Industrial Applications of Computational Mechanics
What are we doing ?

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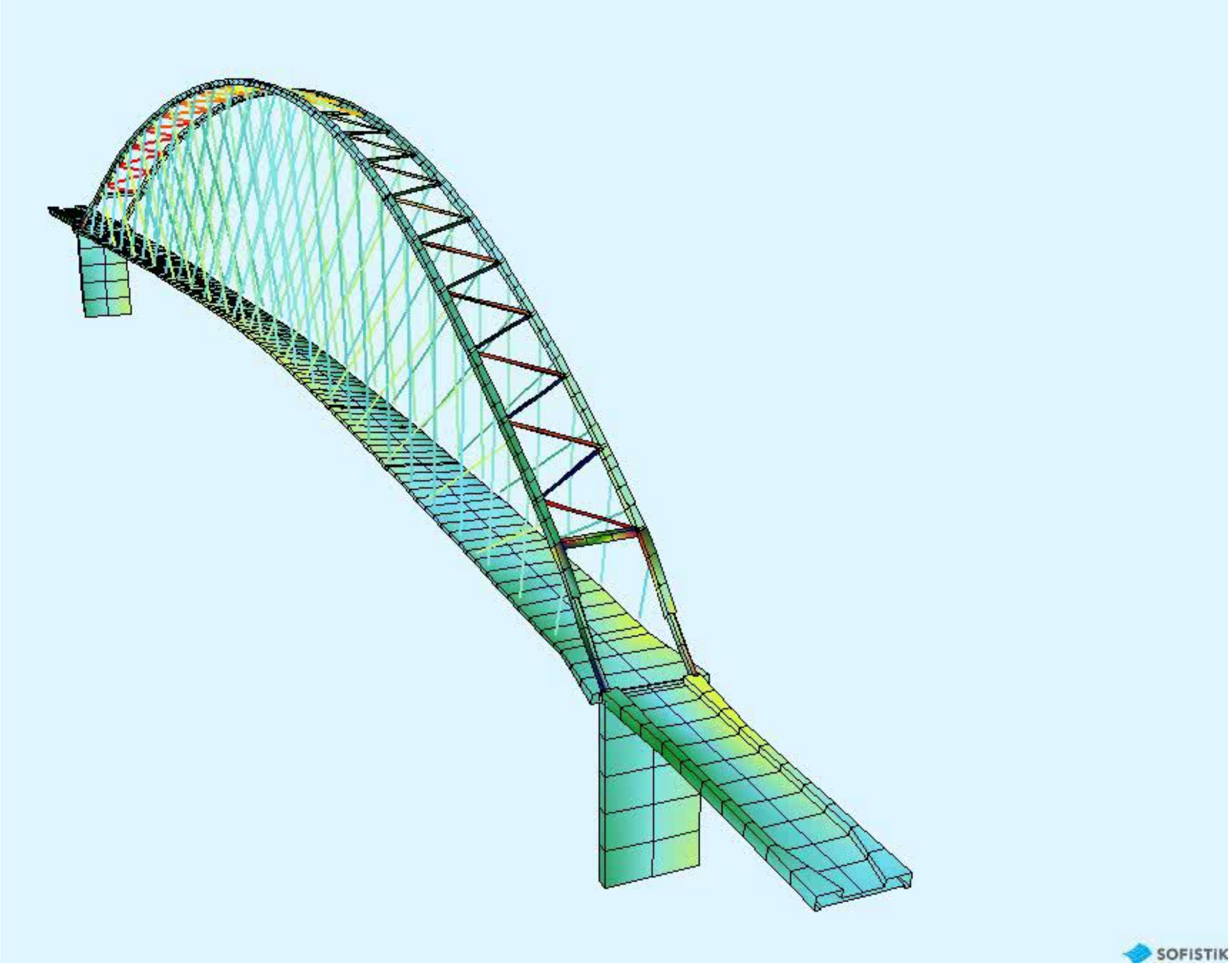
SOFiSTiK AG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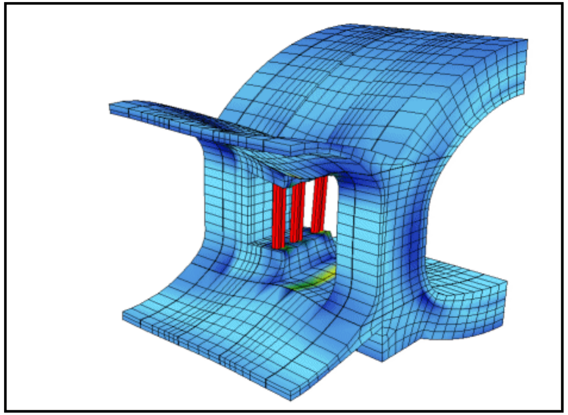
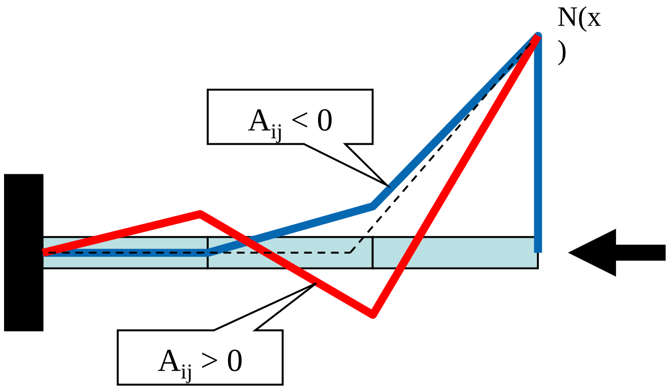
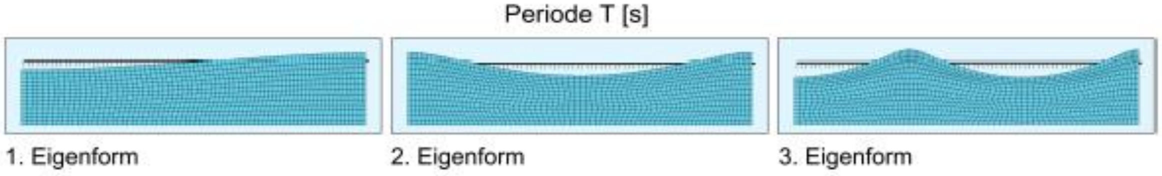






- A deeper look behind the scene – Why things go wrong
- Tricks and Clues about Numerical Tools in Engineering
- SS: Structural Analysis + Structural Design
  WS: Structural Dynamics + Wind + Multi-Physics

Overview

- Structural Statics and Design (SummerTerm)
  - What are Computers doing
  - Beams, Cables
  - Plates and Shear Walls, Lagrangian Fluid elements
  - Design for Concrete and Steel
- Dynamics – Multi Physics – CFD (WinterTerm)
  - Dynamics
  - Heat flow, Groundwater Seepage, Consolidation
  - Wind Engineering (CFD, Flutter, Gallopping)
  - Fire and Explosions

Verification and Validation

- Verification
  - Assure that the Software is solving the equations correctly
  - Usually performed by the Software Developer
  - Independent second Analysis of the same problem
- Validation
  - Assure that the correct equations are used
  - Is the primary responsibility of the user
  - Tutorials may help
  - Profession of the Engineer!

Aim of this lecture

- Nothing is perfect – keep your eyes open
- Murphy's Law: If things can go wrong, they will
- Industrial applications:
  = Histories of Successes and Failures
- How to benefit:
  - Listen and try to get the great idea (it is difficult)
  - Ask if anything is not clear!
  - Remember the keywords for your later career
  - Read the details in literature later (if needed)
  - Examination will check the overview, not the details

Problems easily solvable by a computer

- Algorithms
  - There is a clear rule what and how to calculate
  - Clearly defined criteria when to stop
  - Based on formulas
  - So we should use algorithmic languages e.g. FORTRAN, ANSI-C
- „100 engineers would need 20 years to complete this analysis”
  - But they won’t do such a silly job
  - They invent computers (ZUSE)
  - or FEM (Zienkiewicz, Clough, Argyris)

Limits of computability

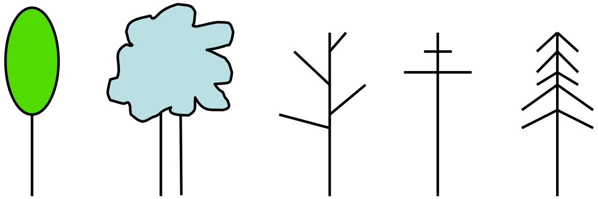
- P - NP
  - P: Polynomial Order of Algorithms: O(1), O(n), O(nlogn) …
  - NP: Verification is polynomial, solution is not
  - NP- complete: There is no polynomial algorithm;
    If a polynomial solution is found to any NP-complete problem, this may be used to solve all those problems.
  - Other difficult problems (e.g. NASH equilibrium)
- Problems
  - where an approximate solution is sufficient
  - where this is not the case

http://en.wikipedia.org/wiki/NP-complete

- Approximation:
  Instead of searching for an optimal solution, search for an "almost" optimal one.
- Randomization:
  Use randomness to get a faster average running time, and allow the algorithm to fail with some small probability. See Monte Carlo method.
- Restriction:
  By restricting the structure of the input (e.g., to planar graphs), faster algorithms are usually possible.
- Parameterization:
  Often there are fast algorithms if certain parameters of the input are fixed.
- Heuristic:
  An algorithm that works "reasonably well" in many cases, but for which there is no proof that it is both always fast and always produces a good result.

Problems difficult to solve for a computer

- **AI-Problems of any kind**
  - Expert systems (data!) / Strategies (real life and games etc.)
- **Language problems**
  - Grammar based translation ?
    - “Dear Serious”
    - „Time flies like an arrow“ versus „Fruit flies like bananas“
  - Context based translation ?
    “When God created man, she was still practising”
  - Understanding commands
- **Complex Pattern recognition**
  - What is a tree ?
  - Is a cat in the picture ?



