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(Not only) Reliability aspects of (not only) fire design

Considerations regarding the choice of the appropriate research topic due to external causes

General outline of the presentation

- Perspectives and difficulties
- The Past

  and

- The Future ???

A few words about myself

- Civil engineer specializing in steel constructions
- PhD in 2007 - not devoted to the structures in fire (on load-bearing capacity and deformability of selected type of self-drilling connections in thin-walled structures)
- Experience in testing structures (in room temperatures) subjected to different loading situations and in testing connections and joints (mainly bolted ones)
- Certified engineer – practitioner for 12 years, designer of steel structures, used to solve more or less <u>but</u> practical problems related to fire engineering in everyday professional life

Explanation of the presentation's title

The title of this presentation is a bit tricky and has additional metaphoric meaning …

The term "reliability" used in the title is closely associated with the probability of failure.

Similarly - scientific achievements and success in research are dependent on many external factors, including - in most cases - the possibility of obtaining funds for the planned research (Luke Bisby, UoE: Everything goes around money!)

The probability of failure in this context is much greater than the probability of success, as I try to prove you later on.

What have I wanted to do so far?

- During last three years we've been trying to obtain funds for construction of the testing stand enabling relatively wide range of tests, and – in consequence - for experimental research on steel members axially and rotationally restrained, considering variety of types of supports (in terms of stiffness)
- Totally we've developed and submitted eight applications, but despite very positive reviews, highly evaluated and high-value content-related applications we haven't succeeded in obtaining any financing
- Reasons ???

Direct reasons of failure – system changes in budget allocation

- Method of budget allocation for research in Poland in recent years has significantly changed
- Two new executive governmental agencies were established to support scientific activities: the National Science Centre (NSC), and the National Centre for Research and Development (NCRD)
- Structural and/or civil engineers DO NOT FIT WELL in a range of interests of any of them and the chances for this group of professionals has dramatically decreased !!! For the new „system" the civil/structural engineering is not a science but a kind of craftsmanship

The National Science Centre (NSC) vs. National Centre for Research and Development (NCRD)

- NSC focuses its attention on a group of „basic scientific disciplines" i.e. those, which are undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, WITHOUT ANY DIRECT PRACTICAL APPLICATION OR USE OF THE RESULTS
- NCRD in contrast favours „applied research", i.e. research undertaken to acquire new knowledge, focused primarily on its practical applications, and makes the grant funding for research DEPENDENT on the promise to establish cooperation with industry (copy of bilateral agreement) and the declaration of the implementation of research results

Argues of funding refusal in our case

- The National Science Centre
  argued that the applications were dedicated to applied research of practical interest
- The National Centre for Research and Development
  argued their refusal with the fact that currently only the conservative prescriptive approach of the assessment of structural fire safety given by codes is acceptable by authorities, so that at the current state of the law there is no chance to implement the results of planned/applied research and/or find their practical application

Parametric study of an axially and rotationally restrained columns under fire

The research was done in cooperation with my friends **Lesław Kwaśniewski** (WUT) and **Krzysztof Łącki** (SGSP), whose knowledge and experience were invaluable when developing numerical models and conducting numerical calculations. Without their involvement the study wouldn't be possible.

The research was focused on a study on numerical modelling of steel columns subjected to axial and rotational restraints at elevated temperatures. The problem was investigated using nonlinear dynamic finite element simulations carried out using general purpose program LS-DYNA®.

It focused mainly on numerical model development and its verification and validation. Several modelling options and strategies for modelling thermal and mechanical, initial and boundary conditions have been considered.

A numerical prediction of structural response during heating was compared with published experimental data. Both test results and numerical analyses show that axial restraint significantly reduces the column fire resistance.

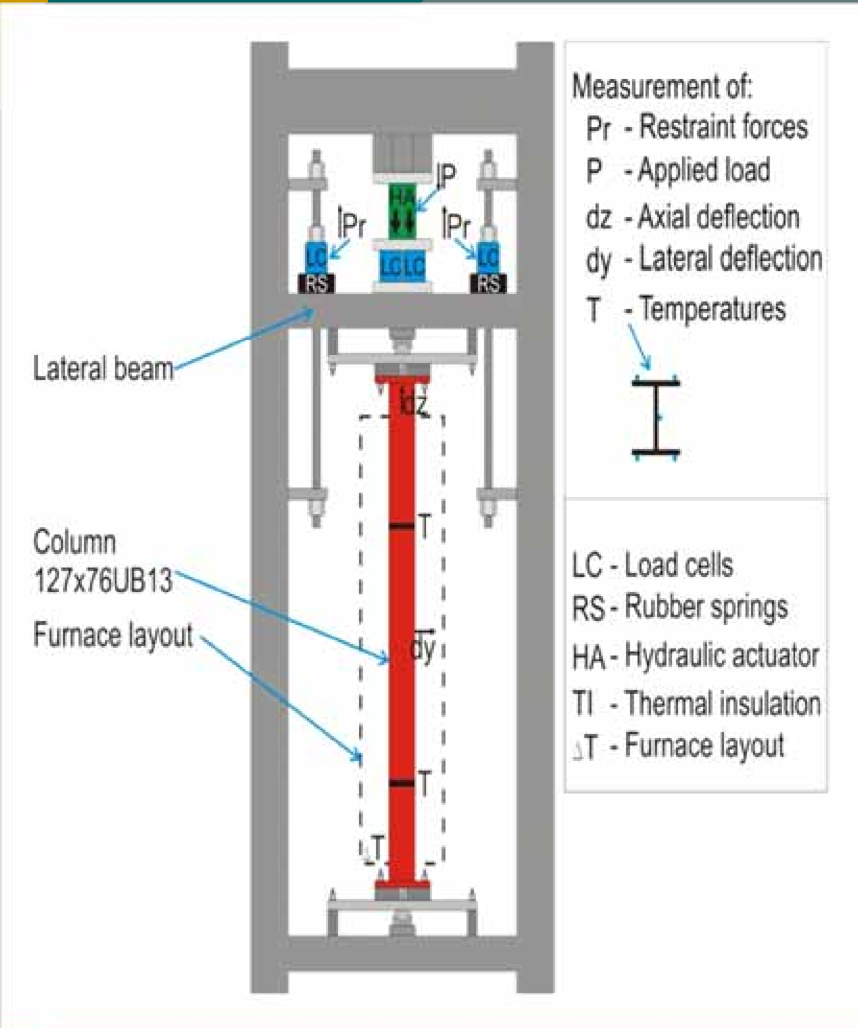
The results are summarised and concluded in:

