The aging infrastructure: a challenge for innovative engineers

Auckland, New Zealand, Oktober 13th, 2016

Joost Walraven

Vermelding onderdeel organisatie

Delft University of Technology

Dealing with the threat of the water: a historical task in The Netherlands

Blue colour: below sea level

Dikes protected by stones

Storm Surge Barrier Hook of Holland

Concern about the (shear) bearing capacity of Dutch bridges

Bridges in highways	1515
Bridges in main roads	930
Other bridges	711
Tunnels	544
Aquaducts	8
Ecoducts	7
Alltogether	3715

Concern about the (shear) bearing capacity of Dutch bridges

Bridges in highways	1515
Bridges in main roads	930
Other bridges	711
Tunnels	544
Aquaducts	8
Ecoducten	7
Alltogether	3715

TU Delft

Development of the traffic intensity

First traffic jam in The Netherlands, Eastern 1955

Change of the traffic characteristics

Traffic jam, at a random day, 2016

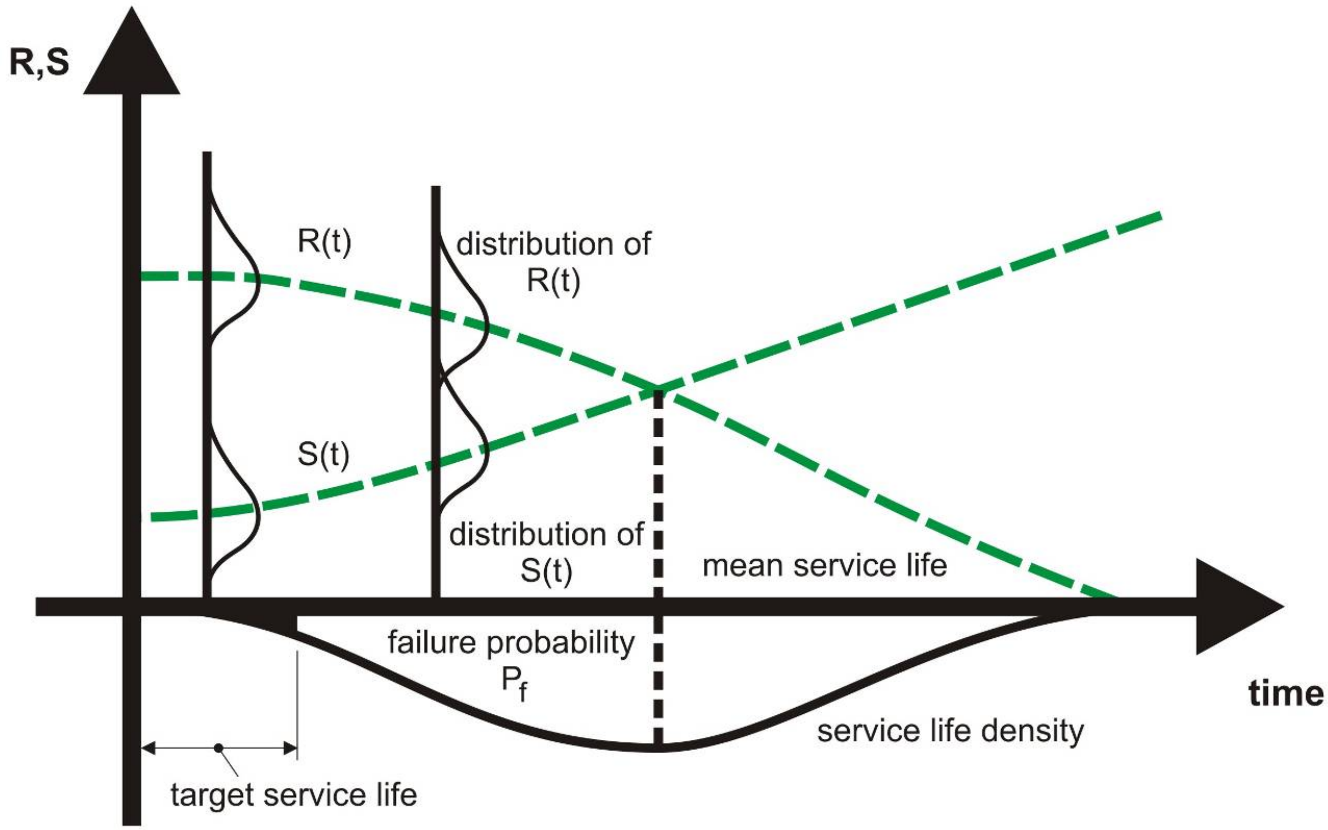
Large traffic loads, 2016

Extraordinary transport: approval required

TU Delft

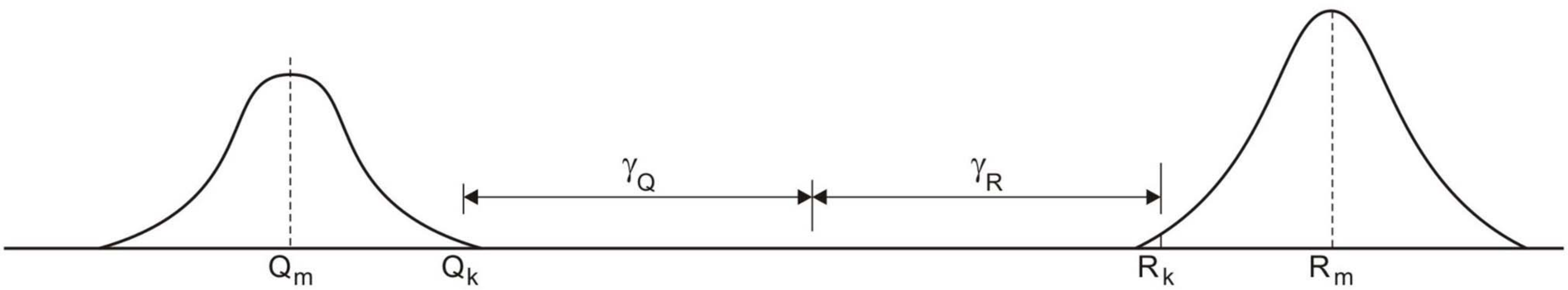
Increasing load and decreasing resistance

Key parameters for service life



TU Delft

Verification of bearing capacity

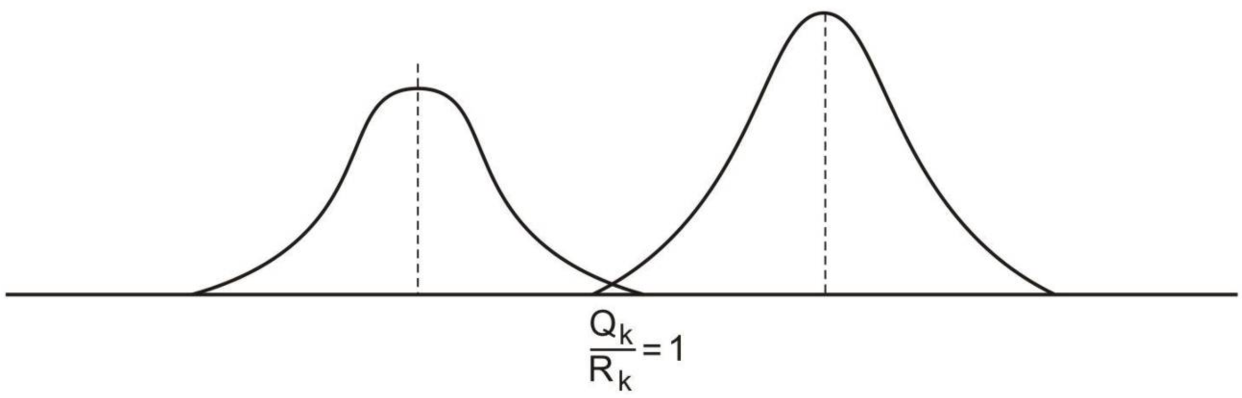


Safety factors: be chosen in such a way that probability of failure is acceptably low: e.g β = 3,8 means 1:10^{-4}

TU Delft

Quick verification of reliability: Unity Check

- Remove safety factors
- Determine UC-Value = Q_k/R_k
- Limit value UC = 1
- Structures are unsafe if UC > 1



TU Delft

Classification of concrete bridges in 6 prototypes

- Reinforced solid slabs
- Box girders
- Bridges made of precast pre-stressed I-beams with thin webs
- Bridges made of T-Beams with very thin webs
- Crossings
- Tunnel roofs

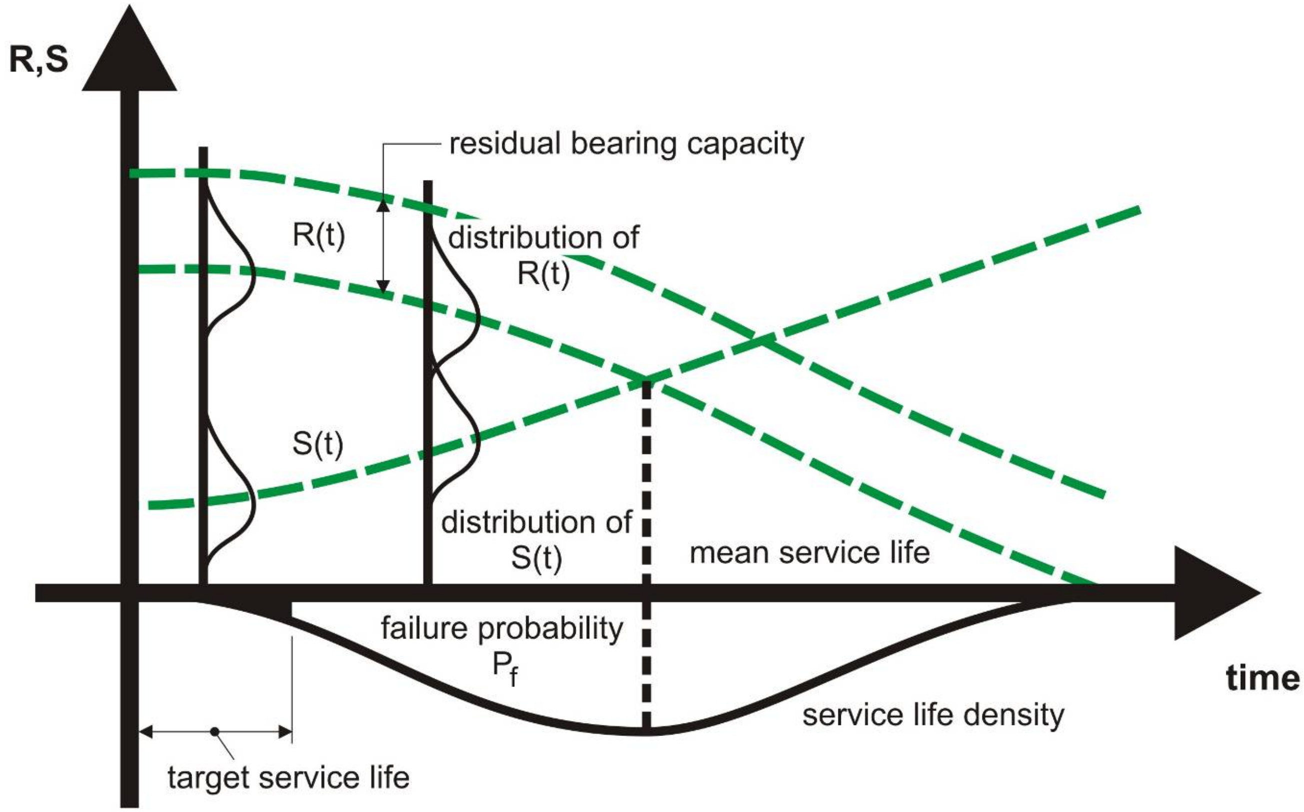
Determination of bearing capacity of 1200 existing concrete bridges in the Netherlands

Results of “Quick Scans (selection)

Bridge number	Categorie	Year	UC-Value
37E-122	Culvert	1996	1,89
37F-110	T-Beam	1970	2,43
38D-103	Straight Solid slab	1936	4,53
38F-108	Crossing	1966	1,61
38G-112	Crossing	1961	1,18
38G-103	T-Beam deck	1959	3,13
39G-114	Straight solid slab	1959	2,85
52G-105	Skew solid slab	1969	3,53

TU Delft

Searching for residual bearing capacity of structures



TU Delft

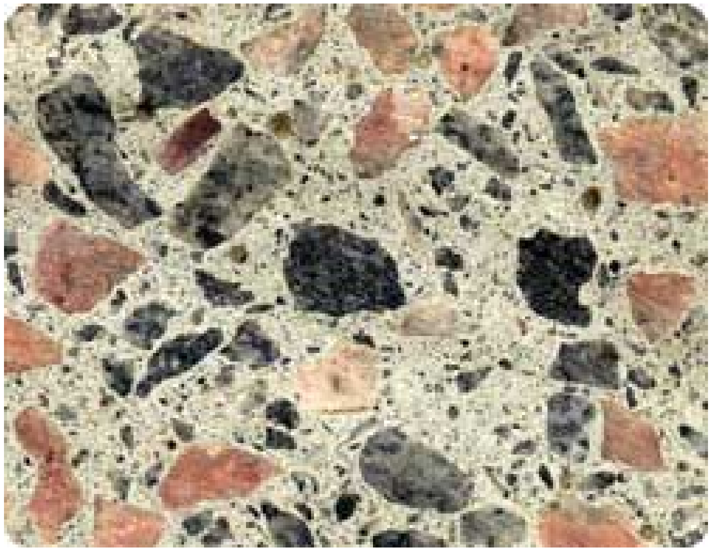
Where is the residual capacity to be found?

- Does concrete strength increase after 28-days?
- Is there a sustained loading effect in shear?
- More favourable punching shear behaviour by compressive membrane action?
- Reliable prediction of behaviour by nonlinear FEM calculations?
- Proof loading?

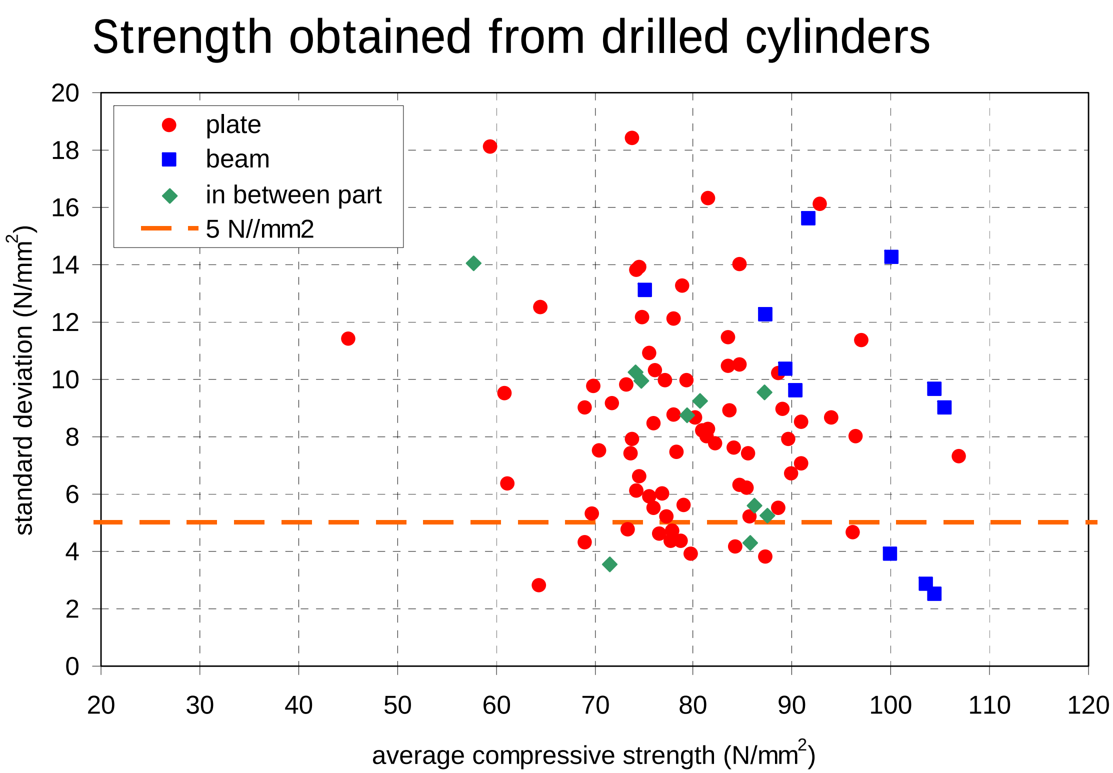
TU Delft

Where is the residual capacity to be found?

- Concrete strength higher than original value determined at 28 days?
- Is there a sustained loading effect in shear?
- More favourable punching shear behaviour by virtue of compressive membrane action?
- More reliable prediction of behaviour by nonlinear FEM calculations?
- Proof loading?