Loss of Information by exchange

- **Allein der Vortrag macht des Redners Glück (Goethe, Faust)**
- Google Translator:
  But the presentation makes the speaker happiness
- Google Translator reverse:
  Aber die Präsentation macht die Lautsprecher Glück
- **A fly can't bird, but a bird can fly (Winnie the Pooh, Chp.6)**
- Google Translator:
  Eine Fliege kann nicht Vogel, sondern ein Vogel kann fliegen
- Harry Rowohlt (professionalTranslator):
  Es kann der Käfer den Specht nicht ertragen.

Important Note

- The most severe errors in computing are introduced by wrong assumptions !
- About the computer itself:
  The computer is not able to fulfil one of the basic group properties of algebra:
  - “The addition of two numbers is a number again”
  - 1.0 + 0.00000001 = 1.0
- About the nature of the problem
  - Gemini Watering
  - Exocet und Sheffield in Falkland war
  - Patriot-Rockets
  - And many more

Quality assured failure

https://en.wikipedia.org/wiki/Genesis_(spacecraft)

Genesis - Mission

- 3 year - Mission crashed during landing
- 4 time redundant acceleration measurement devices did not work to trigger the opening of the parachute
- All 4 devices have been installed bottom up
- As it was drawn in the designs and quality assured !
- There were no tests ?

- So a quality assured software does not mean that your results are correct !
- We have to be aware of hidden effects !

How most programs work

Jurassic Park (The book):

- There is a control program to detect if dinosaurs are missing by counting them in the park with video cameras.
- The algorithm is to search with a pattern recognition program until all have been found.
- The case that there are more species than expected is not treated.

Typical engineering assumption:

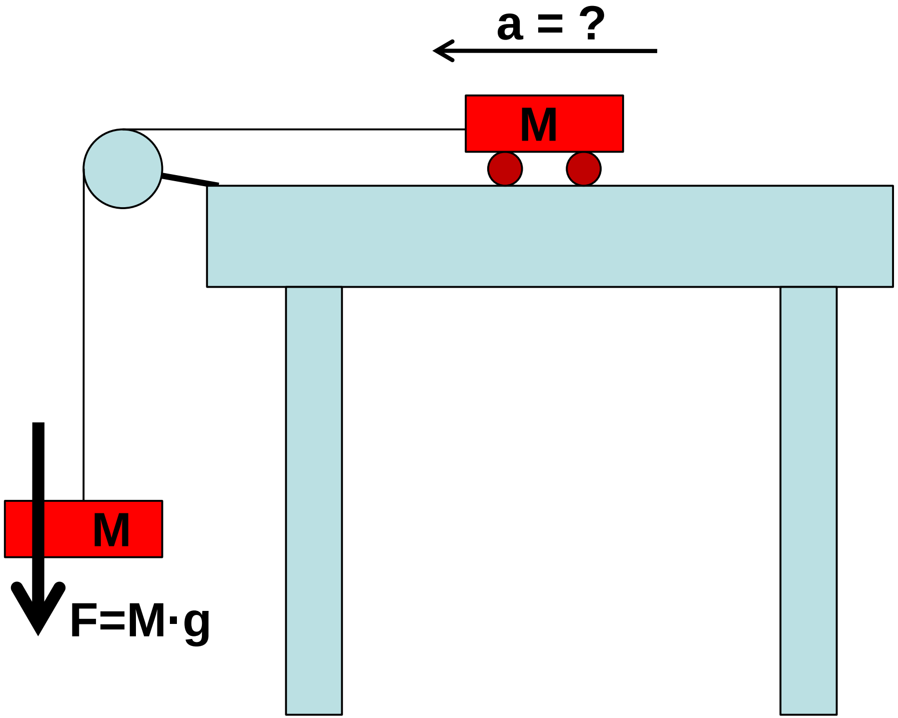
This effect has no importance !

Really ?

Verify or Falsificate your Assumptions ?

- There is an assumption for a theory based on experiments or experience
- A theory gains confidence if it can predict new effects
- The common error is to look only for examples confirming your assumptions
- The good scientist works on those subjects contradicting his theory (Darwin)
- 2 – 4 – 6 ….

Danger of experience



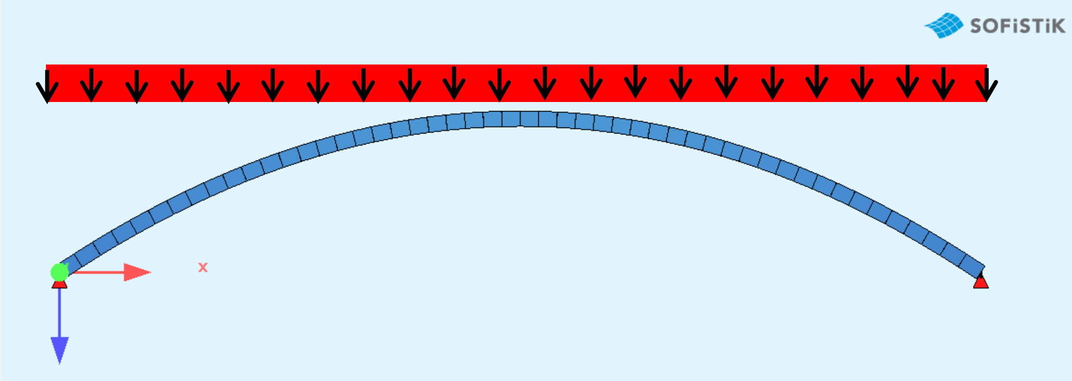
Software is like a car ?

- In the beginning prices were similar
- You drive a device and most of the results are depending on your personal decisions
- In the early times engineers with special knowledge started to use them
- Now the are used by everybody
- Only two years after the invention of the car, there was an established system of drivers licences.
- Software does not need a drivers licence
- However some people argue that we need a “gun licence”
- But there are no such licenses to use a hammer
- And there are no such licenses to bring up children

Should a device control the user ?

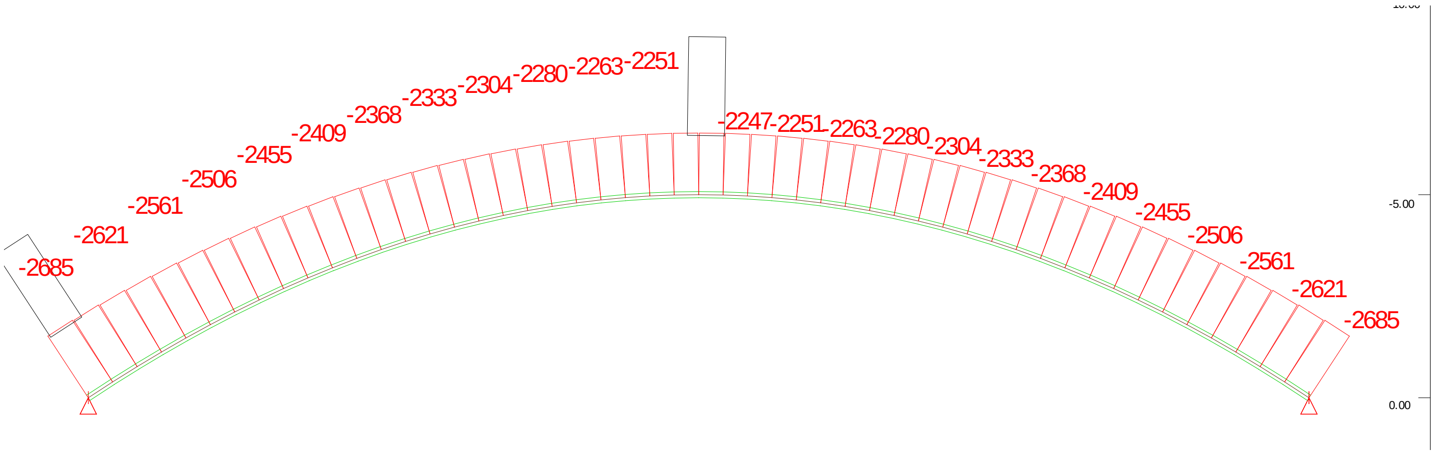
- For cars there are quite a lot of “intelligent” agents
  - Electronic ABS / ESP
  - Your car signals if your seat belt is not fastened
  - It will switch on the lights or the windscreen wipers automatically
  - It may brake automatically if you are approaching an obstacle
  - Do you remember the „Airbus“-Discussion about the captain to be allowed to do risky manoeuvres ?
- Software may contain Know-How not available at the user.
- There is no user on earth knowing everything about a larger software system, and there is no driver knowing everything about his car.
- There are cases where a complete mathematical / mechanical treatment of the problem is possible.
- and there are cases where it is not!

