dimensional numerical model utilizes four-node, thick -shell elements



The *yield stress*, the *proportionality limit* and the *elastic modulus* are supposed to be temperature dependent according to Eurocode 3- Part1.2
and
the Von-Mises yield criterion is used in the numerical analysis

The numerical analysis

Initial imperfections are incorporated in the geometry of the steel beam for a more realistic assessment of the behaviour.

In this study the initial imperfections are introduced to the structural member according to the following :

1. **buckling analysis is conducted**

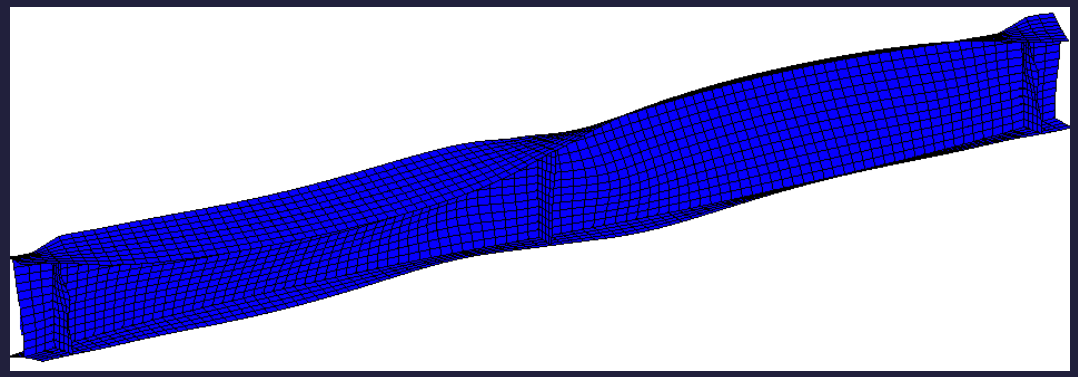
2. **the normalized buckling modes that are extracted, are multiplied by a scale factor, leading to certain maximum amplitude of the initial imperfections**

3. **The resulting “displacements” are added to the initial coordinates of the structural member**

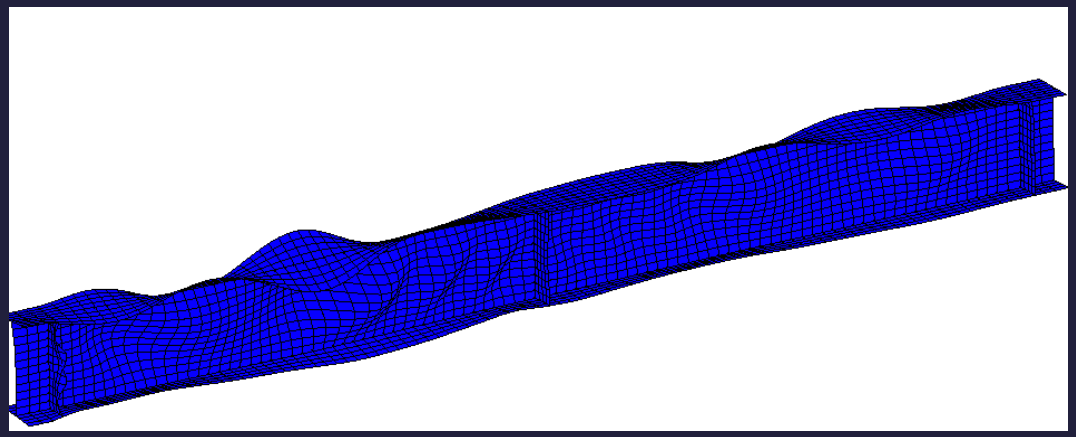
The numerical analysis

For this case study two different eigenmodes are combined:

- **eigenmode related with the lateral torsional buckling of the beam**



- **eigenmode related with the local buckling along the upper flange of the beam**