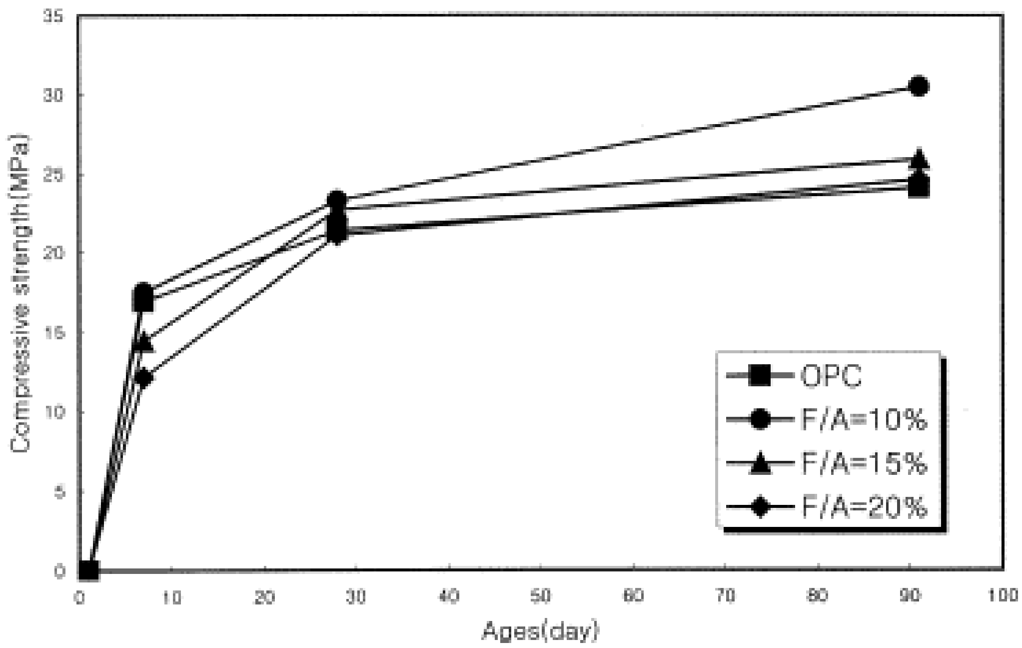


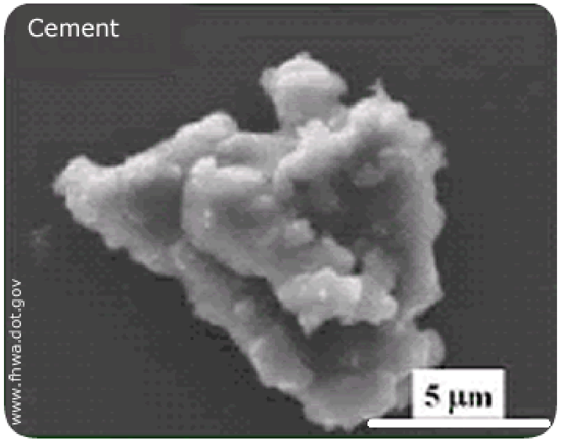
Use of enhanced strength of concrete ?



TU Delft

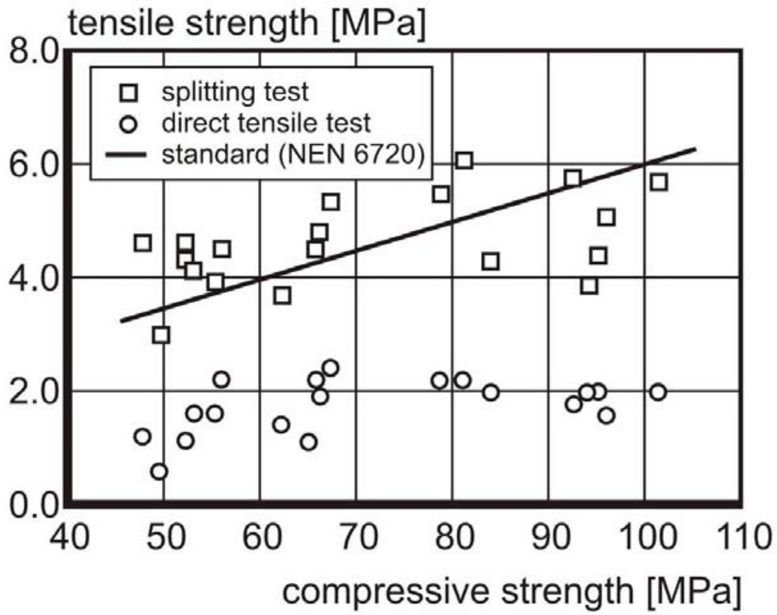
Development of concrete strength in time





Use of enhanced strength of concrete ?

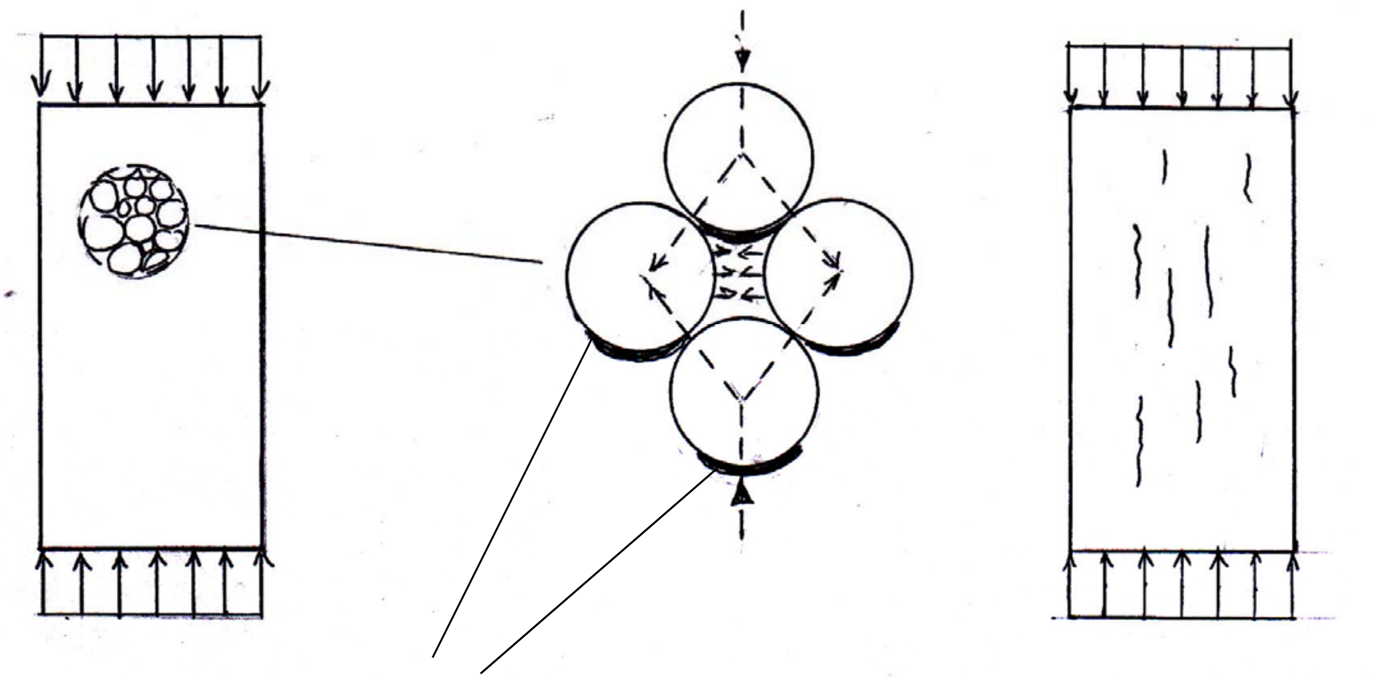
Which strength should be used for the calculation of the shear bearing capacity?



Observation: unexpectedly low axial tensile strength obtained from tests on drilled cores

Use of enhanced strength of concrete ?

Compression test

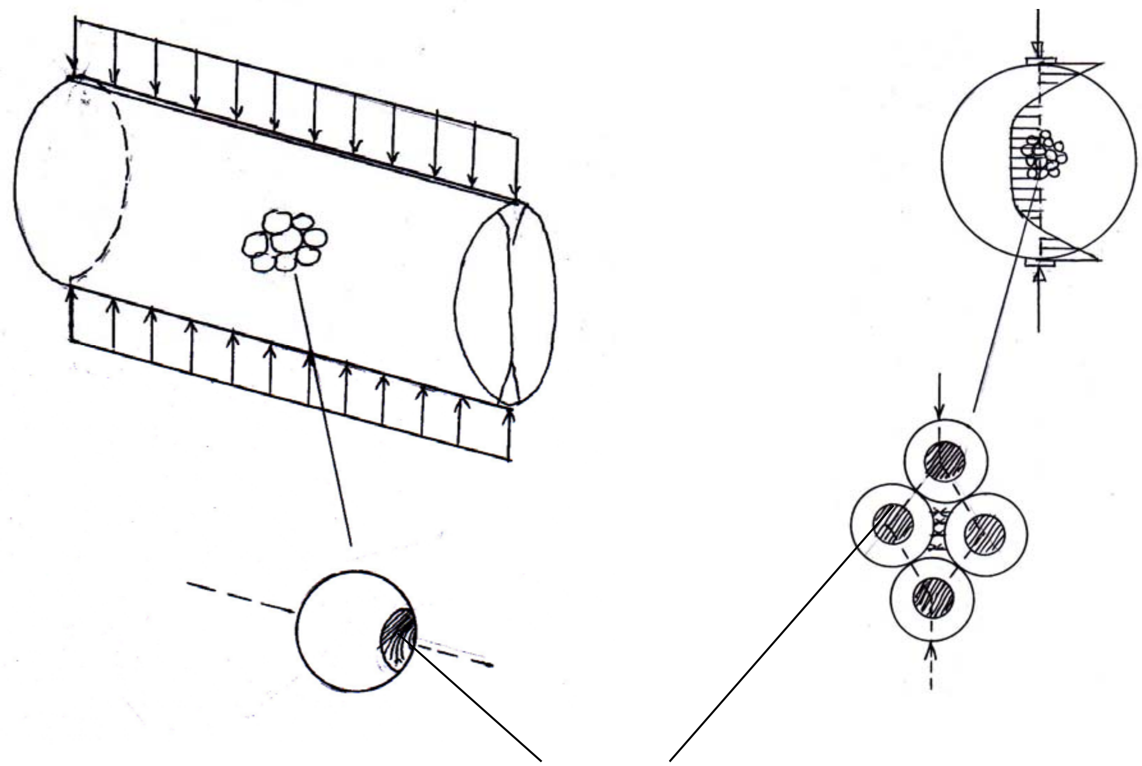


Weakened contact zone:
No influence on behaviour

Announcement of failure in compression

Use of enhanced strength of concrete ?

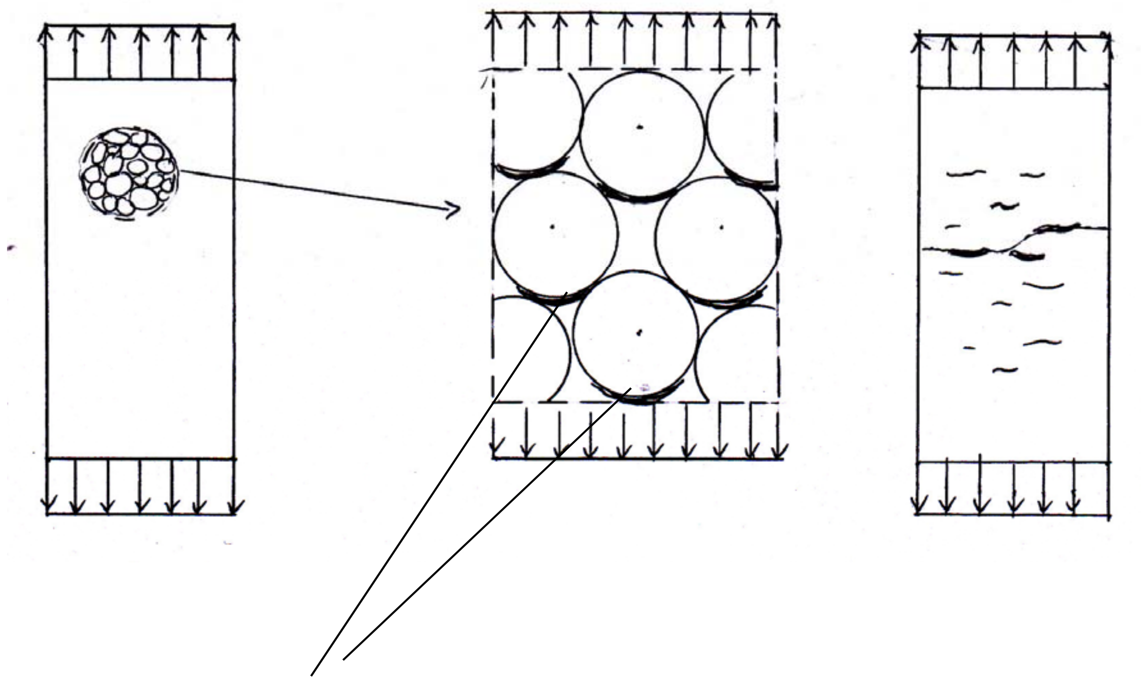
Splitting test



Weakened contact zones: no influence on behaviour

Use of enhanced strength of concrete ?

Uniaxial tensile test



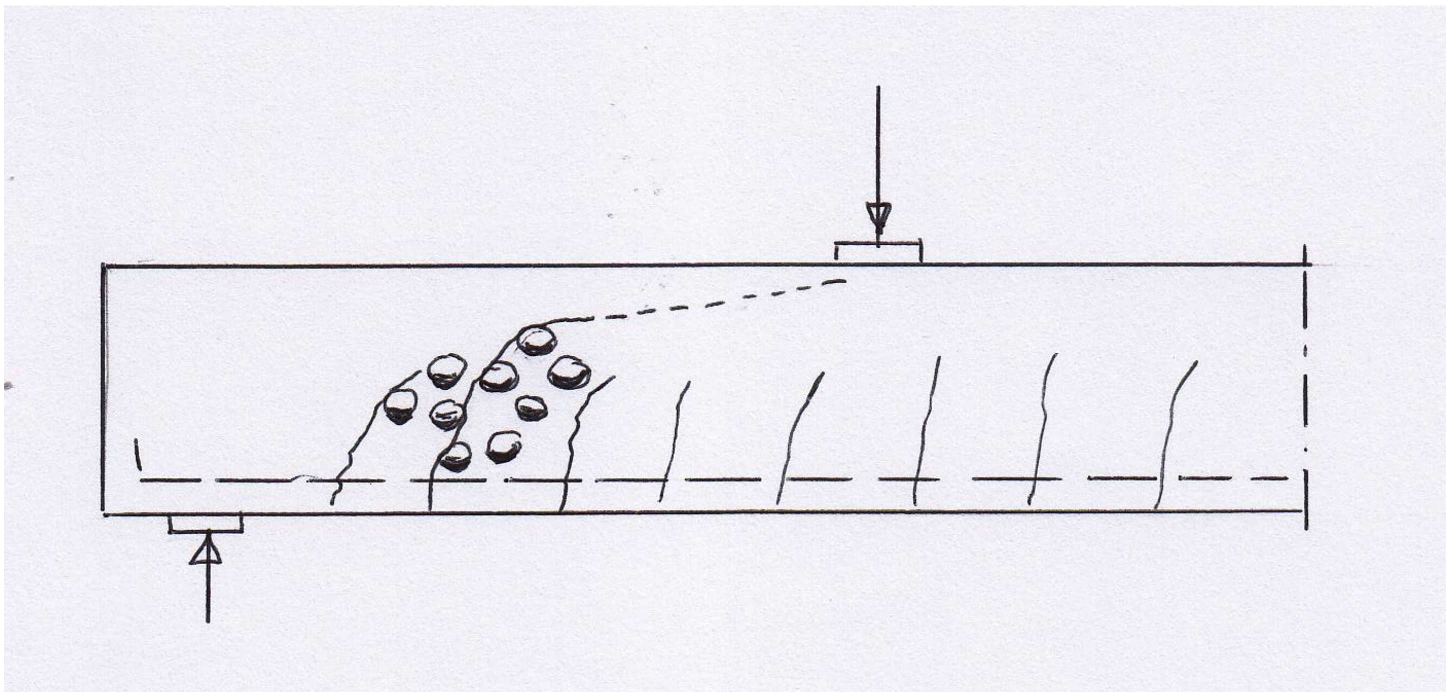
Weakened contact zones: large influence on tensile strength

Use of enhanced strength of concrete ?

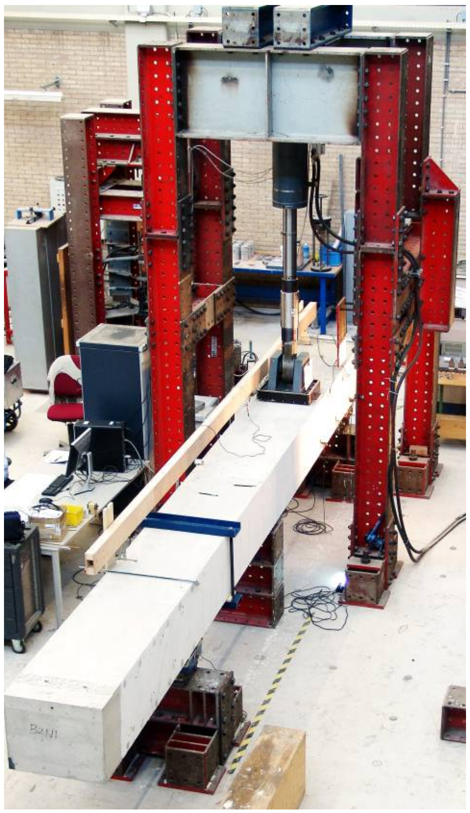
Weak areas under reinforcing bars and coarse aggregate particles

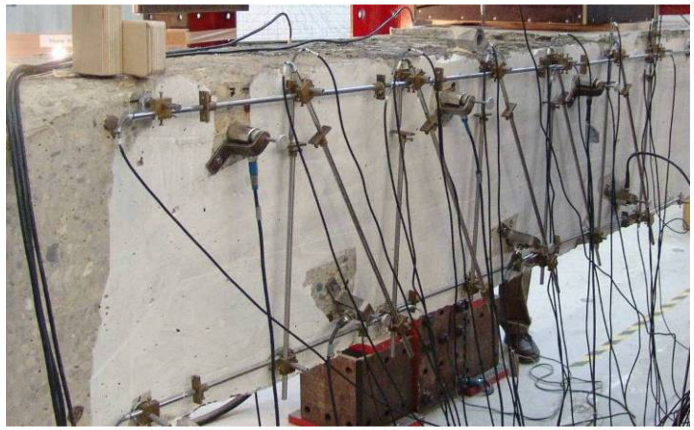
Use of enhanced strength of concrete ?