1) Kwasniewski, L., Krol, P.A., Lacki K., Numerical modelling of steel columns in fire, in: Proceedings of COST Action C26 International Conference: Urban Habitat Constructions Under Catastrophic Events, Naples, Italy, 16-18 September 2010

2) Kwasniewski, L., Krol, P.A., Lacki K., Virtual tests on axially and rotationally restrained steel column under fire, Journal of Structural Fire Engineering, Vol. 2 , No 2, June 2011, pp. 109-121

COST Action TU0904 *Integrated Fire Engineering and Response*
Training School, Malta-Sliema 12-14 April 2012

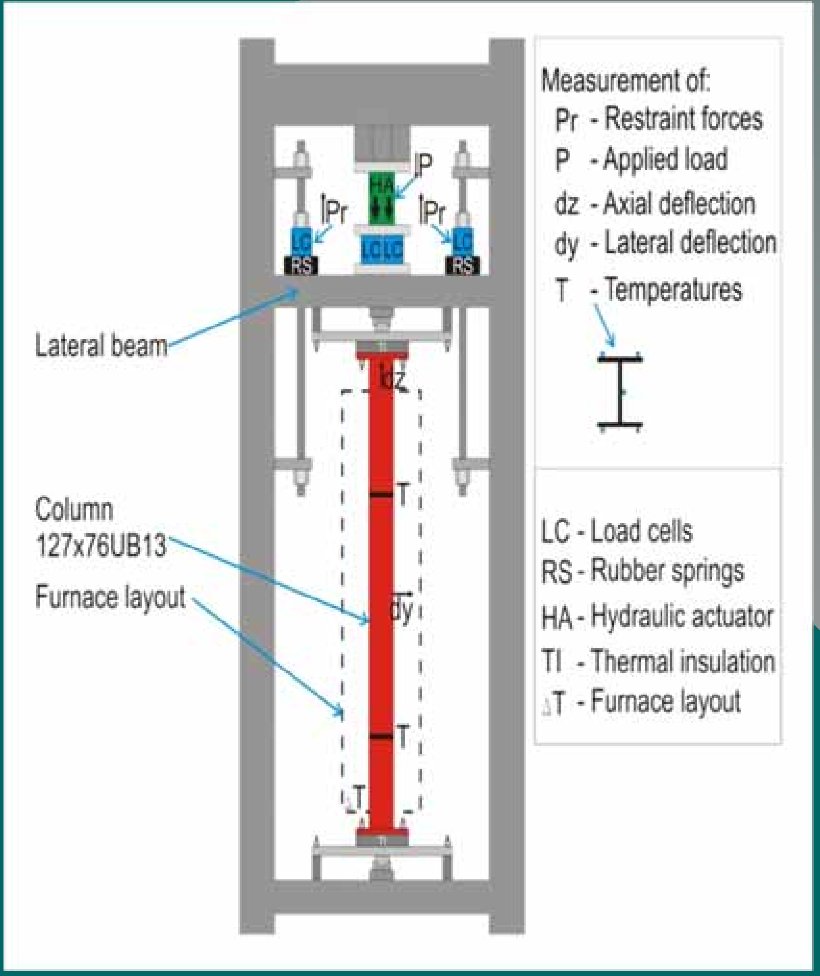
Parametric study of an axially and rotationally restrained columns under fire



The results of experimental investigation for steel columns 127x76UB13, performed at *The Fire Research Centre, University of Ulster* in the collaboration with *The University of Sheffield*, presented by Ali and O'Connor (Ali, F. and O'Connor, D., Structural performance of rotationally restrained steel columns in fire, Fire Safety Journal, 2001, 36, Issue 7, pp. 679-691) were used.

Half scale steel columns were tested in furnace under different values of rotational and axial restraint. For the chosen loading scenario the investigated members were first loaded up to the level of about 205 kN and then heated. During the test, both – axial forces and column expansion as well as lateral displacements in a mid-section were measured and recorded.