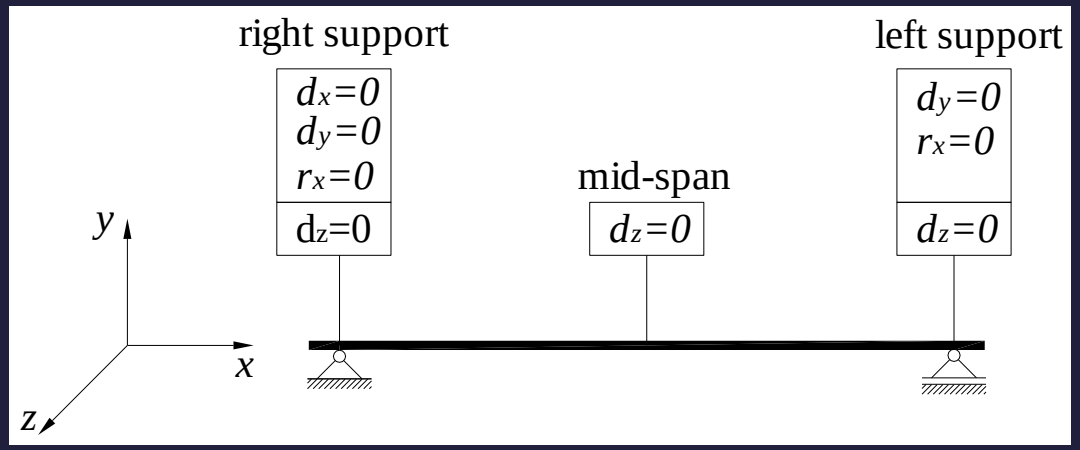
The numerical analysis

The numerical analysis has two different stages.

- **At the first stage the steel beam is heated with a heating rate equal to 7ºC/min until the desired temperature T is reached. During the heating stage the temperature is supposed to be uniform along the member**

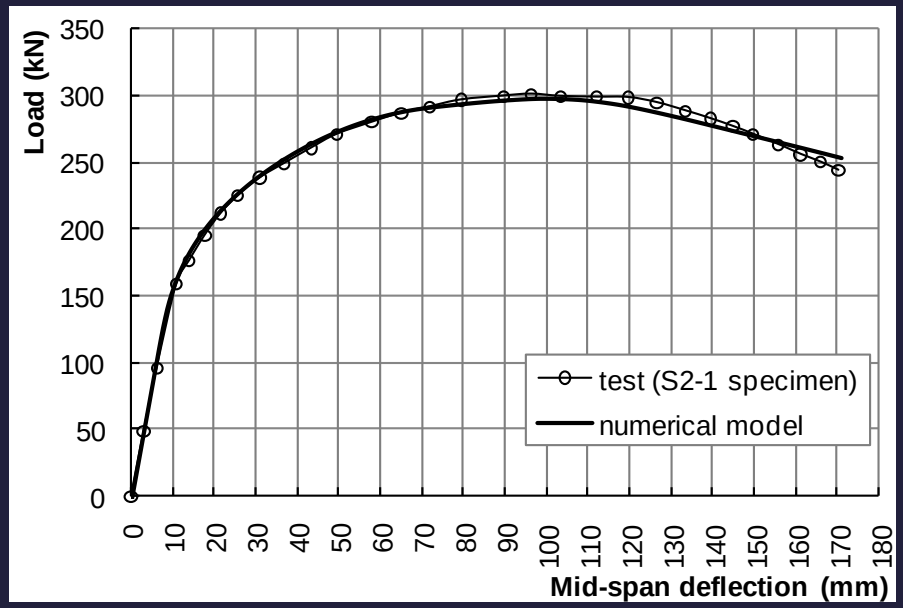
- **At the second stage the temperature remains constant and the beam is submitted to loading at the mid-span until failure occurs.**

