An Idiot's Guide to Modelling and Assessment of Reinforced Concrete Structures

Frank J. Vecchio
University of Toronto

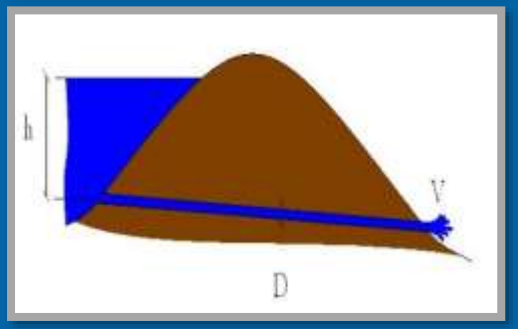
June 2019

UNIVERSITY OF TORONTO
Department of Civil Engineering

Ancient Romans: Masters of Concrete Structures

Lake Fucino

- Source of Malaria; often flooded nearby arable land. Potential source of new land.
- In 40 A.D., Emperor Claudius attempted to drain the lake, requiring 30 000 workers and 11 years to level a hill and tunnel 5.6 km through Monte Salviano. This remained the longest tunnel in the world until the mid-19th century.
- The high hydraulic pressure combined with the small tunnel diameter caused the water to rush out in a torrent. Claudius almost drowned during the opening ceremony, and much of the nearby valley was flooded.
- Tunnel was plugged.



If D is small and h is large, then V is very large!

WE DON'T ALWAYS GET OUR ANALYSES RIGHT!

Suetonius, *The Twelve Caesars,* 121 A.D.

Colle San Magno, Frosinone, Italy

Colle San Magno, Frosinone, Italy

Arpino, Frosinone, Italy

Cicero

Marcus Tullius Cicero was a Roman philosopher, politician, lawyer, orator, political theorist, consul, and constitutionalist.

Born: January 3, 107 BC, Arpinum, Rome
Assassinated: December 7, 43 BC, Formia, Italy

"Any man can make mistakes, but only an idiot persists in his error."

An Idiot's Guide to Modelling and Assessment of RC Structures

- ***Introduction***
- ***Utility - Case Studies***
- ***Reliability***
- ***Traps & Blunders***
- ***Conclusions***

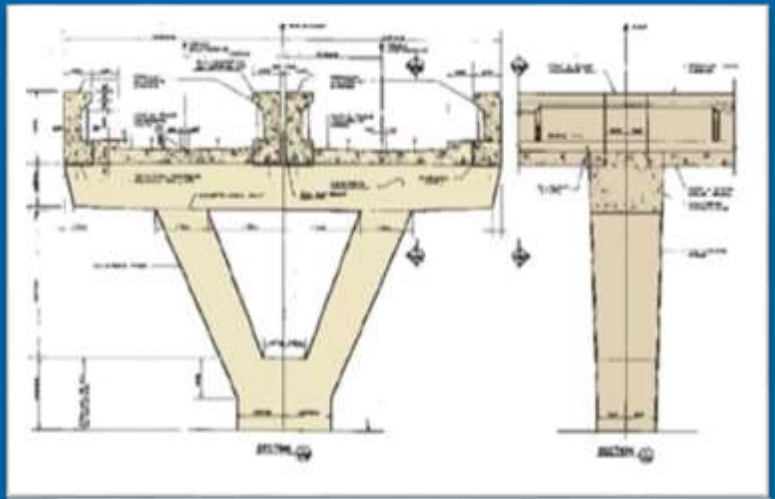
- ***Recent Projects***
- ***Current Research***

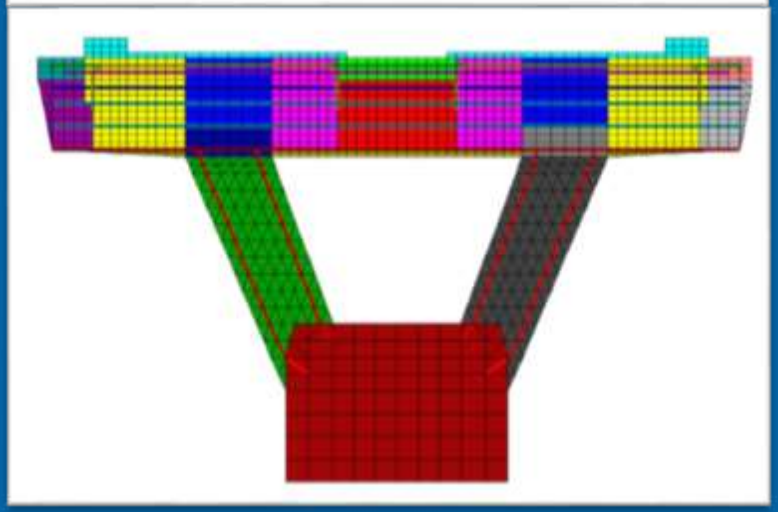
➢ *Truths* about Analysis Software

➢ *Tips* for Idiots

Need for Advanced Analysis Software

- Assessment of damaged or deteriorated structures
- Assessment of structures built to out-dated codes and standards
- Assessment of retrofitted or repaired structures
- Evaluation of alternative design or retrofit options
- Performance-based design
- Forensic engineering





Moore's Law at Work

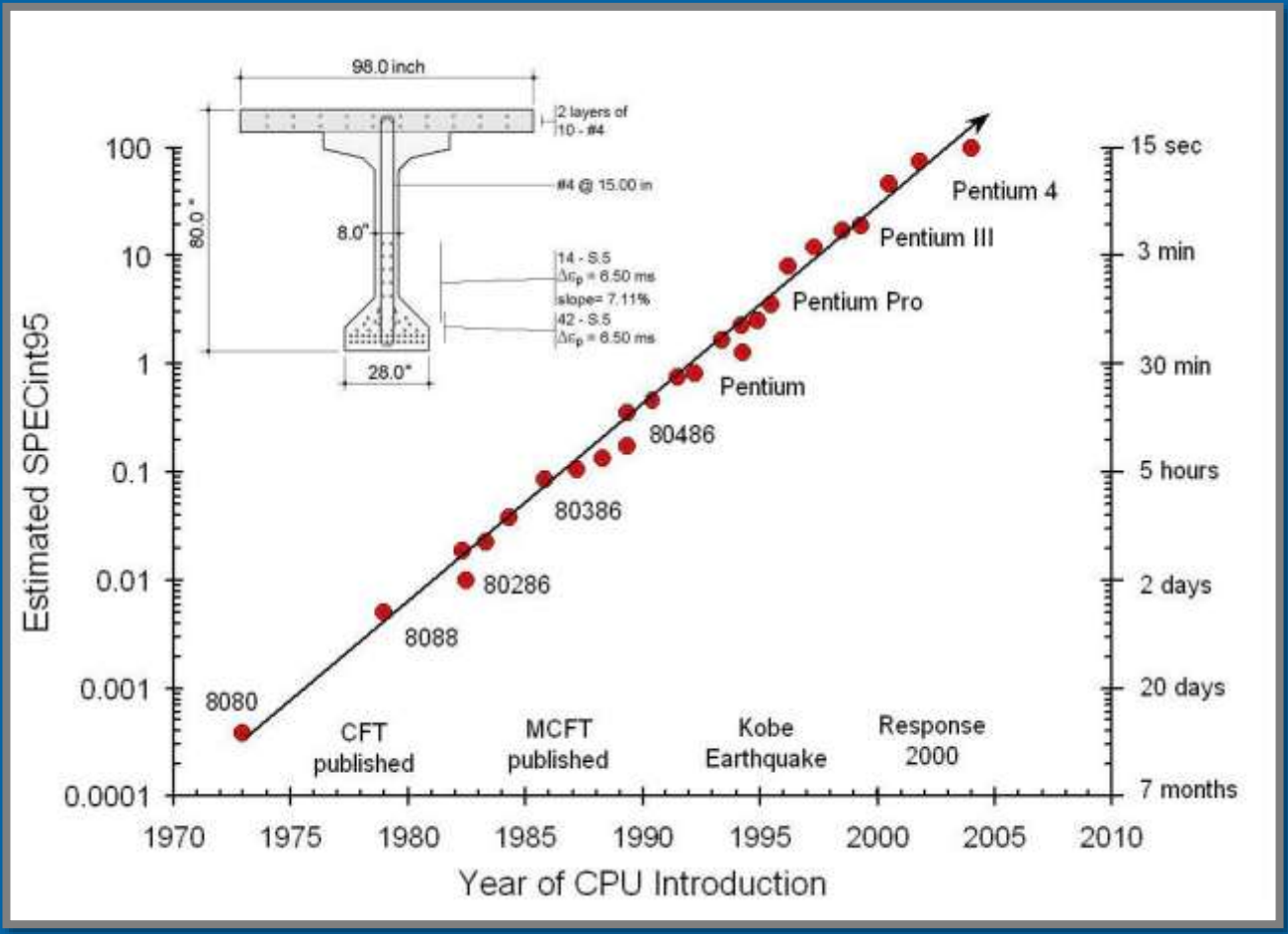


Figure courtesy of E. Bentz

Computing Power Through Time

Truths...About Analysis Software

Truth # 1: We are rapidly embracing advanced computer analysis software.

- Common tools in modern design offices.
- Driven by need in new areas of application.
- Enabled by great advances in computer technology

An Idiot's Guide to Modelling and Assessment of RC Structures

- *Introduction*
- *Utility - Case Studies*
- *Reliability*
- *Traps & Blunders*
- *Conclusions*

- *Recent Projects*
- *Current Research*

Laval Bridge Collapse

- September 30, 2006: De La Concorde Bridge in Laval, Quebec, collapsed killing 5 people.
- Bridge built in early 1970s using 'drop-in span' design detail.
- Shear failure of girder support triggered collapse.

Photograph courtesy of *La Presse*, Montreal

Laval Bridge Collapse

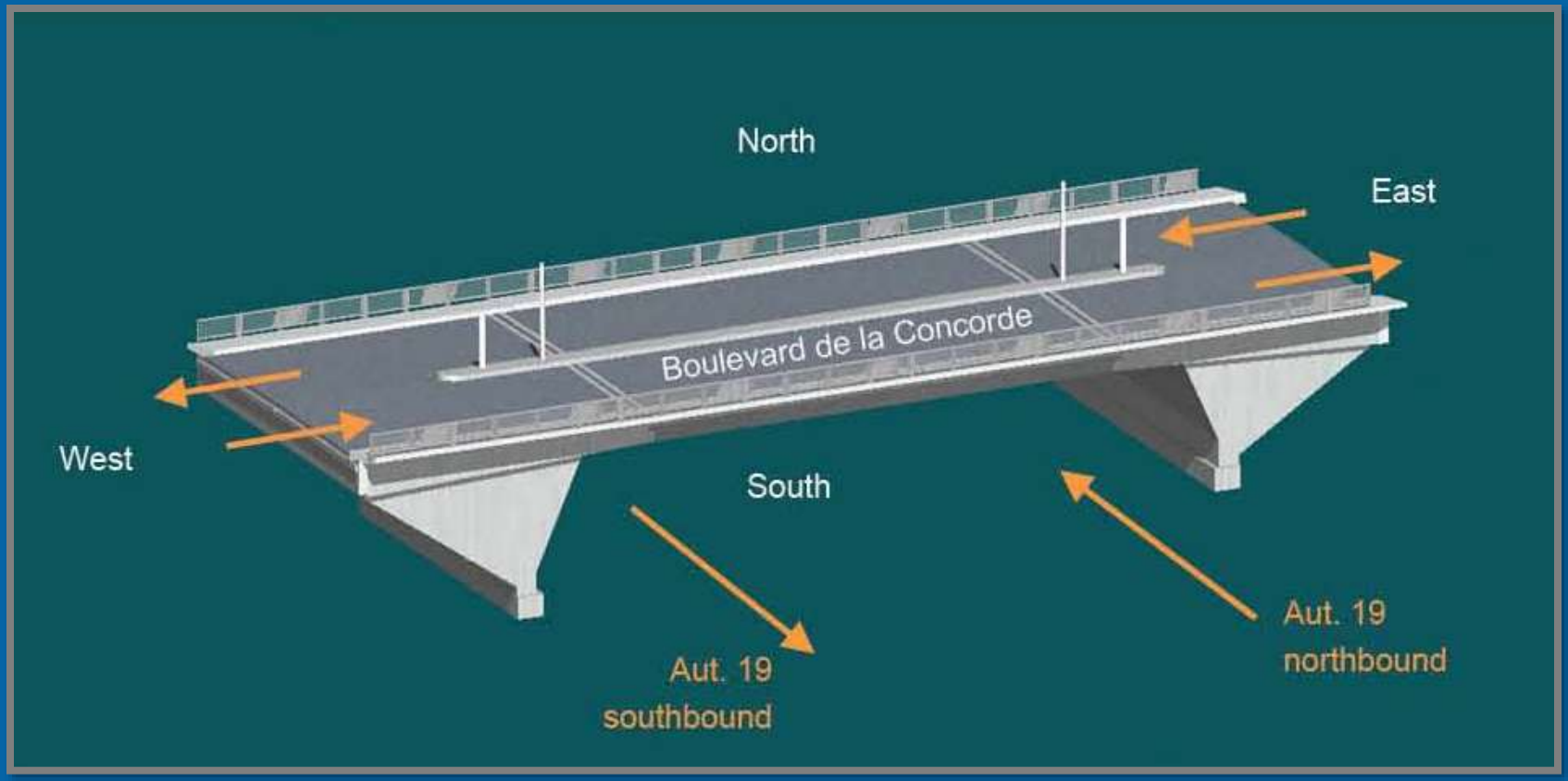
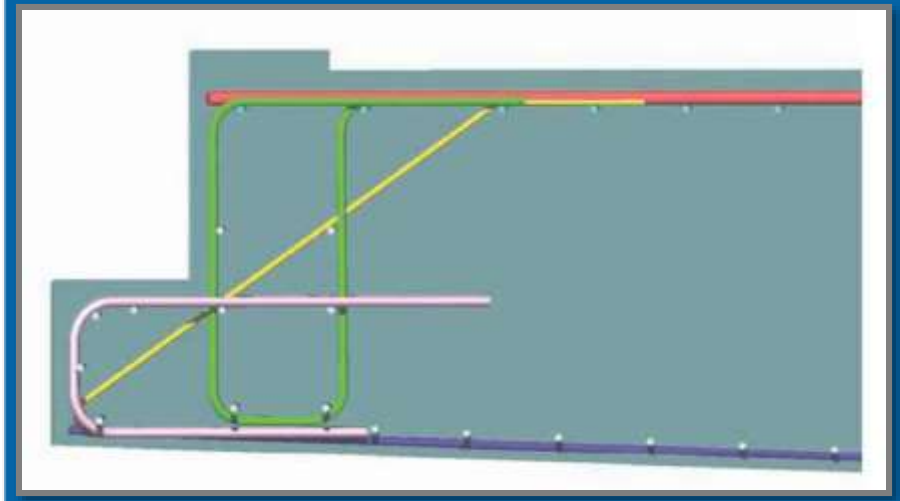


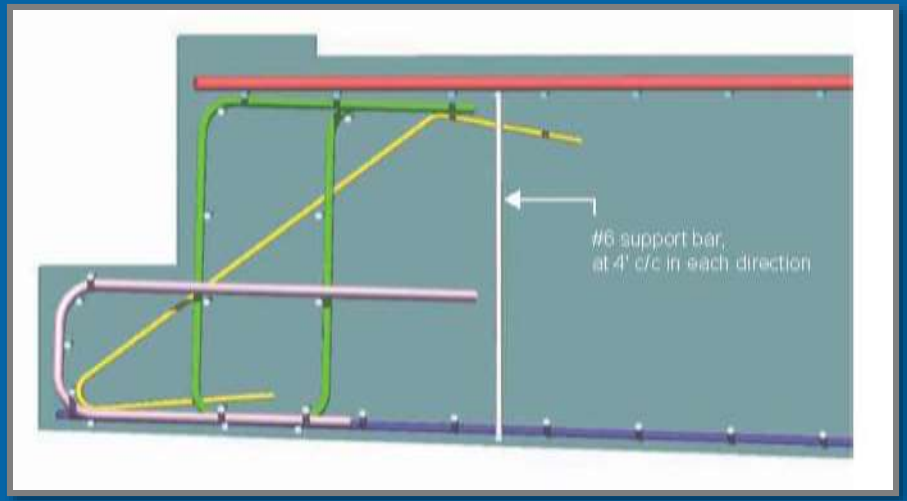
Figure courtesy of Mitchell & Cook, McGill University

Laval Bridge Collapse

Chair Bearing Support Reinforcement



As-Designed



As-Built

Figures courtesy of Mitchell & Cook, McGill University

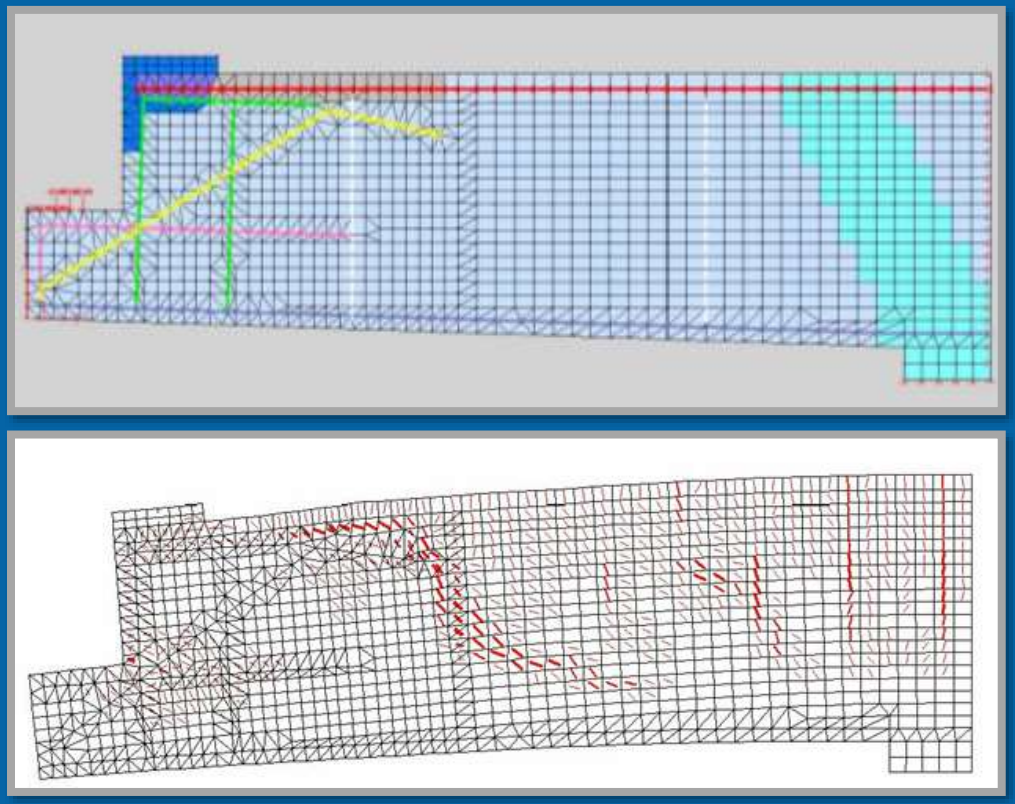
Laval Bridge Collapse

Failure of “As-Built” Test Specimen

Figure courtesy of Mitchell & Cook, McGill University

Laval Bridge Collapse

- VecTor2 software was used to model test specimen.
- Analysis was able to predict correct failure load and failure mode.
- Used to investigate various scenarios leading to bridge deficiency and collapse.