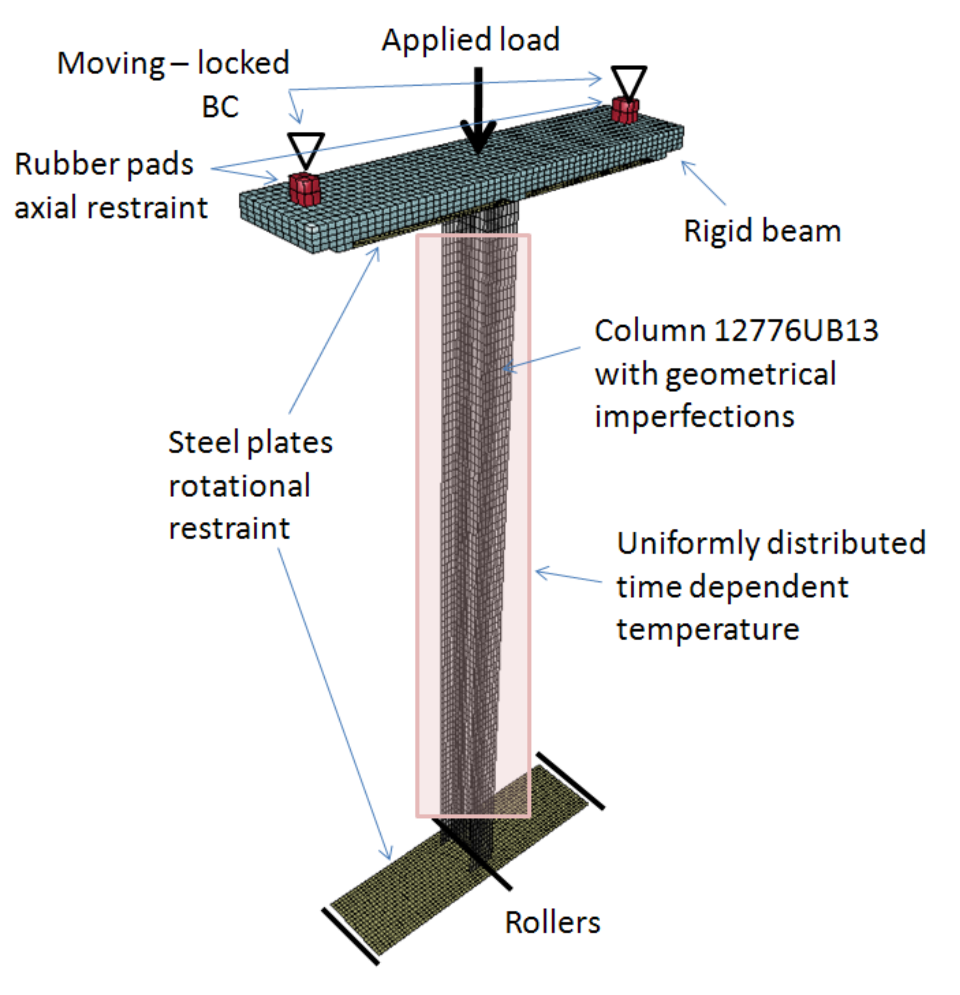
Parametric study of an axially and rotationally restrained columns under fire



During the test temperature was controlled and monitored by the set of thermocouples distributed uniformly at three levels of the furnace and two levels of the tested specimen.

At each level of the column five thermocouples were used in the following arrangement: one attached to the centre of the web and four attached to the column flanges (see the picture).

Finite Element Model of the experimental test setup



Investigation was focused on parametric study which indicated three important modelling parameters affecting numerical results:

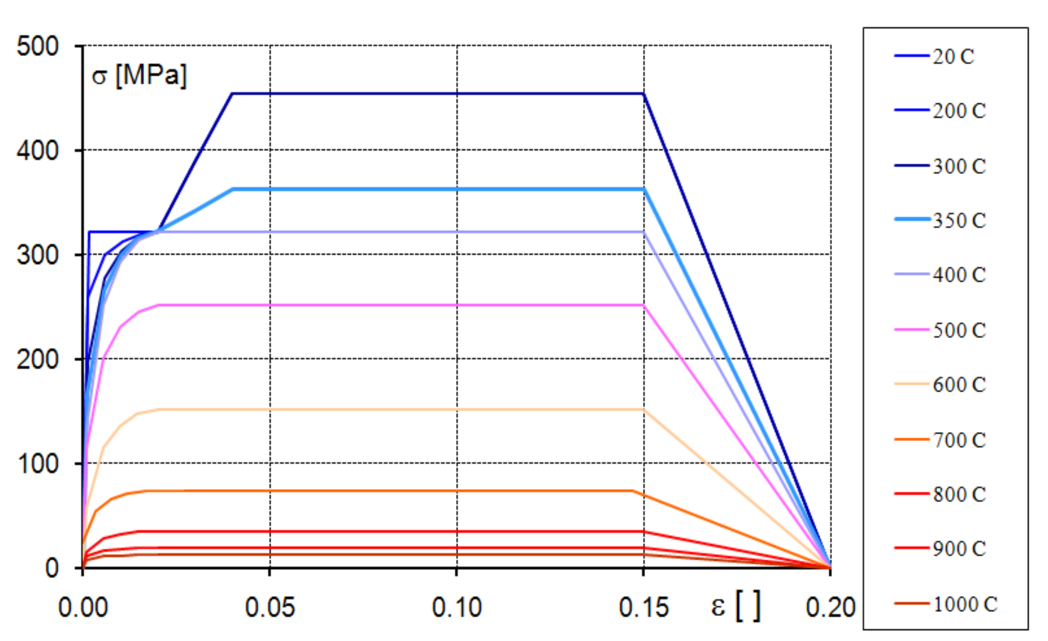
- model description of material properties for the used grade of steel,