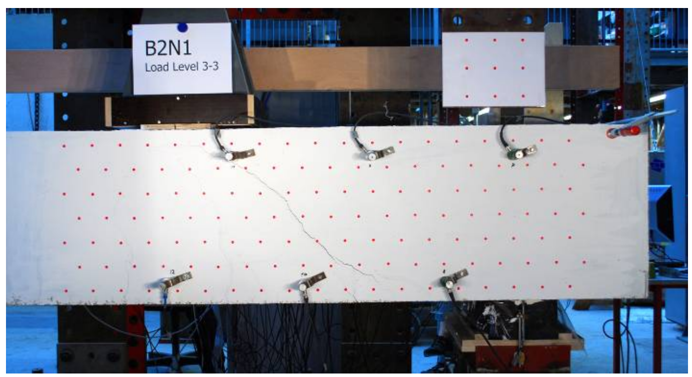
Influence of weak areas on shear capacity is limited



Research comparing the behaviour of old and new beams







Comparison between beams sawn from an old solid slab bridge and beams cast with a new concrete with the same concrete strength

No difference in result

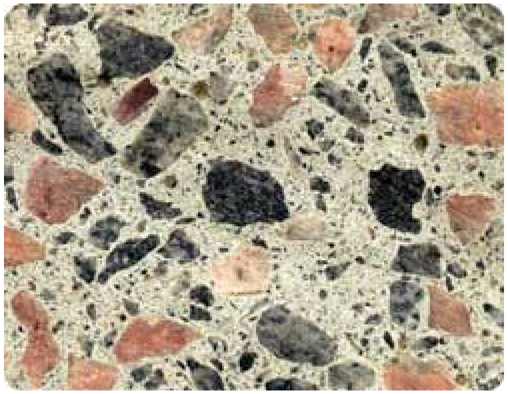
Conclusion: low axial tensile strength is not relevant

So, by higher concrete strength shear capacity increased by 45%

TUDelft

Questions regarding residual capacity

- Higher concrete strength after decades of hydration?
- Is there a sustained loading effect in shear?
- More favourable shear, or punching behaviour by virtue of redistribution or dome effect?
- Reliable prediction of behaviour by nonlinear FEM calculations?
- Proof loading?



TU Delft

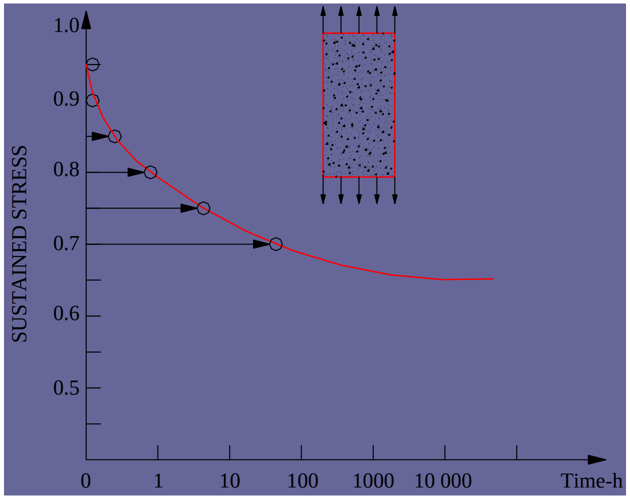
Should the effect of sustained loading be regarded?

$$f_{cd} = \alpha_{cc} \frac{f_{ck}}{\gamma_c}$$

For concrete in compression

$$f_{ctd} = \alpha_{ct} \frac{f_{ctk}}{\gamma_c}$$

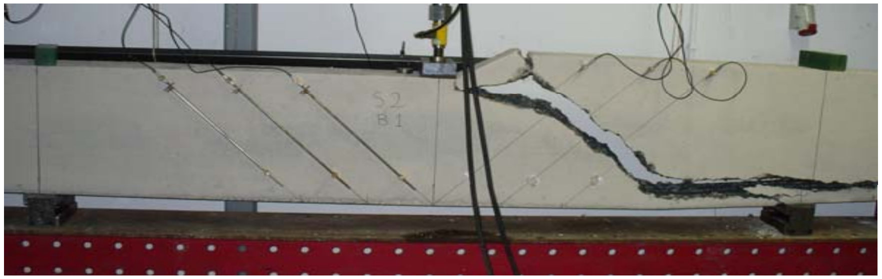
For concrete In tension



Eurocode 2: Values for α_{cc} en α_{ct} can be chosen between 0,8 en 1,0: recommended value 1,0

MC 2010: α_{ct} = 0,6 for concrete in tension

Behaviour of concrete and concrete structures under sustained loading



Do the results of tests on concrete in tension and compression apply as well to shear?

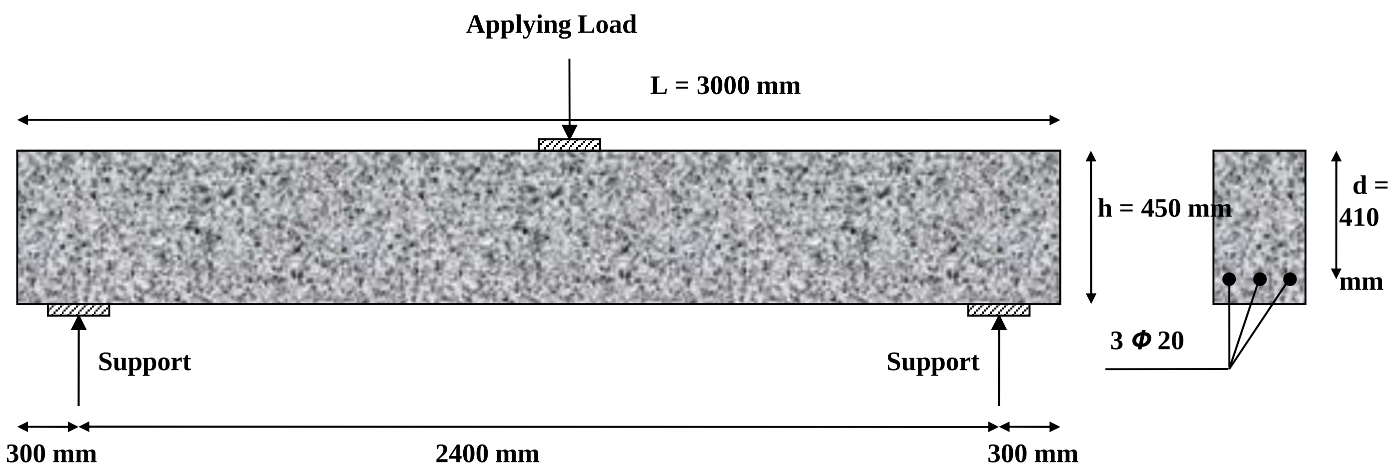
$$V_{Rd,c} = C_{Rd,c} k (100 \rho_l f_{ck})^{1/3}$$

? ?

α_{ct}

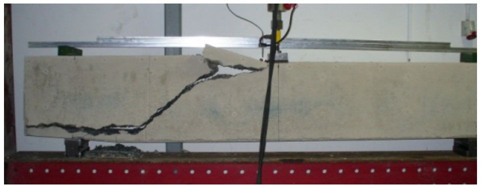
TU Delft

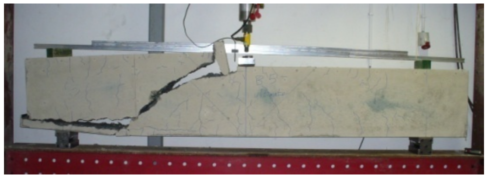
Sustained loading tests on shear loaded RC beams



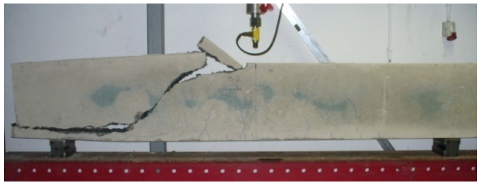
TU Delft

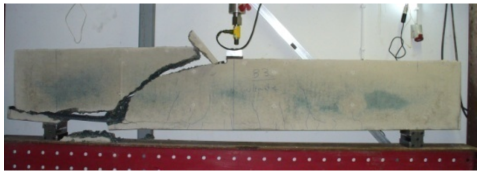
Short term reference failure loads

B1


B5


B6


B2


B3


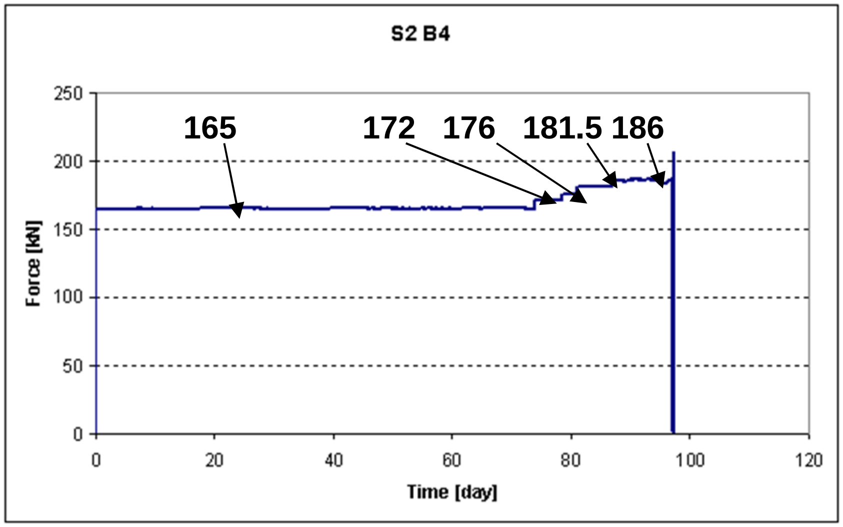
B4

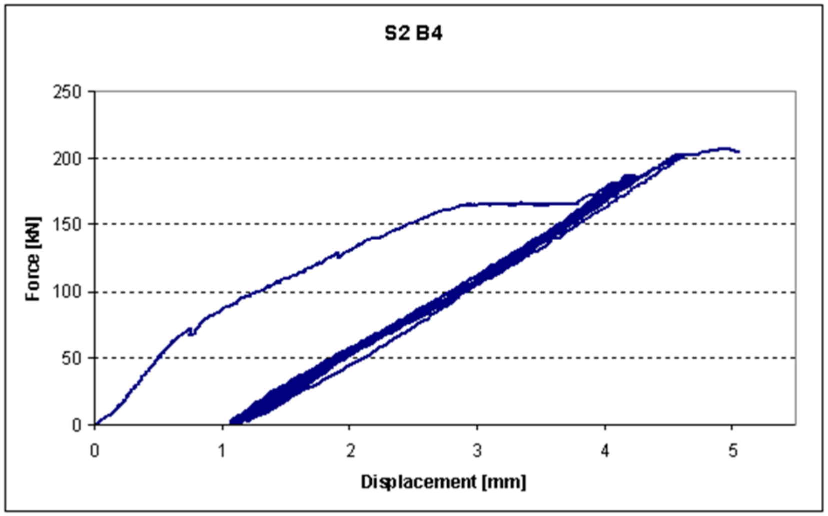

Nr	V_u (kN)
B1	192
B2	176
B3	195
B4	174
B5	188
B6	183

Mean value: 184,7 kN
Coefficient of variation v = 4,6
$V_{5\%}$ = 170.7 kN
Sustained loading at 165 kN = 0.89 V_{mean}

Shear capacity under sustained loading

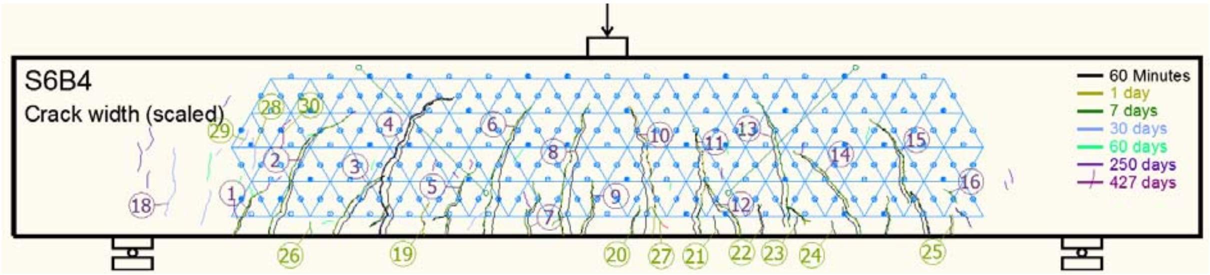
After 75 days stepwise increase

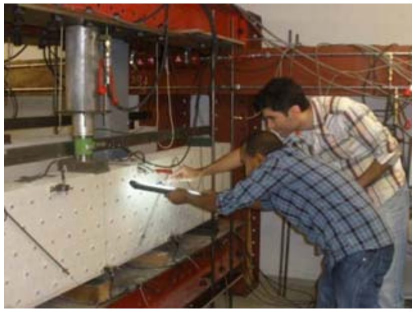


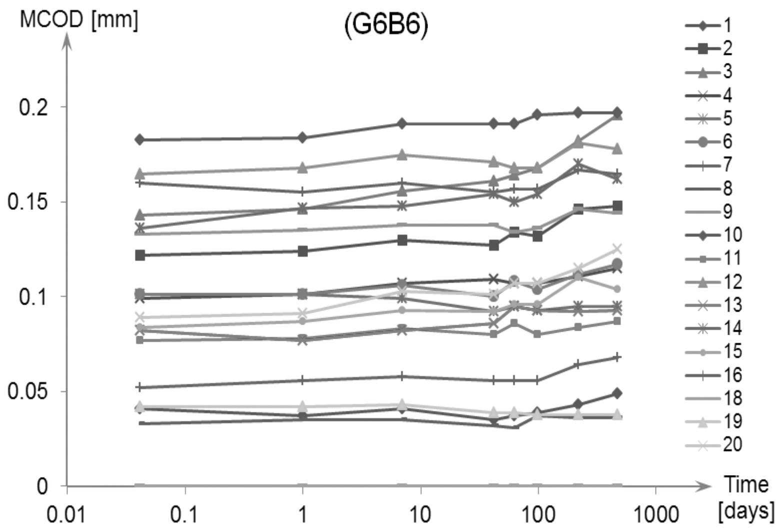


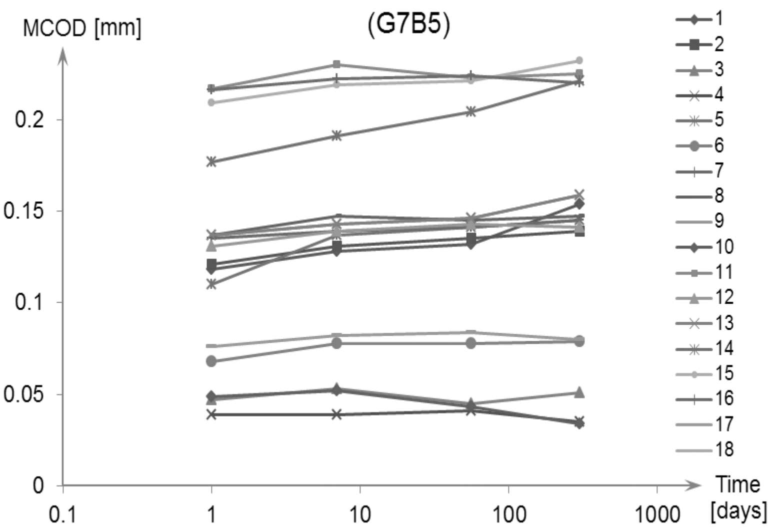
Subsequently 10 load cycles followed by loading to failure

Measuring crack development in time





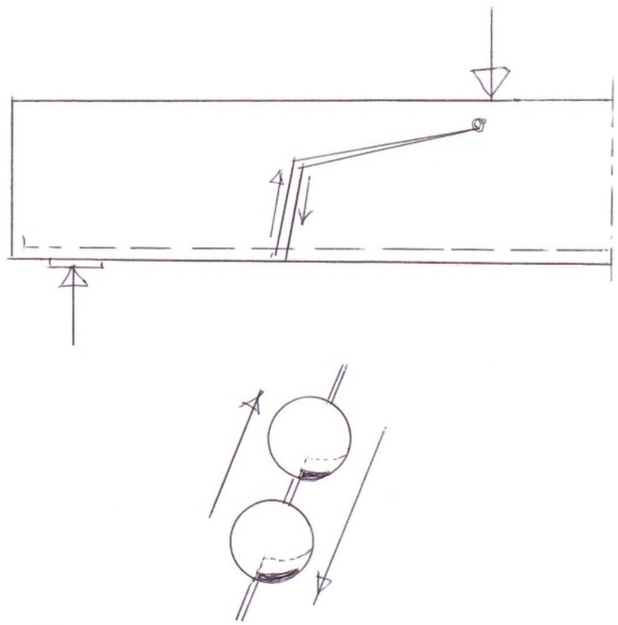




TU Delft

Conclusion sustained loading effect

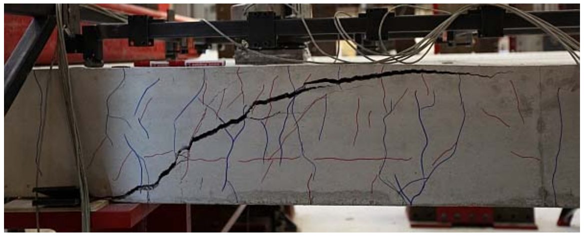
No sustained loading effect for the shear capacity of concrete members without shear reinforcement

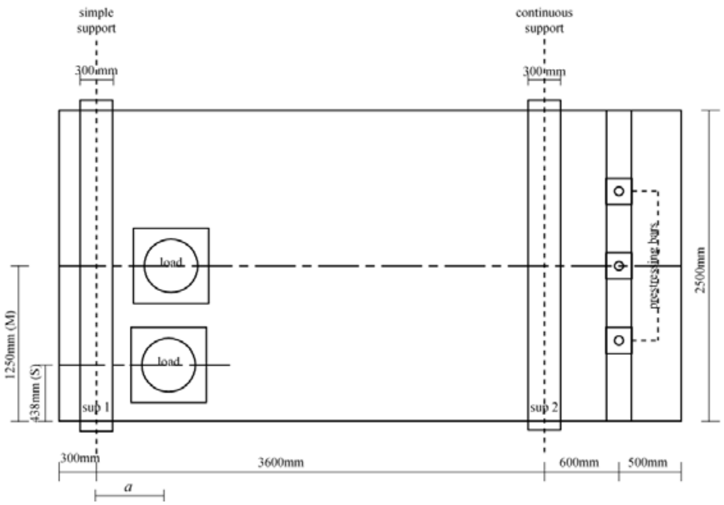


Aggregate interlock in the bending shear cracks plays a major role in generating sufficient shear resistance

Creep in the cement matrix results in a larger contact area, so no loss of aggregate interlock and shear capacity

Tests on solid slabs with large wheel loads near linear support





1. Slab behaviour much more favourable than beam behaviour

Conclusion shear capacity of solid slabs

Elements of residual capacity:

- Concrete strength much higher than assumed in original design
- No sustained loading effect
- Shear capacity under high wheel loads better than expected
- Slab has larger redistribution capacity than beam

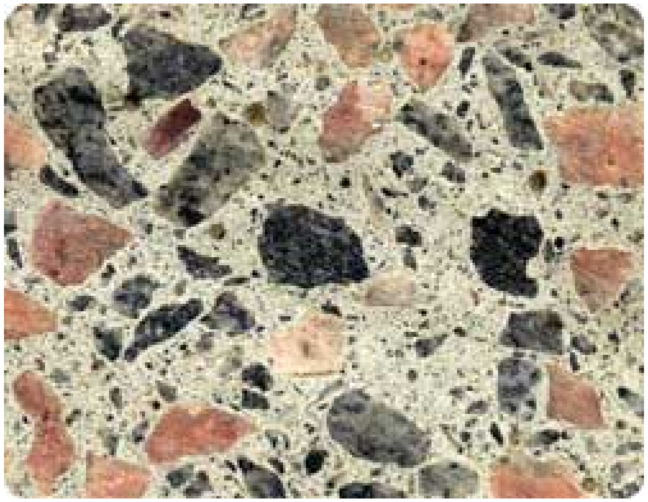
↓

All solid slabs strong enough

TU Delft

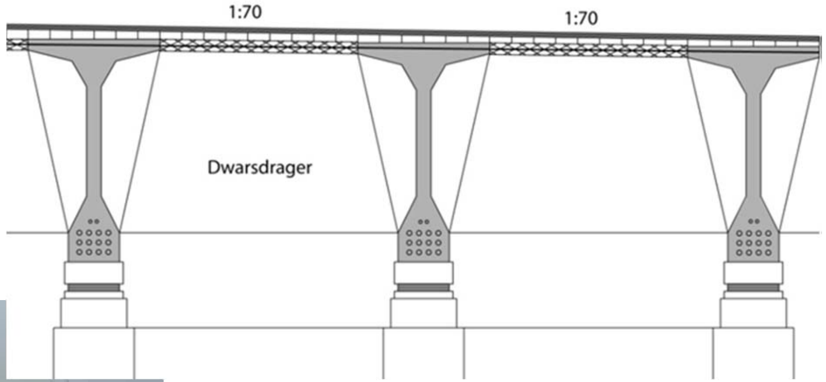
Where is the residual capacity to be found?