VecTor2 Model of 'As-Built' Cantilever

Toronto Trestle Bridge

Above-ground portion of Toronto subway system.

Toronto Trestle Bridge

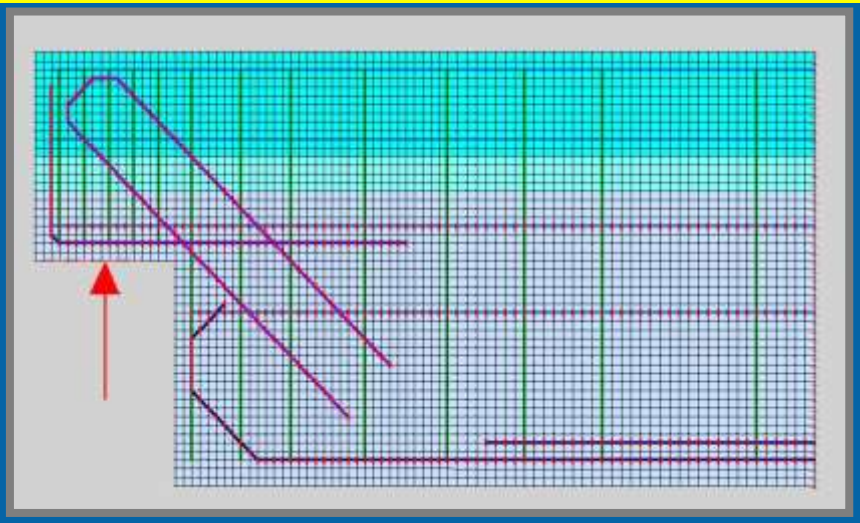
Laval Bridge Detail - 1992

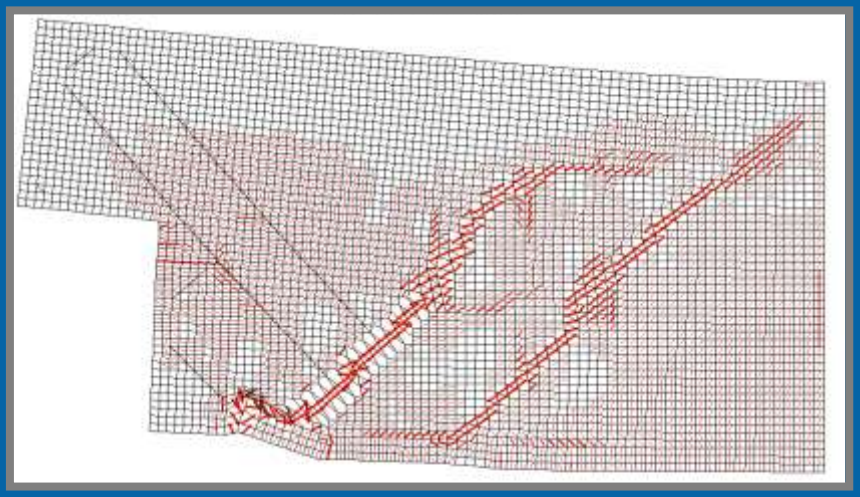
Toronto Trestle Bridge - 2009

Both bridges were built in ~1970 using ‘drop-in span’ girders.

Toronto Trestle Bridge

- VecTor2 software used to model upper half-joint of drop-in girder.
- Analysis showed that shear failure occurs beyond end of inclined hair-pin reinforcement.
- Too little transverse reinforcement provided; insufficient to transfer tension from hairpins to tension chord.
- Strut-and-tie modelling was inconclusive.
- Question: Is it safe? Emergency rehabilitation work was done.

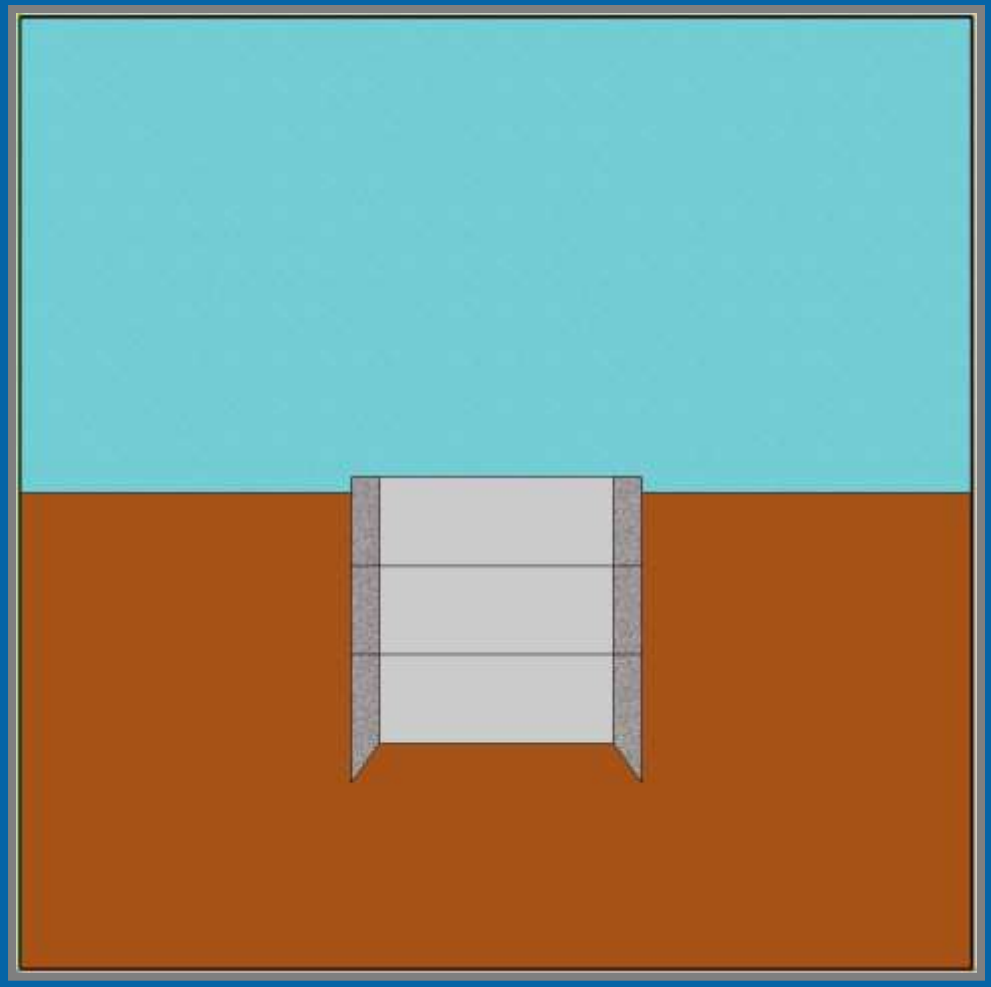




Dearborn Caisson C3

Dearborn Caisson C3

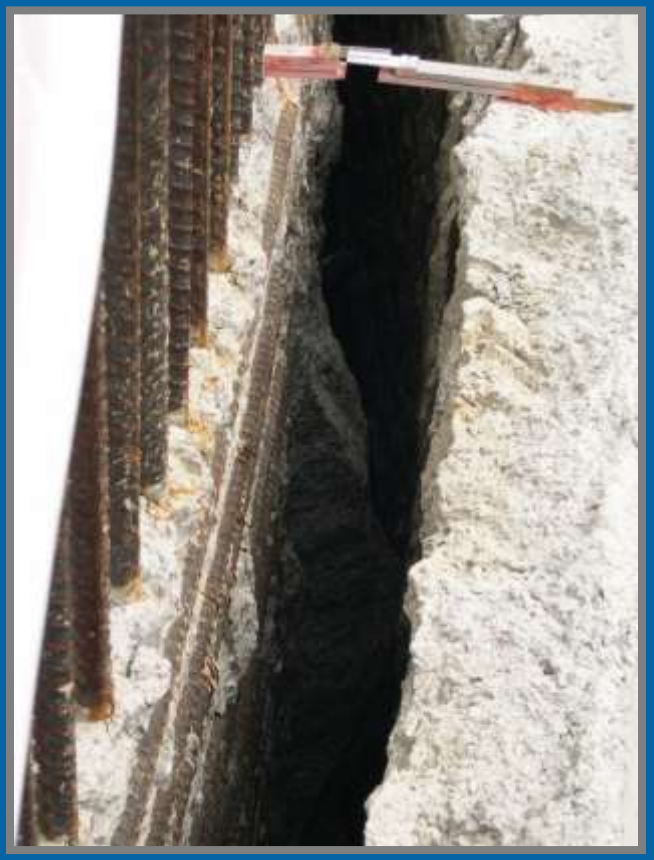
- World's largest caisson built by 'sinking caisson' technology
- 136 ft (41.5 m) I/S diameter.
- 105 ft (32 m) height
- 7 ½ ft (2.3 m) wall thickness
- No shear reinforcement



Dearborn Caisson C3

Stopped in mid-construction.

Dearborn Caisson C3



Circumferential delamination cracks develop over wide arc of structure.

Dearborn Caisson C3

Large flexural cracks appear on inside and outside walls.

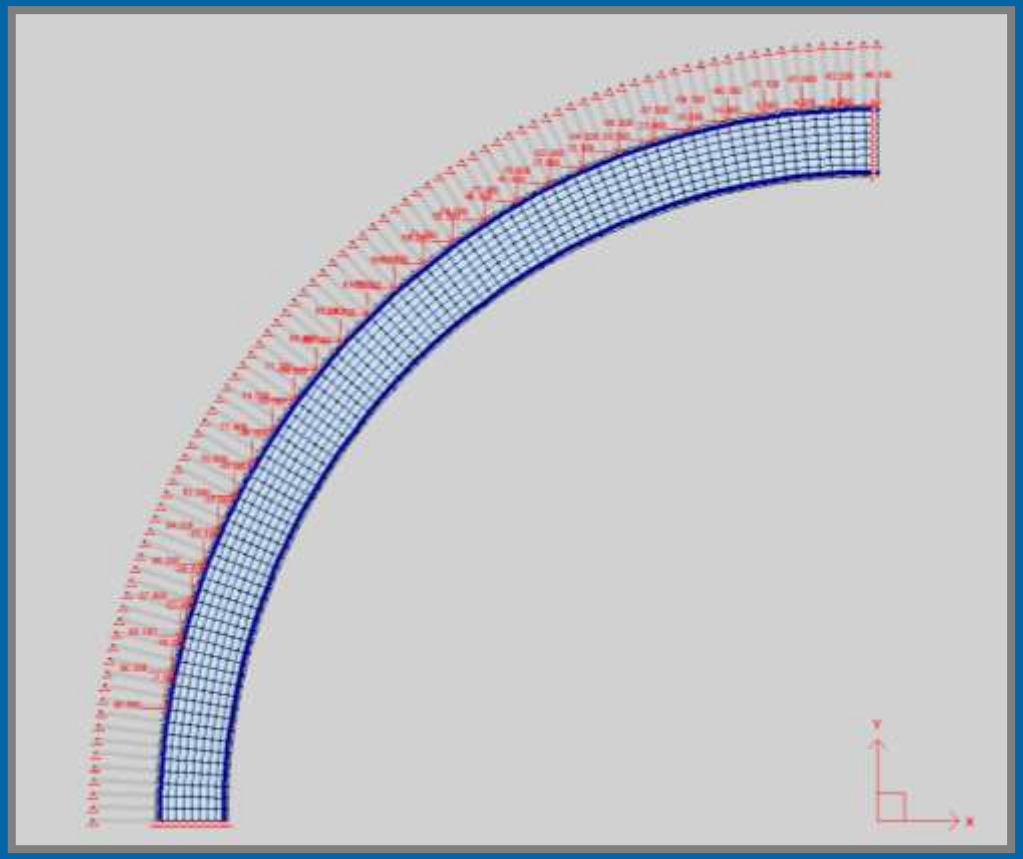
Dearborn Caisson C3

Shear cracks also develop through caisson wall.

Dearborn Caisson C3

Details of VecTor2 Analysis:

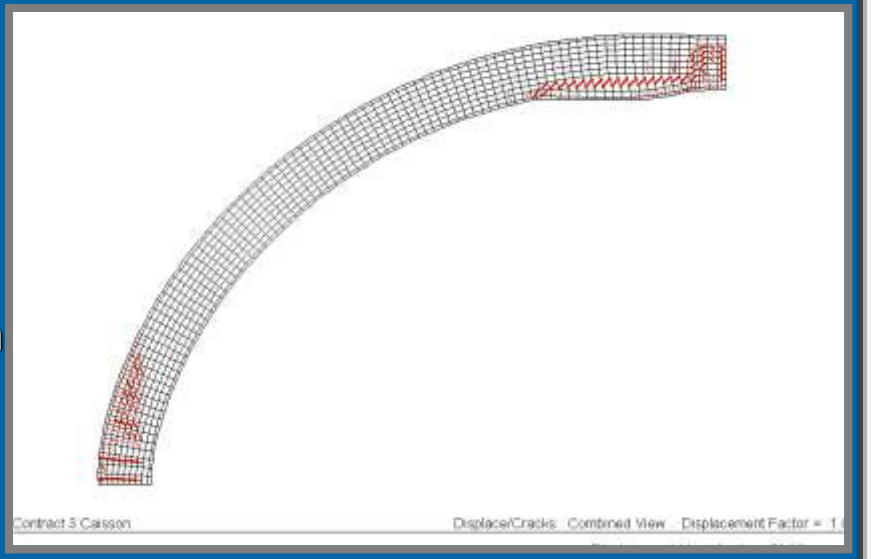
- One quadrant modelled
- Vertical and hoop reinforcement modelled using truss elements
- Soil interactions modelled using spring elements
- 2-inch gap modelled using contact elements
- Uniform active soil pressures applied except for arc of variable length



Dearborn Caisson C3

Results of Analyses:

- Strength, ductility, failure mode governed by delamination cracking
- Delamination arises from tendency of inner hoop reinforcement to straighten
- Nonuniform soil pressures result in ovalling; can take +/- 27% of design pressure (5.25 ksf)
- 2-inch (50 mm) gap closes before failure; soil interactions resist further ovalling; not possible to fail given active pressures all-round



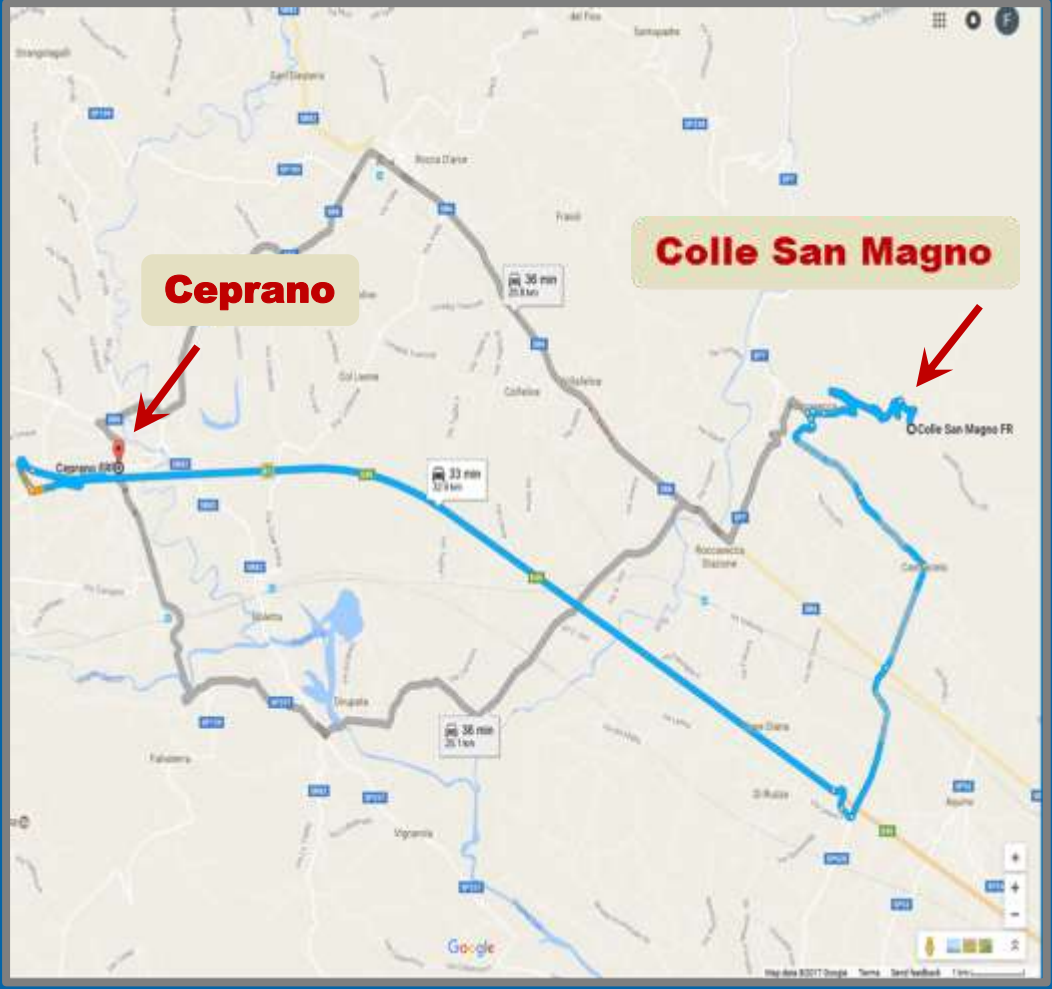
- Loss of confinement over 20-degree arc under design pressure will result in failure shown
- Bond, shear play no significant role in failure
- Sink-hole (loss of soil confinement) likely cause of failure of structure

Truths…About Analysis Software

Truth # 2: Can be a highly powerful tool.

- Useful for various design and investigation purposes which can be difficult or impossible to perform otherwise.

Ceprano, Frosinone, Italy



Ceprano, Frosinone, Italy

A famous skull of *Homo erectus*, dating from 800,000 years ago, represents the most ancient finding of the *Homo* species in Europe.