- geometrical imperfections and

- longitudinal variation of the temperature in the column at the areas close to the furnace walls

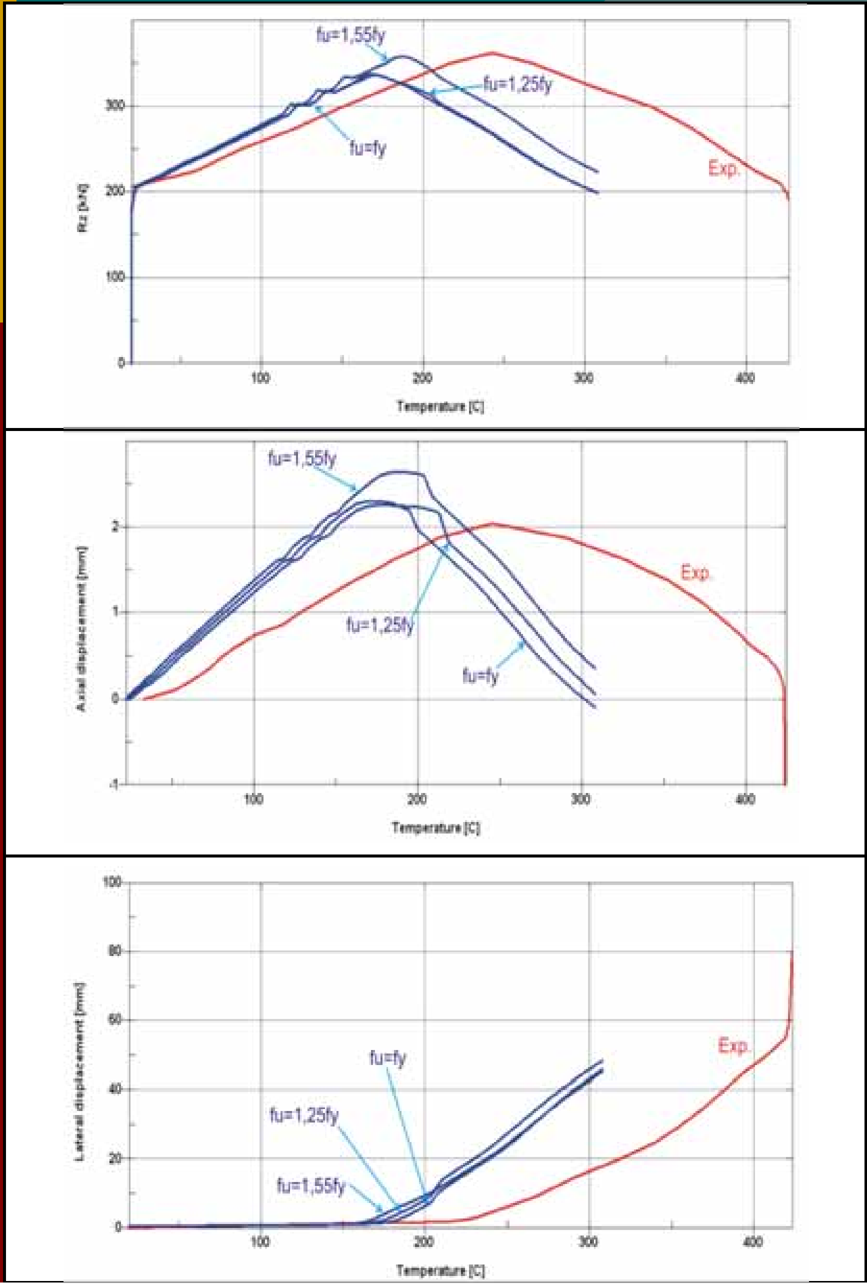
Material model/properties

Three temperature dependent material models were tested for the columns' steel grade assumed as S275.



The temperature dependence of stress strain relationships for all three cases was set based on formulae provided by EN 1993-1-2 for carbon steels

- The first material model applies nominal yield stress f_y without any strain hardening (f_u=f_y=275 MPa)
- The second model takes into consideration nominal yield stress and strain hardening approximated according to EN 1993-1-2, (f_y=275 MPa, f_u=1.25f_y)
- The third material model f_y=303 MPa, f_u=469 MPa (f_u=1.55f_y), is based on the couple of tests presented by Wald et al. (Wald F, da Silva LS, Moore D, Santiago A., Experimental behaviour of steel joints under natural fire, in: ECCS - AISC Workshop, 2004)