- Higher concrete strength after decades of hydration?
- Is there a sustained loading effect in shear?
- More favourable punching shear behaviour by of compressive membrane action?
- Reliable prediction of behaviour by nonlinear FEM calculations?
- Proof loading?



TU Delft

Punching shear check Hollandse Brug

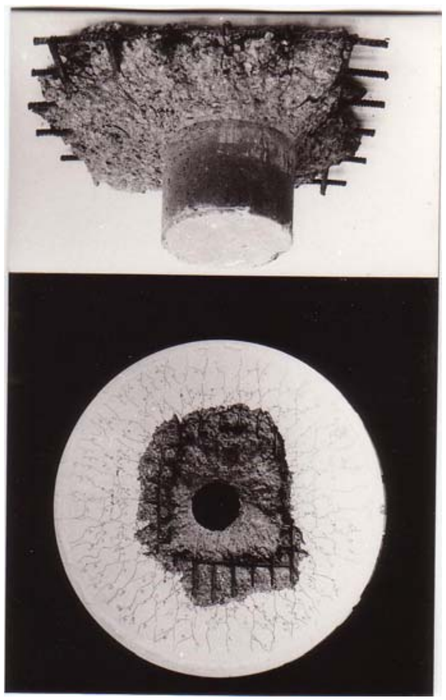


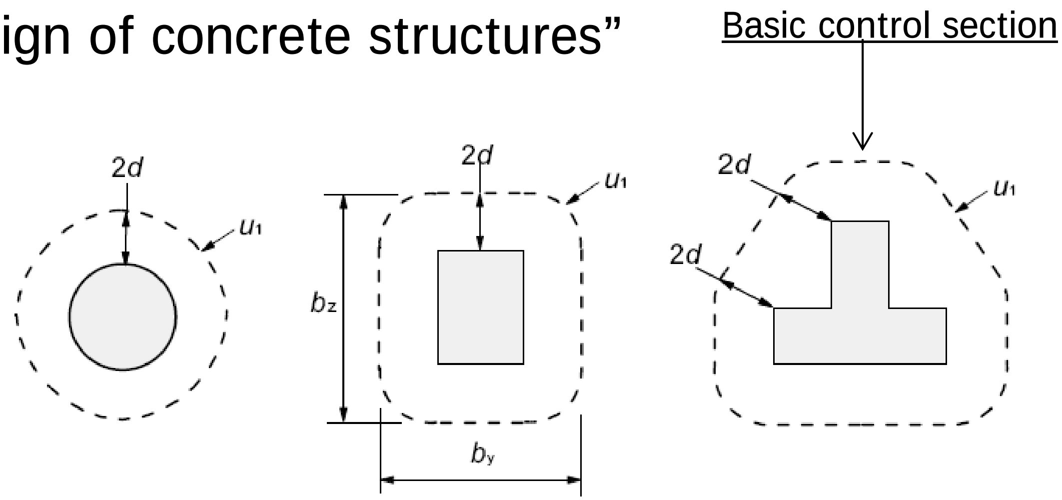
First check: 70 large span bridges do not satisfy the safety demands

TU Delft

Punching shear capacity according to existing codes

Example Eurocode 2 "Design of concrete structures"





$$v_{Rd,c} = 0.12k(100\rho_l f_{ck})^{1/3} + 0.1\sigma_{cp}$$

k = size factor = $1+\sqrt{\frac{200}{d}} \leq 2.0$

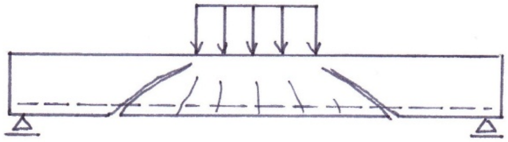
ρ_l = reinforcement ratio

f_{ck} = characteristic concrete compressive strength

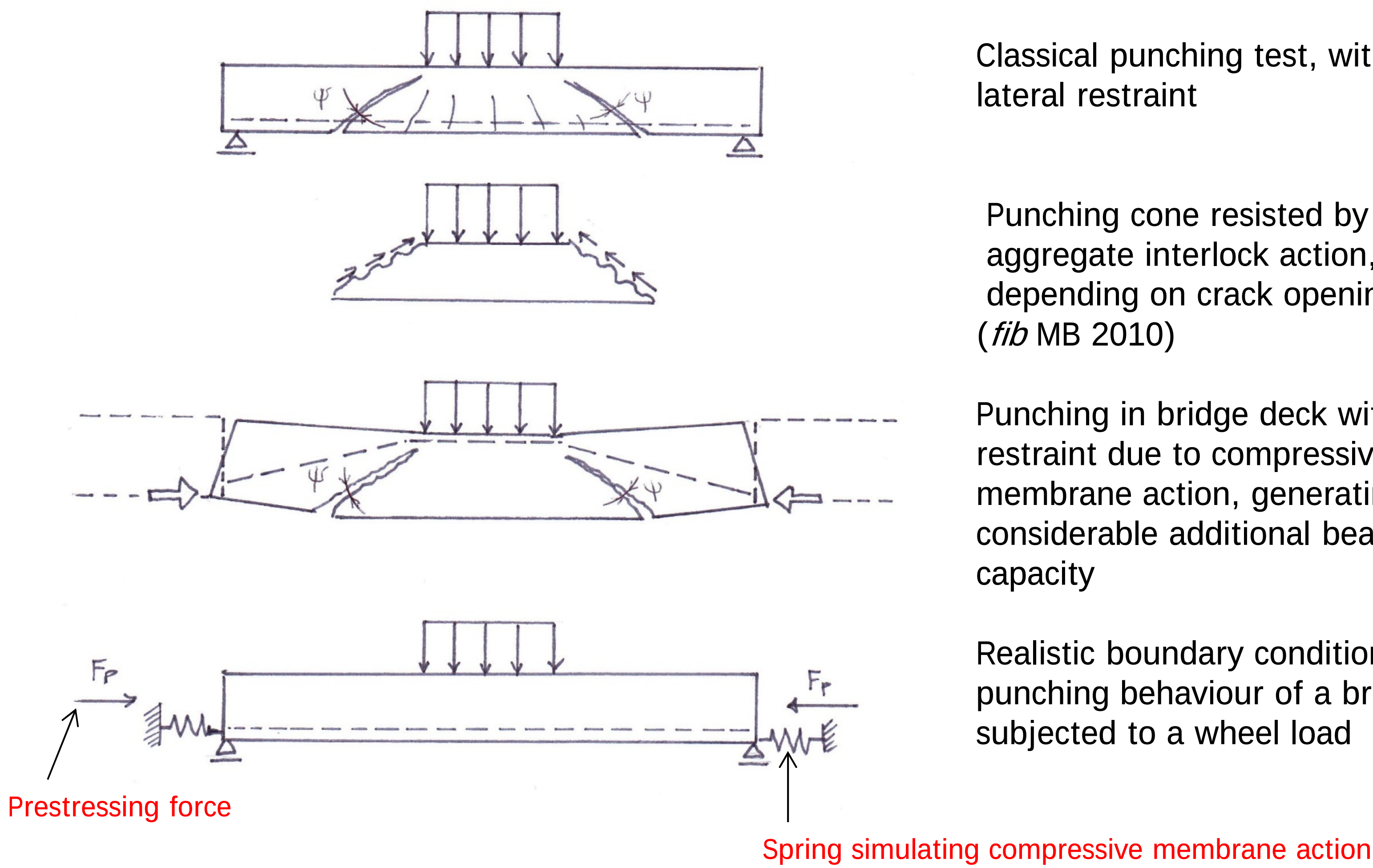
σ_{cp} = average in-plane prestress

Limitation of traditional empirical equations for the punching shear capacity

Traditional punching shear test on free slab specimen



Modelling punching shear in bridge decks



Classical punching test, without lateral restraint

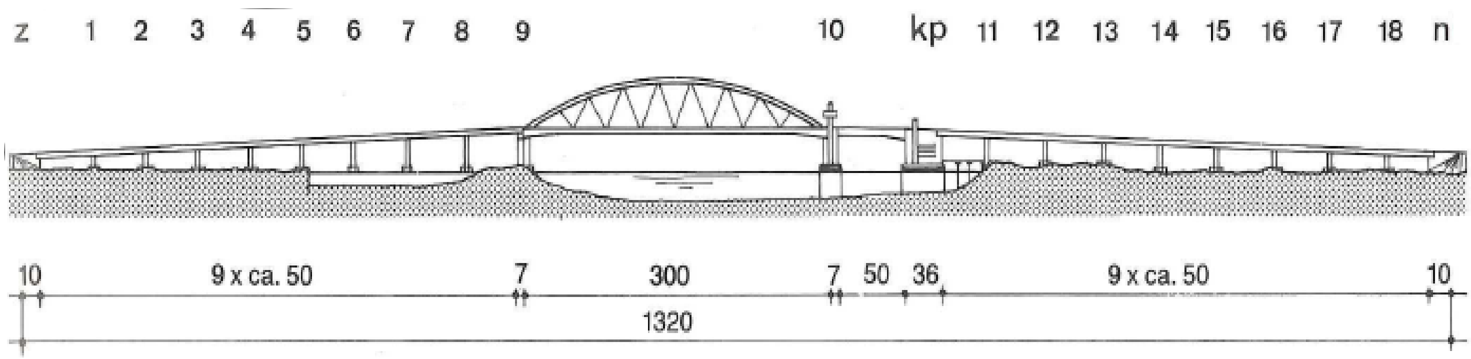
Punching cone resisted by aggregate interlock action, depending on crack opening ψ (*fib* MB 2010)

Punching in bridge deck with lateral restraint due to compressive membrane action, generating a considerable additional bearing capacity

Realistic boundary conditions for punching behaviour of a bridge deck subjected to a wheel load

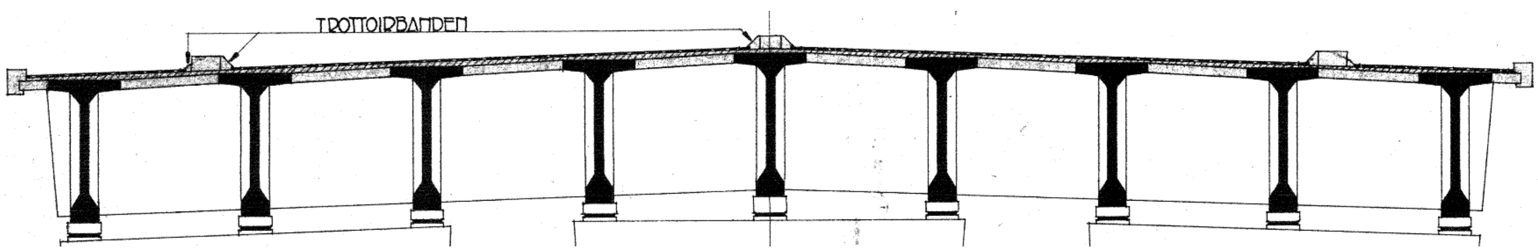
TU Delft

Project Description

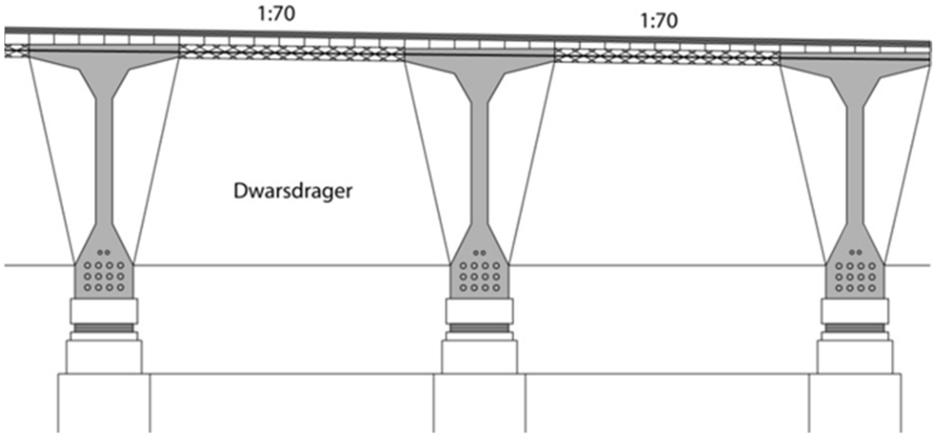


A typical "Approach Bridge"

1:2 Scale Model



Large scale experiment on compressive membrane action

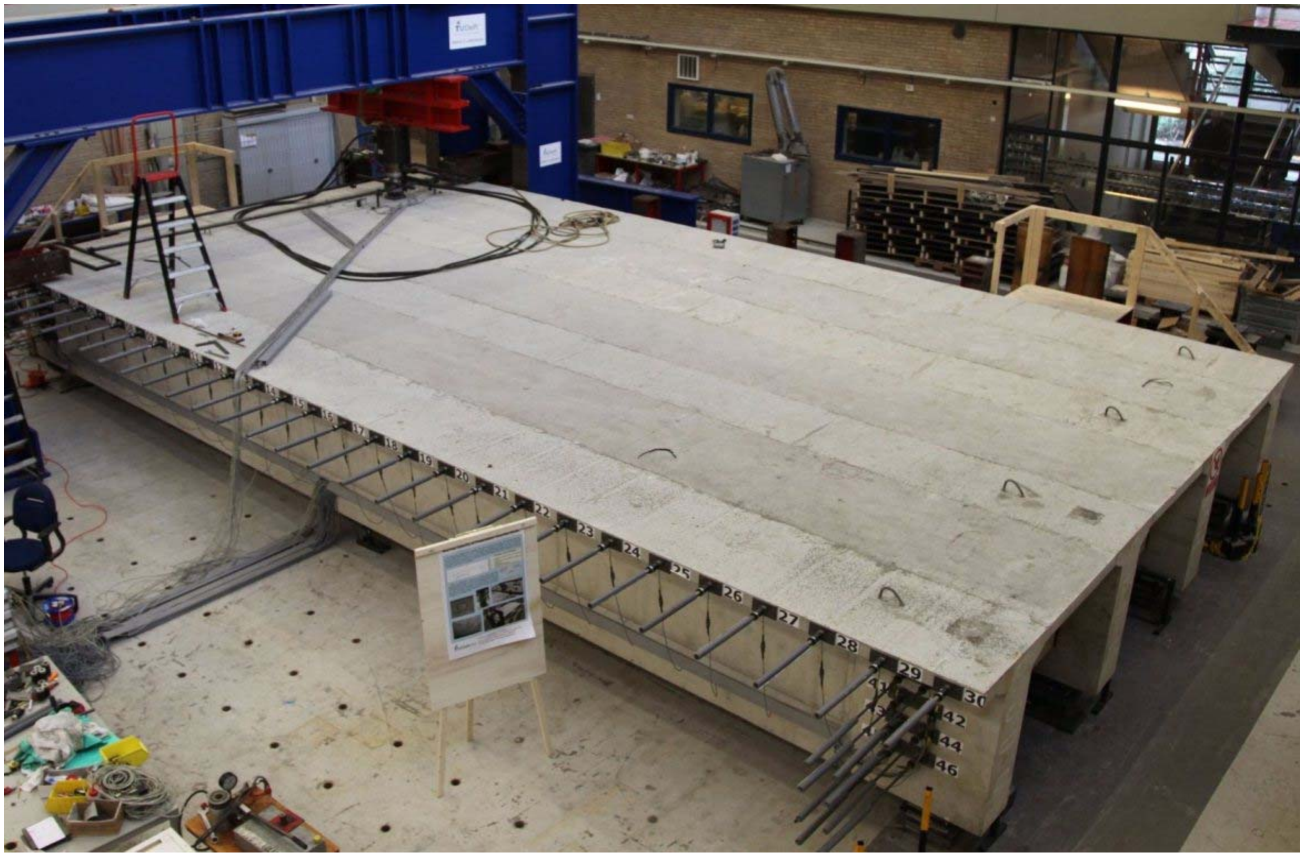


TU Delft, 25 aug. 2012

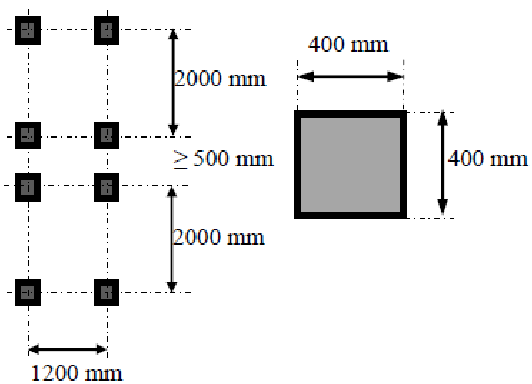
TU Delft

Tests of punching shear resistance including CMA

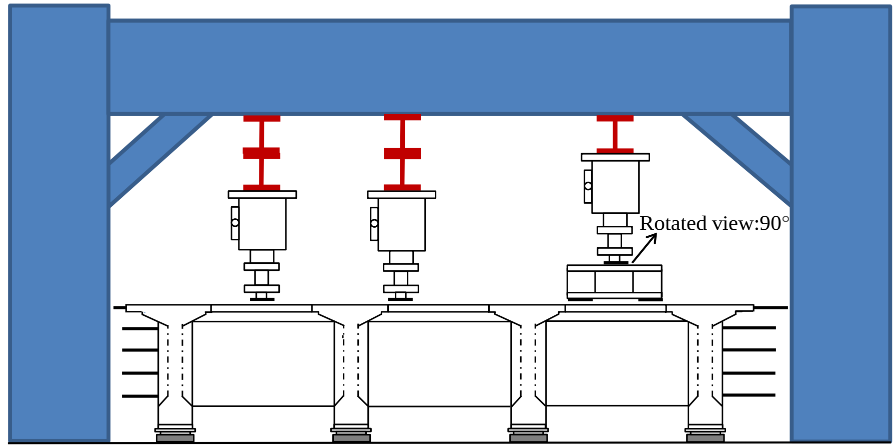
1:2 Sized bridge deck model ready for testing