An Idiot's Guide to Modelling and Assessment of RC Structures

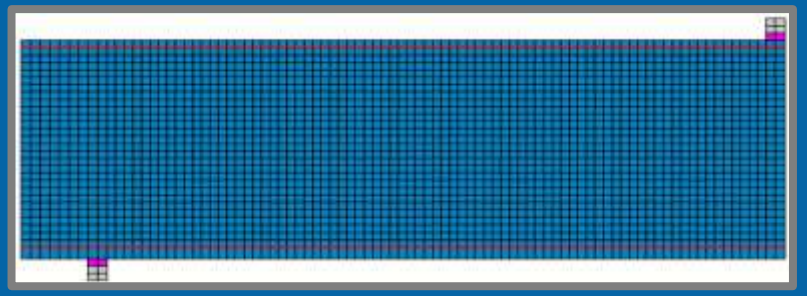
- *Introduction*
- *Utility - Case Studies*
- ***Accuracy & Reliability***
- *Traps & Blunders*
- *Conclusions*

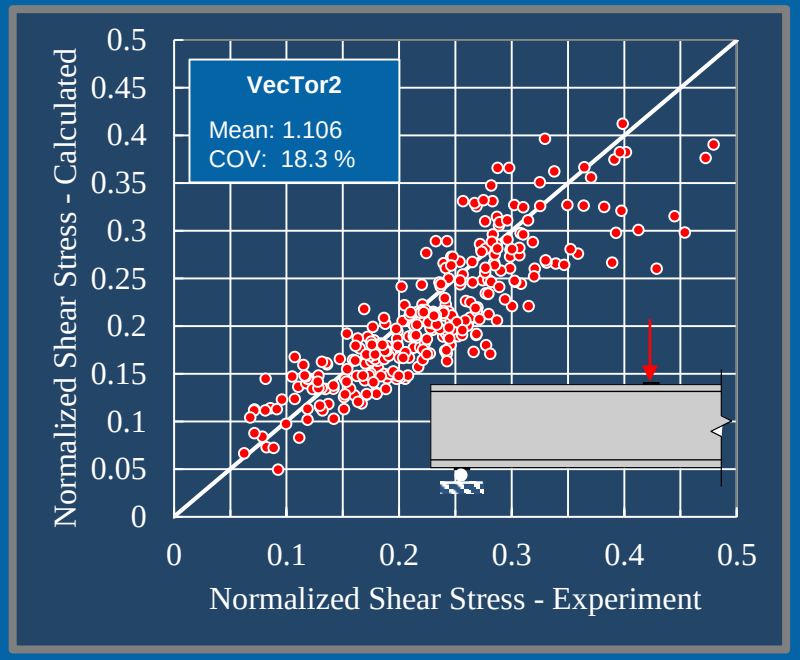
- *Recent Projects*
- *Current Research*

Accuracy and Reliability

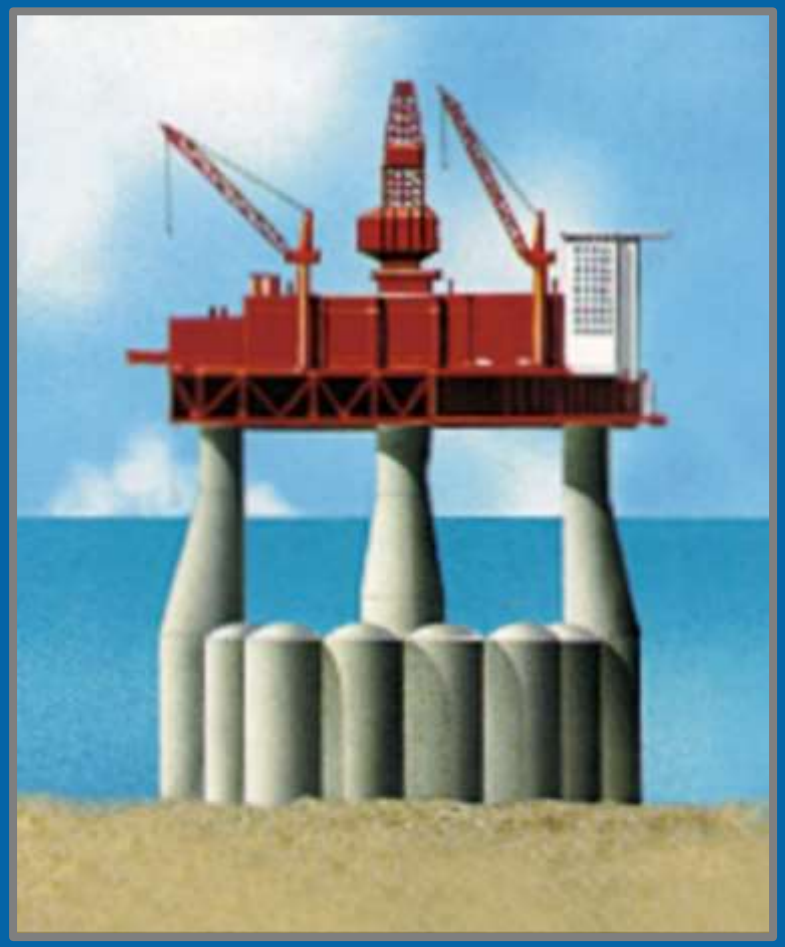
Can be assessed through:

- Experimental Corroborations
  - Numerous (but biased)
- Field Applications
  - Sleipner Offshore Platform
  - Sherway Warehouse
  - Cement Preheater Tower
- Prediction Competitions
  - Delft Competition 1981
  - NUPEC Competition 1995
  - Zurich Competition 2005
  - Collins Deep Beam 2015



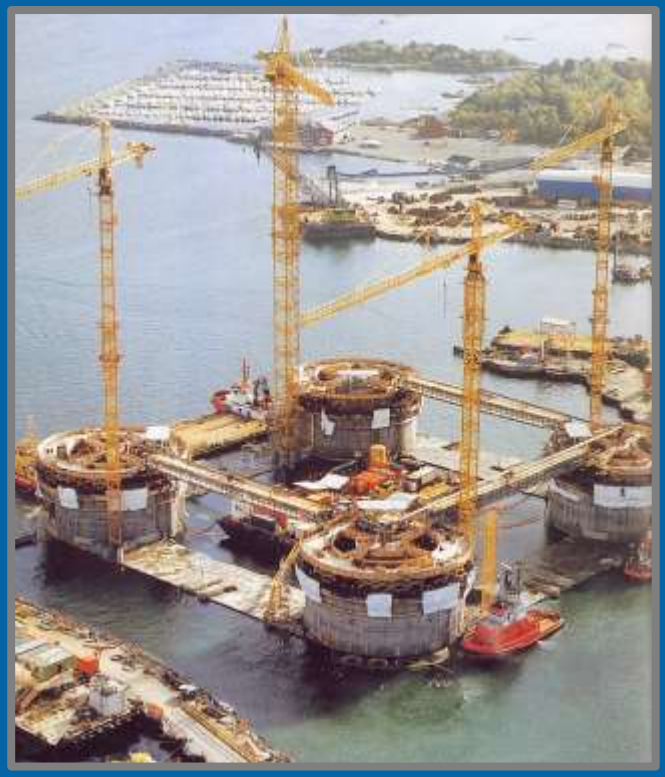


Sleipner Offshore Platform



- Sleipner platform is one of several Condeep platforms in North Sea.
- Required 3 years to construct.
- Failure during deck-mating operation in August 1991.
- Economic loss ~ 700 Million USD.
- Redesigned and rebuilt in 18 months.

Sleipner Offshore Platform

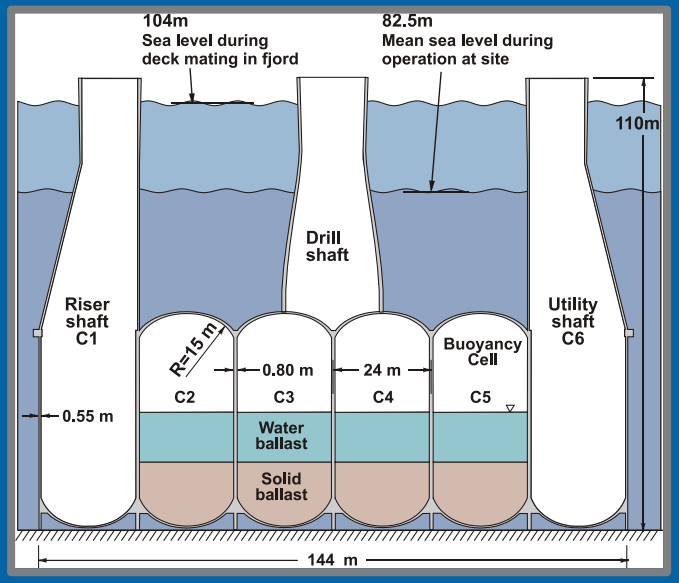


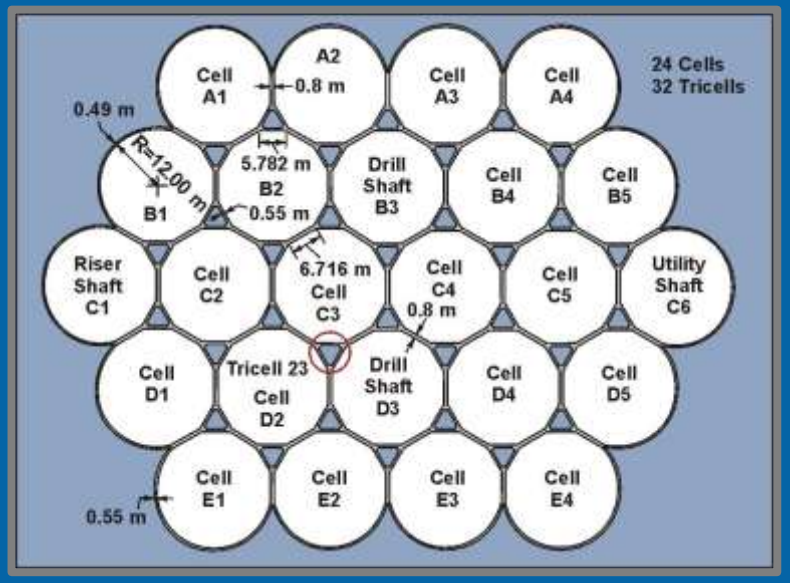
Sleipner Offshore Platform

Deck-mating operation:

- Done in deeper waters.
- Gravity structures see highest hydrostatic stresses.