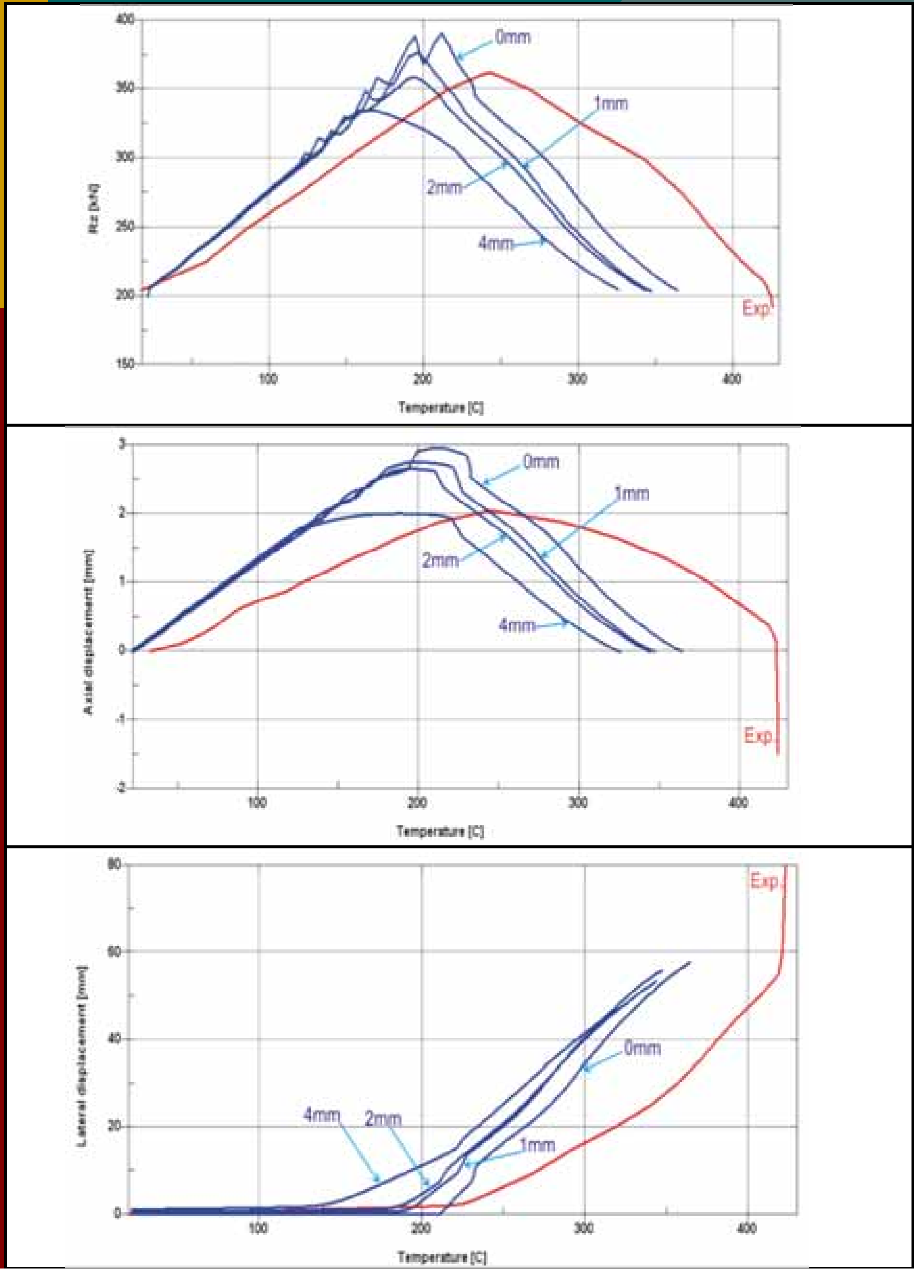


Comparison of experimental data and calculated results for all the material models applied

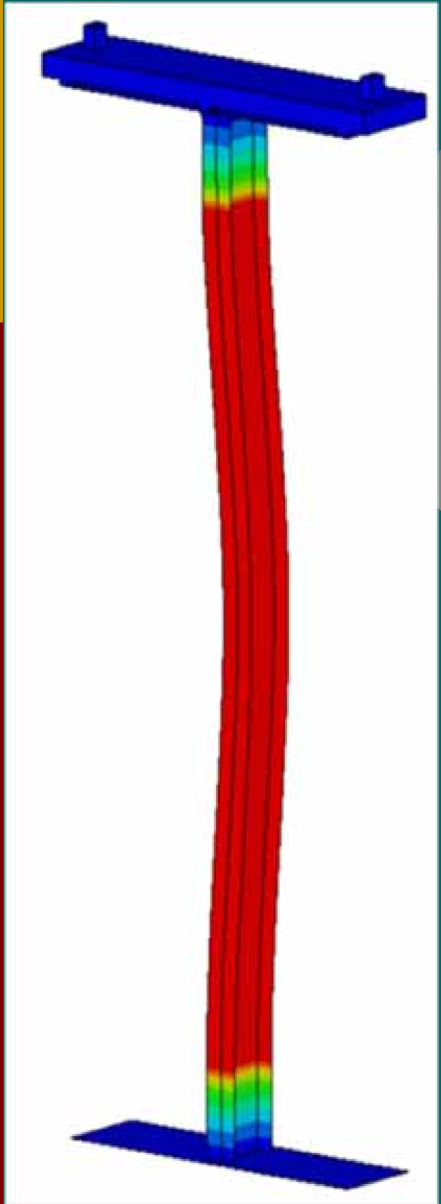
All three figures show that the actual buckling (as obtained in laboratory tests) occurs at higher temperature and that the post-buckling behaviour is less rapid comparing with the numerical predictions.

The comparison indicates that besides material behaviour there other modelling parameters affecting the numerical results.