Reality and Traditional Knowledge



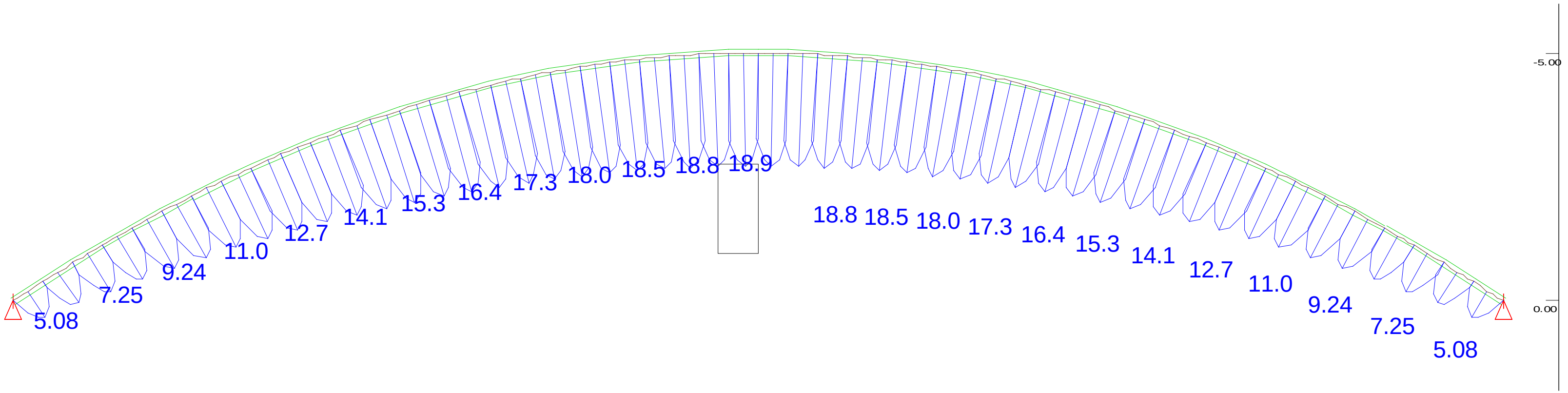
- A parabola is the thrust line (Stützlinie) for a constant loading
- For a thrust line there are only normal forces, no moments, no transverse shear

Normal forces



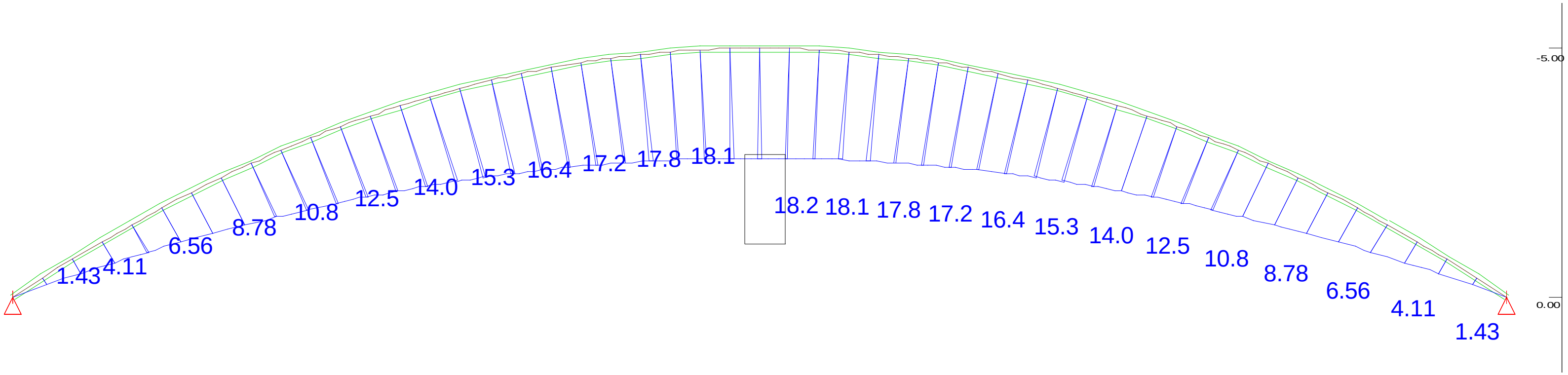
- Span = 30 m, Height = 5 m, Section = 500 x 500 mm
- Loading 100 kN/m projected (PZP)

Bending Moment



- The arch is modelled with straight beam elements
- Every node acts like an elastic support transferring the bending moments to normal forces for the arc

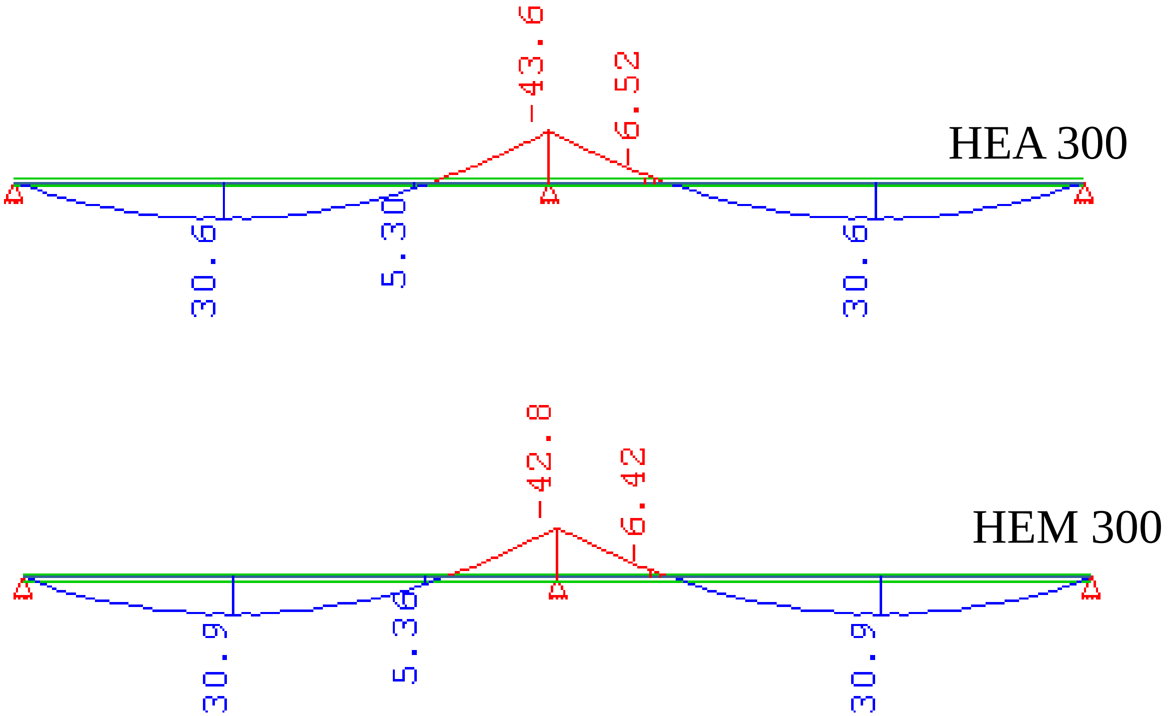
Bending Moment



- The pure nodal loading neglects now any local bending
- The moments are still not zero (e = 8 mm = 0.016h)
- The effect is caused by the stiffness for normal forces, neglected in traditional knowledge

Software bug ?

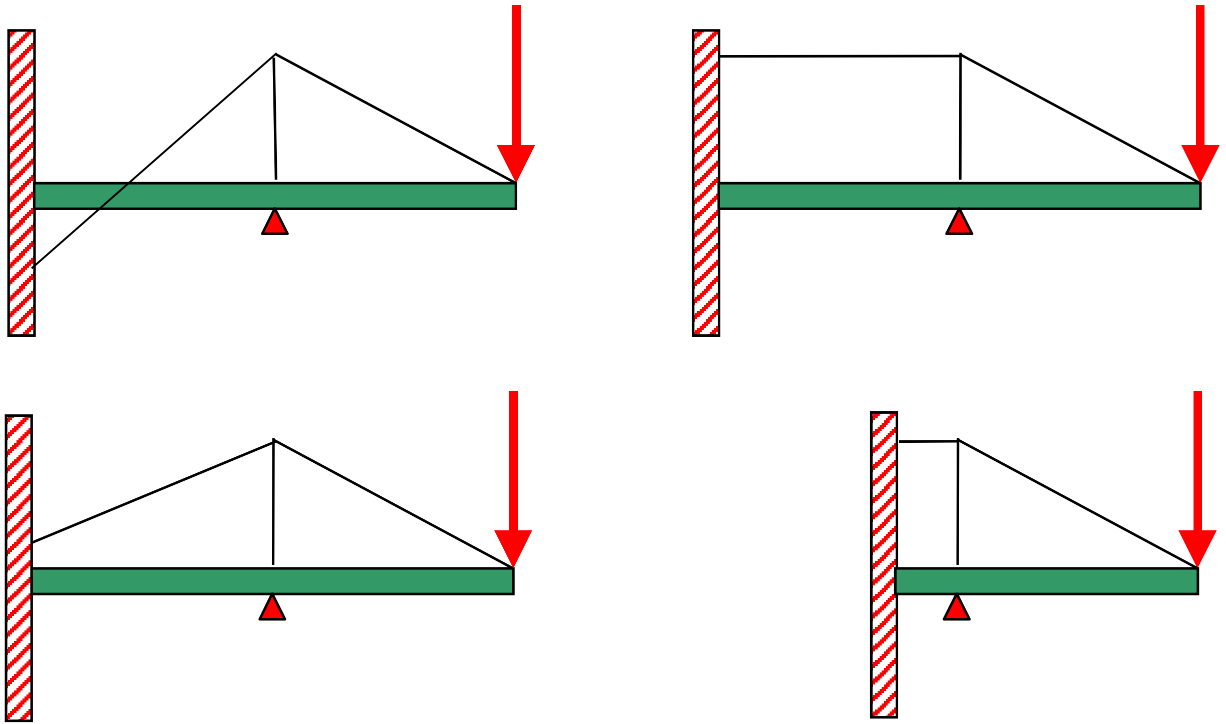
$$\frac{q \cdot l^2}{8} = 50.0$$



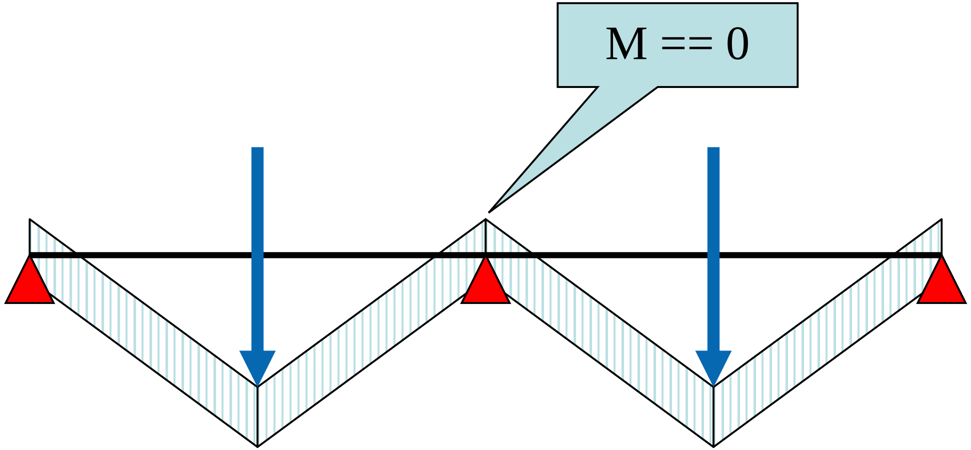
Why is this an issue ?