The boundary conditions



Validation of the numerical model

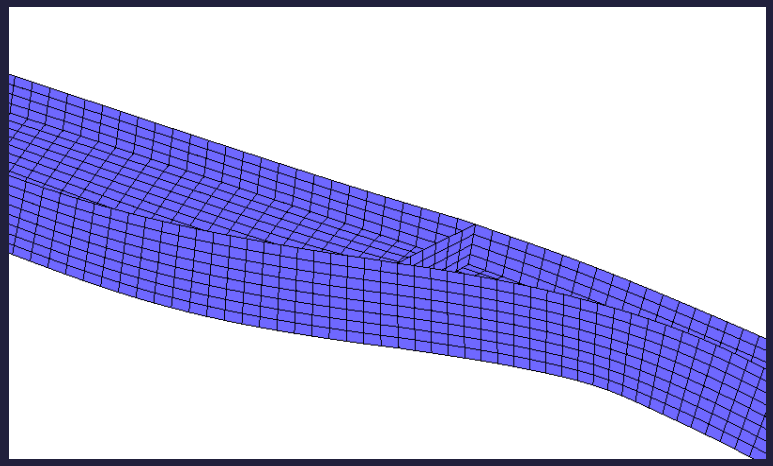
The primary objective is to validate the numerical model against the published experimental results which are presented in the study of R.B. Dharma and K.H. Tan



- ✓ **A very good agreement is obtained for the initial stiffness and for the maximum load of the system**
- ✓ **the softening branch is well approximated.**

Validation of the numerical model

The failure mode that results from the numerical analysis is very close to the experimental results



In both cases the failure is due to *lateral – torsional buckling* of the steel beam.

Parametric analyses

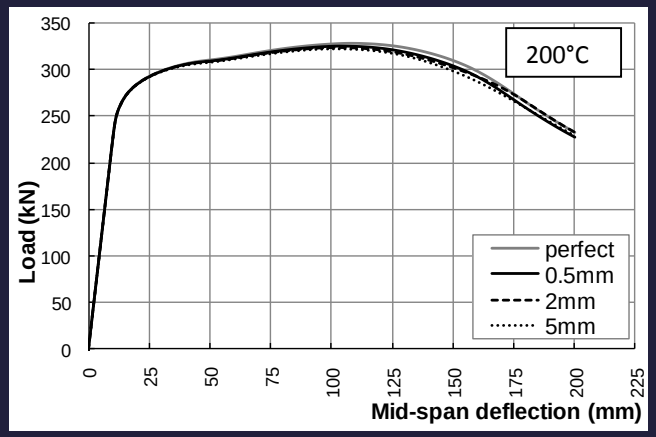
Parametric analyses are conducted at various temperature levels in order to find out the effect of the initial imperfection on the available rotational capacity of the beams.

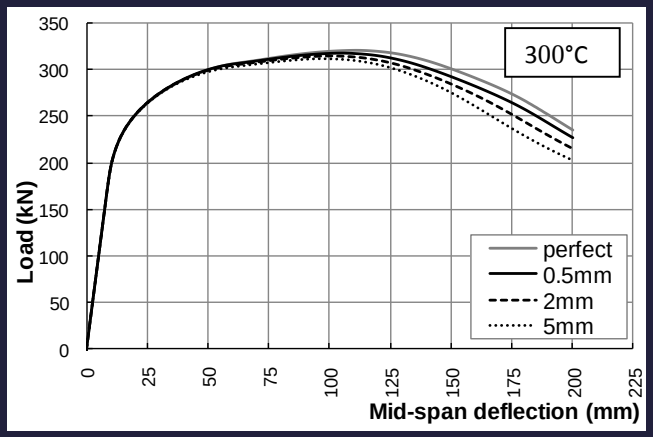
In particular:

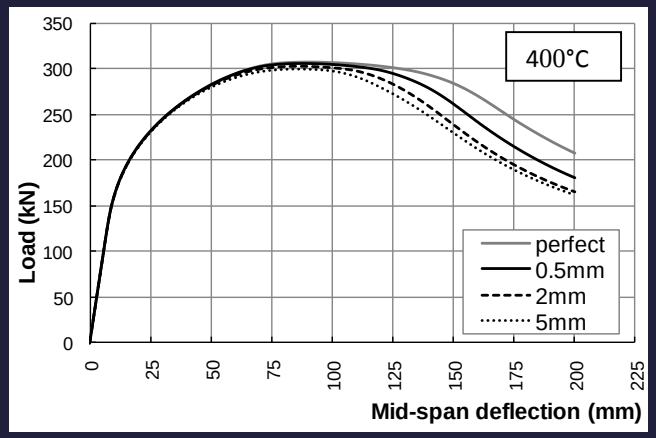
- **the analyses are conducted for temperatures ranging between 200ºC and 900ºC.**
- **the amplitude of the initial imperfections is considered to be between 0.5mm 2mm and 5mm for both the local buckling and the lateral torsional buckling eigenmodes.**

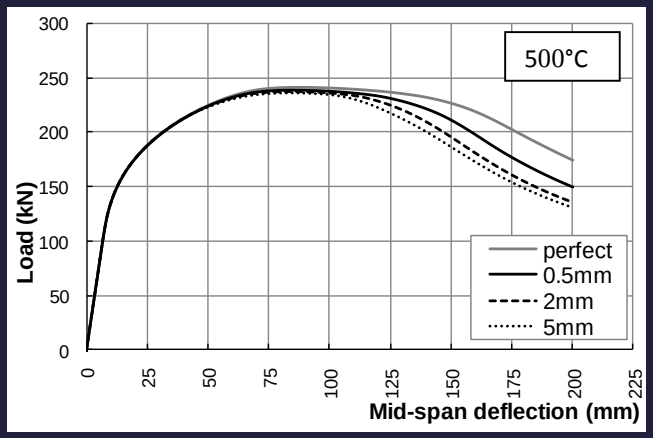
Results of the parametric analyses

Results of the numerical analysis in terms of load – displacement curves for various temperatures levels