Effects of geometrical imperfections applied



- The effect of geometrical lateral imperfections of mid-span cross-section for four prescribed amplitudes: 0 mm, 1, 2, and 4 mm is shown.
- The results of analyses show, that geometrical imperfections initially applied to a specimen significantly affect the final results of the calculations in terms of maximum load and post-buckling behaviour. The curves for higher magnitudes of imperfections much better approximate recorded experimental measurements, however still the actual buckling obtained during lab tests occurred at higher temperature.
- This discrepancy indicated the next important modelling factor which is attributed to the not uniform heating of the column and is discussed on the next slide.

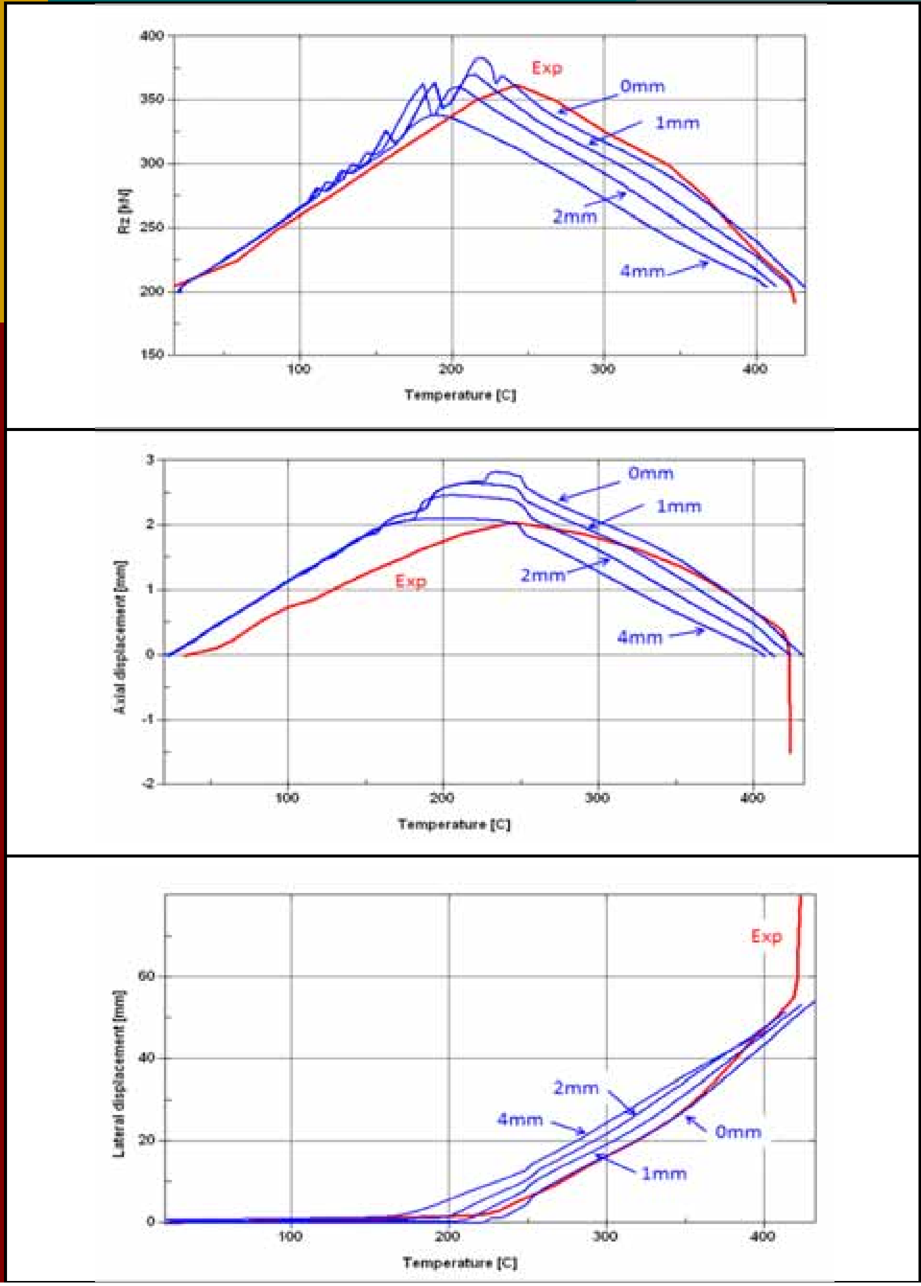


Variation of column temperature

In the first modelling approach, following the description of the experiment presented by Ali and O'Connor, it was assumed that the whole volume of the column part placed inside the furnace, was subjected to the same (time dependent) temperature.

Closer examination of photos showing the considered furnace experiments indicated that the bottom and top segments of the column, located near the furnace walls, were subjected to lower temperatures due to unavoidable heat transfer through the furnace openings.

In the next step the original heated length of the column equal to 1750 mm was reduced to 1460 mm. This central part of the column had been modelled to obtain the uniform distribution of prescribed time dependent temperature along its length, while the rest of the column was subjected to longitudinally varied temperatures, calculated from the heat transfer.



Effects of temperature variation

The temperature variation along the column applied in the FE model reduced total thermal elongation and led to postponed buckling occurring at higher furnace temperatures.

Curves presented in the pictures for temperature variation of the axial force, axial and lateral displacements, show much better correlation with the experimental data than in the previous steps.

In our opinion it was not possible to correlate better numerical results with the existing experimental data without reducing model uncertainties (e.g. imperfection magnitudes) through additional experiments and measurements.

What is „reliability”?
Is it really the future of the fire design?