- The effect is due to shear deformations
- Old frame tables did not include axial deformations
- Old software did not include shear deformations
- Engineers like to be able to control the results by easy formulas
- But
  - He will not be able in all cases to estimate the effects of his simplifications properly.
  - The author of a software even less, cause he does not know the tasks the software is used for !
- Thus software will try in general to cope with all possible effects.
- If the effect is neglect able, it will not disturb!

Maximum Effect: 200 %



Pure Shear deformations:



Shear deformation areas

- Evaluation via an energetic equivalent

$$\Pi = V\theta = \frac{V^2}{GA_s} = \int_A \frac{\tau^2}{G}$$

$$A_s = \frac{1}{G \bullet \Pi(V=1)}$$

- Swains formula may yield off diagonal terms:

$$\begin{bmatrix} \Theta_y \\ \Theta_z \end{bmatrix} = \begin{bmatrix} \frac{1}{GA_y} & \frac{1}{GA_{yz}} \\ \frac{1}{GA_{yz}} & \frac{1}{GA_z} \end{bmatrix} * \begin{bmatrix} V_y \\ V_z \end{bmatrix}$$

Shear deformation areas

- The off diagonal terms are zero or very small in many cases.
- But if they are not zero, there are principal axis not aligning with those of the bending solution
- Problem escalates for buckling in the weaker bending axis. Deviations of 100 % have been observed.
- Special problem: haunched beams
  - Closed formulas with a reduced stiffness are only applicable for prismatic beams.
  - Classical Timoshenko-Beam is not precise enough

    => non conforming Timoshenko Beam

    => Inversion of a “Übertragungsmatrix”, i.e. the exact or numerical integration of the differential equation

Shear stresses in a beam

- Classical beam theory is established for normal stress only
- Post processing step is then based on equilibrium:

$$\frac{\partial \tau}{\partial s} = \frac{\partial \sigma}{\partial x}$$

$$\tau = \frac{V}{I} \frac{S}{b}$$

- This approach is a force based method
- Finite Element Software is deformation based, thus
  - Deformation is the warping of the section
  - Equation system is based on equilibrium

Deformation based shear

$$\tau_{xy} = G\left(\frac{\partial w}{\partial y} - z\frac{\partial \Theta_x}{\partial x}\right)$$

$$\tau_{xz} = G\left(\frac{\partial w}{\partial z} + y\frac{\partial \Theta_x}{\partial x}\right)$$

$$G\Delta w = G\left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = -\frac{\partial \sigma_x}{\partial x}$$

Boundary Condition:

$$\tau_{xy} n_y + \tau_{xz} n_z = 0$$

Deformation based shear

- Primary Torsion

  $d\Theta/dx$ = Warping ; $\sigma_x = 0$

- Transverse Shear

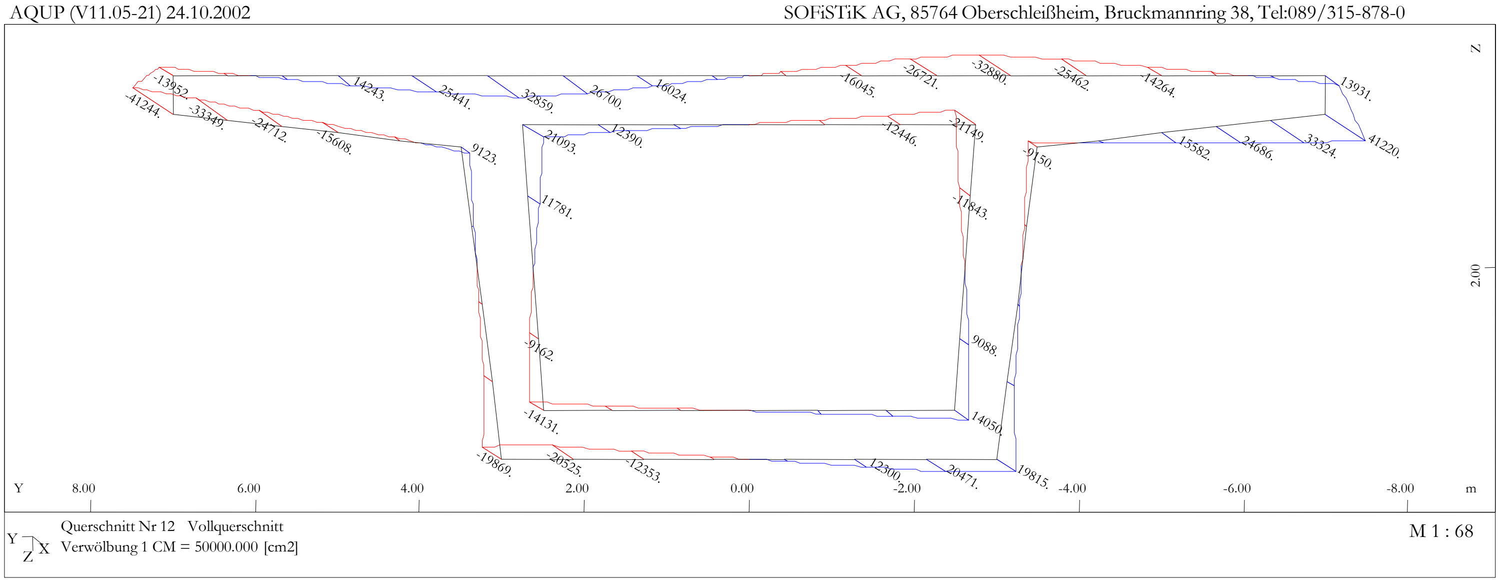
  $d\Theta/dx = 0$; σ_x = taken from moments

- Secondary Torsion

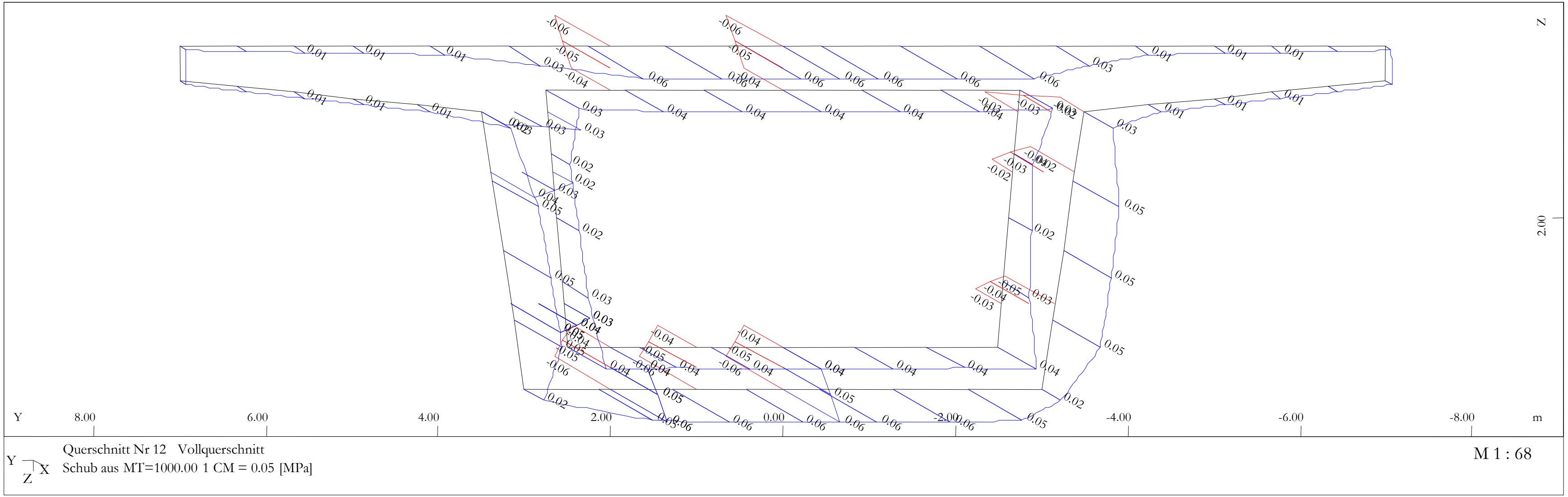
  $d\Theta/dx = 0$; σ_x = from warping moment

- For thin walled sections this is exactly solvable
- For solid sections we need Finite-Elements or Integral-equations
- Results: Detailed shear stress distribution