Results of the parametric analyses

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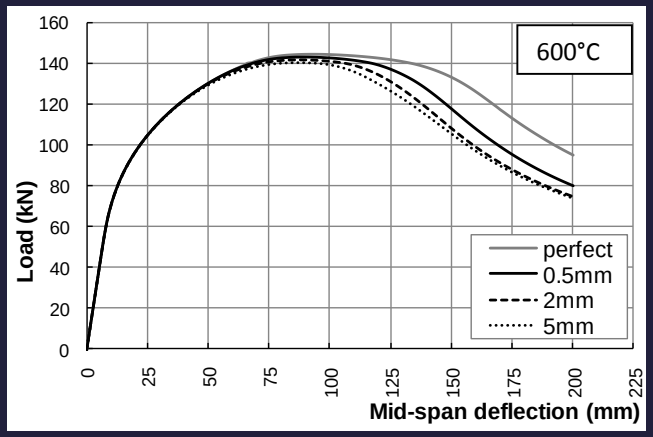
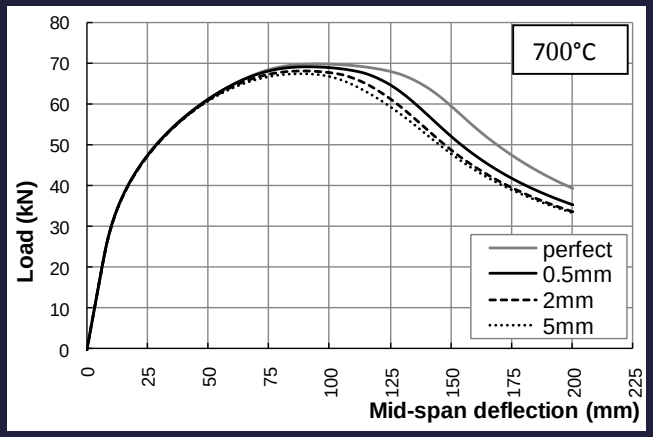
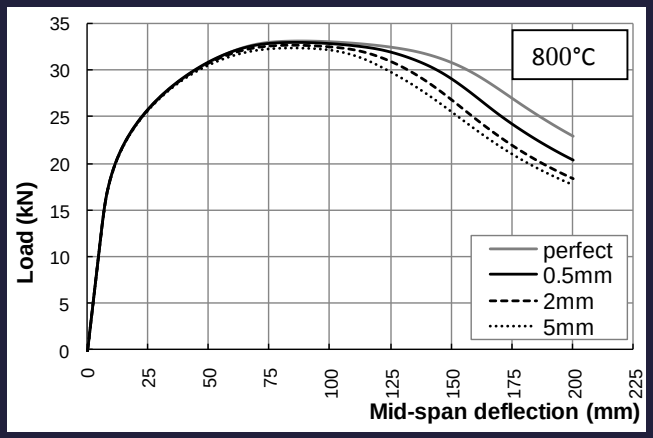
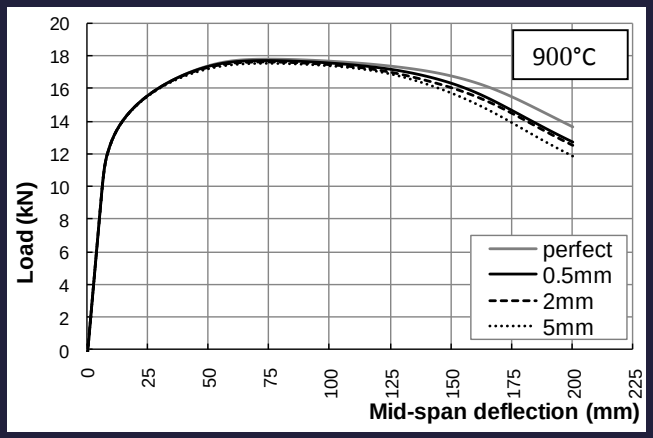








Results of the parametric analyses

It is observed that:

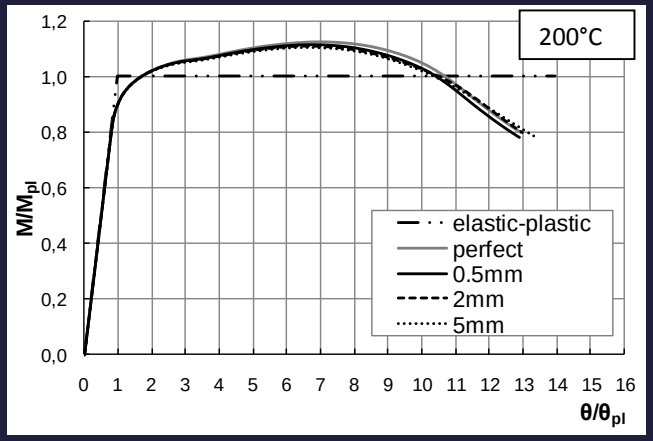
- **The initial imperfections do not affect the maximum load bearing capacity of the beam. This result holds for all the temperature ranges.**

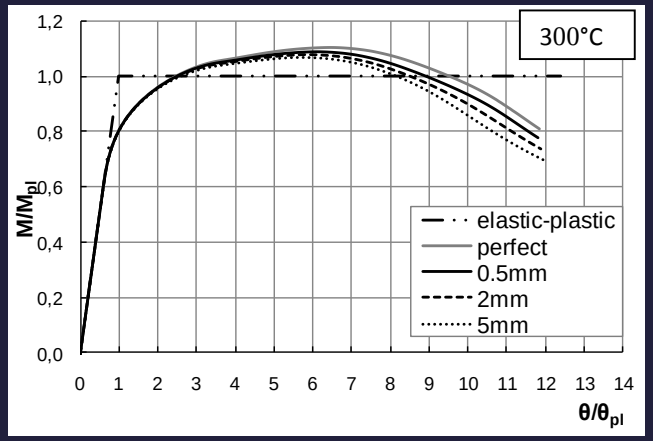
- **For temperature values less than 300ºC the incorporation of the initial imperfections to the geometry of the steel beam has a minor effect to the softening branch of the diagram**