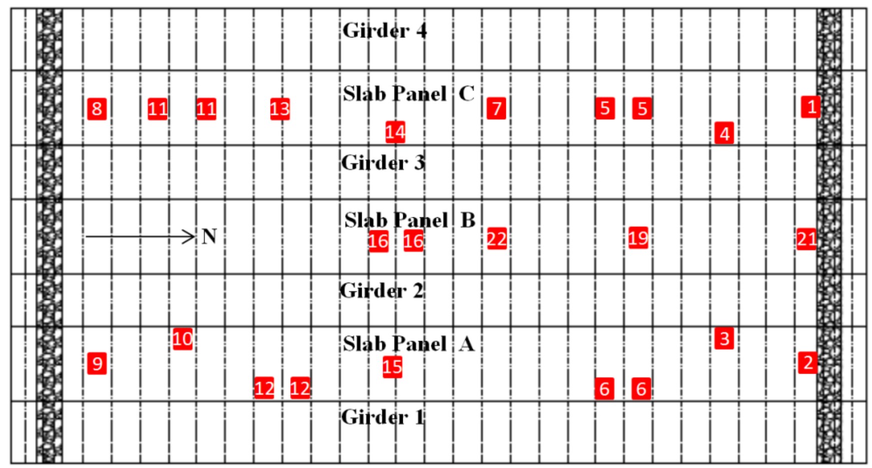
Application of point loads or double loads at various positions



Eurocode load configuration and wheel print



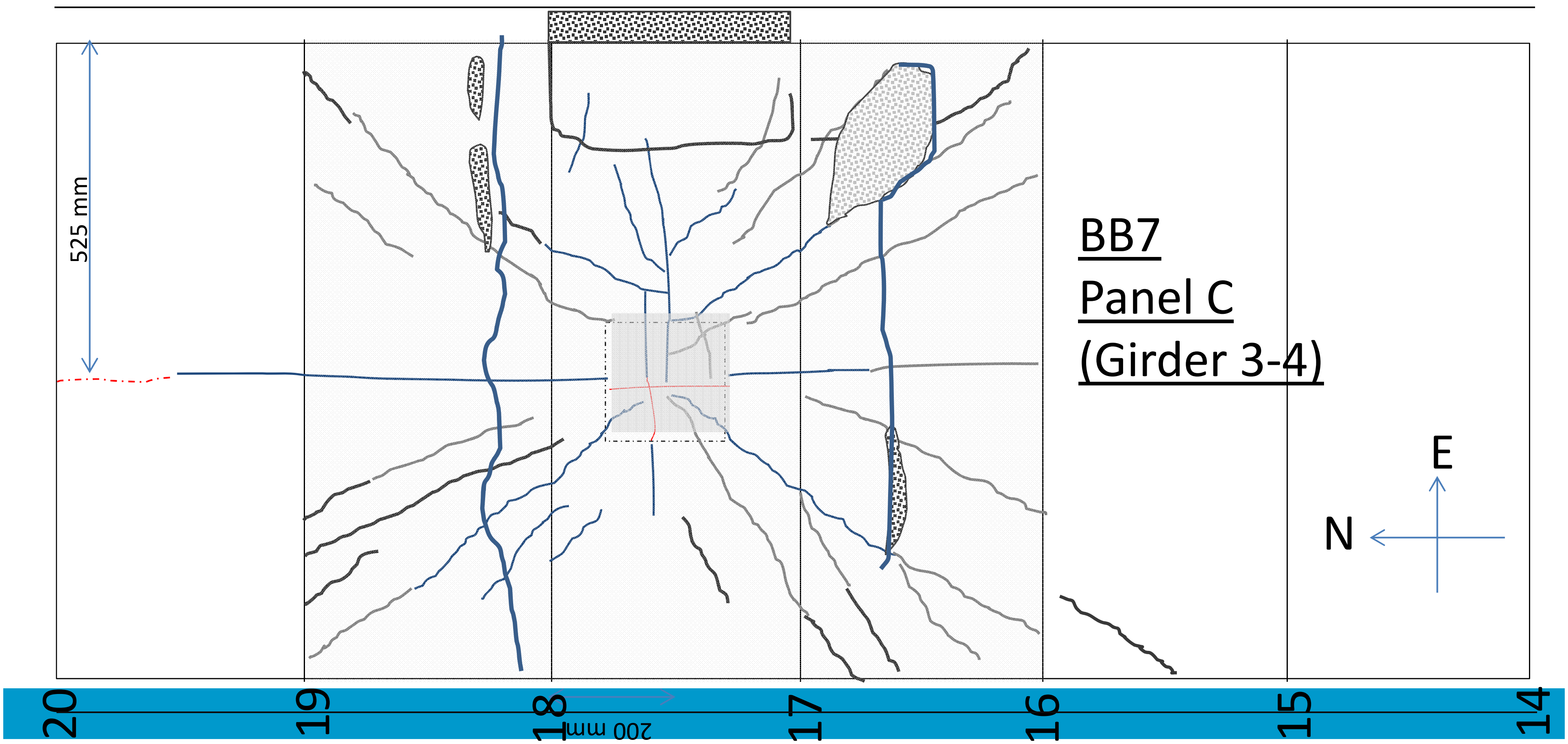
Cross section of deck with possible loading positions



Top view on slab with different load positions (single tests)

TU Delft

- First hairline cracks under the loading plate.
- Radial cracks. Propagation previous cracks.
- More radial cracks. Propagation of previous cracks in all directions.
- Punching failure. Large circumferential cracks. Spalling of interface (concrete cover) at bottom side of deck. Top side punched through the loading plate.



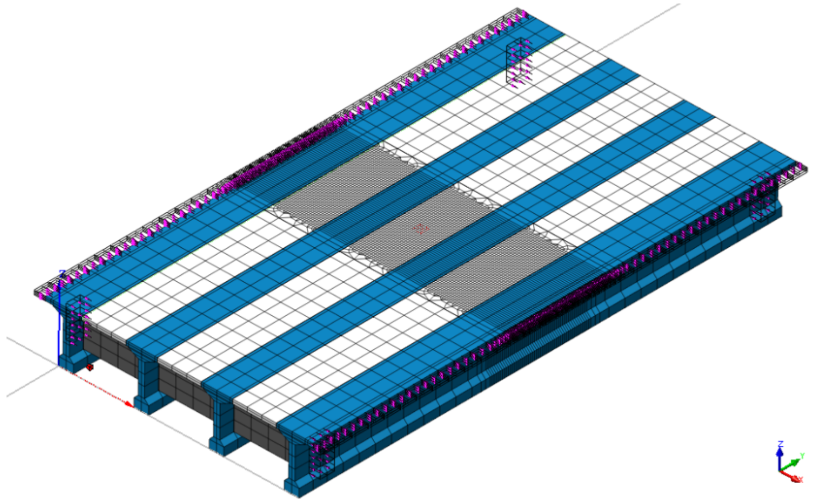
TU Delft

Analysis of results: NLFEM

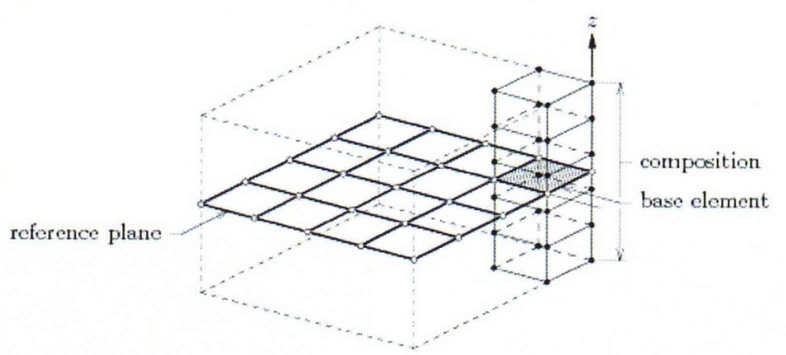
1. Analysis with NLFEM DIANA 9.4.4
3D solid elements (CHX60 and CTP45)

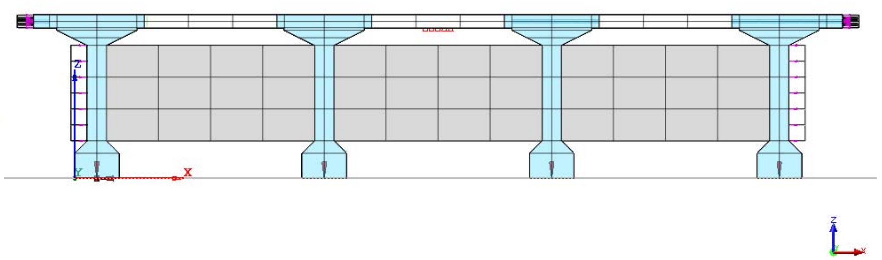
Fine mesh in loaded area, course mesh in more remote areas

In fine mesh area layer of composed elements (CQ8CM) is provided to cope with compressive membrane forces



3D solid finite element bridge model





Transverse cross-section of the 3D solid, finite element bridge model

TU Delft

Punching shear determination including CMA with NLFEM

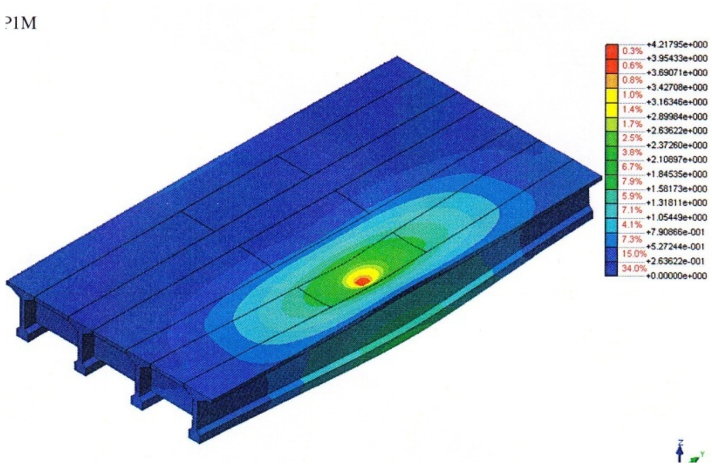
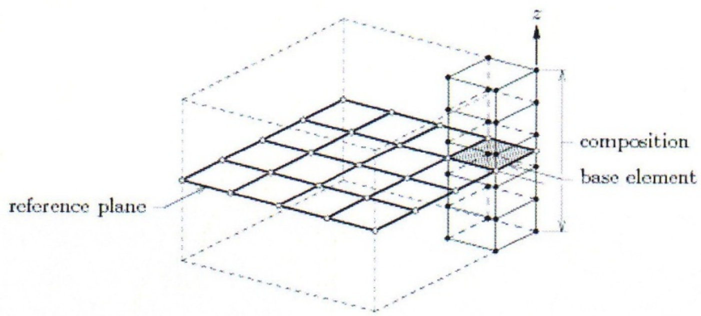


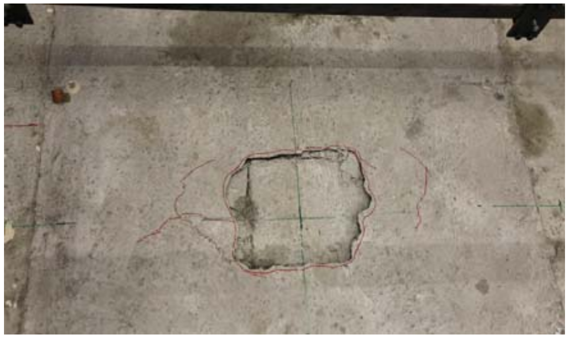
Table 6.8 Comparison of finite element analyses and experimental ultimate loads.

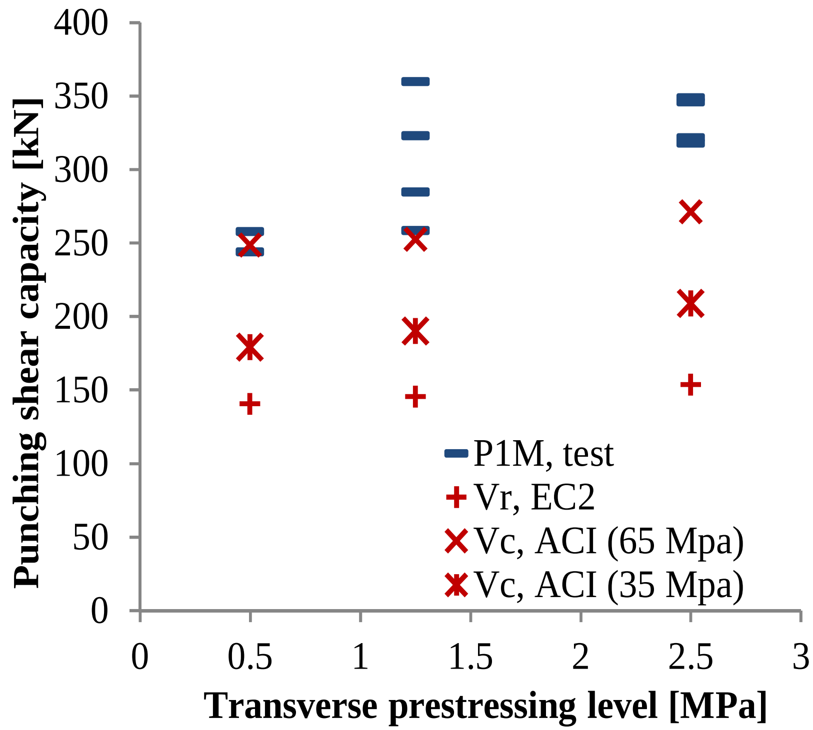
Test BB.	TPL	Designation	P_T	P_{FEA}	Test *FMODE*	P_T/P_{FEA}
	[MPa]		[kN]	[mm]		
1.	2.5	C-P1M	348.7	302.3	Brittle punching	1.15
2.	2.5	A-P1M	321.4	302.3	Brittle punching	1.06
3.	2.5	A-P1J	441.6	429.9	Brittle punching	1.03
4.	2.5	C-P1J	472.3	429.9	Brittle punching	1.10
5.	2.5	C-P2M	490.4	529.9	Flexural punching	0.93
6.	2.5	A-P2J	576.8	537.0	Brittle punching	1.07
7.	2.5	C-P1M	345.9	302.3	Brittle punching	1.14
8.	1.25	C-P1M	284.5	271.4	Brittle punching	1.05
9	1.25	A-P1M	258.2	271.4	Brittle punching	0.95
10.	1.25	A-P1J	340.3	300.7	Brittle punching	1.13
11.	1.25	C-P2M	377.9	453.4	Flexural punching	0.83
12.	1.25	A-P2J	373.7	454.9	Brittle punching	0.82
					Mean	**1.02**
					Std. deviation	**0.11**
					COV	**0.11**



TU Delft

Test results for punching shear capacity compared with predictions based on code expressions (without CMA)



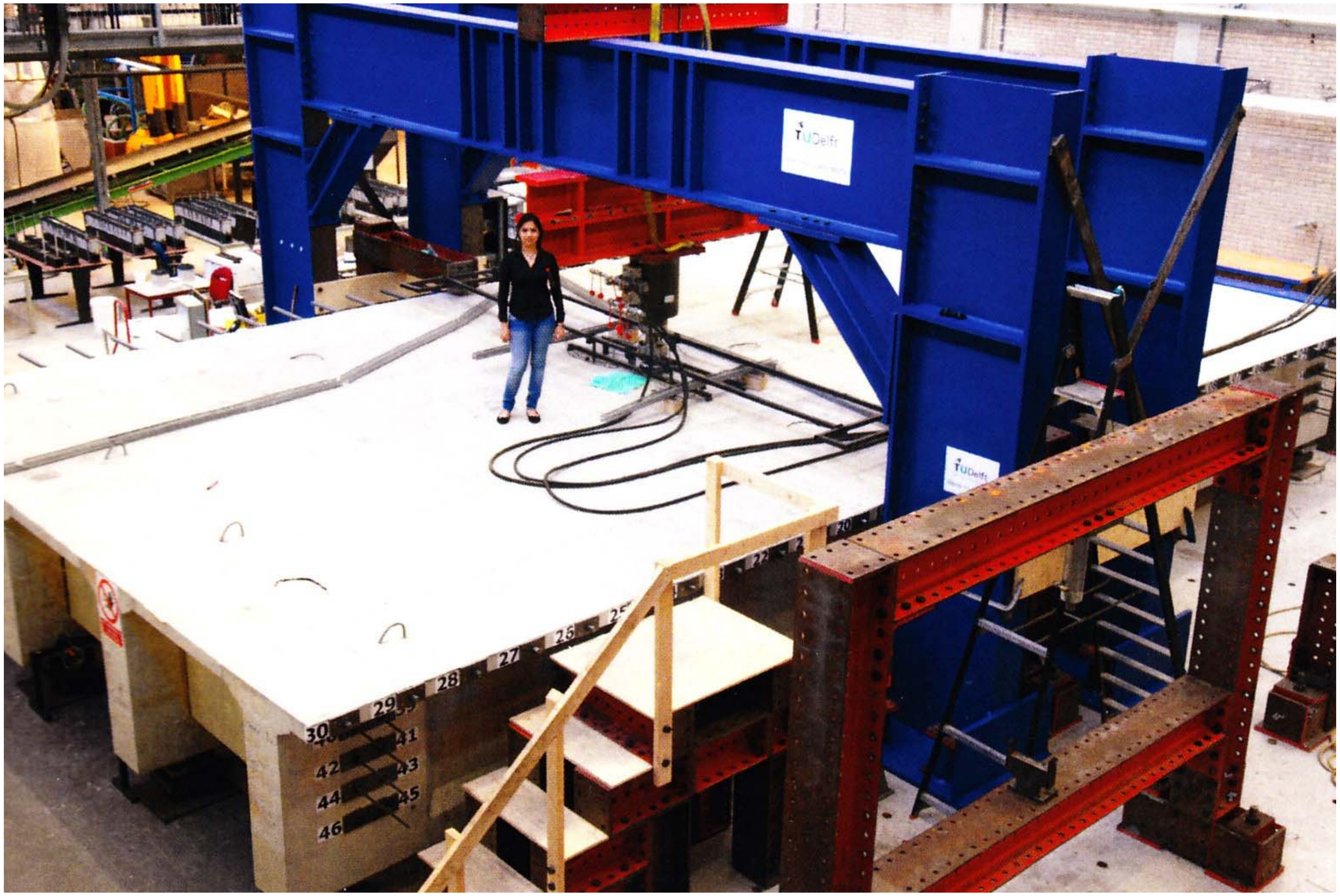


Prediction of mean values on basis of code expressions

Factor of Safety (FOS) for the 70 bridges, involved in the research, according to the different methods od analysis

Calculation of FOS for the model bridge deck using the actual analyses results.