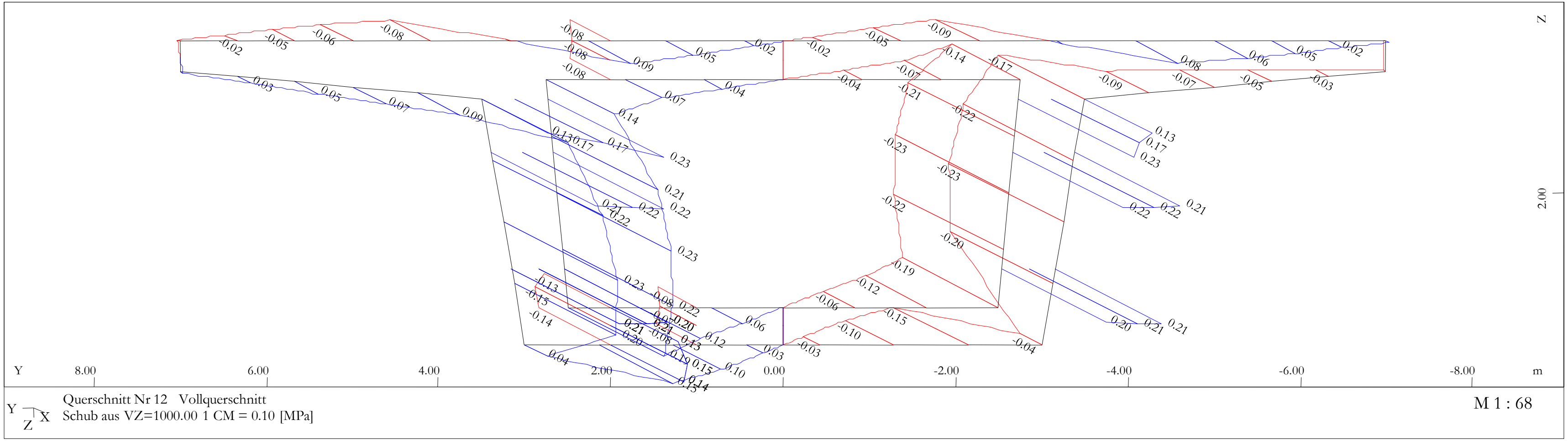
Unit Warping



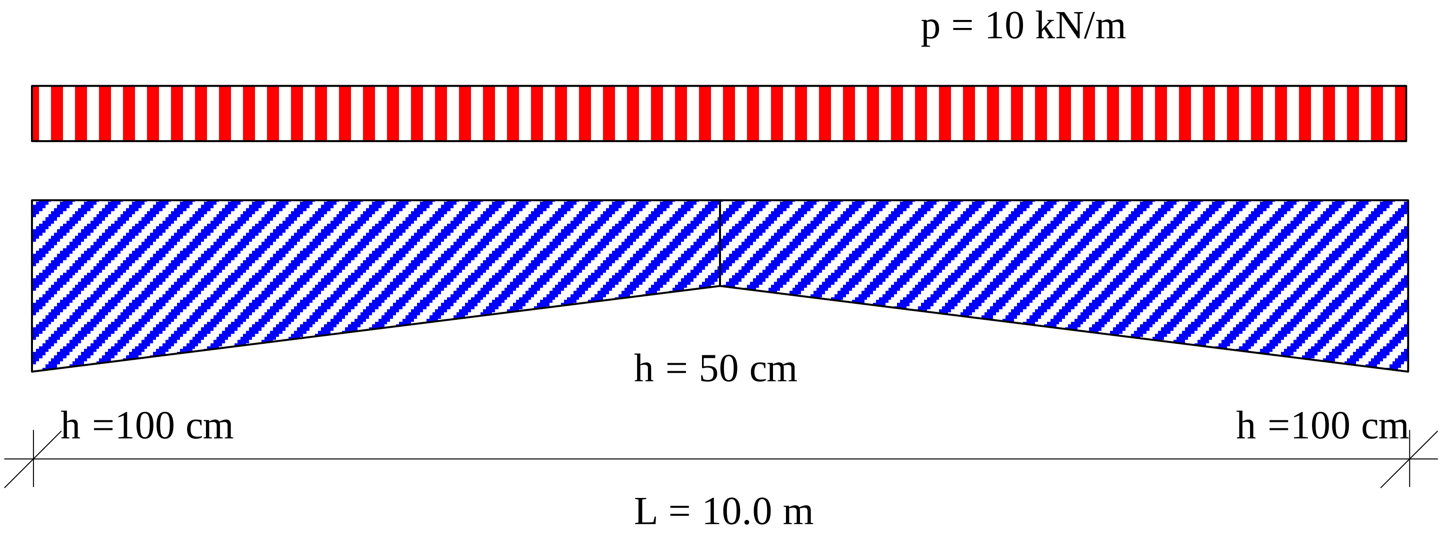
Shear from primary torsion



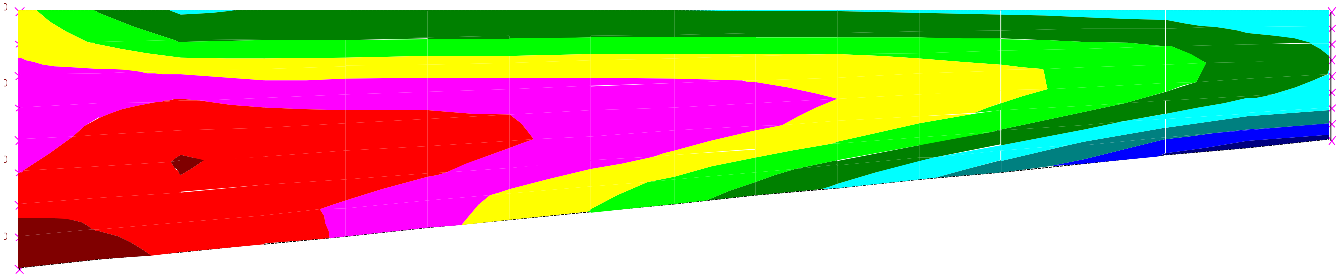
Transverse shear Vz



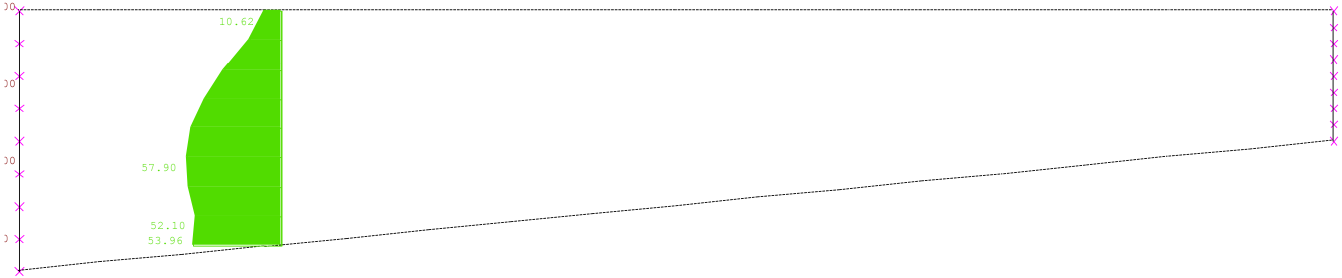
Shear in haunched beams



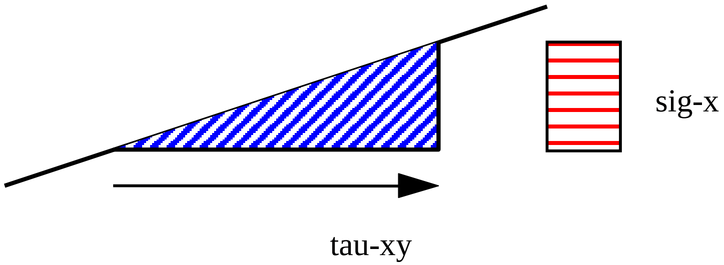
FE-Analysis

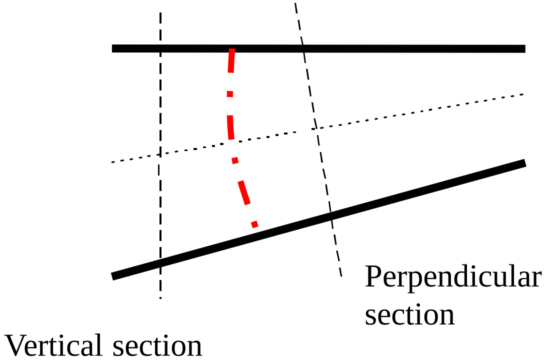


tau-xy

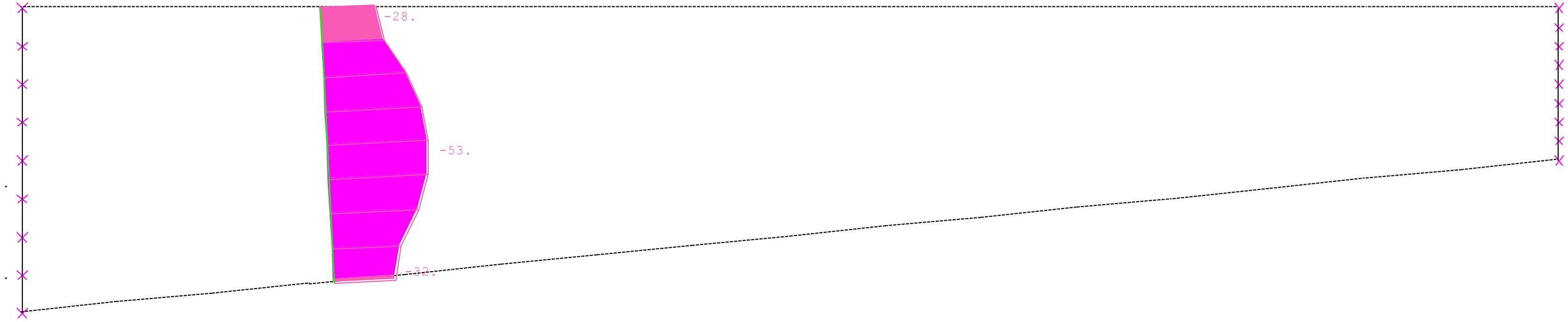


Shear in Haunches





FE-Analysis



tau-nq

And many more questions !

- Shear stresses are depending on the orientation of the coordinate system
- Principal stresses are Invariants of a tensor an not dependant
- DIN 1045-1 does not use the word “shear stress” any more!
- Do you know the difference between transverse shear and transverse force ? (2nd Order Theory for a hinged column)
- Warping Torsion ?
  - When will it become important ?
    e..g: a slender beam taken from Petersen

Bending stress	σ = 84.3 N/mm^2
2nd order torsional buckling	σ = 136.1 N/mm^2
warping stress	σ = 82.8 N/mm^2

- Plastic Resistance Factor Design ?