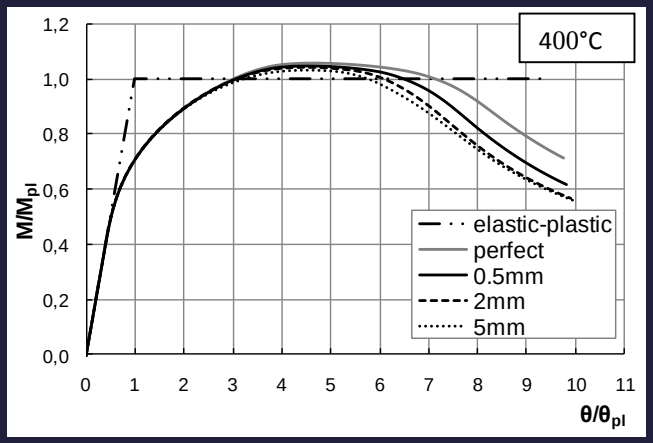
- **On the contrary, for temperature ranges between 400ºC and 800ºC, as the amplitude of the imperfection increases, the softening branch becomes steeper.**

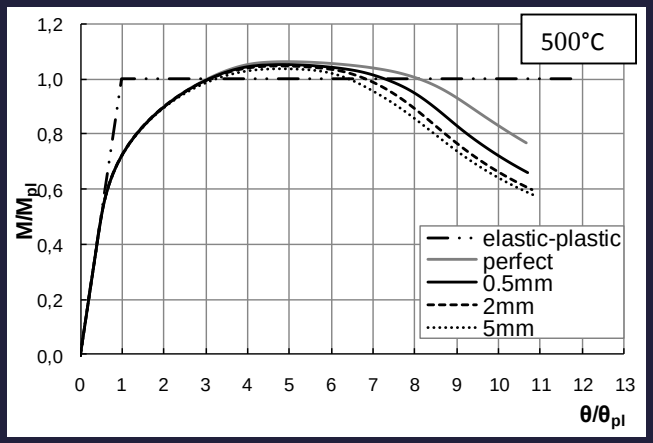
Results of the parametric analyses

Results of the numerical analysis in terms of dimensionless moment – rotation curves for various temperatures levels