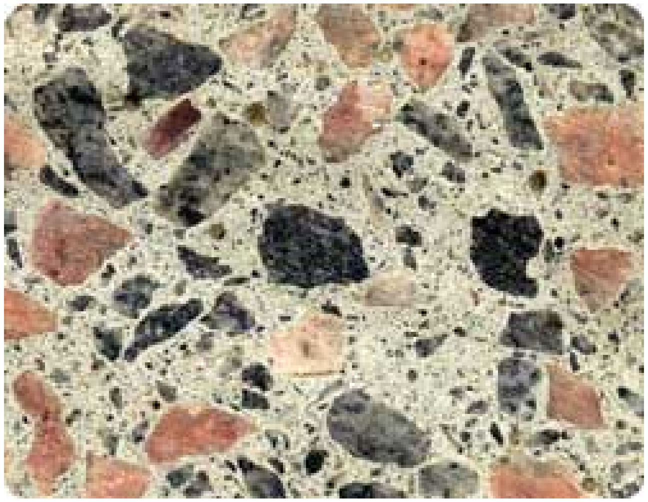
BB	TPL	P_T	P_{FEA}	P_{CSA}	$R_{md,T}$	$R_{md,FEA}$	$R_{md,CSA}$	Test FOS	FEA FOS	CSCT FOS
					P_T/γ_T	$P_{FEA}/\gamma_{GL'}$		$R_{md,T}/F_{md}$	$R_{md,FEA}/F_{md}$	$R_{md,CSA}/F_{md}$
	[MPa]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]			
1.	2.5	348.7	302.3	311	232	202	234	4.13	3.58	4.16
2.	2.5	321.4	302.3	311	214	202	234	3.81	3.58	4.16
3.	2.5	441.6	429.9	422.4	294	287	325	5.23	5.10	5.78
4.	2.5	472.3	429.9	422.4	315	287	325	5.60	5.10	5.78
5.	2.5	490.4	529.9	453.3	327	353	346	2.91	3.14	3.08
6.	2.5	576.8	537.0	482.3	385	358	346	3.42	3.18	3.08
7.	2.5	345.9	302.3	311	231	202	234	4.10	3.58	4.16
8.	1.25	284.5	271.4	295.7	190	181	222	3.37	3.22	3.95
9	1.25	258.2	271.4	295.7	172	181	222	3.06	3.22	3.95
10.	1.25	340.3	300.7	310.9	227	200	234	4.03	3.56	4.16
11.	1.25	377.9	453.4	431.3	252	302	329	2.24	2.69	2.92
12.	1.25	373.7	454.9	432.1	249	303	329	2.21	2.70	2.92
16.	2.5	553.4	592.7	482.3	369	395	369	3.28	3.51	3.28
19.	2.5	317.8	306.0	281.9	212	204	208	3.77	3.63	3.70
					Factor of safety			**3.65**	**3.56**	**3.93**
					Average factor of safety				**3.71**	



PhD-thesis “”Compressive membrane action in prestressed concrete deck slabs”, Sana Amir, TU Delft, June 2014

Where is the residual capacity to be found?

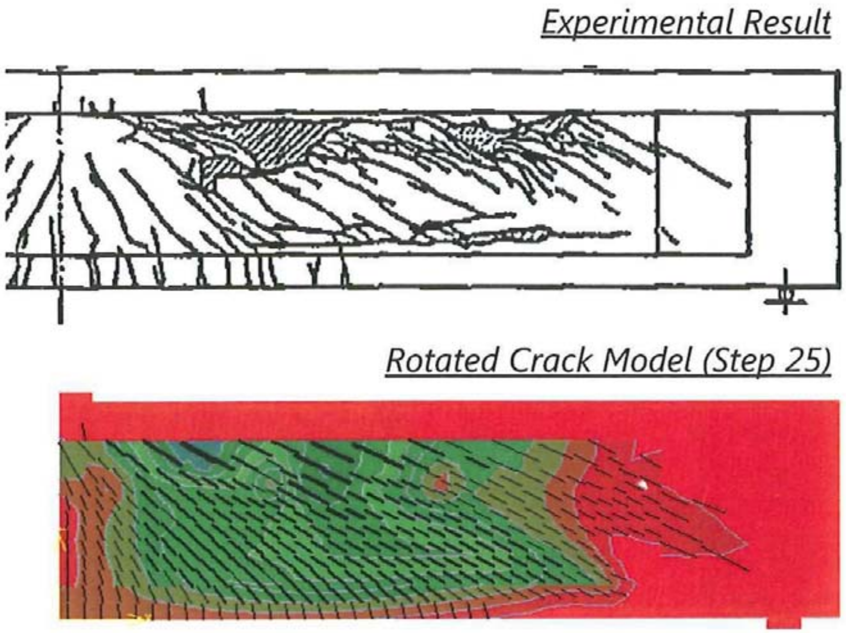
- Higher concrete strength after decades of hydration?
- Is there a sustained loading effect in shear?
- More favourable shear, or punching behaviour by virtue of redistribution or dome effect?
- Reliable prediction of behaviour by nonlinear FEM calculations?
- Proof loading?



TU Delft

Optimum prediction of shear capacity of slender prestressed beams.

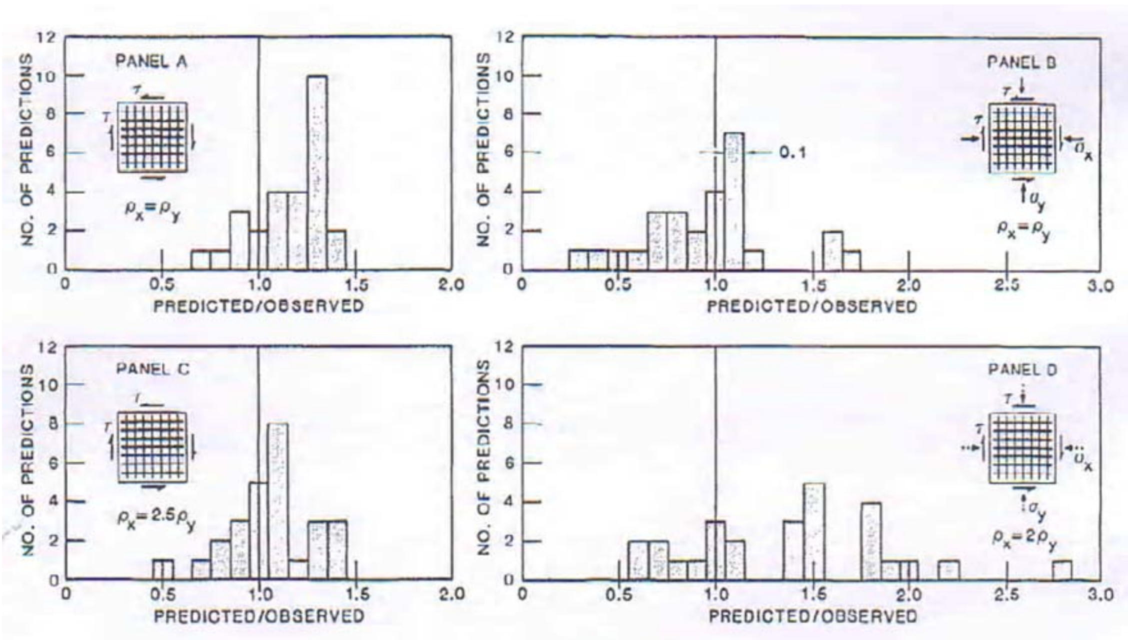
How can a NLFEM calculation be made more reliable?

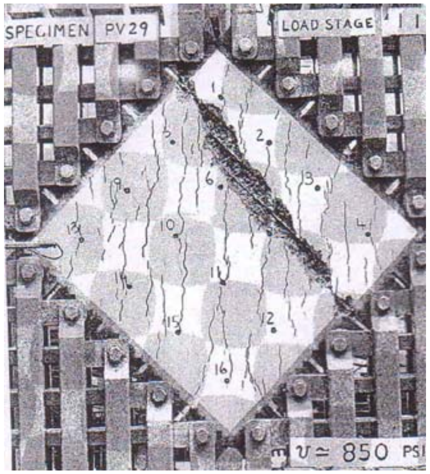


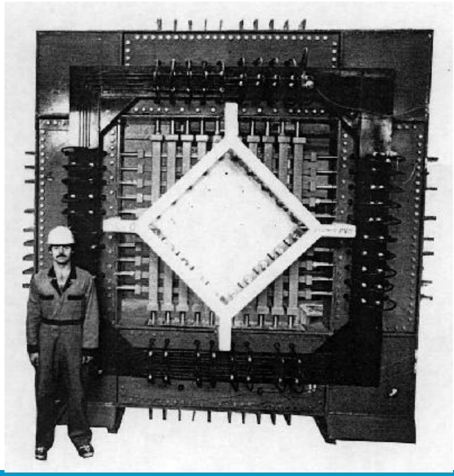
TU Delft

Competition of prediction of behaviour of reinforced panels under various loading combinations

Collins, 1982







Codes for application of tailor-made nonlinear FEM-analysis

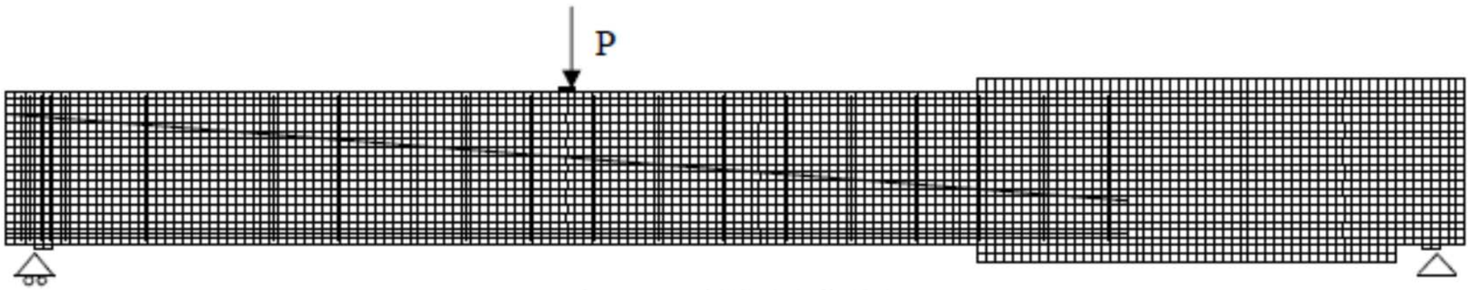
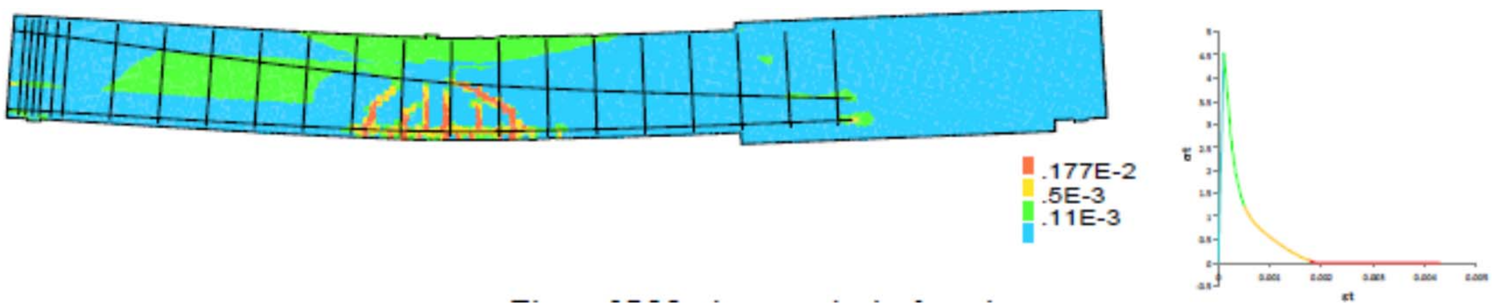
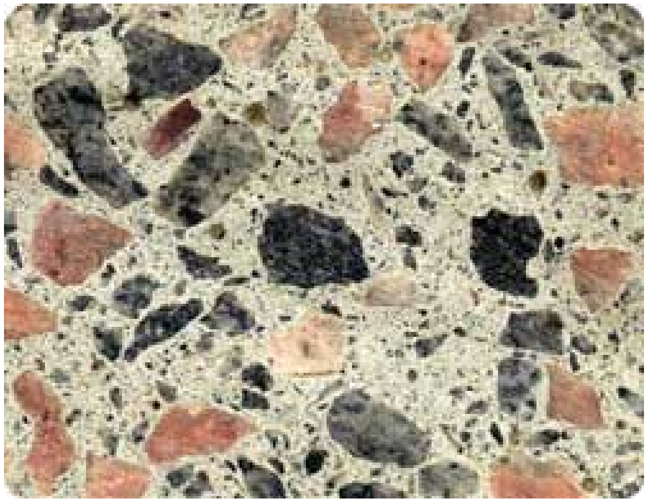


Figure 7 NLFE Model



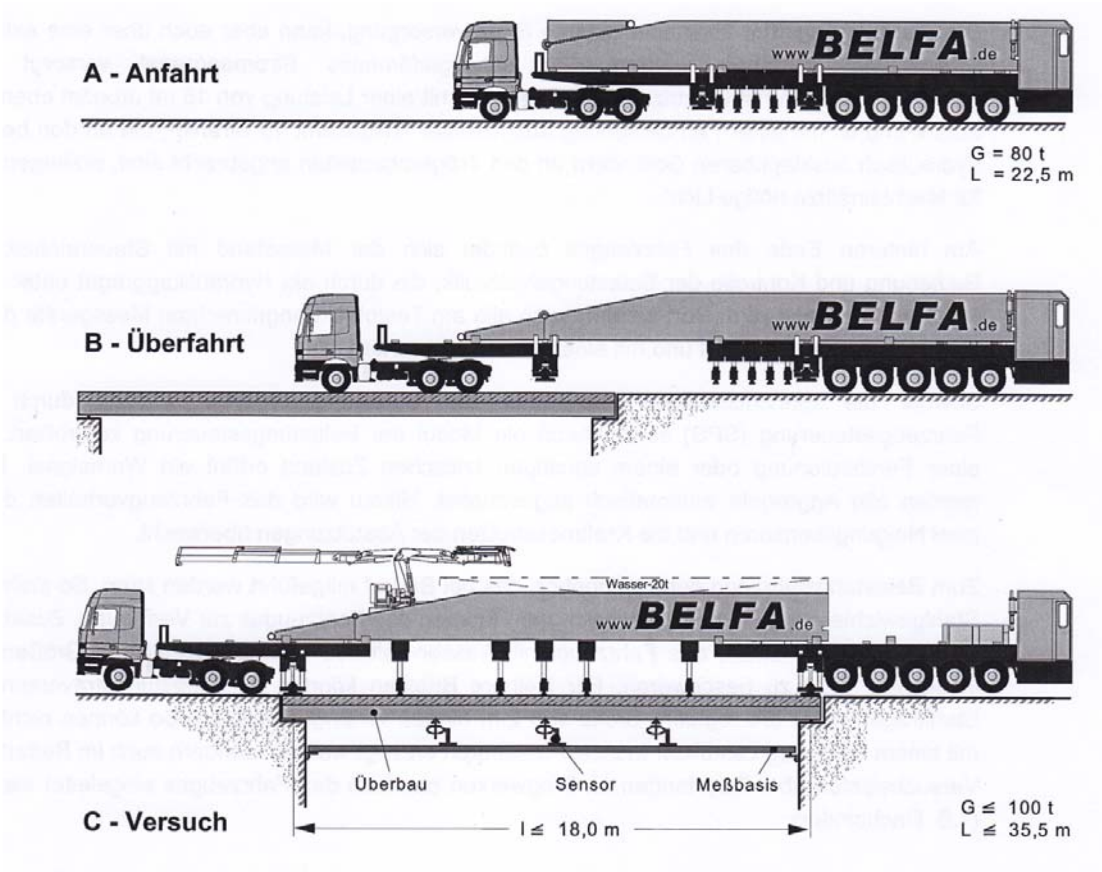
Where is the residual capacity to be found?