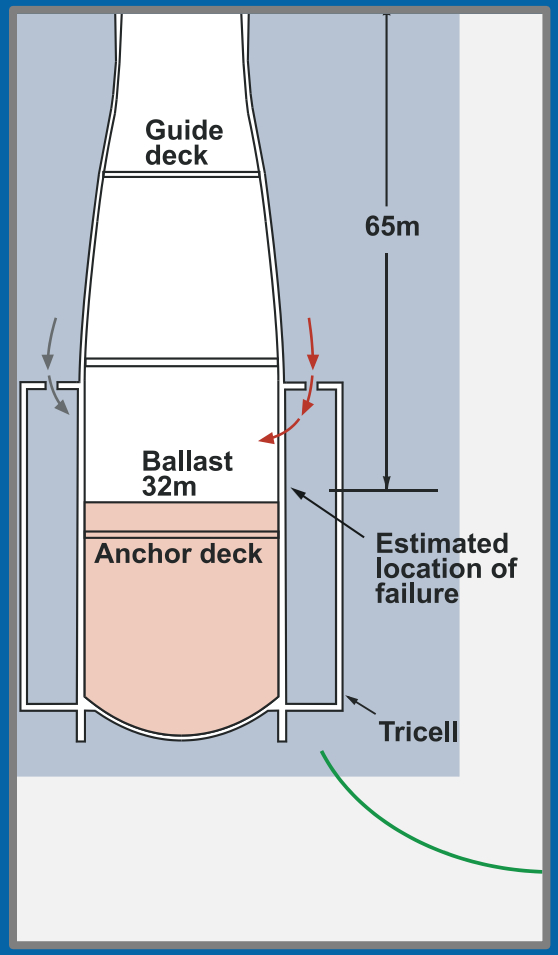
Sleipner Offshore Platform

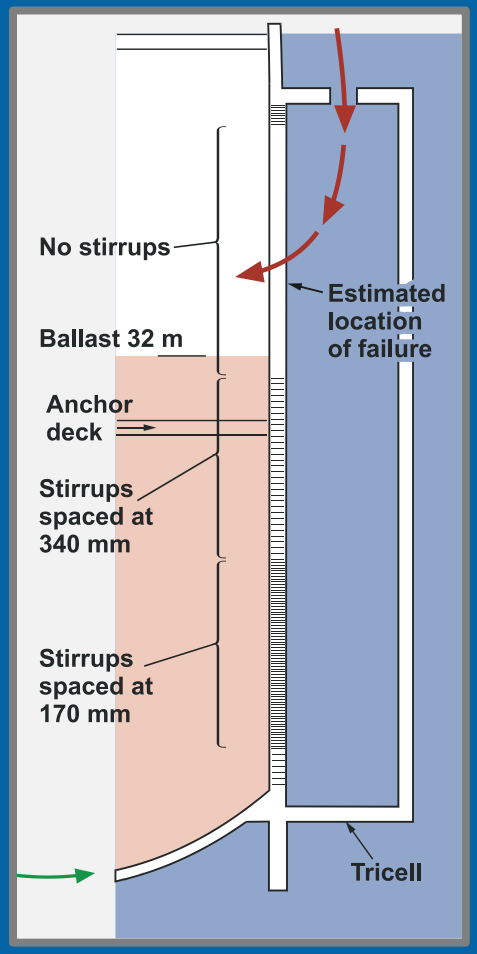




Details of Sleipner Concrete Base Structure

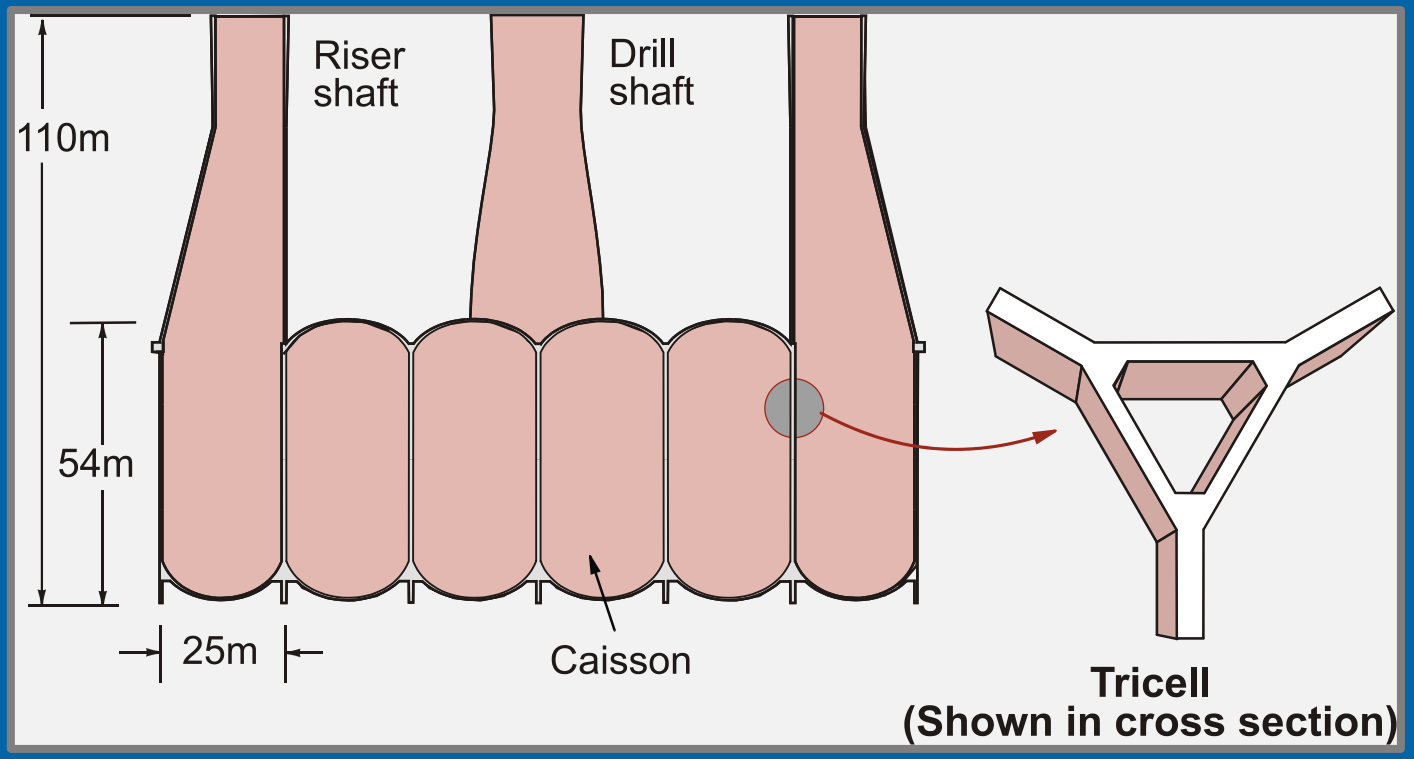
Sleipner Offshore Platform





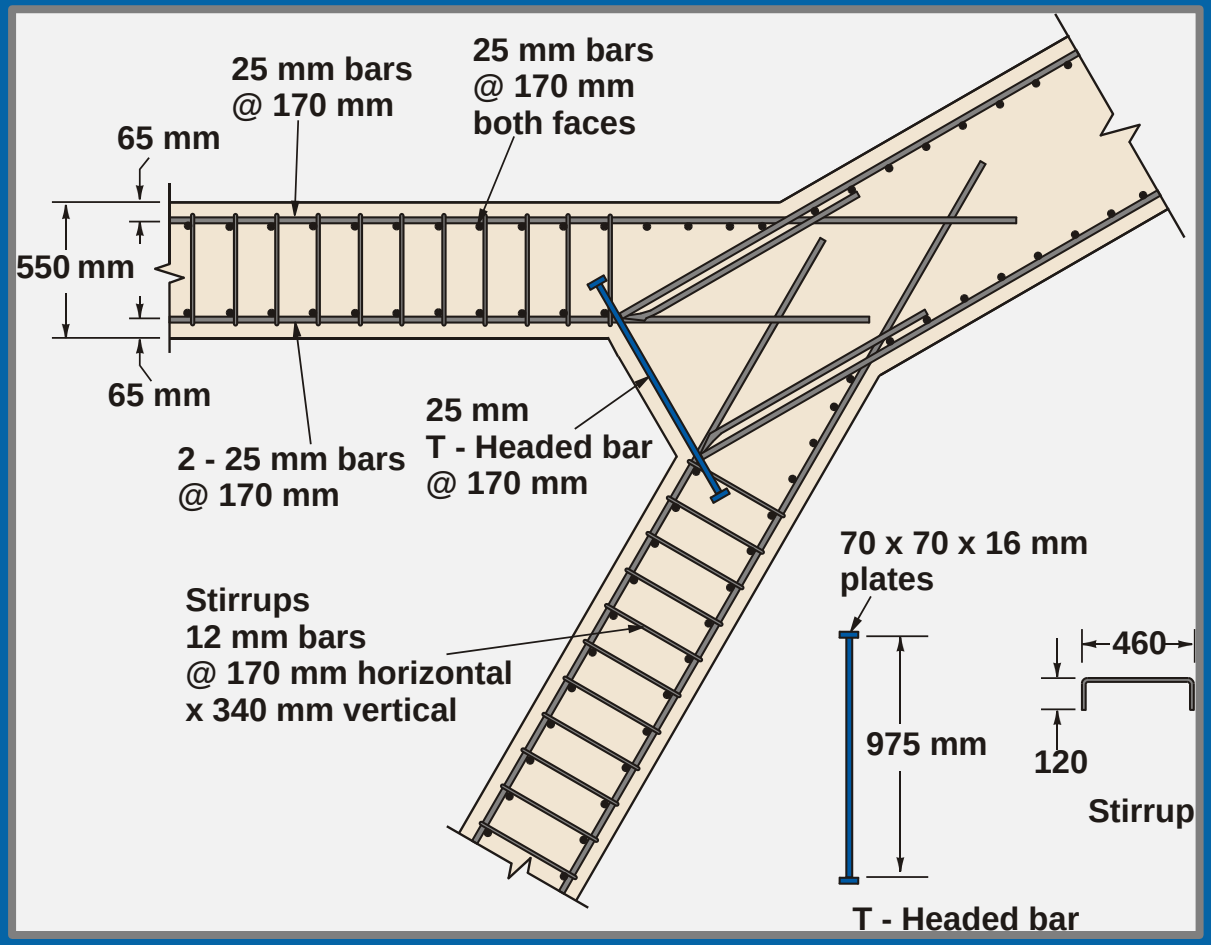
Elevation Details for Tricell 23

Sleipner Offshore Platform



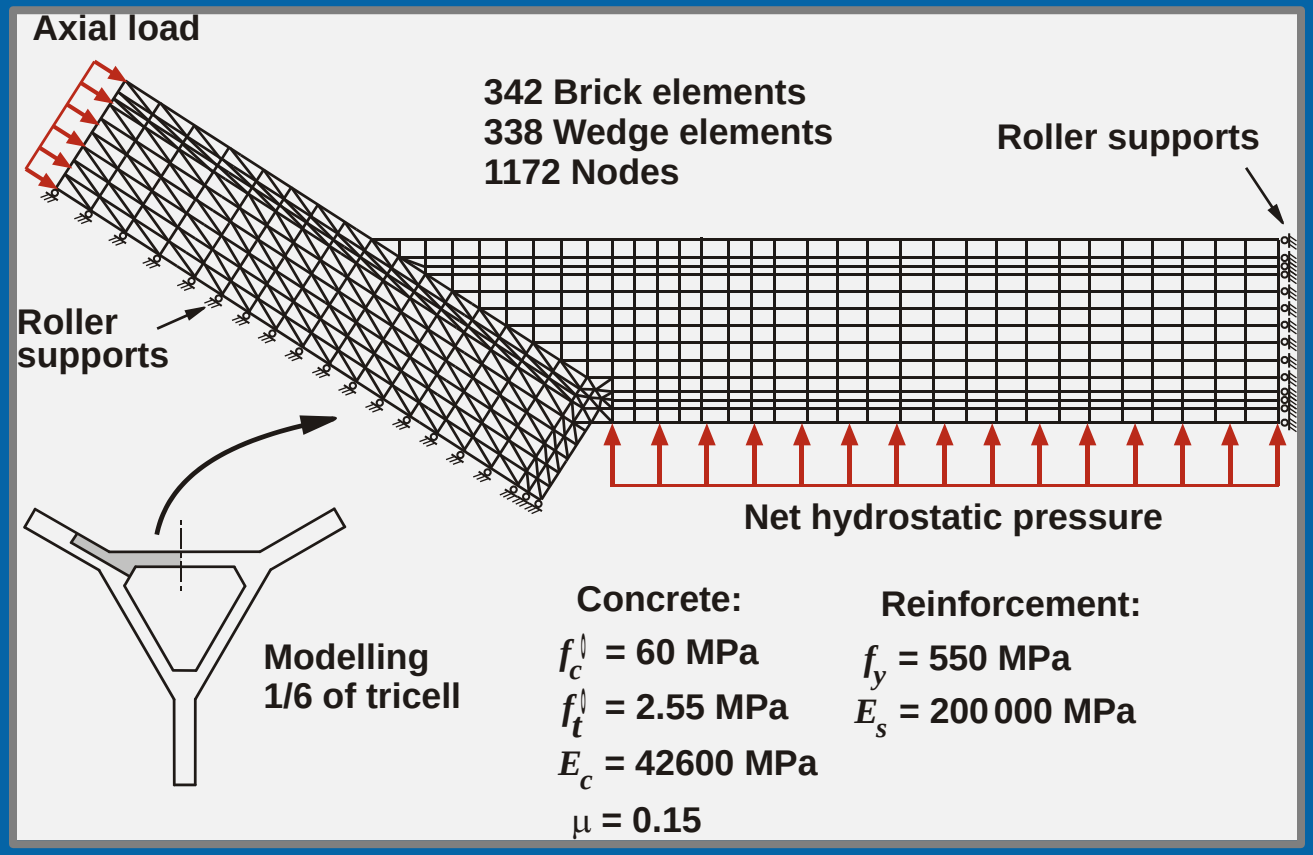
Detail of Tricell

Sleipner Offshore Platform



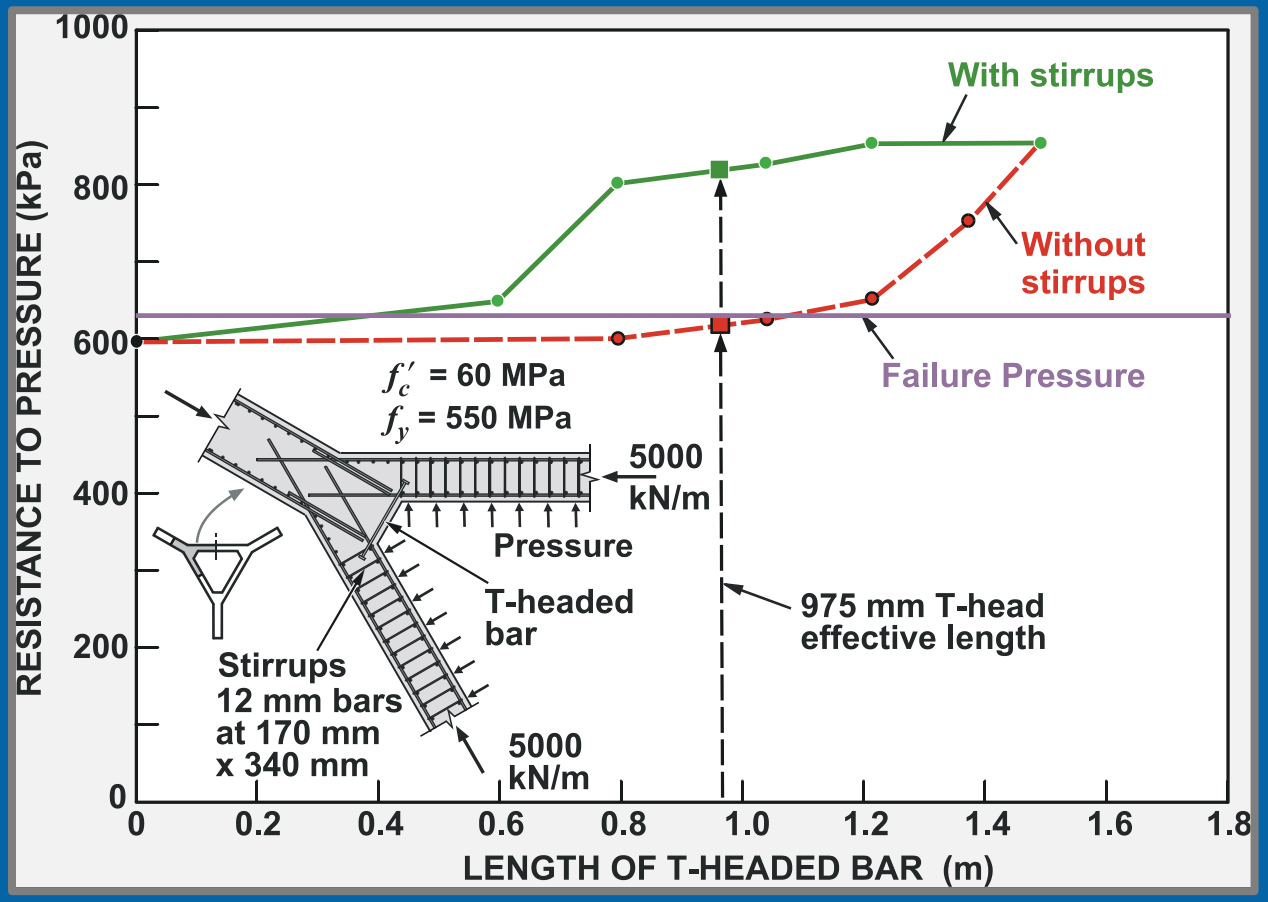
Section Detail for Tricell 23

Sleipner Offshore Platform



Finite Element Model of Tricell 23

Sleipner Offshore Platform



Analysis Results

Prediction Competition - Delft 1981

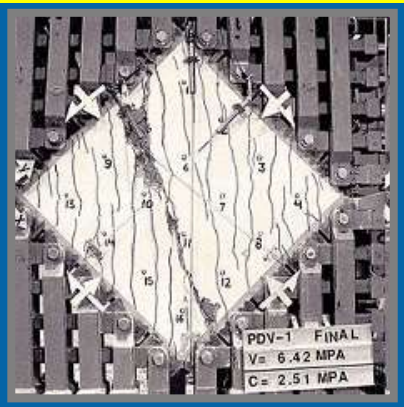
Panel Element Tester

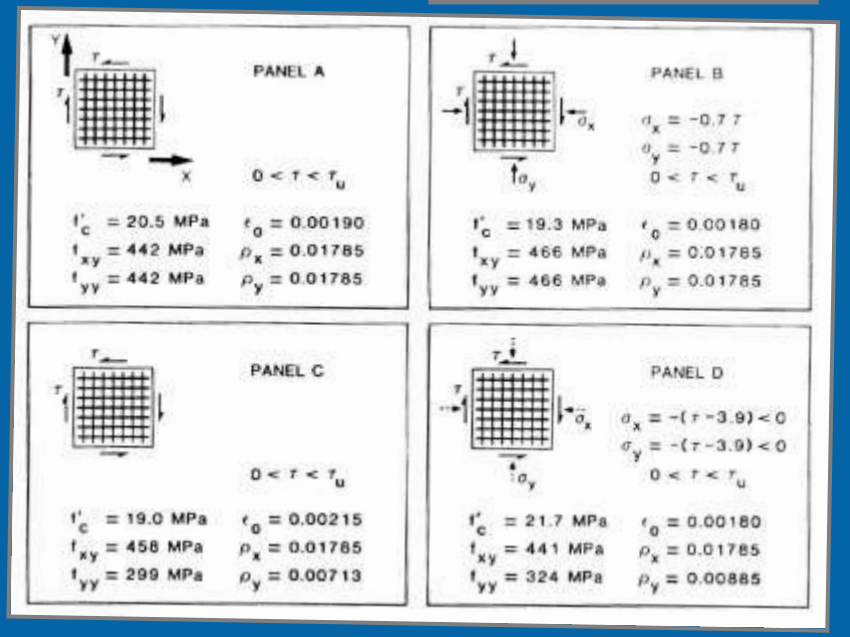
- Applies arbitrary in-plane stresses to thin RC panels using 38 - 10,000 psi hydraulic jacks and its own control apparatus.
- Used to determine realistic nonlinear constitutive models for RC elements.
- First of its kind in the world (built 1979).

Shear Panel Tester

Prediction Competition - Delft 1981

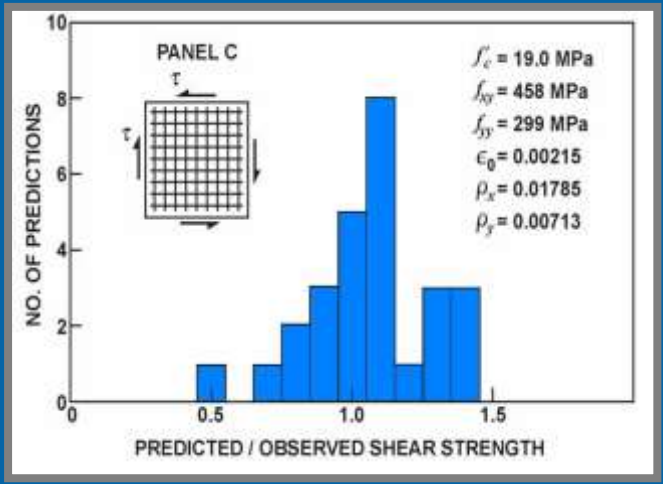
- Four panels were subjected to varied two-dimensional stress states.
- Analysts were required to predict the ultimate strength (*Vu*) and the load-deflection response (*V* - *γ*) of the panels.
- 27 entries from 13 countries, representing the foremost researchers in the field of reinforced concrete.
- Analysis methods ranged from simple hand calculations to advanced FEA programs.

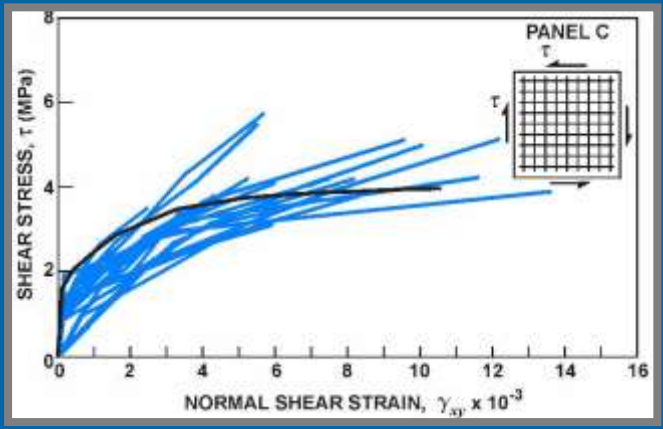




Prediction Competition - Delft 1981

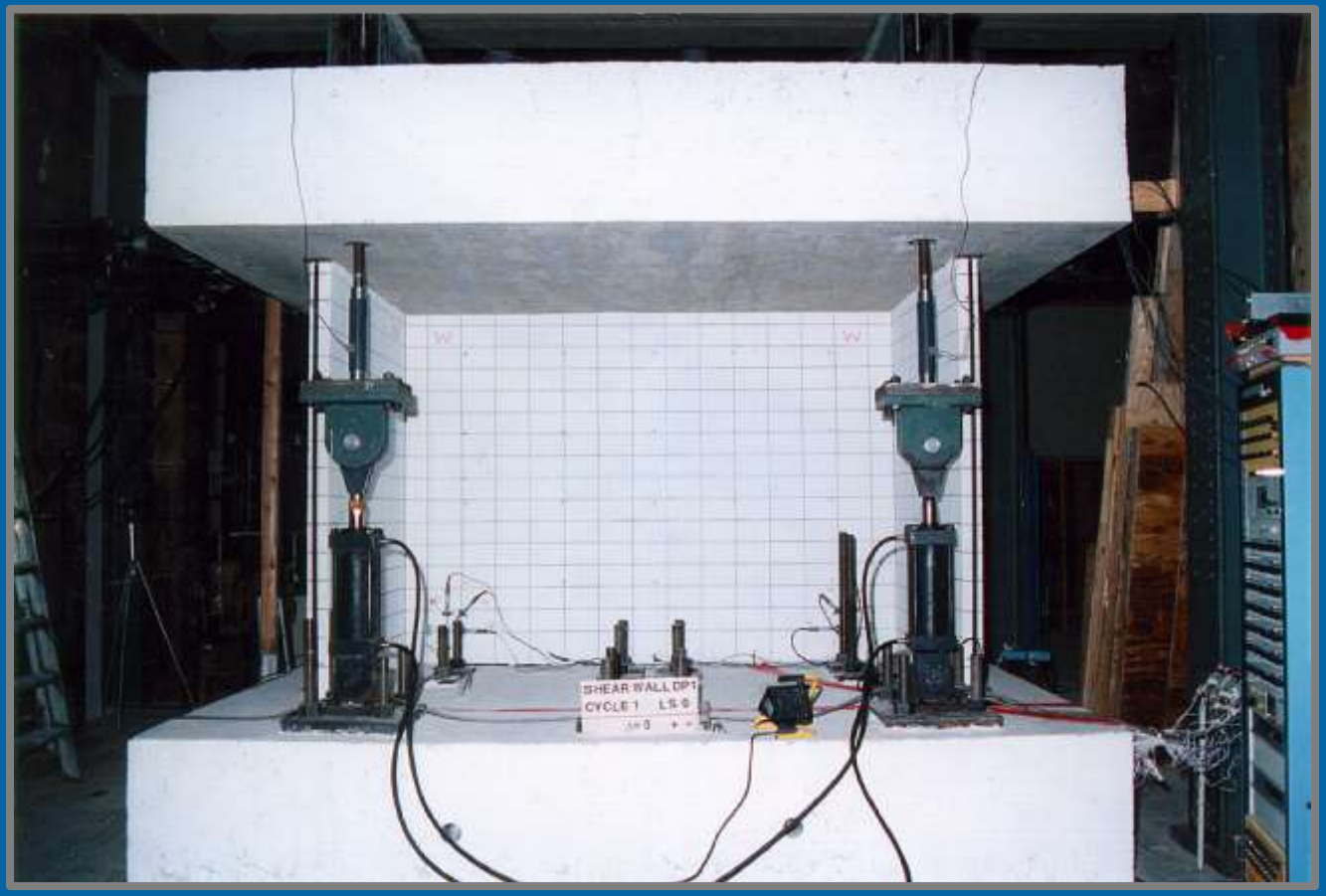
- Large variations in predictions.
- Predictions of ultimate strength were generally higher than the experimental values:
  - Coefficients of variation were as large as 40%.
- Predicted strains were also much higher than those observed:
  - The coefficients of variation ranged from 50 - 100%.
- Sophisticated FEA software did not always do the best job:
  - Hand calculations performed equally well in some cases.



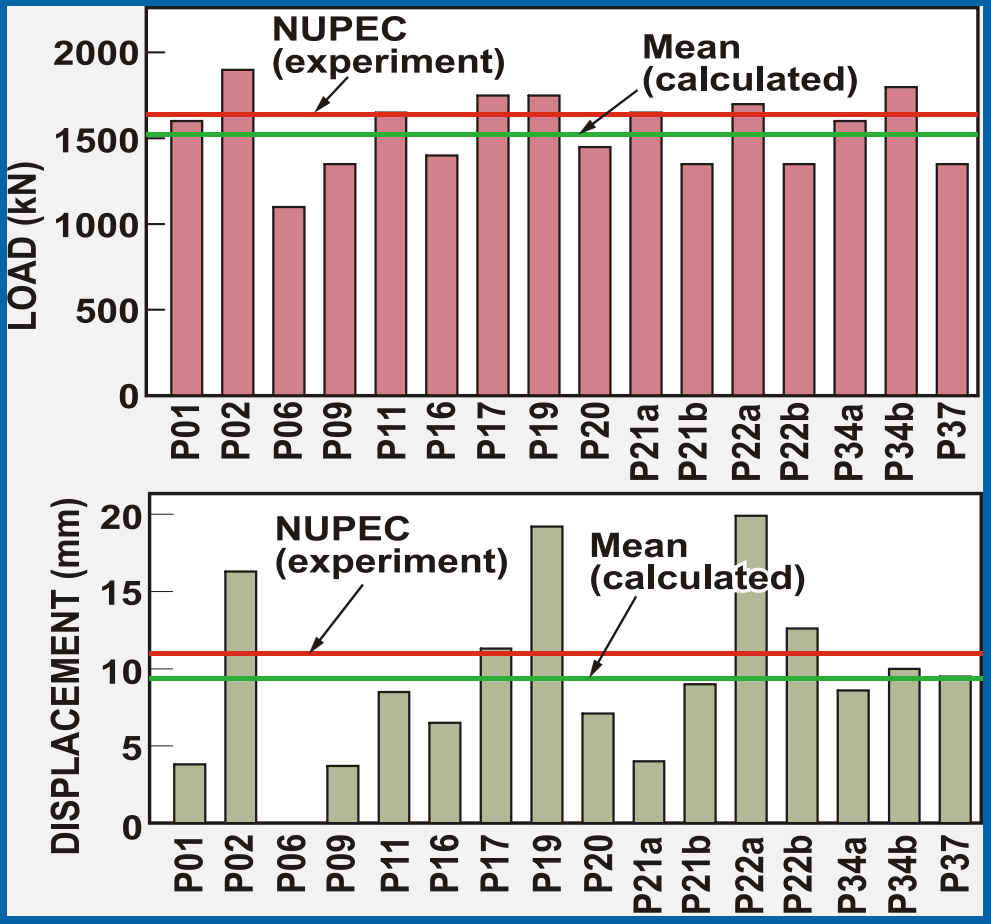


Panel C Predictions

Prediction Competition - NUPEC 1995



Prediction Competition - NUPEC 1995

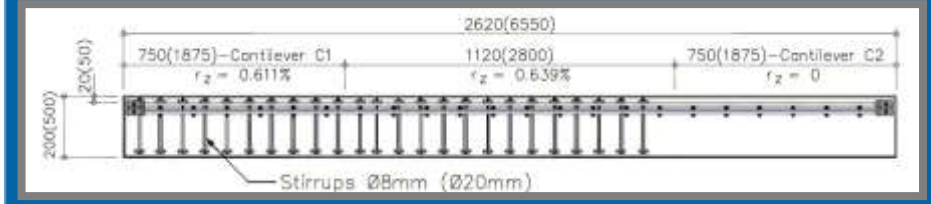


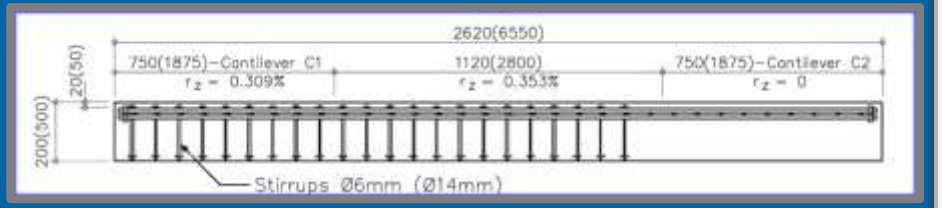
Prediction Competition - Zurich 2005

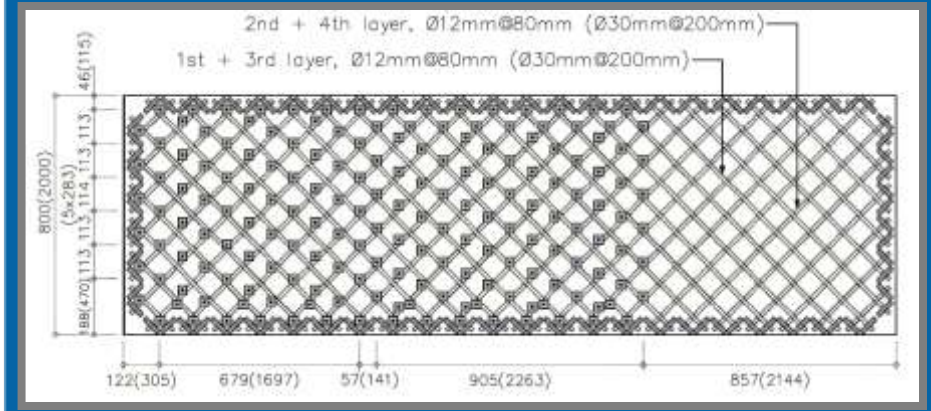
Tests were conducted at ETH Zurich to investigate the shear strength and deformation capacity of reinforced concrete slabs.