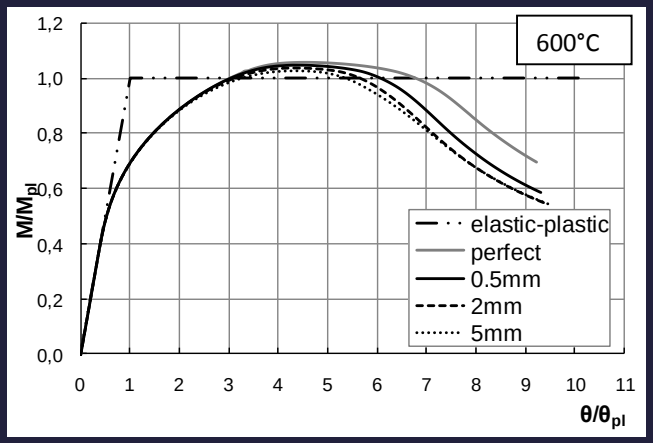


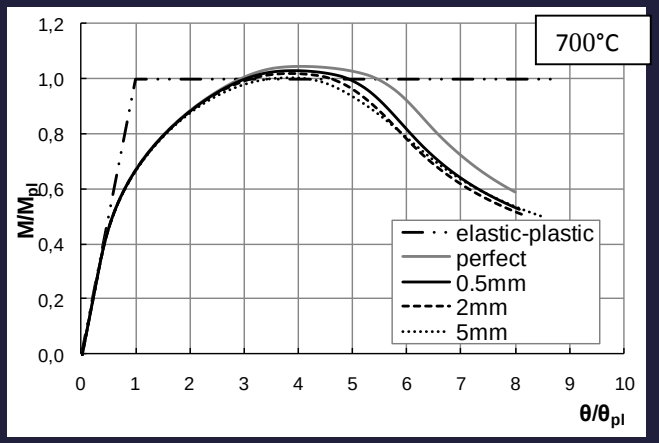


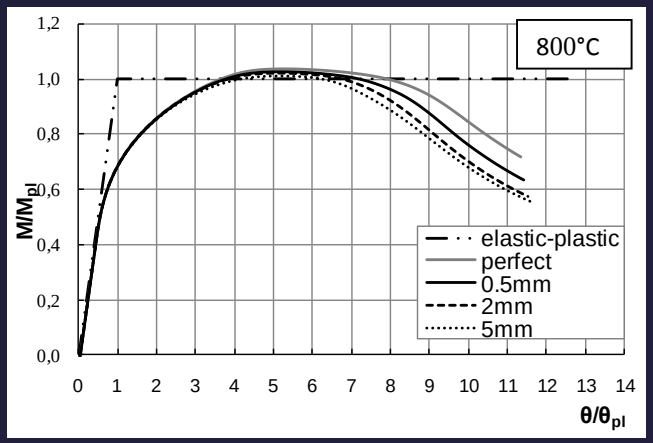


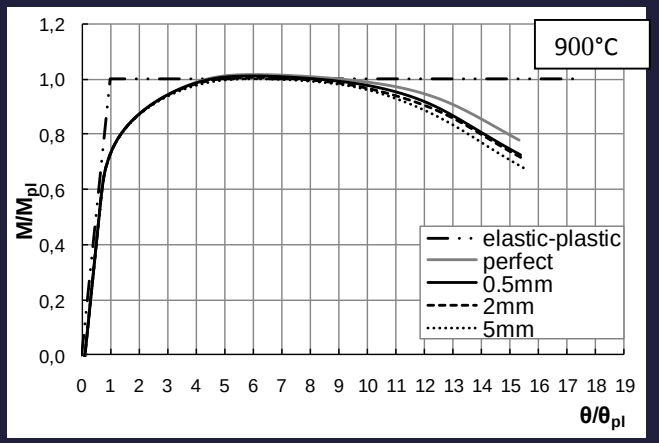
Results of the parametric analyses

Results of the numerical analysis in terms of dimensionless moment – rotation curves for various temperatures levels









Results of the parametric analyses

It is observed that:

- **For all the temperature levels the steel beam is able to reach the plastic moment resistance, since no local or lateral torsional buckling takes place in the elastic region.**