- Higher concrete strength after decades of hydration?
- Is there a sustained loading effect in shear?
- More favourable shear, or punching behaviour by virtue of redistribution or dome effect?
- Reliable prediction of behaviour by nonlinear FEM calculations?
- Proof loading?



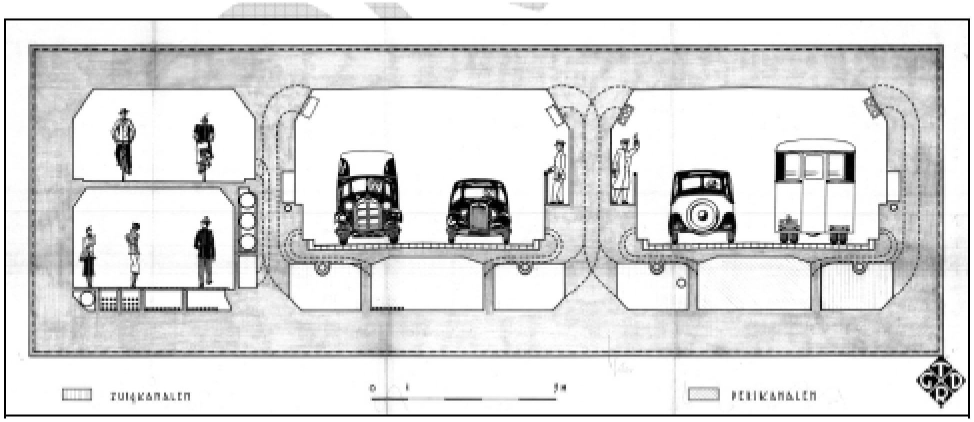
Determination of bearing capacity of bridges without data

Proof loading as a solution?



Proof loading of a bridge
With the special loading vehicle
Belfa

From bridges to tunnels: Maastunnel Rotterdam



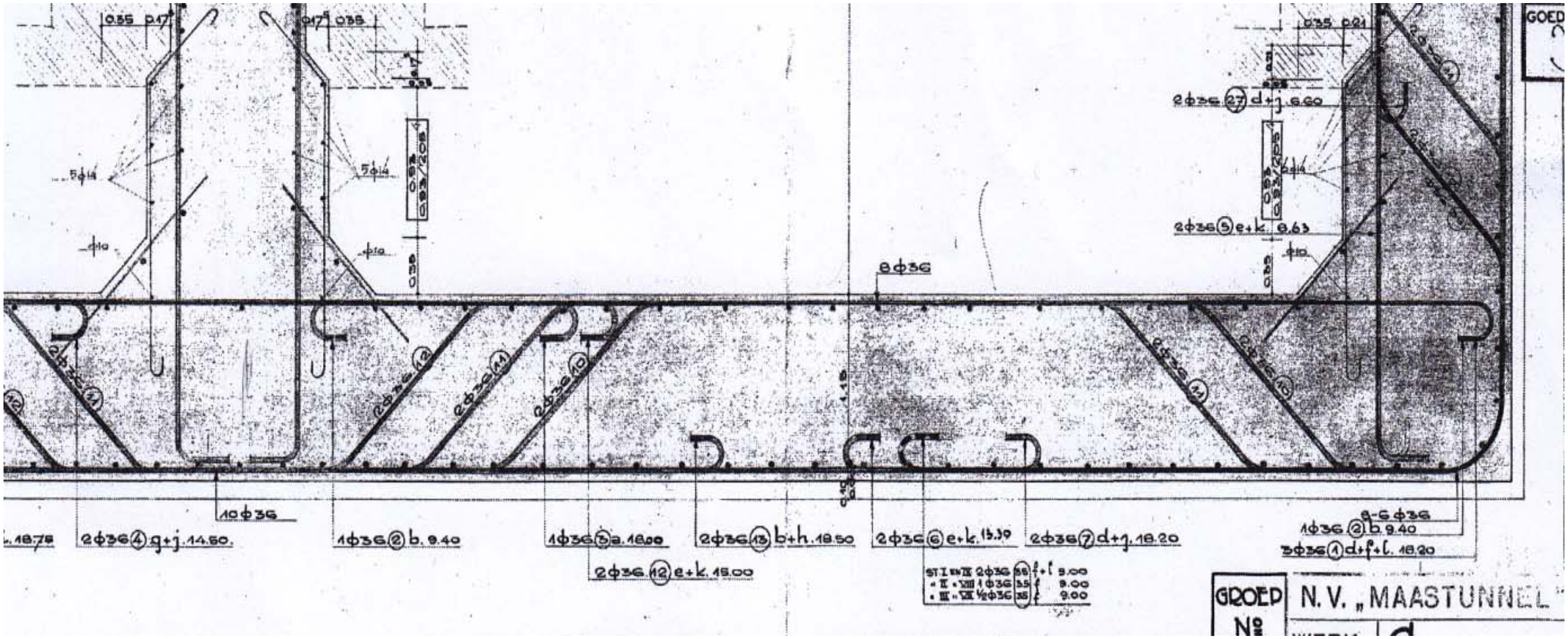
Built :1937 - 1942
Length: 580m
Element length: 61m
Element height: 8,70m
Element width: 25m
Construction with the submerged tunnel method

Assessment of the bearing resistance of the tunnel floor subject to reinforcement corrosion

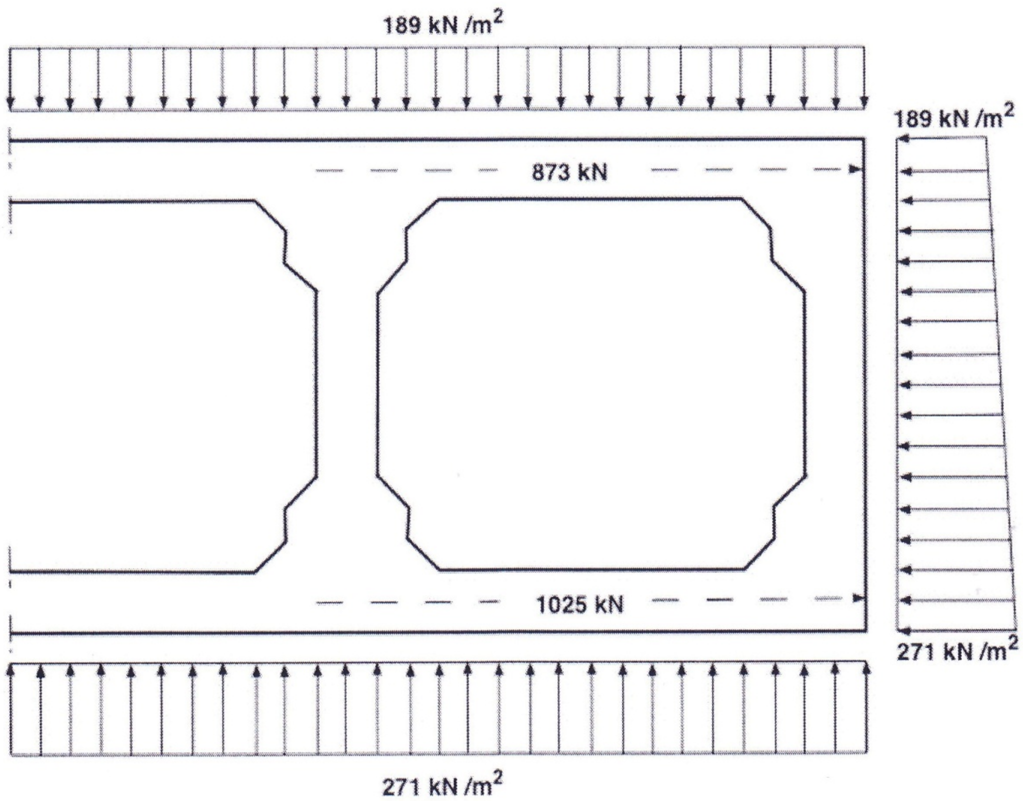
Corrosion of steel in bottom slab

Steel bar with reduced cross section

Bottom slab designed for 18,7 m upward water pressure

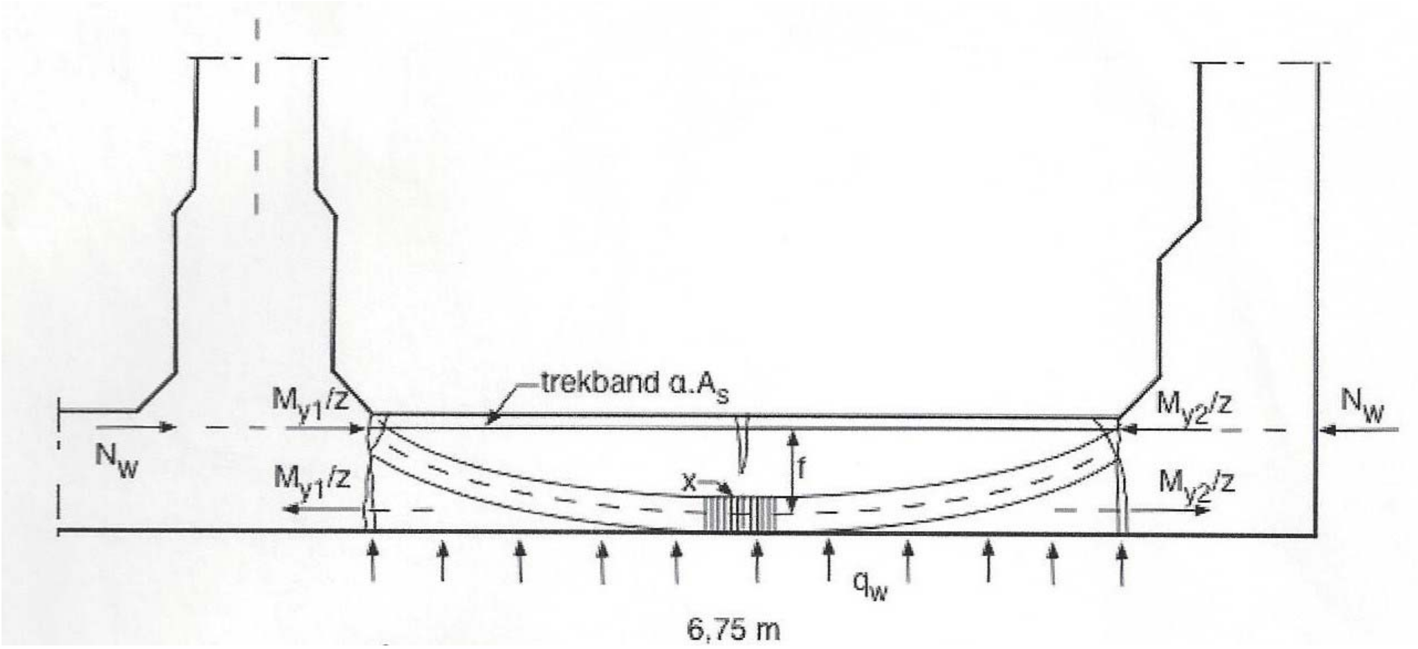


Water pressure at tunnel bottom at maximum SLS level



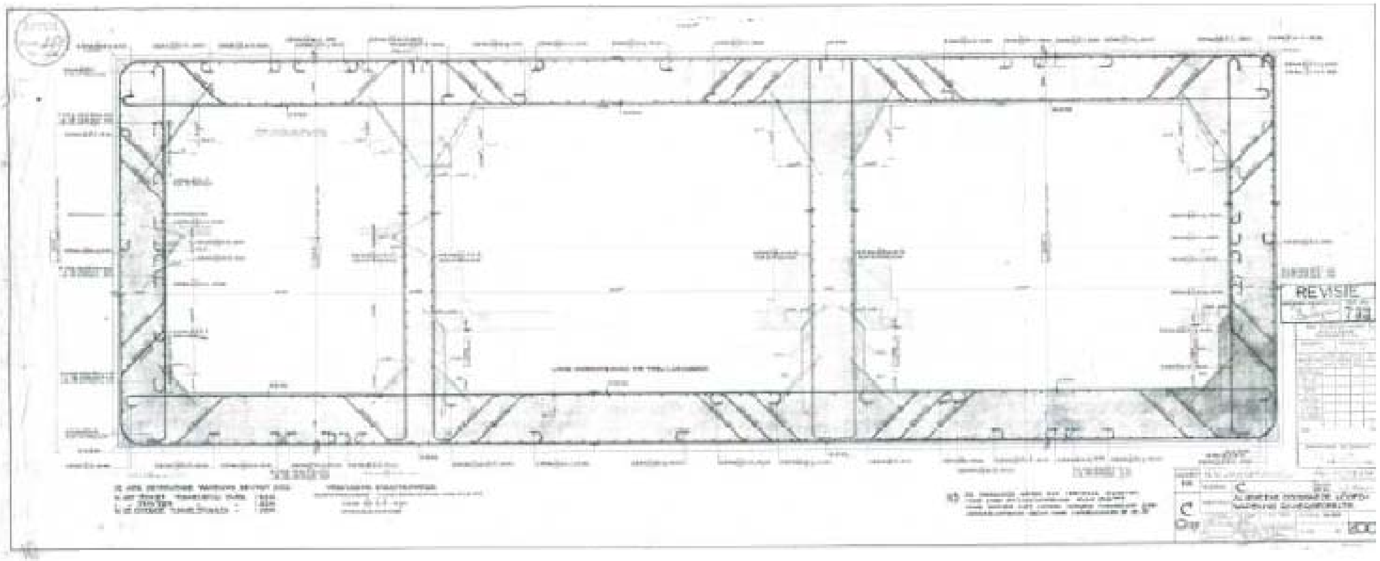
TU Delft

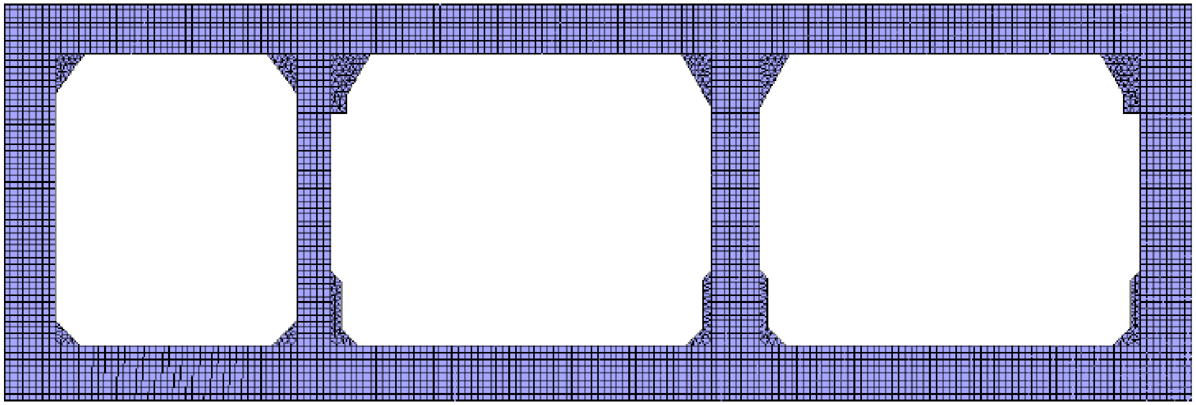
Water pressure at tunnel bottom at maximum SLS level



Simplified analysis: arch model with transversal support:
Conclusion: overnight closure of tunnel unjustified

NLFE Analysis with NLFE program ATENA

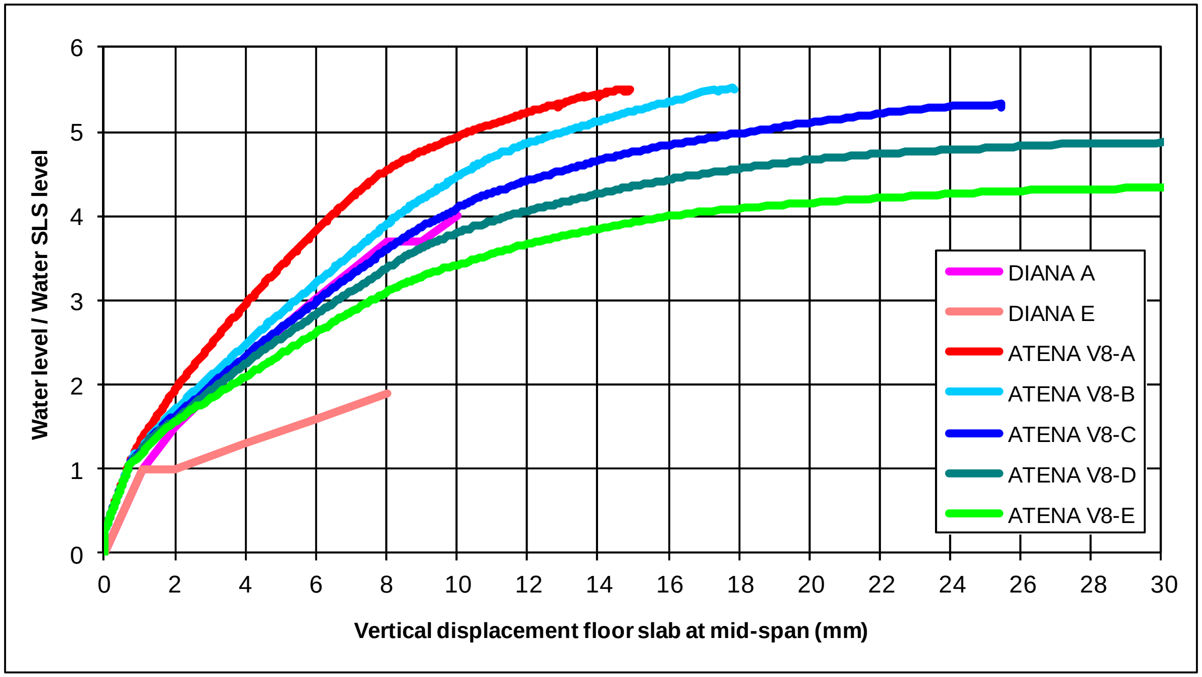




Situations analyzed

case	Description
A	100% steel area, full bond
B	100% steel area, no bond
C	60% steel area, no bond
D	30% steel area, no bond
E	0% steel area, no bond

Load displacement relations

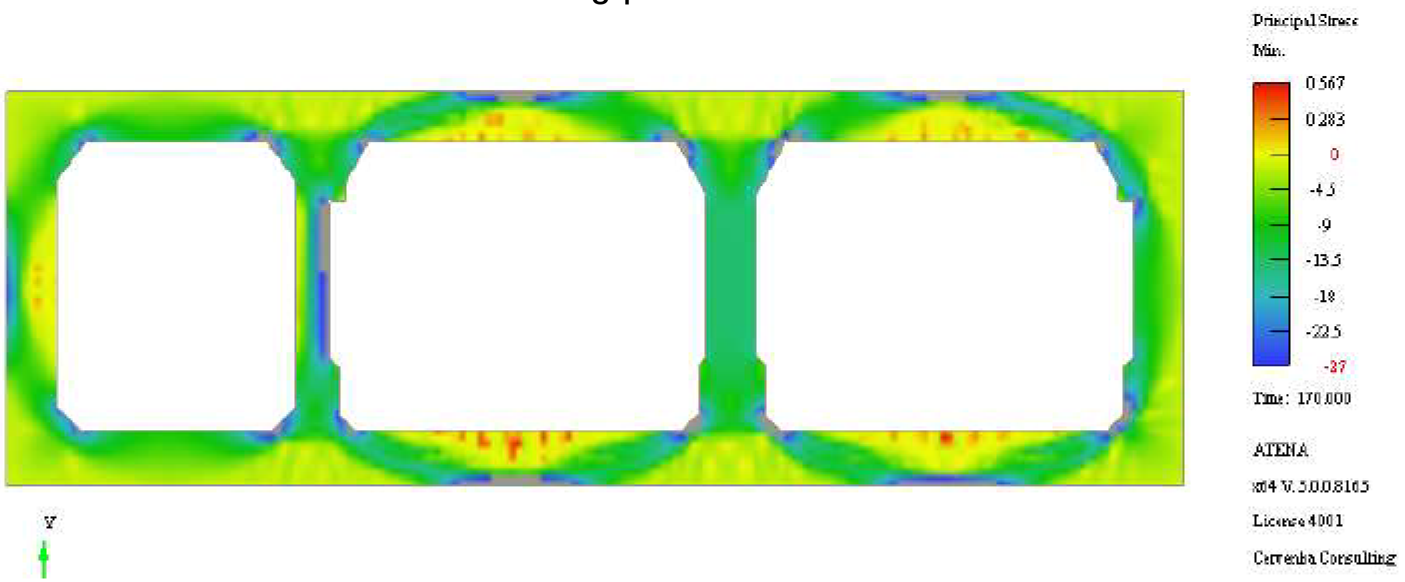


TUDelft

Results of ATENA analysis

At the maximum water level 149 m (end of analysis).