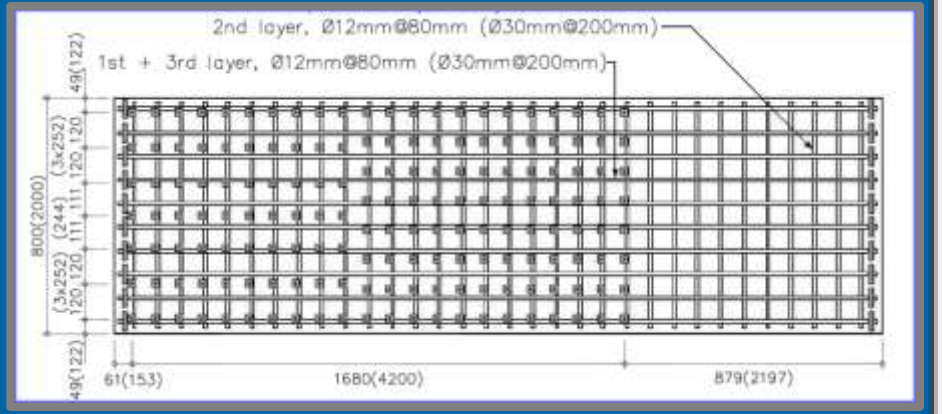
- Blind Competition was held to predict test results for 8 slab tests.
- Variables:
  - Depth (200 mm, 500 mm)
  - Longitudinal reinforcement orientation (0 deg, 45 deg)
  - Shear seinforcement (ρ_v = 0%, 0.61%)

Prediction Competition - Zurich 2005







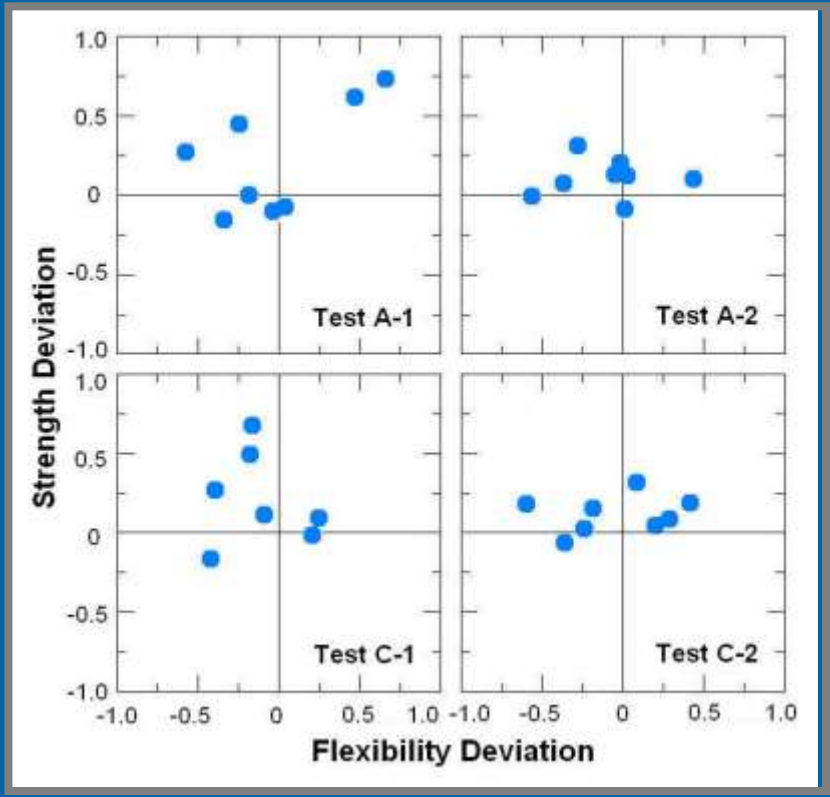


Dimensions – Slab A (Slab C) - mm

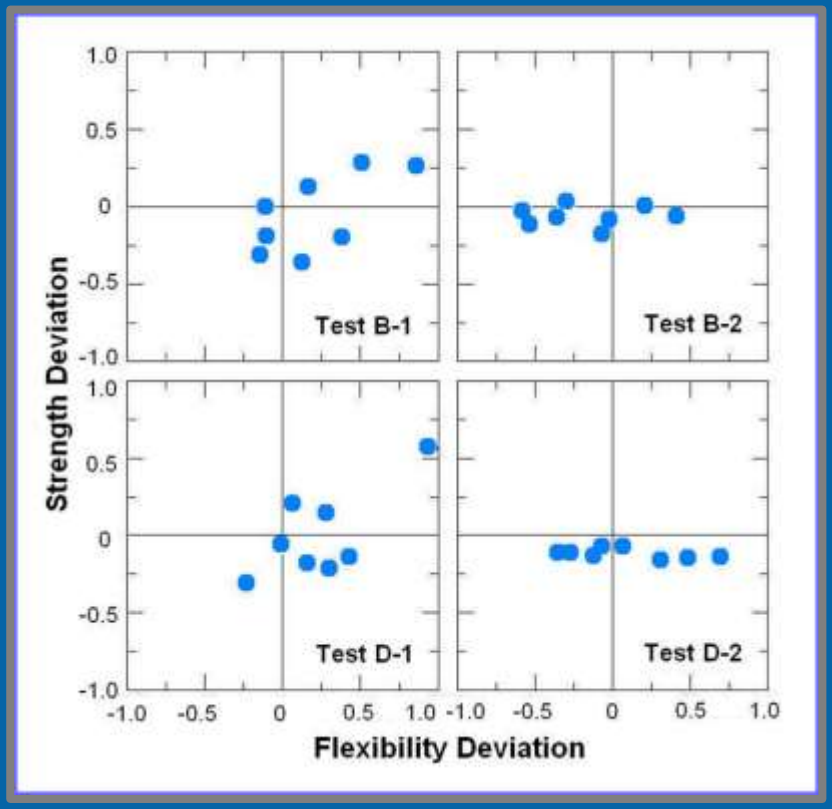
Dimensions – Slab B (Slab D) - mm

Figures courtesy of Thomas Jaeger, ETH Zurich

Prediction Competition - Zurich 2005



Slabs A and C



Slabs B and D

Prediction Competition - Zurich 2005

" The prediction competition revealed that the modelling of cracked reinforced concrete still poses significant problems, even for experienced researchers equipped with sophisticated analytical tools. "

Jaeger and Marti, 2009

Truths…About Analysis Software

Truth # 3: Can produce inaccurate results.

- Can fail to properly represent important mechanisms, producing incorrect and possibly dangerous results.

An Idiot's Guide to Modelling and Assessment of RC Structures

Why modelling and assessment of concrete structures can be like….

…ice-fishing in Tel Aviv.

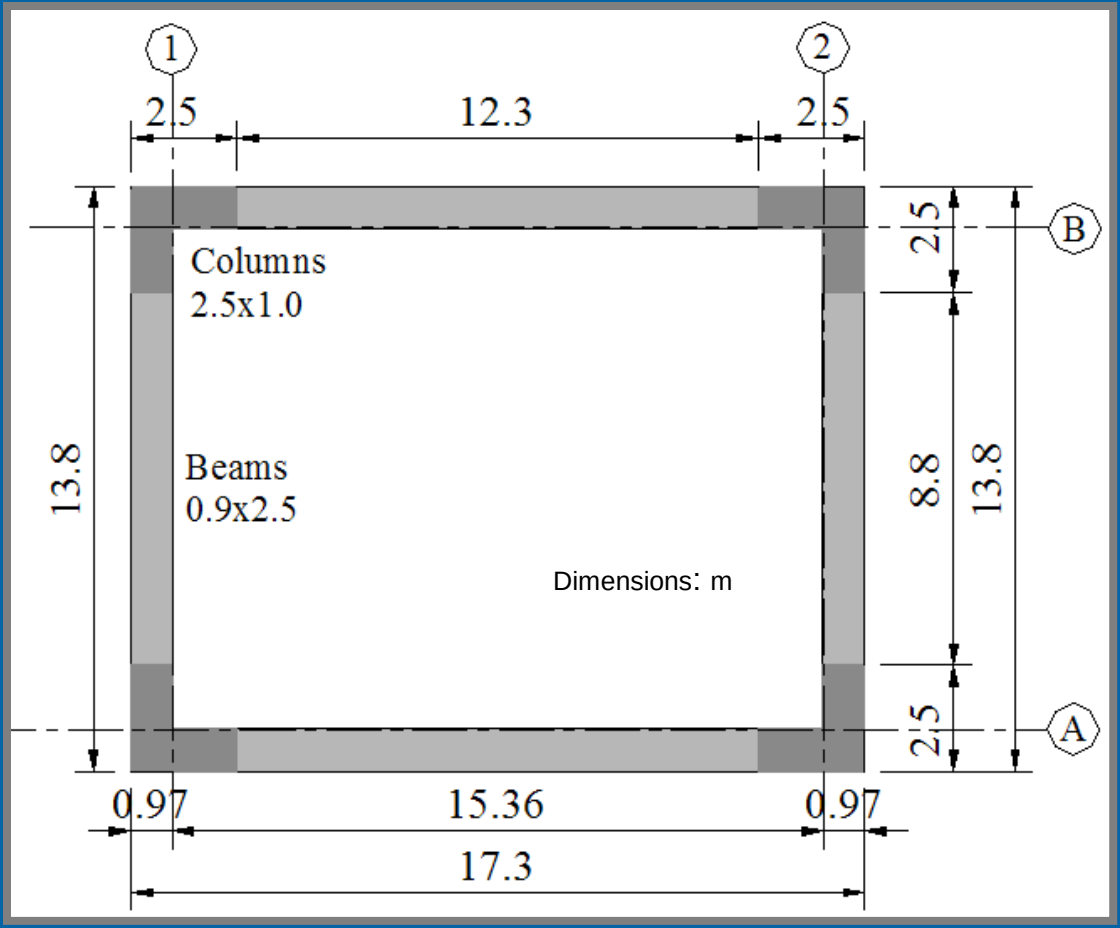
An Idiot's Guide to Modelling and Assessment of RC Structures

- *Introduction*
- *Utility - Case Studies*
- *Accuracy & Reliability*
- ***Traps & Blunders***
- *Conclusions*

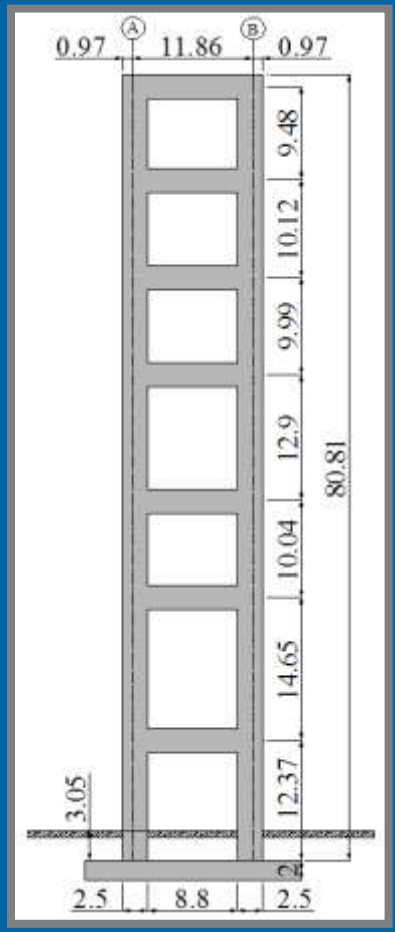
- *Recent Projects*
- *Current Research*