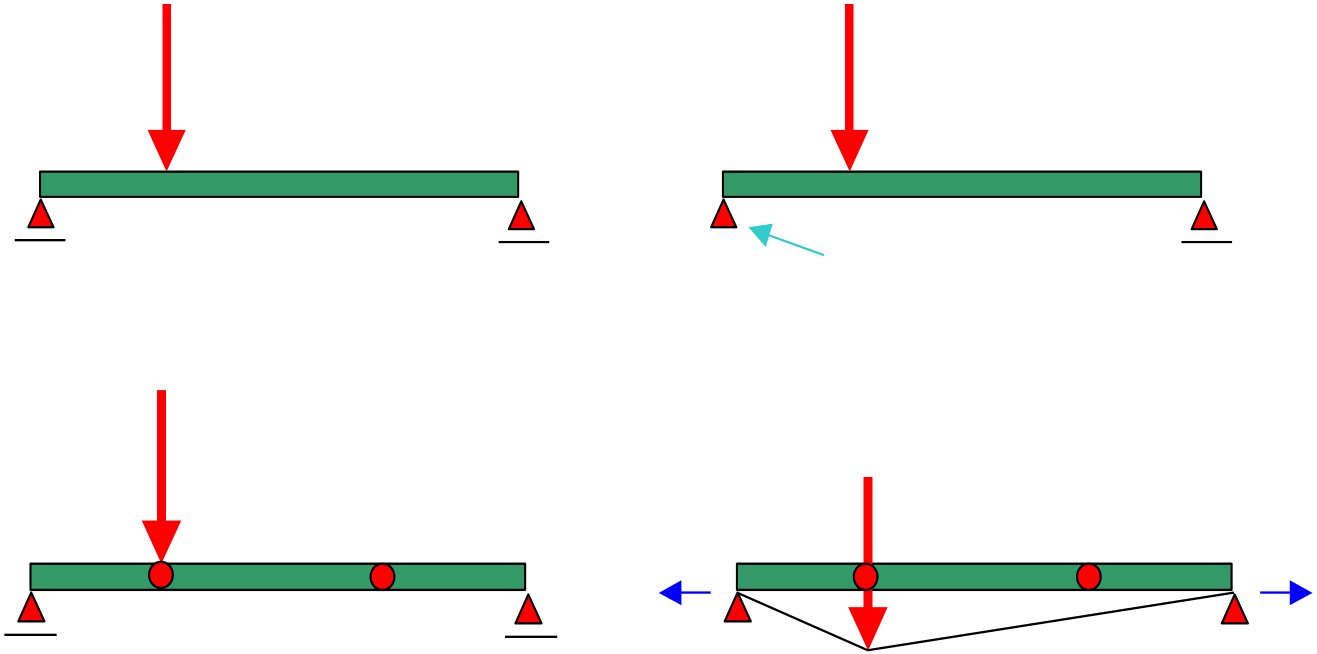
Save Software ?

- Unexperienced users should not get results on the unsafe side
- But they will not like to get results not within the economical range.
- Thus the optimum software would start a dialogue with the user:
  - Are you really sure, that you want to neglect this effect ?
  - Did you remember to think of …
  - I would not do it in such a way, because ...
- But,
  even if you would like such a parental software, would you be able to pay for it ?

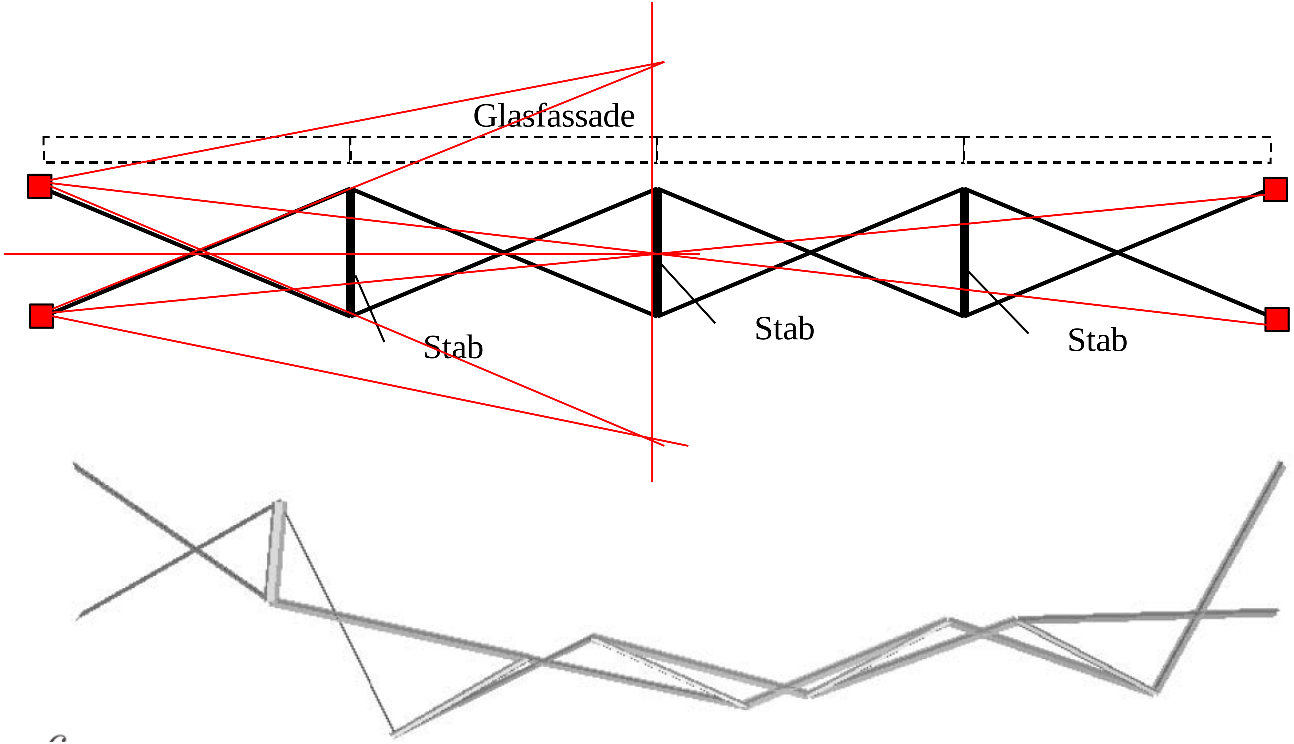
Checks by the program

- The „Maximum Credible User” MCU = “Dümmste anzunehmende Benutzer“
- This is an extremely complex software design problem:
  What is an error and what is exactly intended like it is specified ?
- e.g. formal number checking
  - 100.000.00
  - 1O00
  - 25E38
- e.g. Young’s Elasticity-Modulus
  - 340000 MPa
  - 1 MPa
- Dynamic growth of checks
  (but new version with warnings where the old version passed without ?)

MCU Support Conditions



Indefinite Cable Structure



Possible Solutions

- Check for Diagonal values <= 0.0
  = gamble at the lottery
- Remove all degrees of freedom without stiffness
  = equivalent to make it rigid
  = extremely dangerous
- Introduce tolerances for the equation solver
  = what value ?
  = thus a typical MCU-Problem
- Apply a tiny stiffness to all degrees of freedom without stiffness and check the magnitude of deformations
  = you will get a message if there is a problem
  (but only if there is a loading for that degree)
  = otherwise there is little impact on the solution

Dilemma Engineer > Software

- Software implements algorithms / Algorithms have to be complete
- Available input is often scarce / Engineering disciplines are often empirical / Assumptions are not well known
- Gaps have to be closed by the software
- Design codes favour manual analysis, which has to be extended for more general cases
- Design codes have to be interpreted
- So is the writer of the Software the better engineer ?
- What do you buy with a software ?
    - A Tool or the Know-How ?

Dilemma Software > Engineer

- Moment resistance for Double-T-shapes
  - DIN in section (750) defines for local limited yielding for biaxial bending allows to assume that the ultimate limit moment resistance is given by

    $$M_{y,pl} = 1.14 * M_{y,el}$$
  - Schneider Bautabellen:
    „Values in Table 8.23a are determined as follows:
    max($\sigma_{R,d} \cdot 2 \cdot S_y$; $1.14 \cdot \sigma_{R,d} \cdot W_y$)
  - Thus he uses either the correct value or the estimate not applicable here, whichever is more favourable.
  - Values are up to 7 % on the unsafe side !

- Should a software follow this common nonsense ?

Dilemma Software > Codes

- Design codes are made for the general case
- Software has to cope with all thinkable special cases
- Example: Combined resistance for shear and normal stress
  - Classical Method: reduce the web thickness
    - Does not work if the total capacity is exceeded V > Vplas
  - Closed Interaction formula
    - Only available for certain classes of sections
  - Mechanically sound solution (costly)
    - Does not follow the design code, is it allowed ?
    - May be less economical than the rule of thumb
      => Rules of thumb may be unsafe, but they shouldn’t

Dilemma Software > Codes

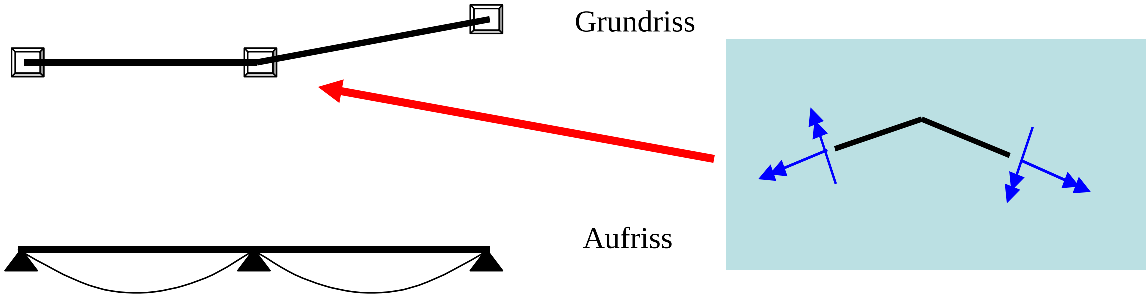
- Moment Resistance DIN 18800
  „If the shape coefficient α_{pl} > 1.25 and the use of 1st order theory is not allowed, then the bending resistance in presence of normal or shear forces has to be reduced by a factor of 1.25/ α_{pl}"
- Why ? One question, four answers form experts:
  - The aim is to limit the plastic deformations. Thus it is a simplified rotation check.
  - The redistribution of forces for the non linear analysis should be limited
  - Interaction formulas are not precise for that case.
  - The imperfection for plastic hinge methods are not sound otherwise, There is no need to do so in non linear analysis.
- How would you like to program this ?