- The reliability of structure can be understood as its ability to fulfil its design purpose for some expected design time. Reliability is often understood to equal the probability that the structure will not fail to perform its intended function.
- The sufficient and widely expected reliability level is generally ensured by application of rules and meeting the requirements provided by codes and standards of design; (Luke Bisby, UoE: Everything we do is probabilistic, everything relates to some level of risk)
- In case of fire design, prescriptive approach in many countries is still the only accepted solution to prove that the structure is well designed. It leads to costly, and not economical solutions.

Historic evolution of design and assessment using traditional methods – advantages and disadvantages

- Prescriptive approach – has yielded adequate performance, but is considered too conservative and simplistic because it doesn't account for actual loading conditions and real fire scenarios.
- Performance-based approach – allows for more rational engineering solutions, better reflects the real fire conditions dependent on many parameters, but is not fully accepted by the authorities in many countries. Can be based on alternate analytical methods provided in informative ECs, using Load and Resistance Factor Design philosophy, fully consistent with the Limit State Method and applied in eurocodes.

Other methods of assessment

- Design assisted by testing – reliable, but expensive tools. Used mainly for testing singular structural elements, and for that reason is not able to answer all questions or doubts.
- Advanced numerical models (utilizing CFD solutions and FEM codes) – based on very sophisticated numerical tools, reserved only for very narrow group of specialists having big theoretical knowledge on fundamental sciences. To be fully reliable requires verification and validation by comparing with experimental tests. Not cheap. Less sophisticated models/software are possible to use but in majority they reflect procedures given in eurocodes although are very useful as they simplify manual calculations.

Reliability-based design philosophy

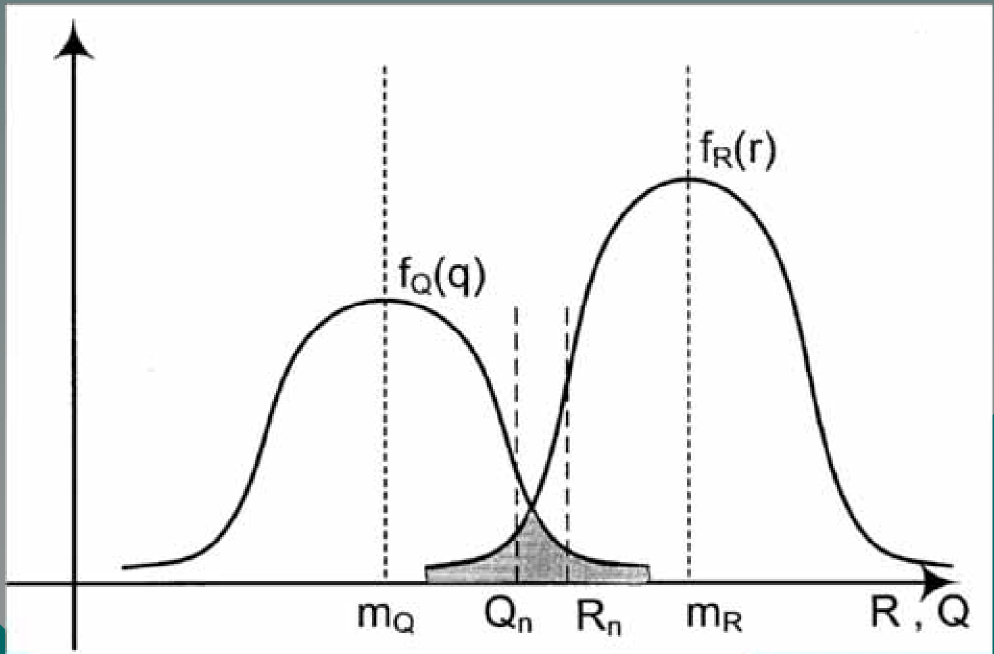
- Can be developed in conformity with the general philosophy of the limit state method and the Load and Resistance Factor Design (LRFD) philosophy, so can be treated as the development of eurocode's provisions
- Allows for moderate differentiation in the partial factors for actions and resistances corresponding to the consequences/reliability classes
- A design using EN 1990 with the partial factors given in annex A1 and EN 1991 to EN 1999 is considered generally to lead to a structure with a β (reliability index) value greater than the minimum value suggested for 50-year reference period.

Advantages of reliability-based design philosophy

- Allows for designing structures with preselected target reliability index, that directly leads to less costly solutions,
- Allows for designing structures considering the service life shorter than 50 years (important e.g. for high-bay warehouses with wall structure supported by racks)
- Allows for reducing the probability of failure in reducing the probability of occurrence by accounting for effects of active fire protection systems (sprinklers, smoke and heat detectors, etc.)
- Allows for calibrating individual capacity reduction/load factors for different structural elements, depending on individually proposed technical solutions and other important parameters, considering different types of occupancies.