South American Cement Preheater Tower

South American Cement Preheater Tower

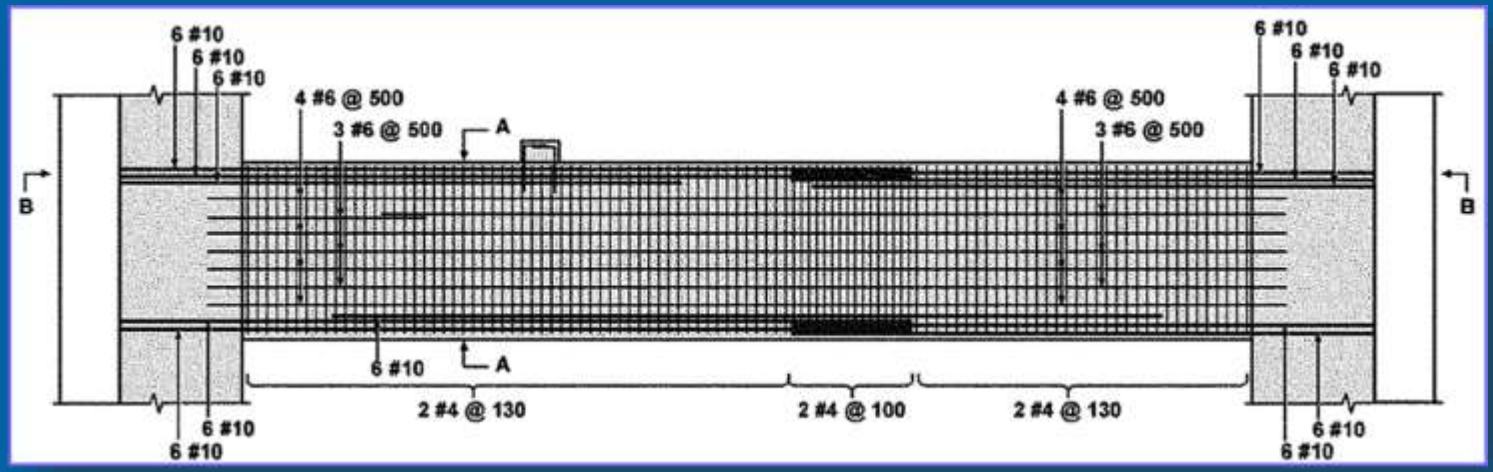


Plan

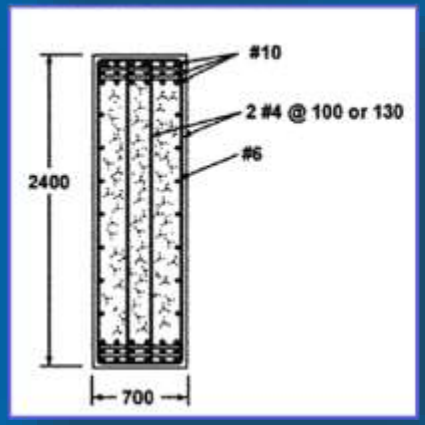


Elevation

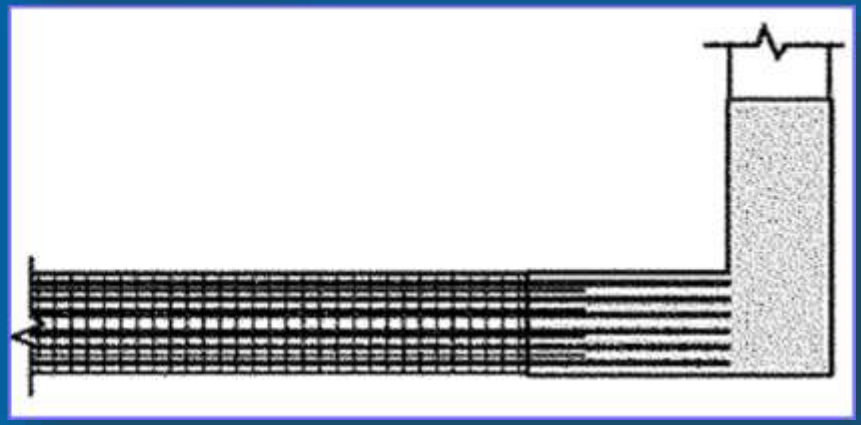
South American Cement Preheater Tower



Section A-A



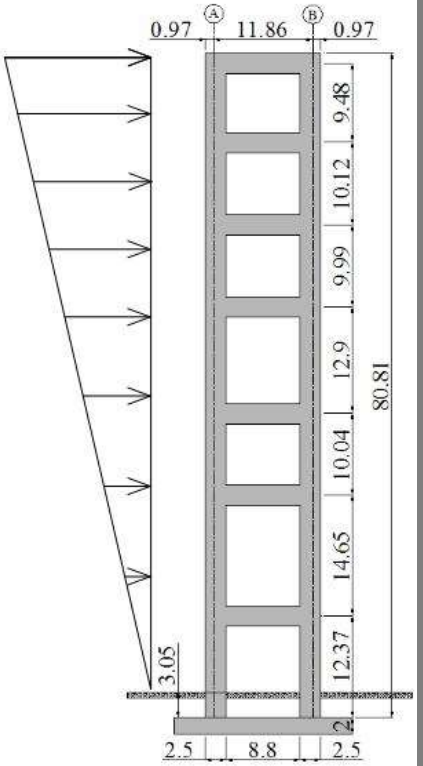
Section B-B

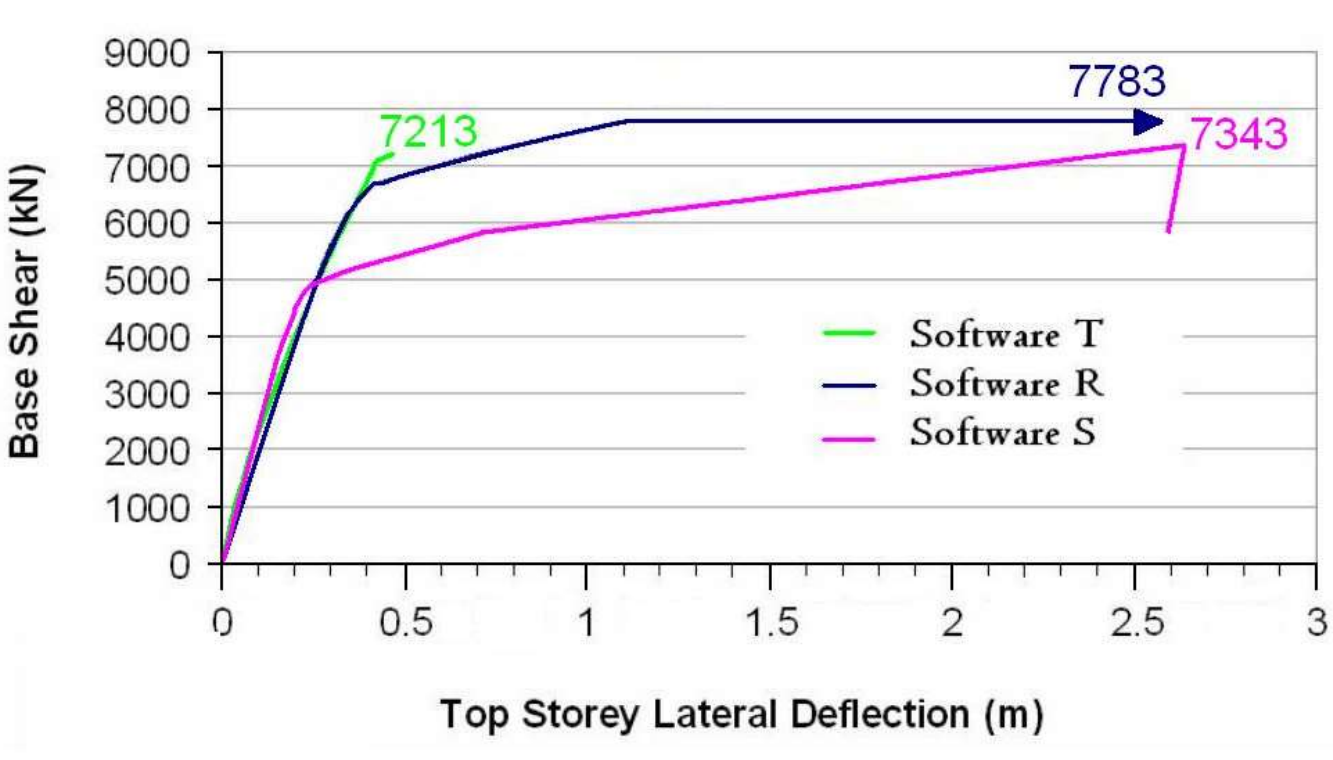


South American Cement Preheater Tower

South American Cement Preheater Tower

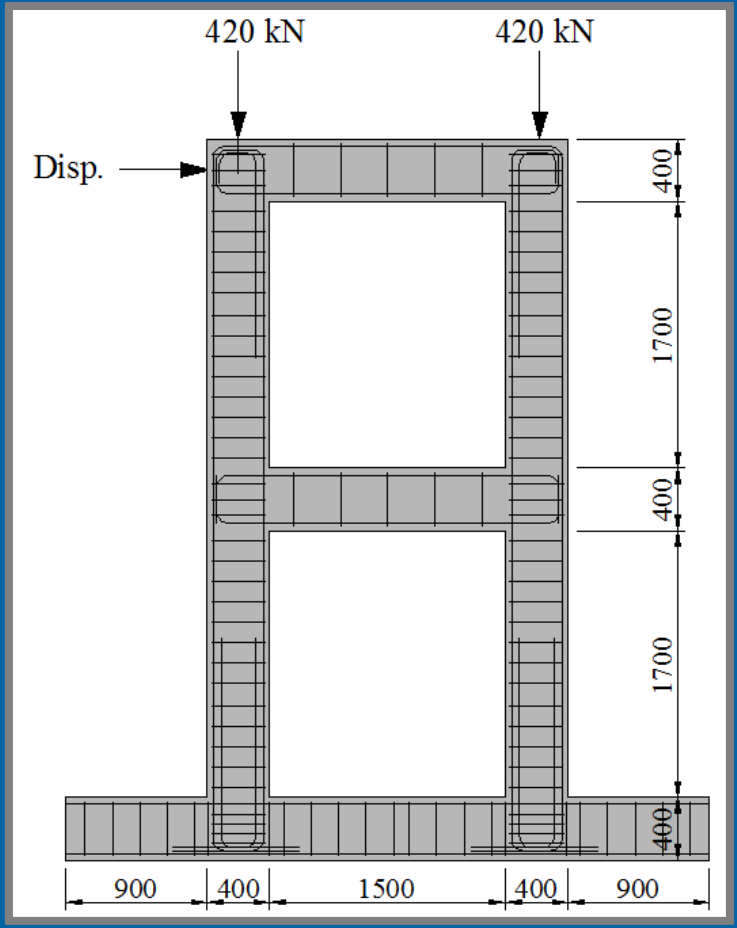
Static Push-Over Analysis Results





Contradictory Results! Which one is right?

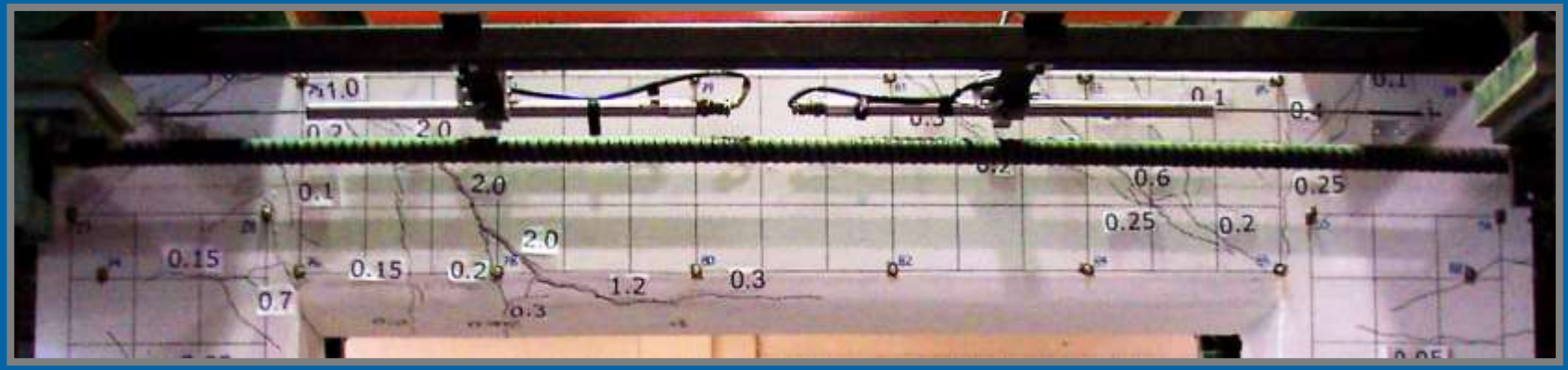
Static Push-Over Test: Duong Test Frame



Prior to Testing

Static Push-Over Test: Duong Test Frame

Upper Beam



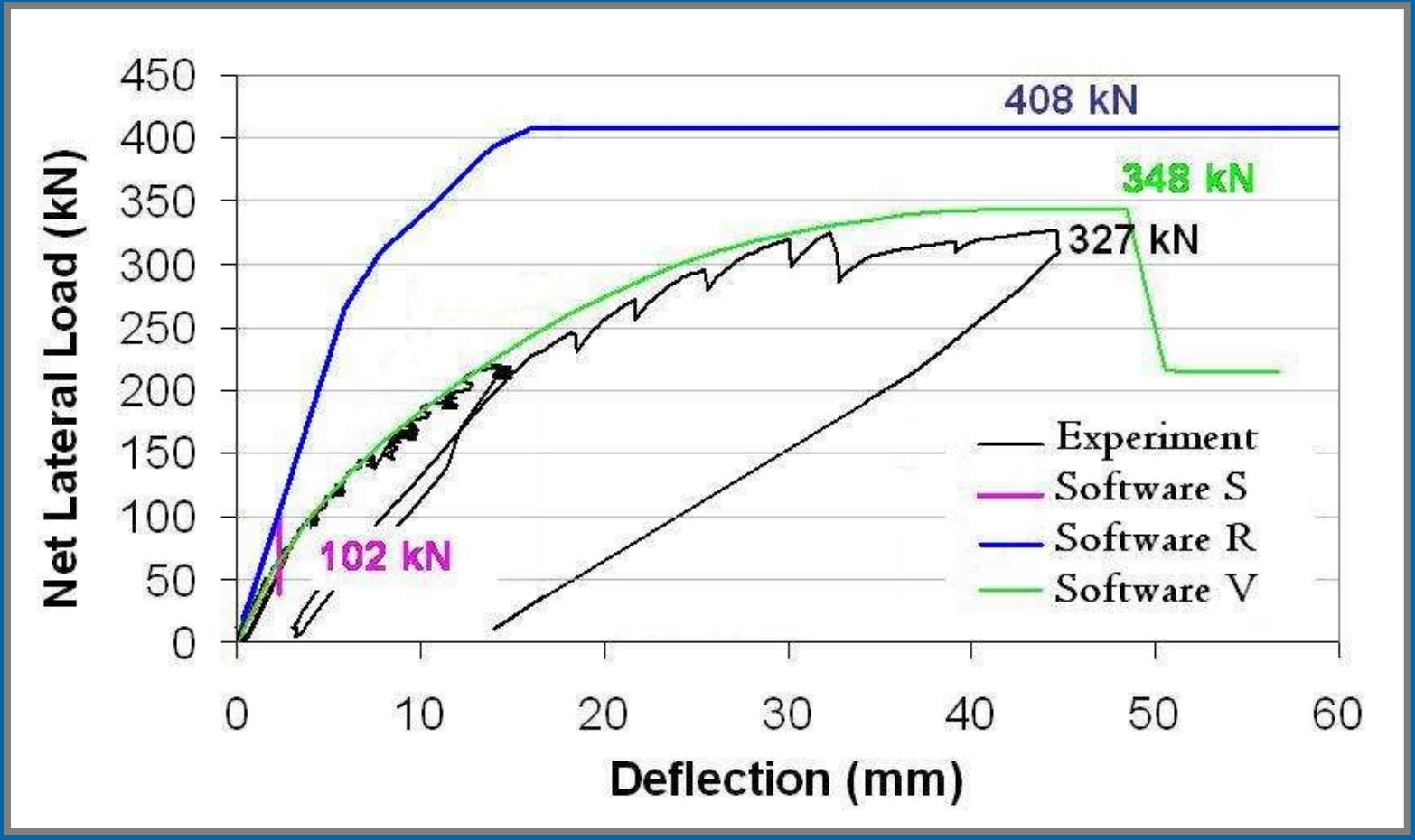
Lower Beam

After Testing

Damage mode: flexural-shear

Photos courtesy of K. V. Duong

Static Push-Over Test: Duong Test Frame



Static Pushover Analysis Results

Truths...About Analysis Software

Truth # 4: Can be applied incorrectly.

- User must be aware of range of application and limitations of software; should not be applied to cases for which it is not suitable.

Cicero

Marcus Tullius Cicero was a Roman philosopher, politician, lawyer, orator, political theorist, consul, and constitutionalist.

Born: January 3, 107 BC, Arpinum, Rome
Assassinated: December 7, 43 BC, Formia, Italy

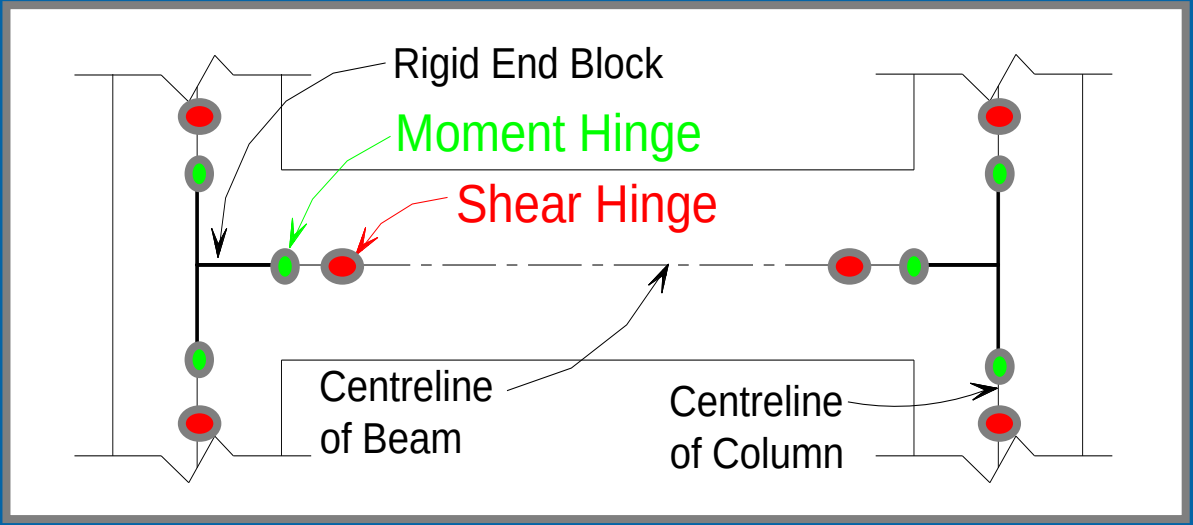
"It is the peculiar quality of a fool to perceive the faults of others and to forget his own."

Application of Program S

1. **No transverse reinforcement modelling.**
2. **Major decisions to make:**

Default Hinges vs. Custom Hinges

- Will default shear hinge work properly?
- If custom hinges used, how to generate shear hinge?
- Where to put hinges?



Application of Program R

1. **Modelling takes considerable time**
   - Provide complete N-M Interaction Responses for all sections.
   - Specify Fixed End Forces for each member.

2. **Several major decisions to make:**
   - Select one of 52 hysteresis models..?
   - Assume a failure mode before Modelling..?

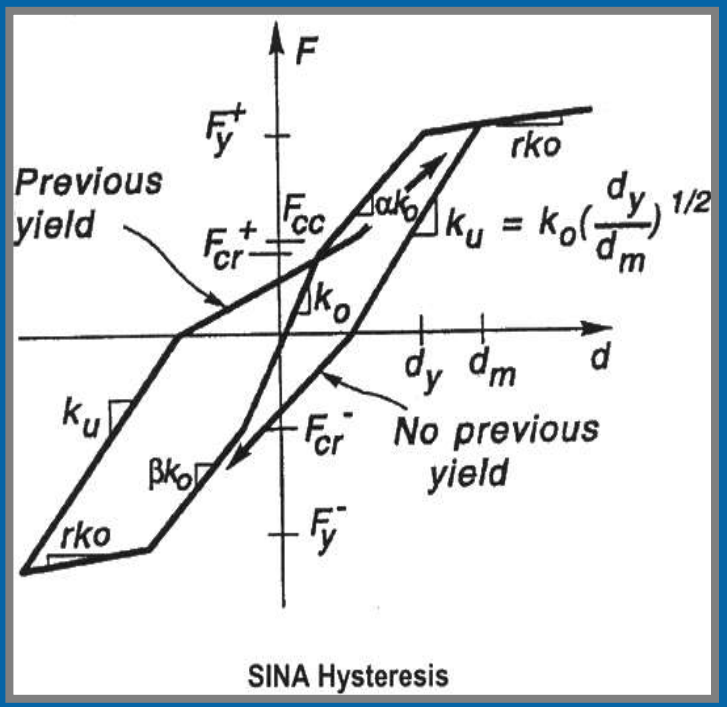
Application of Program R

Shear Deformations

Default: Elastic Analysis

For Inelastic Analysis, provide:

Vy	Shear yield strength	(> 0.0)
Vcr	Shear cracking strength	(> 0.0)
Vcc	Shear crack closing corce	(> 0.0)
Alfa	Bi-linear factor, cracking to yield	(R < Alfa < 0.0)
R	Tri-linear factor after yield	(> 0.01)
Duct1	Shear ductility where strength degradation starts If less than 1.0 then no shear strength degradation	
Duct2	Shear ductility where shear strength degradation stops	(> Duct1)
Vres	Residual shear strength as proportion of Vy	(0.01 ≤ Vres < 1.0)
Phi1	Flexural ductility where shear strength degradation starts If less than 1.0 then no shear strength degradation	
Phi2	Flexural ductility where shear strength degradation stops	(> Phi1)
Pres	Residual shear strength as proportion of Vy	(0.01 ≤ Pres < 1.0)
	(Note: Vres*Pres*Vy must be somewhat greater than Vcr)	
Ido	= 0; In-elastic shear yield may occur (default)	
	= 1; Retrofit assumed, message printed, shear remains elastic.	
	= 2: Failure assumed, message printed, analysis terminated.	



SINA Hysteresis

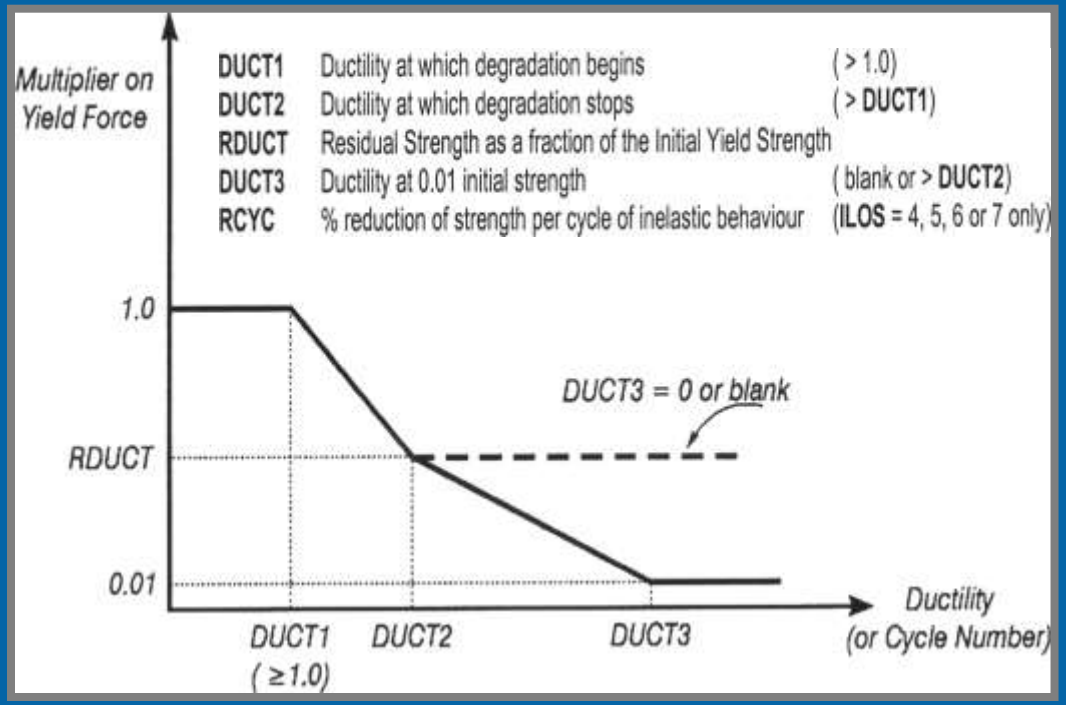
How does one calculate those values?