Dilemma „Manual“

- Engineers want a precise description of their current task.
- But even if it is there, he has to find it.
  (Remembers me of an examination where a student looked on the correct page in his book and still did not recognize the solution)
- If you have not yet encountered a problem you will not understand the description of its solution.
- Programmers like to describe the complete and exact behaviour of the program.
- Users need a „How to“-Guide where all secondary effects are omitted.
- How would you decide then if the Software is suited for your analysis task ?

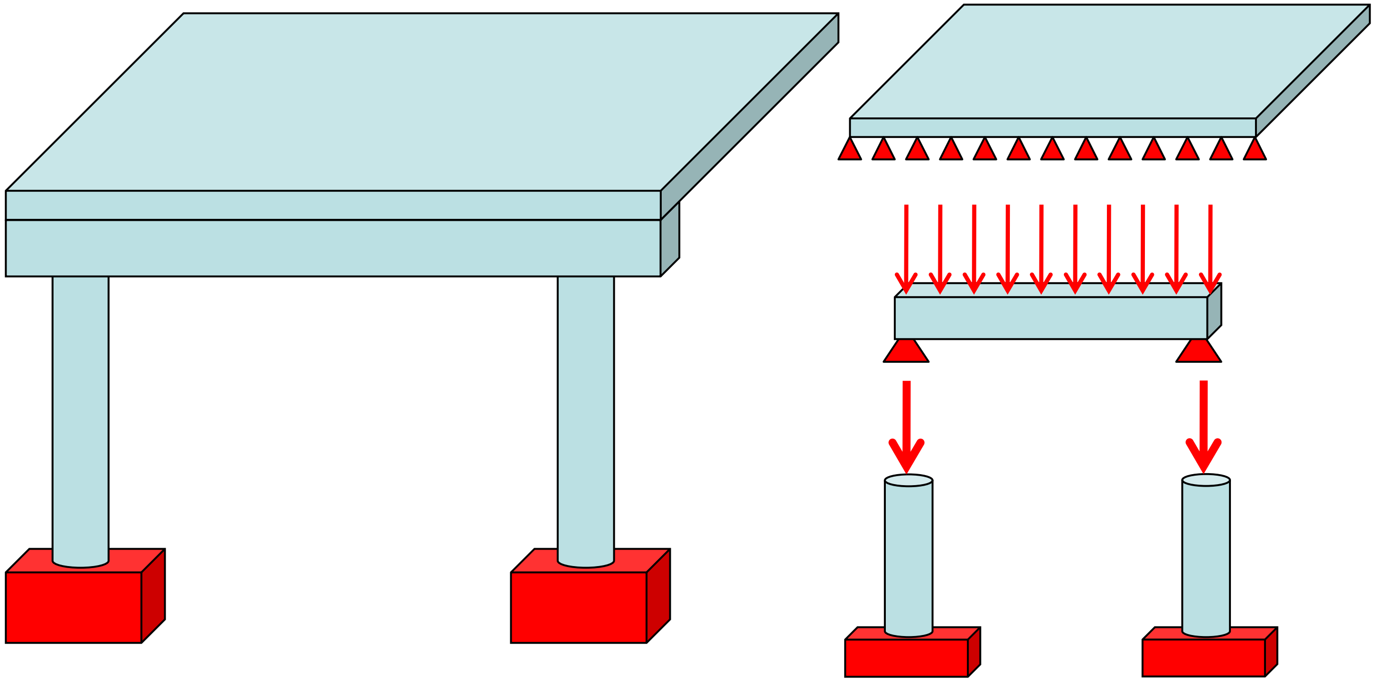
Prerequisites and their pitfalls

- Remember all about round off errors
- Beams:
  - Bernoulli-Hypothesis for planar sections = no shear deformations
  - Bend beam with pinned support has no hogging moment:

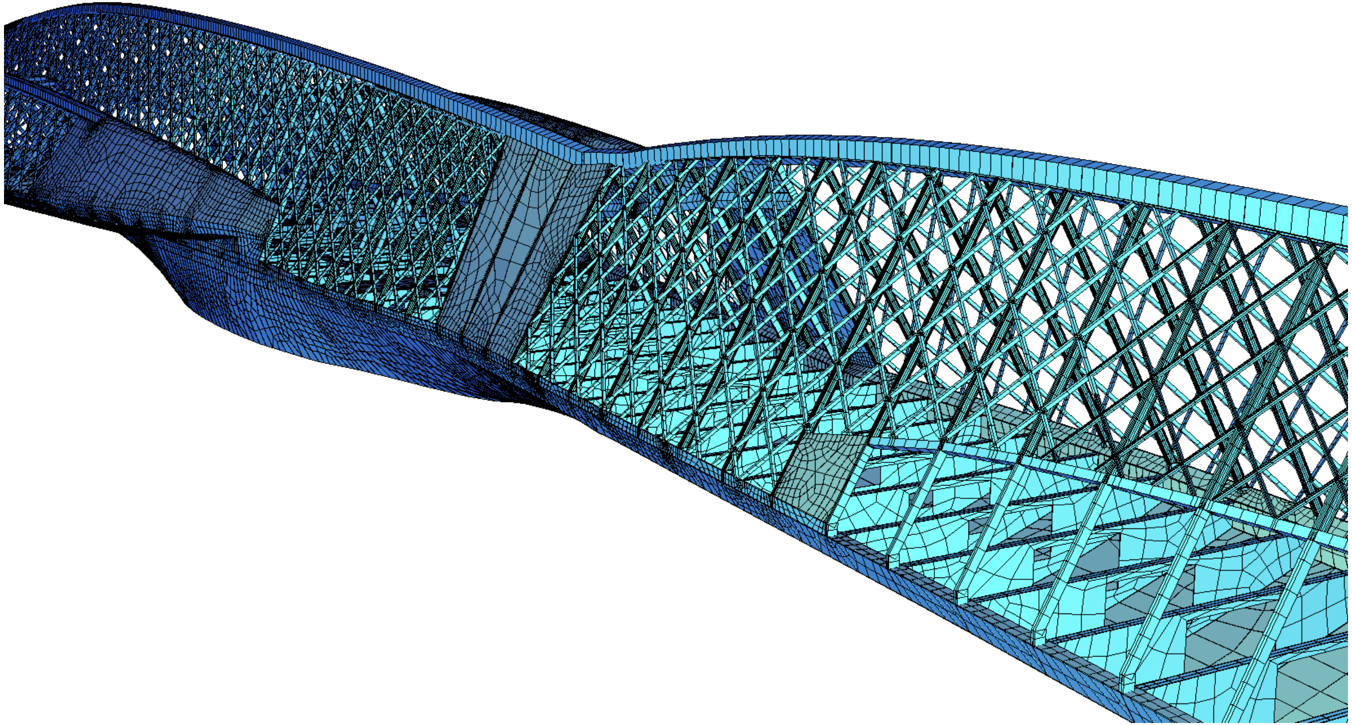


- Effect will occur even for very tiny bends !

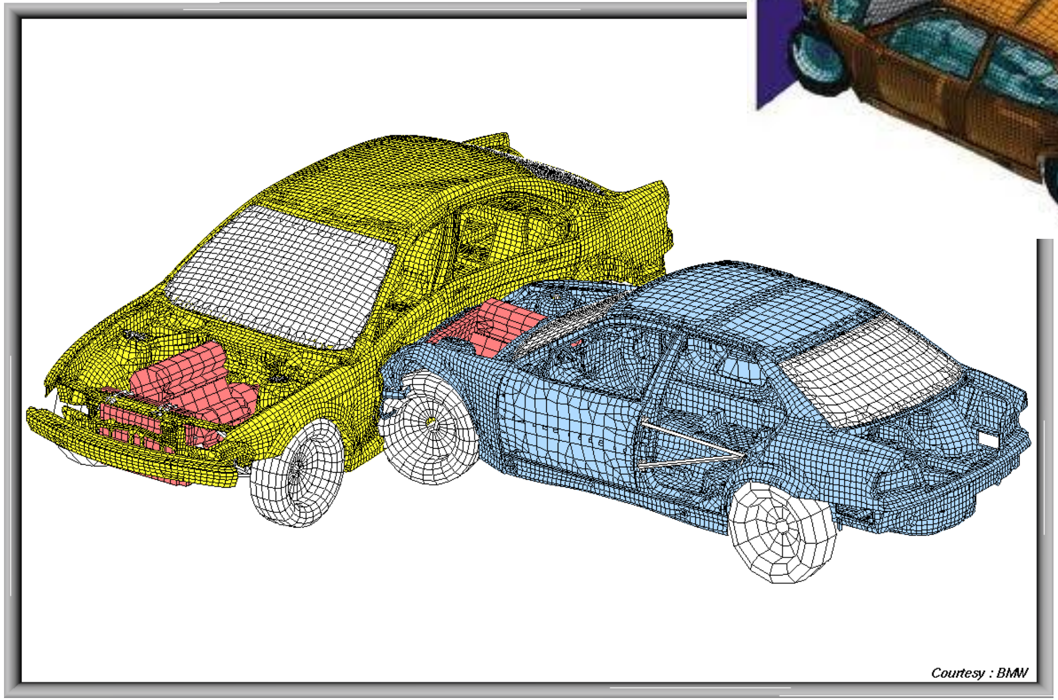
Classical Civil Engineering Analysis



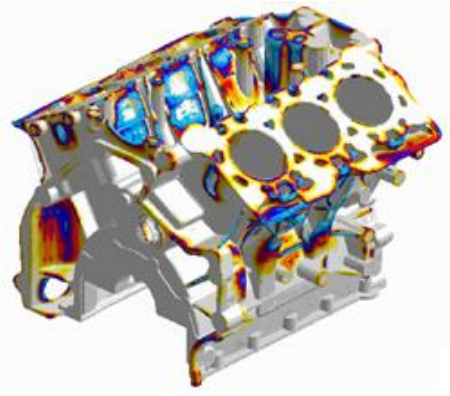
Today: Total Systems
Saragossa Bridge-Pavillon