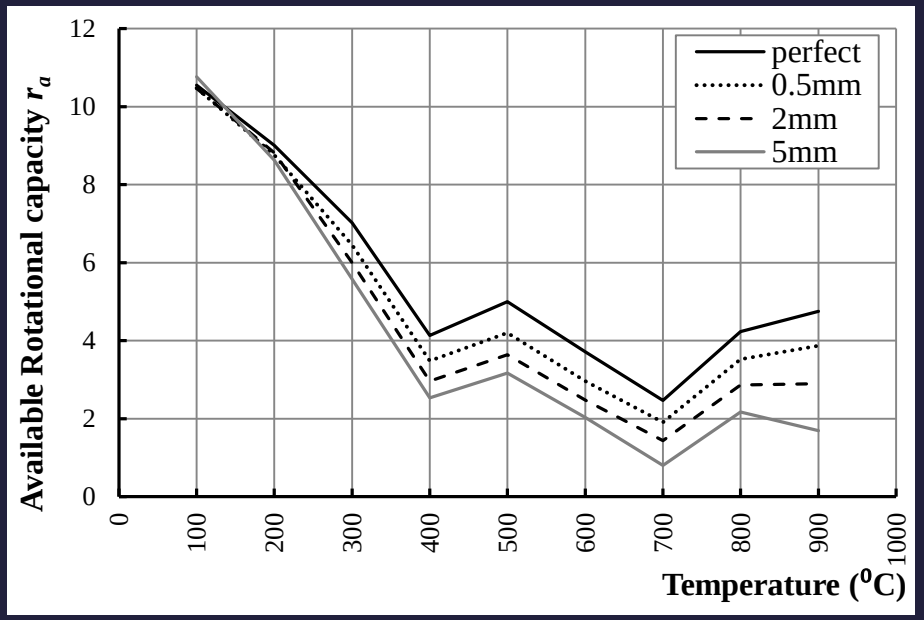
- **Despite the fact that according to Eurocode 3 for temperatures ranging between 20ºC and 400 ºC the ultimate strength of the steel is 1.4 times greater than the plastic moment, the ultimate moment that results from the numerical analysis is 1.1 times greater than the plastic moment of the section. This can be attributed to the fact that geometric nonlinear phenomena arise as the deflection of the beam increases.**

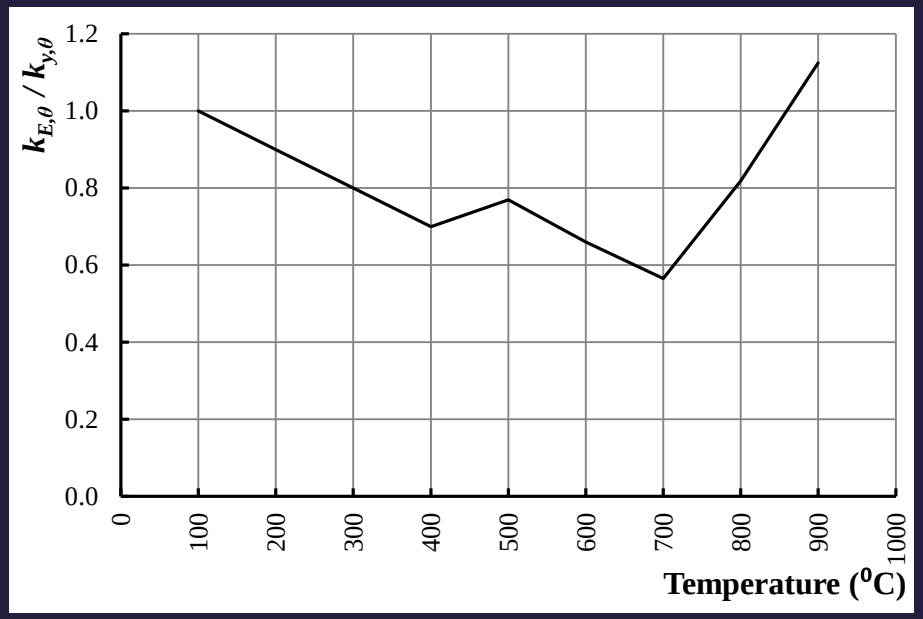
- **It is clear that for temperatures ranging between 400ºC and 900ºC, the rotational capacity of the steel I-beam is considerably reduced.**

- **The available rotational capacity reduces as the amplitude of the initial imperfections becomes larger.**

Results of the parametric analyses

Available rotational capacity of the steel beam at various temperature levels





It is noticed that

- **both the initial imperfections and temperature have a significant effect on the available rotational capacity**

- **the rotational capacity seems to be increased for temperatures above 800ºC with respect to the values obtained for lower temperatures**

Thank you for your attention

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