Application of Program R

Strength Degradation

Default: No Strength Degradation due to Cyclic Loading

To consider, provide:



How does one calculate those values?

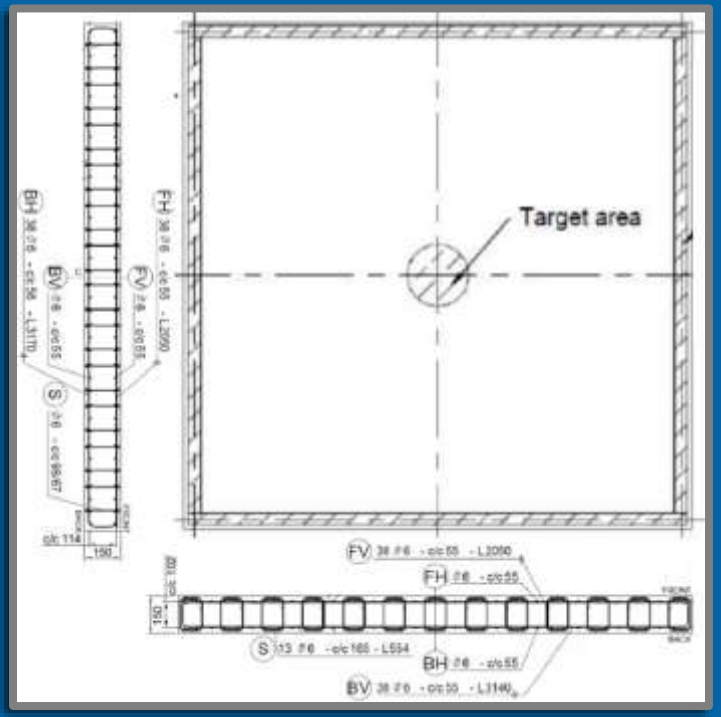
Truths...About Analysis Software

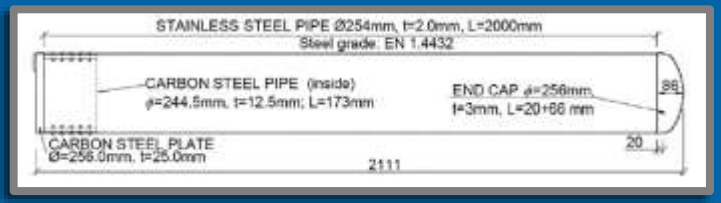
Truth # 5: Can be complex & difficult to use.

- May require extensive pre-analysis calculations.
- May require predetermination of failure mode or governing mechanisms.
- May require difficult modelling decisions.
- May require comprehensive auxiliary analyses.

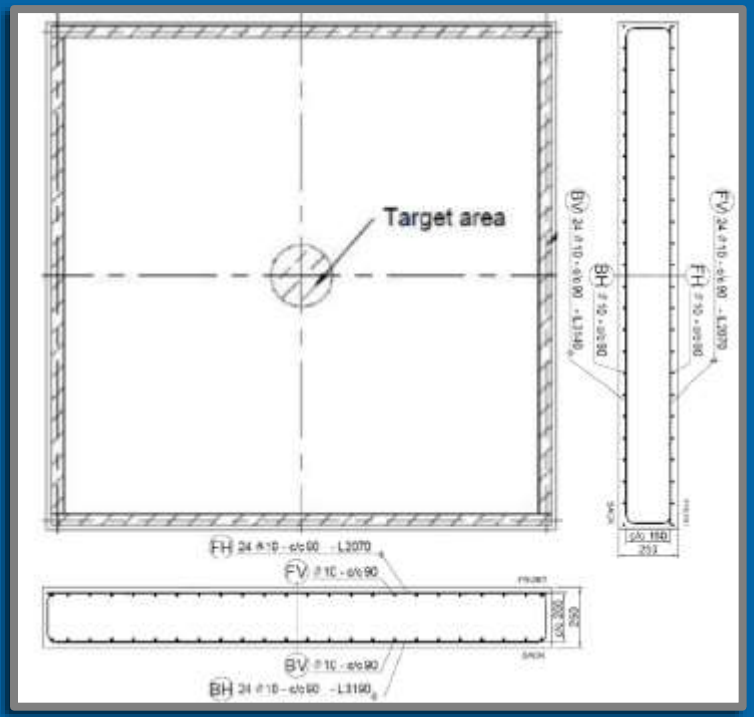
IRIS 2010 Prediction Competition

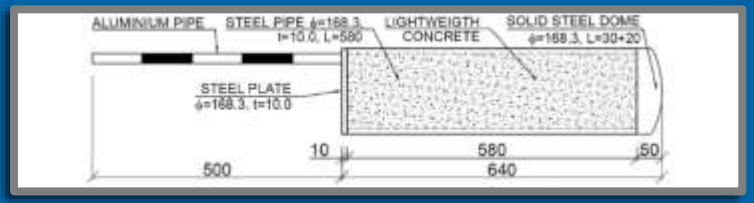
VTT-B1



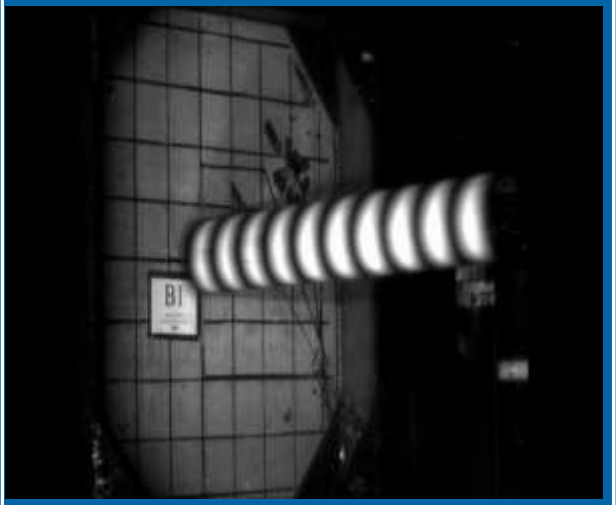


VTT-P1

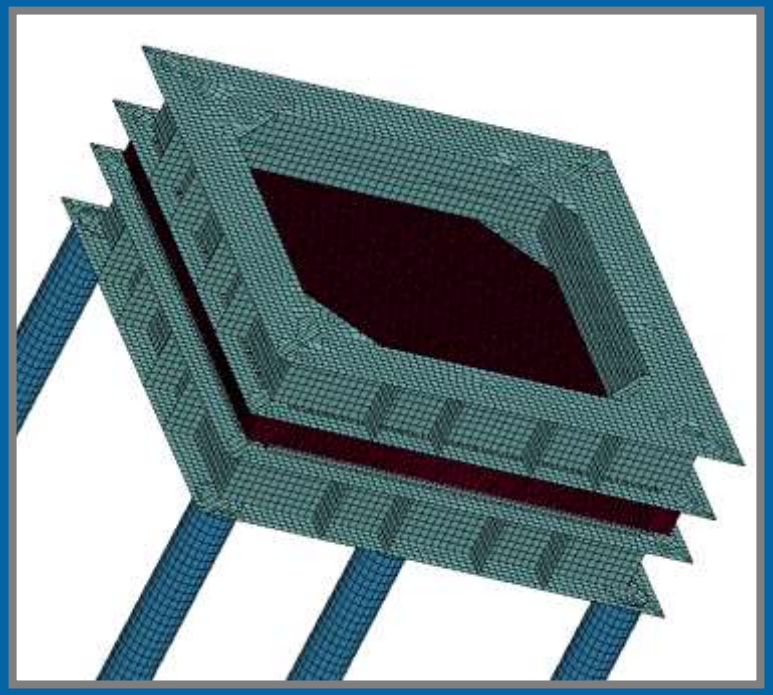




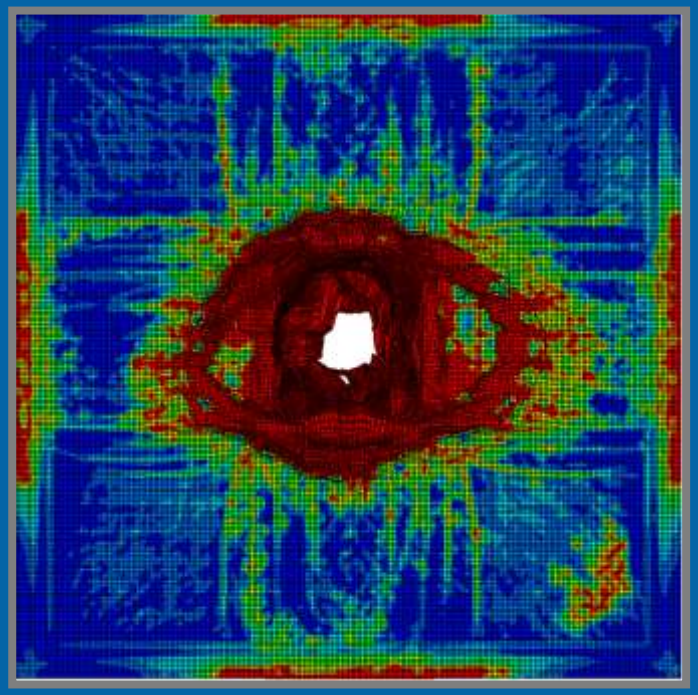
IRIS 2010 Prediction Competition

VTT-B1	VTT-P1	
	Front view	Back view
		

IRIS 2010 Prediction Competition



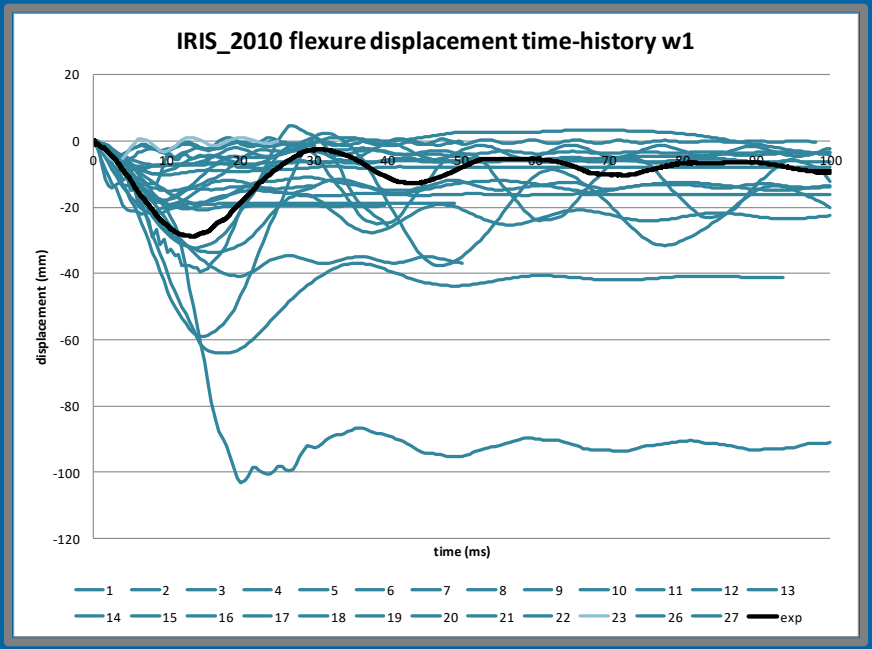
LS-Dyna model of IRIS_2010
Specimen VTT-P1



Calculated perforation failure of
Specimen VTT-P1

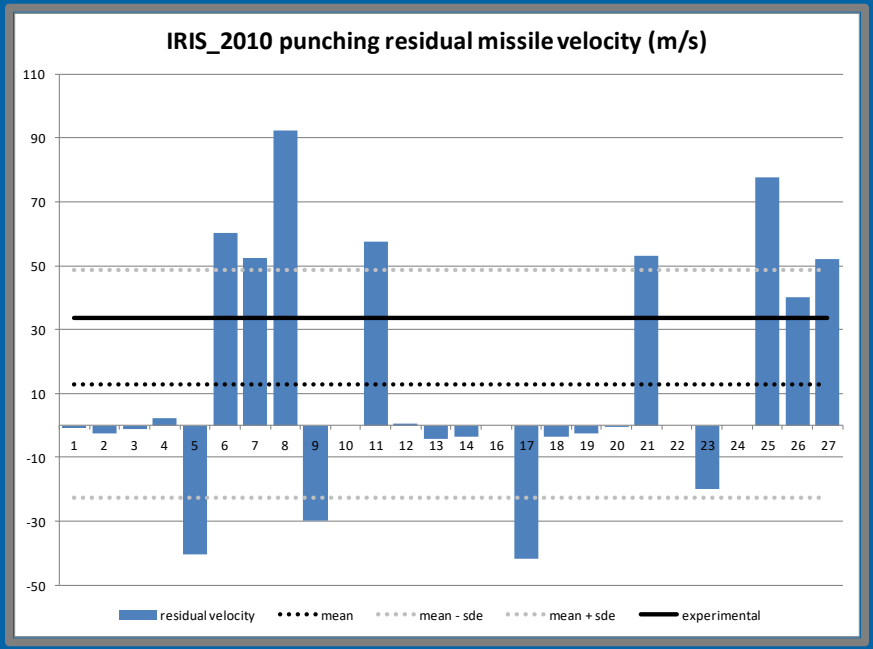
IRIS 2010 Prediction Competition

Soft Missile Impact



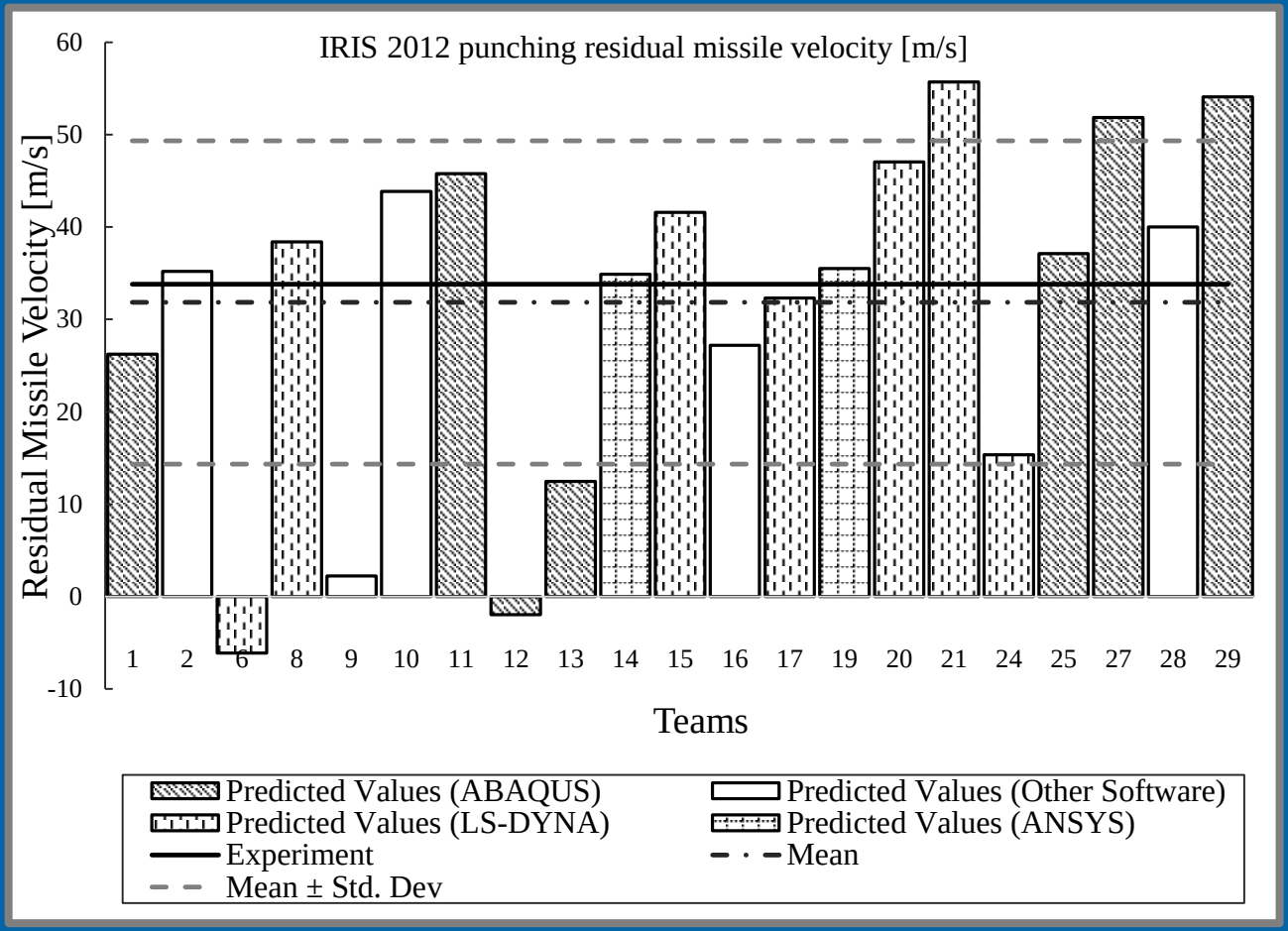
Centre displacement history of VTT-B1
(blind simulation results from IRIS_2010)

Hard Missile Impact



VTT-P1 missile residual velocity
(blind simulation results from IRIS_2010)

IRIS 2012 Prediction Competition



Truths...About Analysis Software

Truth # 6: Can be non-objective.

- More of an art than a science.
- Numerous modelling decisions (wrt structural details, loading, material calibration, analysis parameters) will affect results obtained.
- Interpretation of results may vary.

Broccostella, Frosinone, Italy

Lady Gaga

Lady Gaga, also known Stefani Joanne Angelina Germanotta, is the great-grandchild of Vincenzo "James" Ferri (died in 1967) and Filomena "Minnie" Campana (née Ferri) (died in 1940). Vincenzo (in 1905) and Filomena (in 1913) immigrated to the United States from Broccostella, Frosinone, Italy.

NLFEA

"~~Love~~ is like a brick. You can build a house, or you can sink a dead body.."