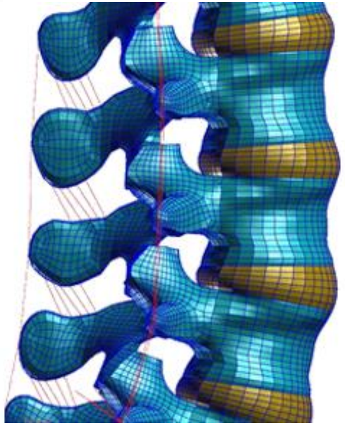


Today: Digital Mock Up



Everywhere





http://www.traffgo-ht.com/press/index.html

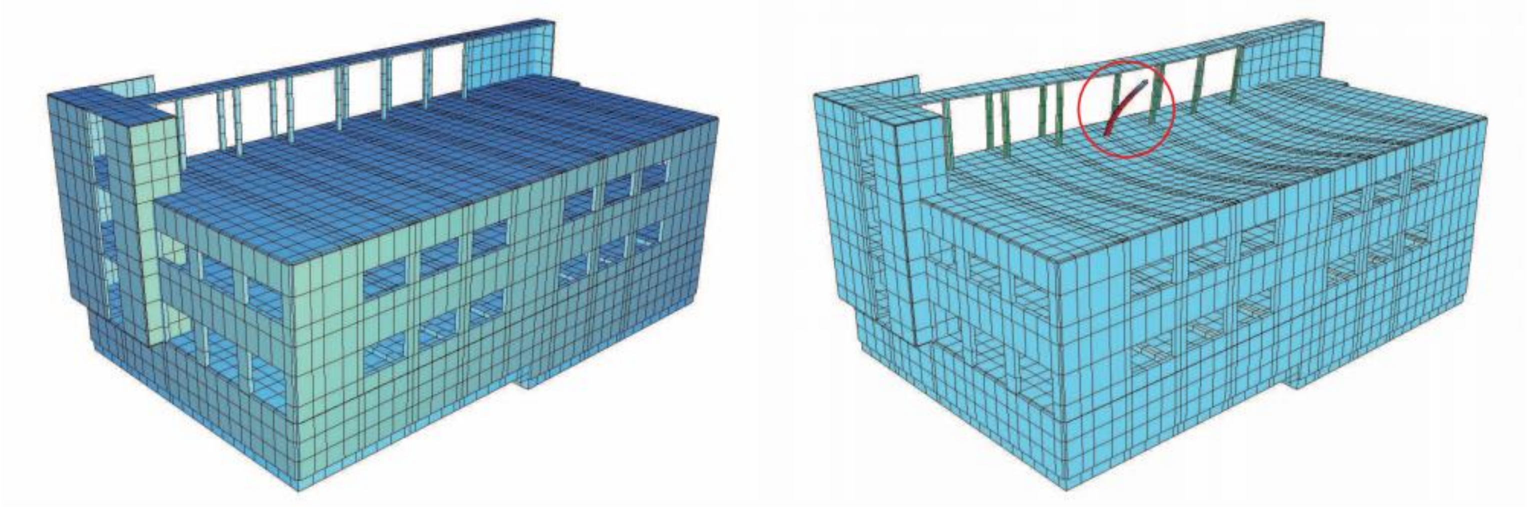
Structural Analysis of Entire Systems

- Required for
  - General complex structures
  - Stability of total system
  - Dynamic Analysis
  - Soil structure Interactions
  - Accidental load cases
- Expected benefits
  - Presentations for the owner
  - Optimisation of structural system
  - Interface to the architectural model
  - Subdivision in positions is not needed ?

General remarks for entire systems

- Small details may have a critical influence !
- Construction phases have to be considered as new parts are added stress free with their load on existing elastic parts, accumulating stresses
- There is no infinite stiffness!
- Horizontal support may have a significant influence on the results.
- Support of rotational degrees of freedom may have an important influence (Shear deformations)

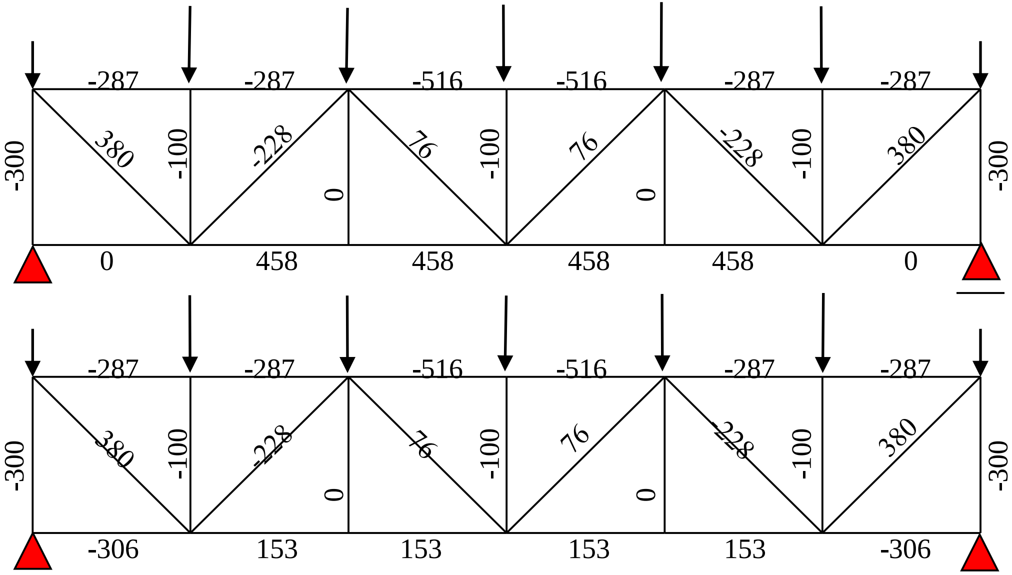
Small errors ?



Always calculate dynamic or buckling Eigenvalues !

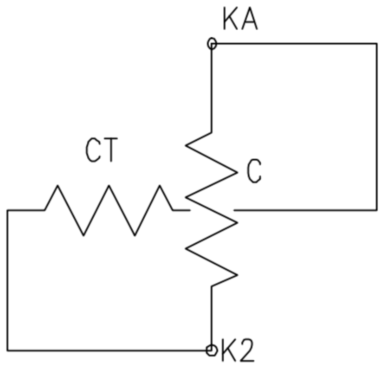
Support of a Truss

- Horizontal support changes the lower truss forces from 0 / 458 / 0 to -306 / 153 / -306

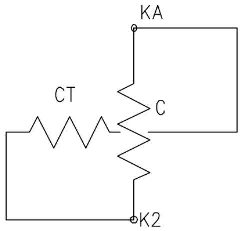


Coupling spring elements

- Two nodes are connected with a normal spring C and a transverse spring constant CT.
- The coupling allows the modelling of contact and friction problems



Stiffness matrix for isotropic transverse spring constant



$$\Delta\bar{u} = \bar{u}(KA) - \bar{u}(K2) \quad ; \quad \Delta u_n = \Delta\bar{u} \cdot \bar{n}^t \quad ; \quad \Delta\bar{u}_t = \Delta\bar{u} - \bar{n} \cdot \Delta u_n$$

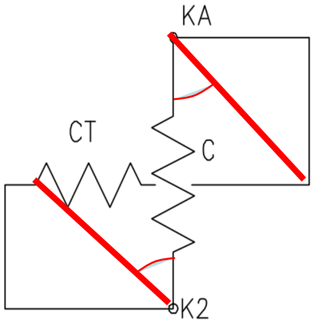
$$\bar{f} = \begin{bmatrix} f_x & f_y & f_z \end{bmatrix}^T = \bar{n} \cdot \Delta u_n \cdot C + \Delta\bar{u}_t \cdot CT$$

$$K = \begin{bmatrix} k_{ii} & -k_{ii} \\ -k_{ii} & k_{ii} \end{bmatrix} \quad ; \qquad k_{ii} = E_3 \cdot CT + \bar{n}^t \left(C - CT\right) \cdot \bar{n}$$

Moments

- If the nodes do not coincide, this element will violate the equilibrium of moments
- Correction by excentricity to an assumed centre point

$$\Delta\bar{u}_E = \begin{bmatrix} \Delta u_x \\ \Delta u_y \\ \Delta u_z \end{bmatrix} + \begin{bmatrix} 0 & -\Delta z & \Delta y \\ \Delta z & 0 & -\Delta x \\ -\Delta y & \Delta x & 0 \end{bmatrix} \cdot \begin{bmatrix} \Sigma u_{xx} \\ \Sigma u_{yy} \\ \Sigma u_{zz} \end{bmatrix}$$



Total Stiffness of element

$$k_{ii,E} = E^T \cdot k_{ii} \cdot E \ ; E = \begin{bmatrix} 1 & & & 0 & \mp\Delta z & \pm\Delta y \\ & 1 & & \pm\Delta z & 0 & \mp\Delta x \\ & & 1 & \mp\Delta y & \pm\Delta x & 0 \end{bmatrix}$$

- Next problems:
  If the connecting nodes do not have a stiffness for rotations, cinematic indifferent systems will occur.
- Automatic recognition of those degrees of freedom is required

And now ?

- Software becomes more and more complex
- Innovations are not only done at universities, there should be always an expert to be asked for difficult questions.
- There is no way to introduce a “drivers licence” for the use of software. It would hamper innovations completely. The best quality assurance is a large user base. And this users are an important part of the “Commonly Adopted Rules of Practice”!
- A discussion with the software writers is essential to let you decide if the software really does what you expect it should do.
- Most important is awareness to all unexpected effects:
  Do not believe results, especially if they are just full of colours.