Cracking pattern

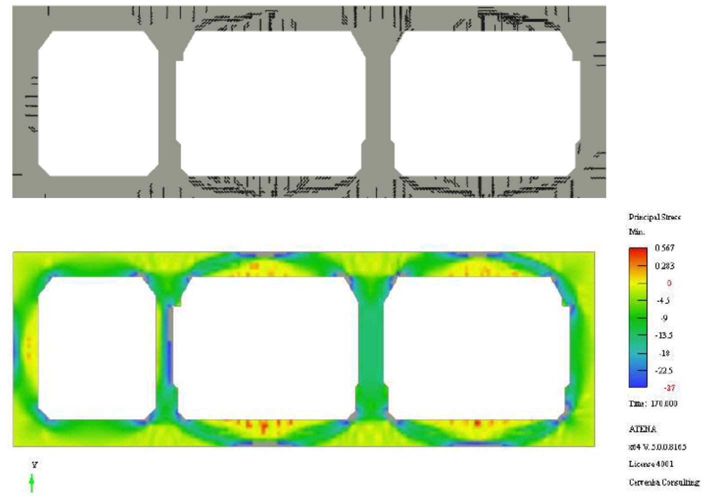


Principal compressive stresses in concrete

Safety margin calculated with NLFEM analysis

% effective reinforcement	$q_{w,u}/q_{w,SLS}$ ATENA	$q_{w,u}/q_{w,SLS}$ DIANA
100%	4,0	5,6
60%	3,1	5,2
30%	2,7	4,7
0%	2,1	4,3

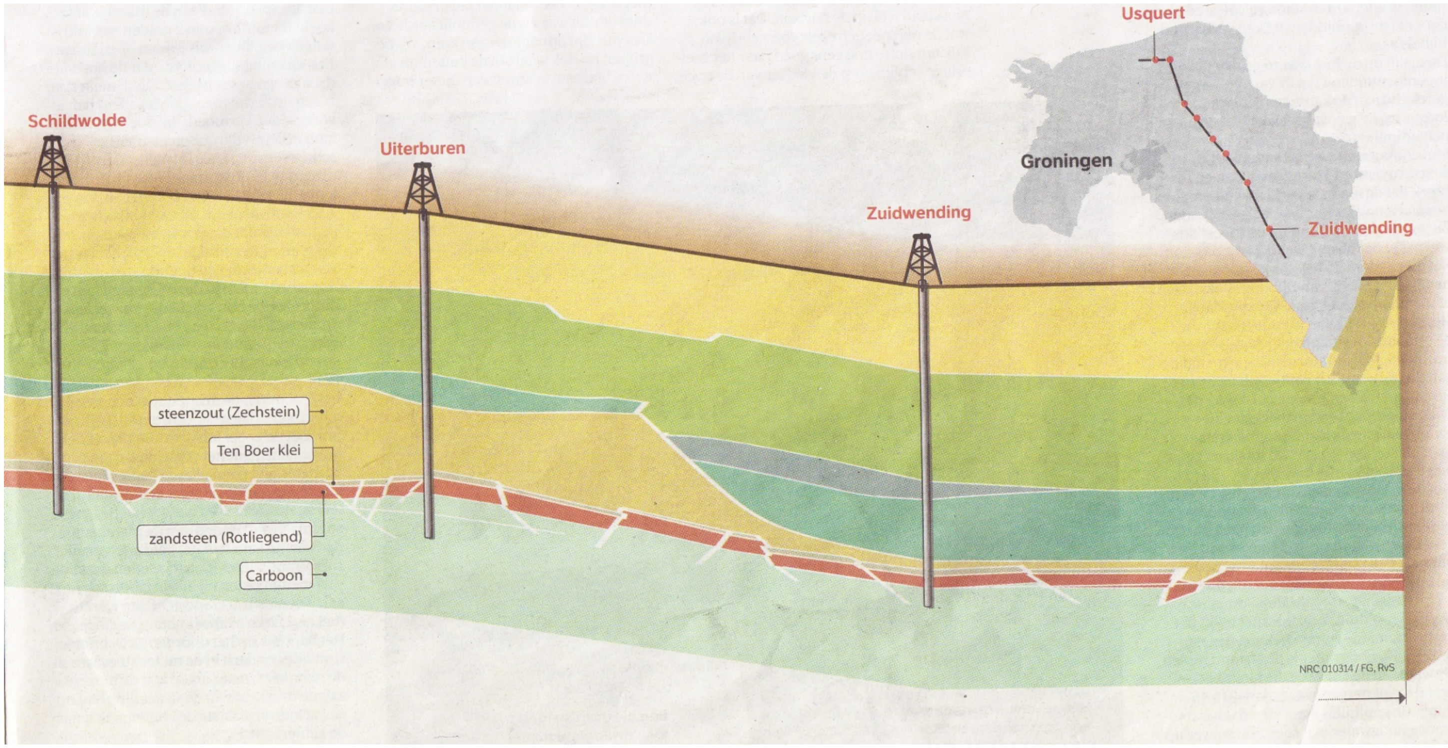
At the maximum water level 149 m (end of analysis).



A new new large-scale national problem

Damage due to seismic action in Groningen

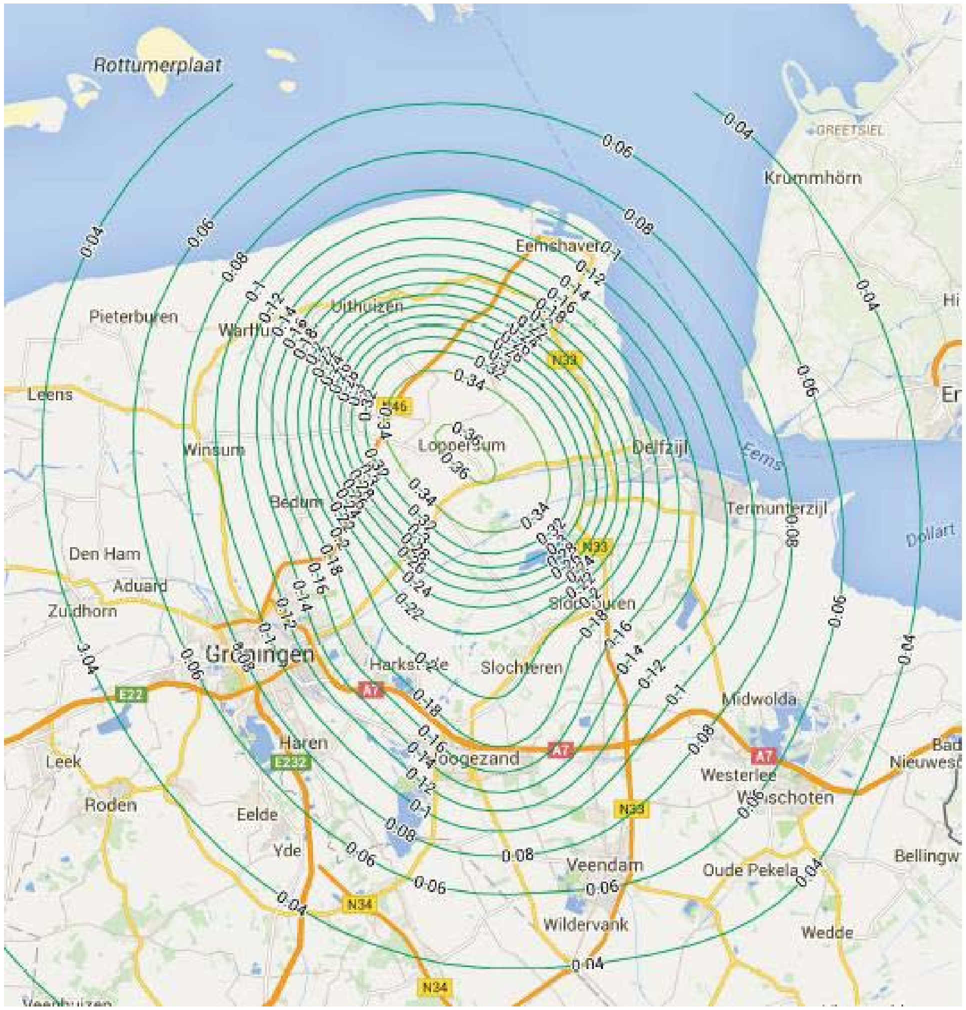
Induced earthquakes in the Netherlands



Sandstone layer (200m thick, 3km deep)
The pressure in the sandstone layer decreased from 320 bar in 1963 (start of gaz extraction) to 100 bar now
Induced earthquakes due to volume reduction of sandstone layer: shear along old vaults (approximately 1500) in the sandstone.

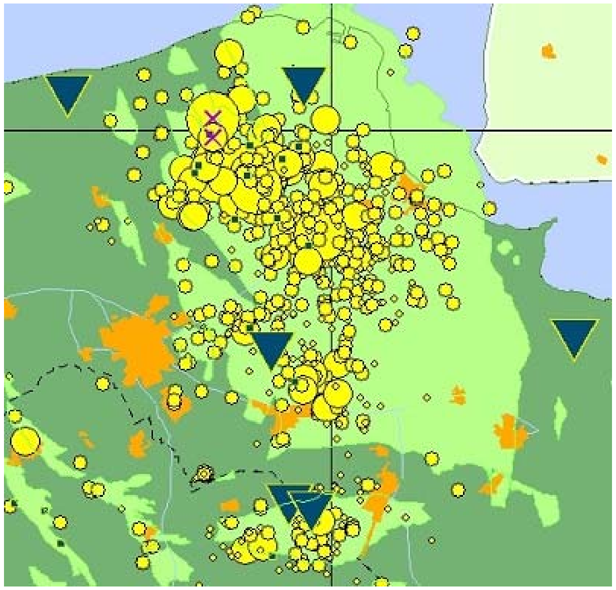
TU Delft

Map with peak ground accellerations



Groningen 2015

180.000 structures: development of an assesement - and strengthening strategy

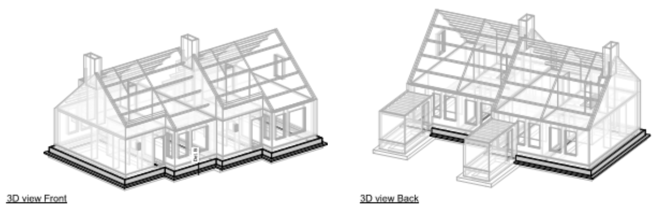


How to classify structures?

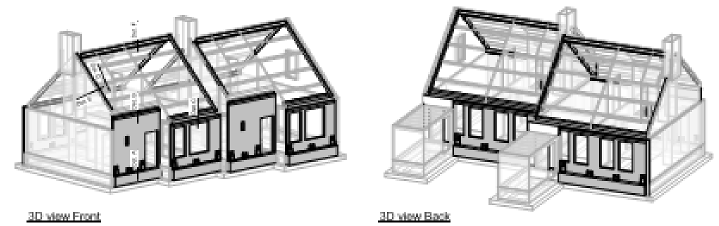
Looking for appropriate strengthening measures.

In dependence of pga, bottom, and building type an appropriate strengthenig method can be chosen.

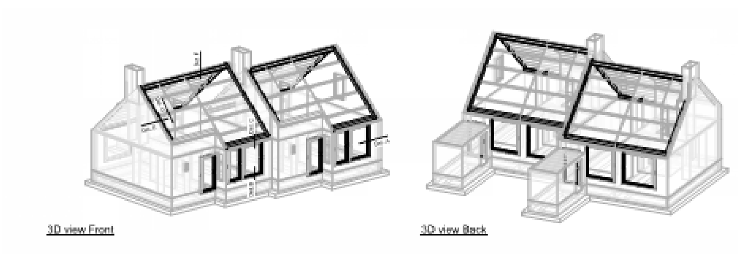
Option 1: base isolation



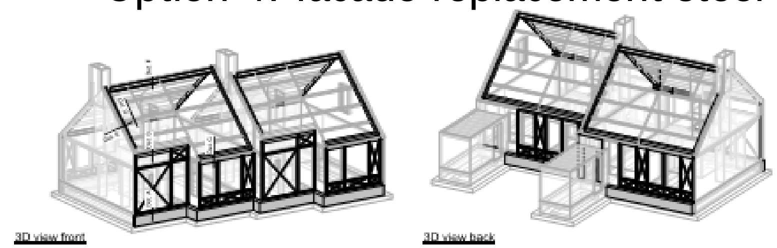
Option 3:facade replacement



Option 2:additional frames



Option 4: facade replacement steel



(Wilford, Arup), 2015

TU Delft

Push-over test TU Delft 2015

Construction of a house in the Stevinlaboratory TU Delft

A push-over calculation is a very slowly conducted. In this way it is possible to study the behaviour in detail. It is as well a valuable test to verify calculations.

It is also possible to determine the q-factor (ductility factor) for the structure regarded.

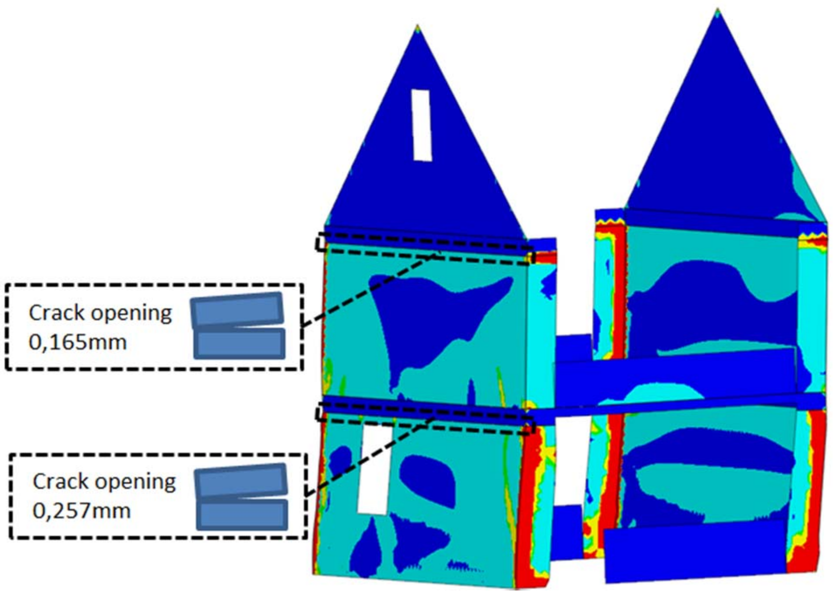
Preparing a shaking table tests in Pavia Italy

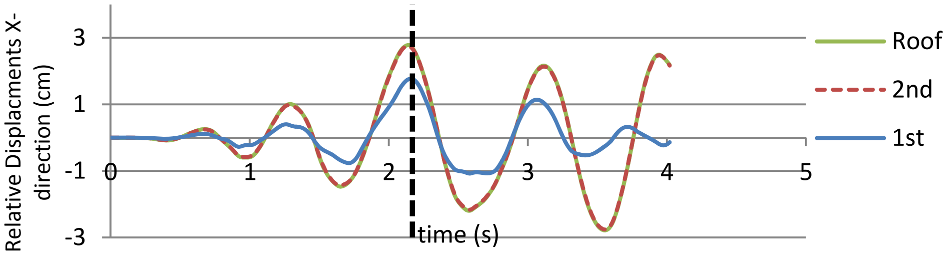
The house, typical for Groningen, is subjected to a “Groninger earthquake”. This does not only give important information for a representative house but also with regard to the reliability of a nonlinear time step analysis.

Nonlinear time history analysis

Most advances analysis, including dynamic loading and nonlinear response of material and structure.

Applicability for general use?





Conclusions

1. Most structures have a significant residual capacity, which is essential for the decision whether to strengthen (groups of) structures or not.
2. For being able to determine the residual bearing capacity of structures, fundamental knowledge on the behavior of structures is essential.
3. The value of fundamental knowledge increases with the number of older structures to be retrofitted.
4. Teaching the fundamental behavior of structures at universities is at least as important as training design of new structures.