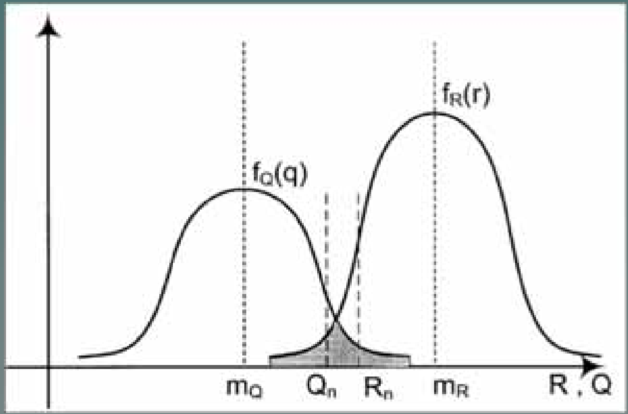
Fundamentals of reliability-based design evaluation

- Q – load applied to the structure
- R – capacity of the structure
- Both Q and R are random variables, and their randomness is characterised by their means - m_Q and m_R, standard deviations – σ_Q and σ_R, and corresponding probability functions $f_Q(q)$ and $f_R(r)$



The area of overlap (the shaded region in a picture) represents the probability of failure

Fundamentals of reliability-based design evaluation - continuation



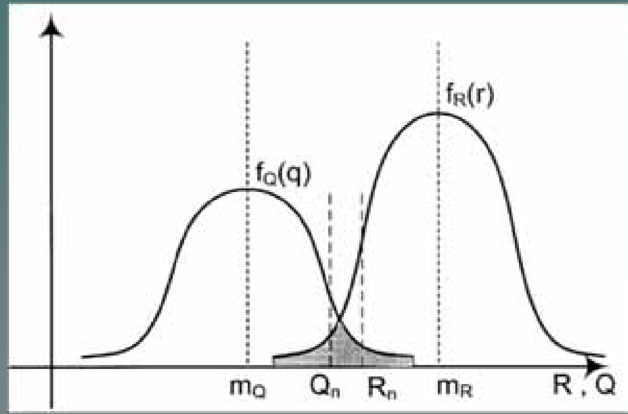
- The area of the overlap depends on 3 factors:

(1) The relative position of the two curves (as the distance between two curves increases the overlapped area reduces and the probability of failure decreases. The position of the curves is represented by the means of the variables)

(2) The dispersion of the two curves (if the two curves are narrow, then the area of the overlap and the probability are small. The dispersion is characterized by the standard deviations of the variables)

(3) The shape of the two curves (the shapes are represented by the probability density functions and affect the area of overlap and thus the probability of failure)

Fundamentals of reliability-based design evaluation - continuation



- In traditional deterministic design procedures the required level of safety is achieved by selecting the design variables in such a way that the overlap between two curves is small
- In the reliability-based approach (based on the risk-based concept) the more rational strategy assumes that the risk is computed by accounting for all three overlap factors so that an acceptable risk of failure is achieved.

Evaluation of risk

- A variety of approaches can be used to estimate the risk associated with a particular design situation. A review of the various approaches has been presented for instance by Magnusson S.E., Frantizich H. & Harada K. in „*Fire Safety Design Based on Calculations, Uncertainty Analysis and Safety Verification*"; Report 3078, Dept. of Fire Safety Engineering, Lund Institute of Technology, Sweden 1995
- As an example, the most popular of them can be: First Order Second Moment (FOSM) methods, conventional probabilistic risk assessment or Monte Carlo simulations, to list just a few.

Case studies

- Some of the first attempts to apply the reliability-based approach for developing capacity reduction and fire load factors for LRFD for beams and/or steel columns considering some specified conditions were carried out at Michigan State University (Iqbal S.: Capacity Reduction and Fire Load Factors for LRFD of Steel Members Exposed to Fire"; a PhD Dissertation, MSU, East Lansing, 2010) and Cracow University of Technology (Maślak M. – couple of conference papers, i.e. Vilnius, Stambul)
- Statistics of a variety of parameters were obtained from data reported in the literature (going back to what was emphasized at the very beginning, it shows that no additional money is necessary for research)
- Based on the information available about the effectiveness of active fire protection systems in reducing the probability of occurrence of a severe fire a range of target reliability index value was established for US office compartment ranging in floor area from 25 to 500m^2 (Iqbal) and for EU conditions (Maślak)

Recommendations and needs for future research

- The case study of first attempts of the reliability-based approach application (to the calibration of capacity reduction and fire load factors for LFRD) made in the MSU, USA and CUT, PL shows that the application of the method is possible and leads to satisfactory results
- Further research in this area is welcome and can be, for example devoted to the development of safety factors for all types of structural steel members used in different types of occupancies
- In the years to come a further acceleration in the development of analytical methods used to model the behaviour of structural systems is expected as the natural consequence and the response for society needs. It’s expected that the tendency to design whole structural systems will lead to additional applications of reliability theory at the system level.

Questions to the audience

Which way to go (numerical modelling/virtual testing, reliability analyses) with the further research, considering some really important issues I'd like to point out:

- lack of money (for lab tests and not only)
- limited availability of test data published in the literature (most information is secret due to variety of reasons)
- limited reliability of the furnace tests carried out on individual structural members and neglecting the scale effect (Luke Bisby, UoE: All test except the full-scale fire tests can be suspected of the lack of reality)
- lack of valuable statistical data connected for instance with institutional disinterest or thought-out strategy of governmental agencies (Jean-Marc Franssen, UoL: Insurance companies are not interested in reducing risk)
- limited quality and reliability of officially published statistical data (probability of occurrence of the severe fire, reliability of distinguishing systems, etc. as discussed during the meeting and the training school as well /Gianluca de Sanctis/)

When you consider all these difficulties you may conclude that really <u>nothing</u> makes sense.

THANK YOU FOR YOUR KIND ATTENTION

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