Cicero

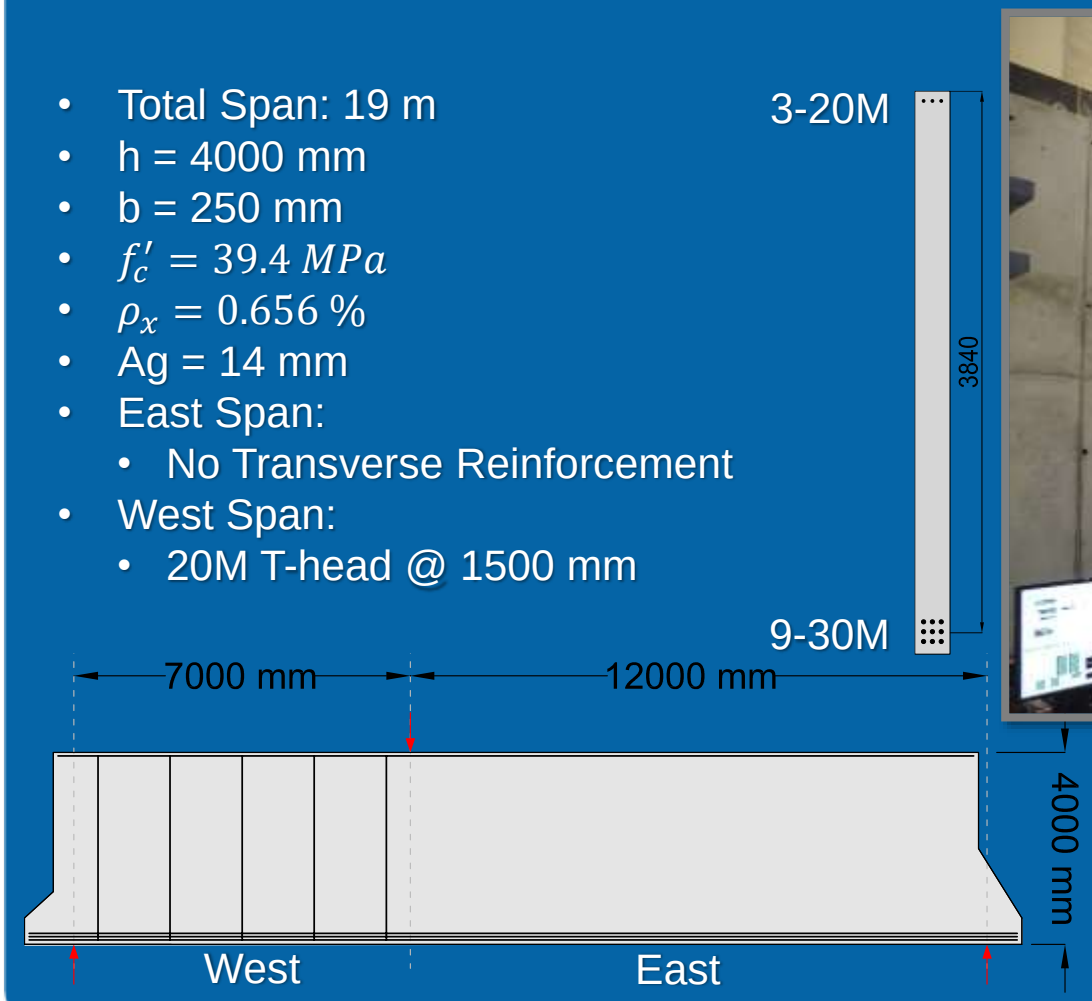
Marcus Tullius Cicero was a Roman philosopher, politician, lawyer, orator, political theorist, consul, and constitutionalist.

Born: January 3, 107 BC, Arpinum, Rome
Assassinated: December 7, 43 BC, Formia, Italy

"While there is life, there's hope."

Deep Beam Prediction Competition - Toronto 2015

- Total Span: 19 m
- h = 4000 mm
- b = 250 mm
- $f_c' = 39.4\ MPa$
- $\rho_x = 0.656\ \%$
- Ag = 14 mm
- East Span:
  - No Transverse Reinforcement
- West Span:
  - 20M T-head @ 1500 mm



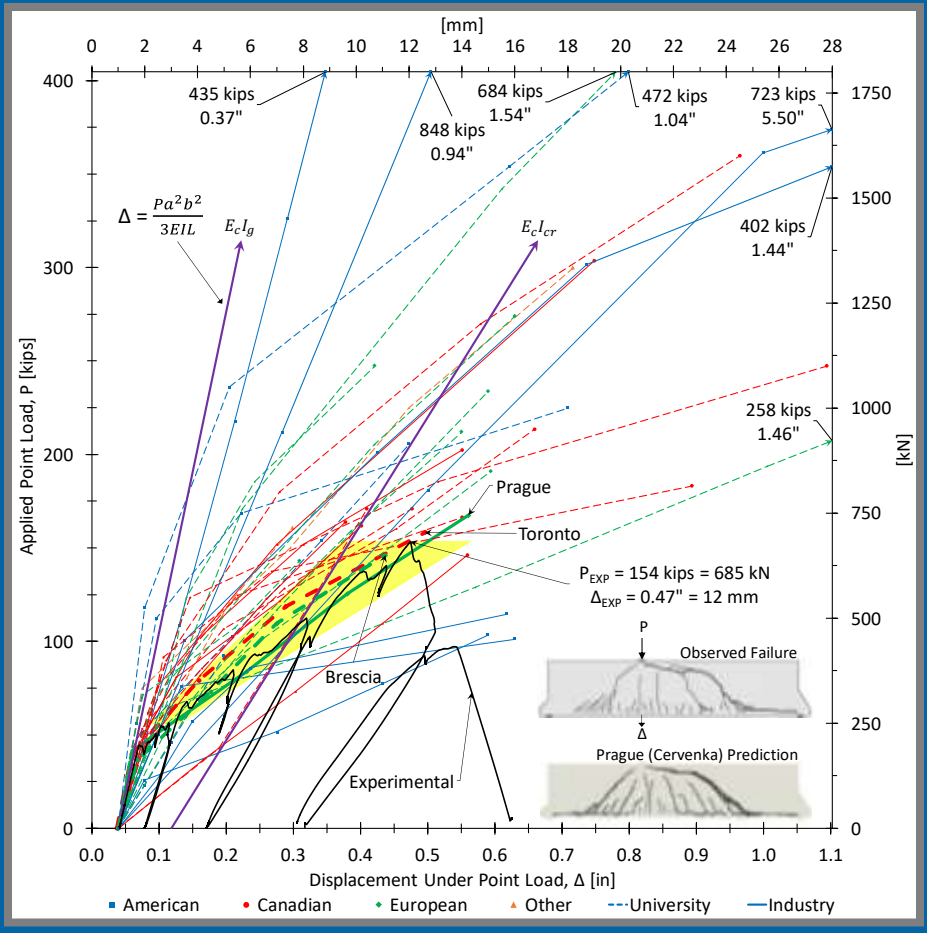
Tested by Collins et al. 2015

Deep Beam Prediction Competition - Toronto 2015

PLS4000 - Experimental Results

Deep Beam Prediction Competition - Toronto 2015

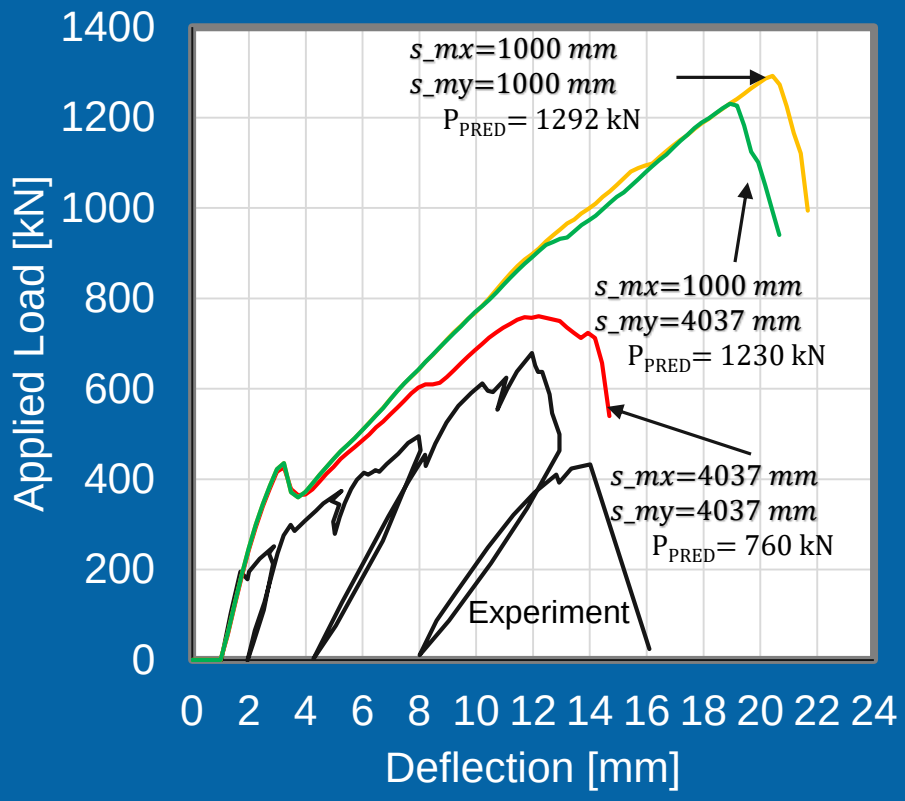
PLS4000 – Prediction Competition Results



Prediction	P_{pred} [kN]	$P_{pred.}/P_{exp.}$
CSA A23.3	623	0.91
ACI-318	2375	3.46
VecTor2	760	1.11
Prediction Competition Statistics		
Country/ Region	Mean Pred. [kN]	C.O.V.
USA	1436	0.70
Canada	925	0.30
Europe	1053	0.55
Overall	1165	0.64

Deep Beam Prediction Competition - Toronto 2015

Effect of Crack Spacing Input



Blind prediction crack spacing:

- For West Span:

$$s_{mx} = 2\left(c_x + \frac{s_x}{10}\right) + 0.25k_1\frac{d_{bx}}{\rho_x} = 4037\ mm$$

$$s_{my} = 2\left(c_y + \frac{s}{10}\right) + 0.25k_1\frac{d_{by}}{\rho_y} = 2477\ mm$$

- For East Span:

$$s_{mx} = 2\left(c_x + \frac{s_x}{10}\right) + 0.25k_1\frac{d_{bx}}{\rho_x} = 4037\ mm$$

$$s_{my} = s_{mx} = 4037\ mm$$

Truths...About Analysis Software

Truth # 7: Require knowledge, judgment, and experience.

- Requires firm understanding of structural behaviour, material behaviour, constitutive modelling, use and limitations of software.
- Requires experience and good judgment for correct anticipation of governing factors and behaviour mechanisms, selection of proper software, and correct interpretation of results.

An Idiot's Guide to Modelling and Assessment of RC Structures

- *Introduction*
- *Utility - Case Studies*
- *Reliability*
- *Traps & Blunders*
- ***Conclusions***

- *Recent Projects*
- *Current Research*

Monte Cassino, Frosinone, Italy


Monte Cassino


Colle San Magno

Monte Cassino, Frosinone, Italy

The monumental four-month WWII battle for Monte Cassino saw the Allies launch assaults against the Gustav Line in Italy.

The Allies were trying to clear the path to Rome, but the route was blocked by the rugged Monte Cassino massif.

The Allies were confronted by rocky slopes and mountains where German soldiers with guns lay in wait.

The capture of Monte Cassino resulted in 55,000 Allied casualties, with German losses estimated at 20,000.

Winston Churchill

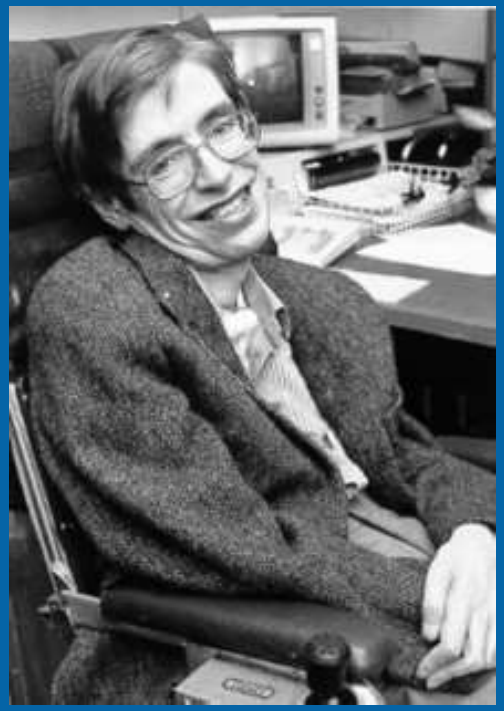
Sir Winston Leonard Spencer-Churchill was a British statesman, army officer, and writer. He was Prime Minister of the United Kingdom from 1940 to 1945, when he led Britain to victory in the Second World War, and again from 1951 to 1955.

A strong proponent of the offensive that involved the attacks on Monte Cassino.

Born: November 30, 1874, Oxfordshire, England
Died: January 24, 1965, London, England

"Success is going from failure to failure without a loss of enthusiasm."

Stephen Hawking



Stephen William Hawking was an English theoretical physicist, cosmologist, and author who was director of research at the Centre for Theoretical Cosmology at the University of Cambridge. He was known primarily for his work on black holes.

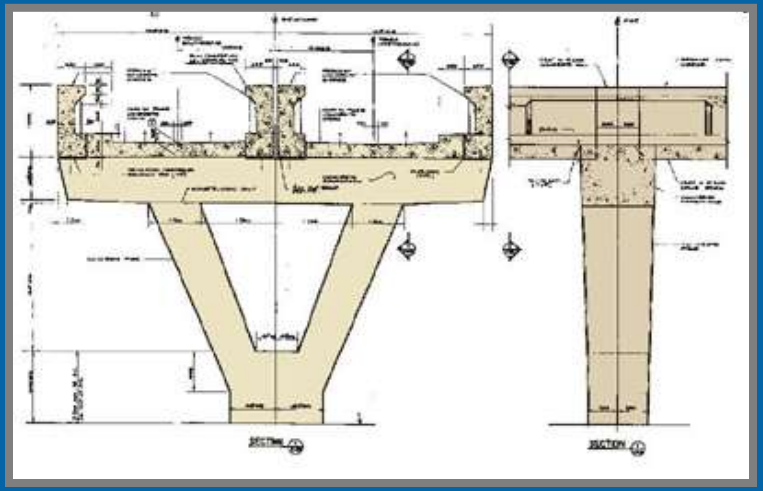
Born: January 8, 1942, Oxford, England
Died: March 14, 2018, Cambridge, England

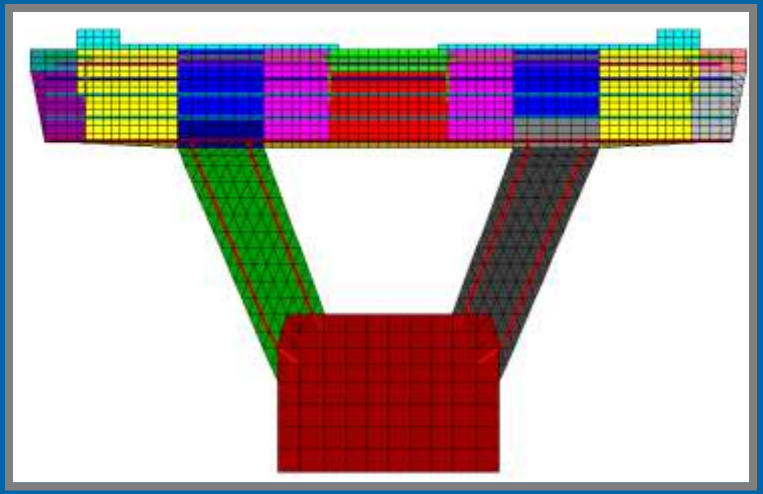
"We spend a great deal of time studying history, which, let's face it, is mostly the history of stupidity.."

Conclusions

Applications for Analysis Software:

- Assessment of damaged or deteriorated structures
- Assessment of structures built to out-dated codes and standards
- Assessment of retrofitted or repaired structures
- Evaluation of alternative design or retrofit options
- Performance-based design
- Forensic engineering





Conclusions

Truths…About Analysis Software:

1. We are rapidly embracing them unconditionally.
2. Can be a highly powerful investigative tool.
3. Can produce inaccurate (sometimes dangerous) results.
4. Can be applied incorrectly.
5. Can be complex and difficult to use.
6. Can be non-objective.
7. Require knowledge, judgment, and experience.

The Seven Deadly Sins?

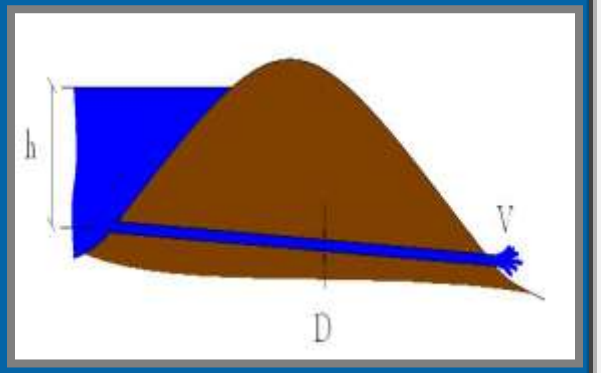
Conclusions

Don't Be An Idiot :

1. Avoid 'Blackbox' software.
2. Avoid software requiring extensive input of material properties.
3. Avoid software requiring definition of numerous analysis parameters.
4. Avoid software requiring extensive calibration of properties or parameters.
5. Understand capabilities and limitations, and appropriate range of application.
6. Employ databanks and benchmark problems to verify capabilities of software and of analyst.
7. Use alternative procedures and software; fill toolbox with different tools.
8. Call a friend.

Lake Fucino

- Further attempts to drain the lake by emperors Trajan and Hadrian in ancient times, as well as the Holy Roman Emperor Frederick II in medieval times, met with only limited success.
- In the 19th century, Prince Alessandro Torlonia commissioned the Swiss engineer Franz Mayor de Montricher to drain the lake. Work began in 1862.
- De Montricher built a new tunnel in place of Claudius' tunnel, approximately three times the original diameter, as well as a 6.3 km-long and 21 m-wide canal.
- By 1875, the lake was completely drained.



$Q=f(h,\ldots)$

$V=Q/A$, $A=\pi D^2/4$

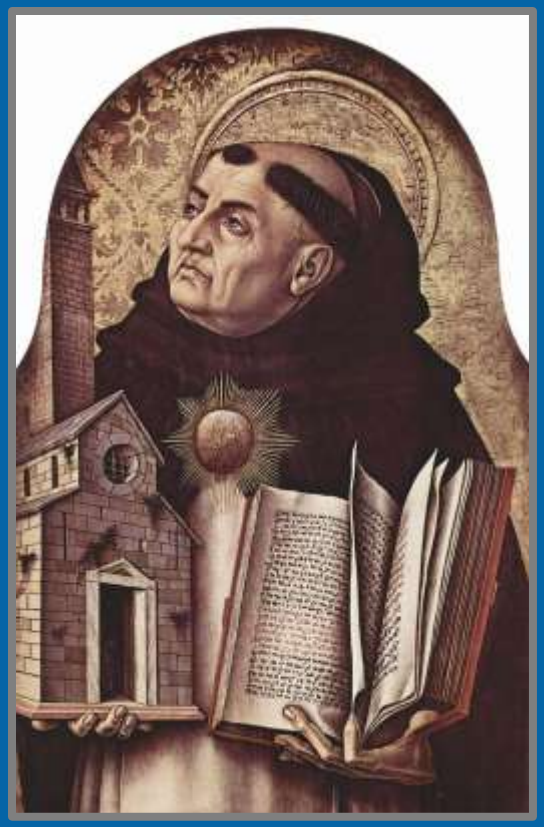
If D is large enough, then V will be relatively slow and safe.

EVENTUALLY WE GET OUR ANALYSES RIGHT!

Lake Fucino - Today

Roccasecca, Frosinone, Italy

Thomas Aquinas



Tommaso d'Aquino, also known as Saint Thomas Aquinas, was an Italian Dominican friar and Catholic priest who was an immensely influential philosopher, theologian and jurist.

Born: 1225, Roccasecca, Italy

Died: March 7, 1274, Fossanova Abbey, Italy

"Friendship is the source of the greatest pleasures, and without friends even the most agreeable pursuits become tedious."

Any Questions?