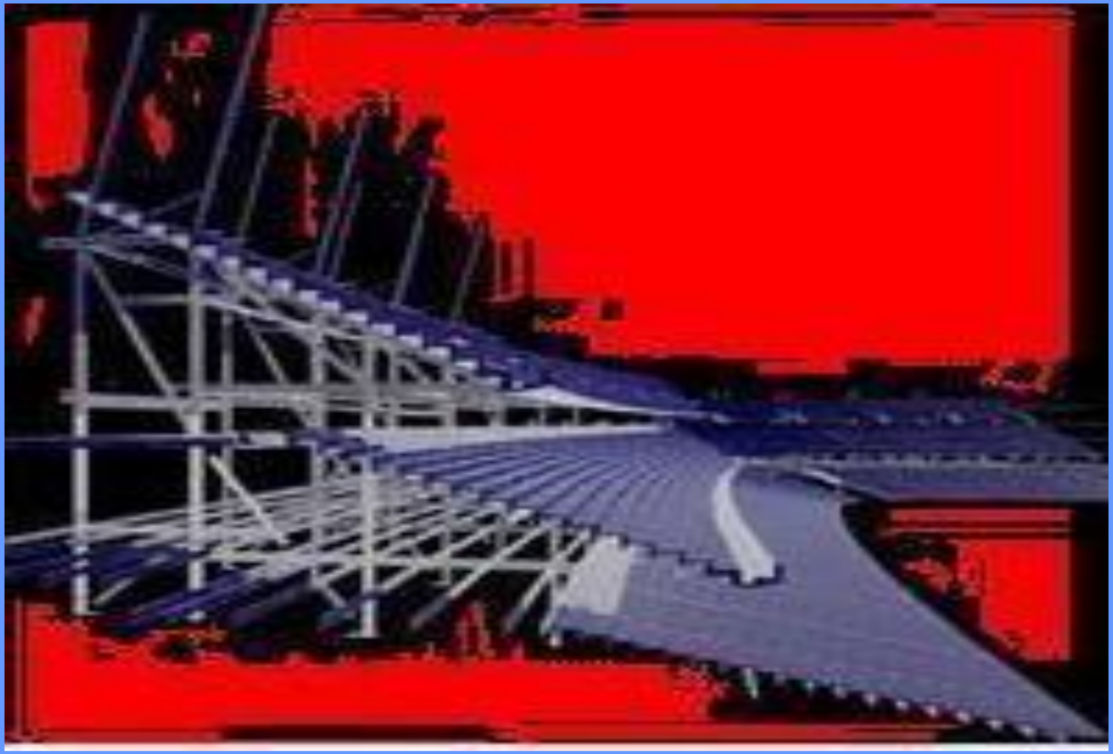
Strength and Failure Studies of Precast Concrete Grandstand Terraces. _A Numerical Model.



by:
john karadelis

COVENTRY UNIVERSITY

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Introduction

- *This is the first part (statics approach) of an on-going research study, examining the behaviour of hybrid (steel skeleton-concrete terraces) Grandstands under LIVE loads.*
- *The behaviour of RC, particularly at its cracked state, that is its strength, deflection, ductility, failure modes, is affected by:*

Compression softening,

Stiffening,

Tension softening,

Aggregate interlock,

Crack shear slip,

Rebar dowel action,

Creep,

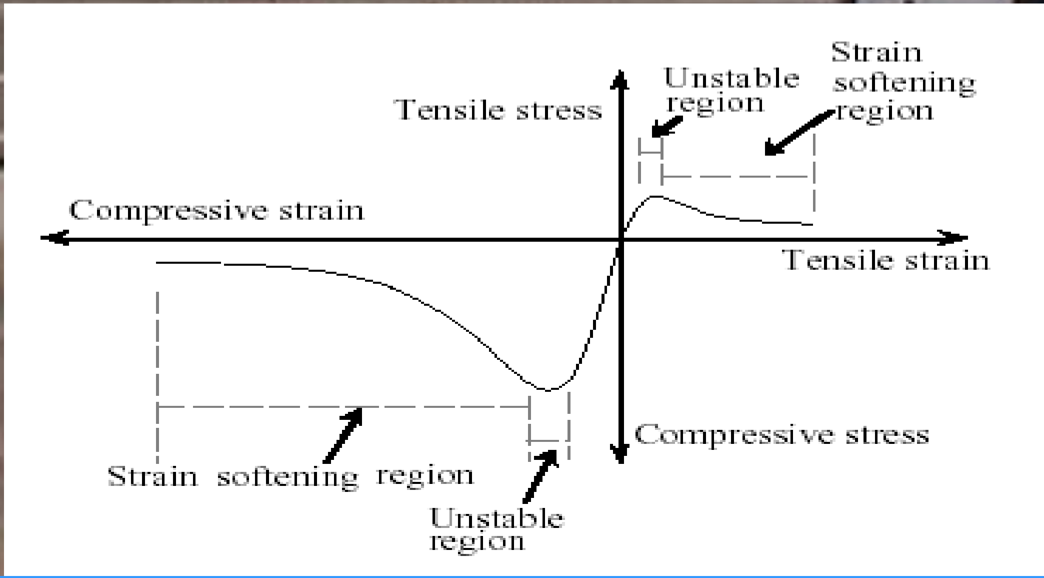
Shrinkage, etc.

The complexities involved in developing an accurate FE model for the above problems are the subject of on-going research and wisdom.

Identifying the problem

This could be attributed to the following:

- The distinct non-linearity of its stress-strain path especially in the near peak domain, due to generation and propagation of microcracks and its subsequent reduction in stiffness.
- The softening tendency of concrete in the post peak domain.
- The elastic stiffness dilapidation caused by successive opening-closing of cracks due to loading+unloading.
- The irrecoverable volume loss at high compressive loads and the increase in Poisson's ratio.



RC properties, failure theories & criteria for numerical modelling.

- *Elasto-plastic behaviour of steel:*

Yield criterion= von Mises, 525 N/mm^2 (routine lab tests)

Flow rule= Plastic strain flow (uniaxial conditions assumed)

Hardening rule= isotropic plastic behaviour

Final solution achieved by using the linear solution modified with an incremental and iterative approach:

$$\varepsilon n = \varepsilon n(ela) + \Delta \varepsilon n(pla) + \varepsilon n - 1(pla)$$

Convergence is achieved when:

$$\Delta \varepsilon n(pla) \,/\, \varepsilon n(ela) < 0.01$$

This means, very little plastic strain is accumulated and therefore the theoretical curve is very close to the actual.

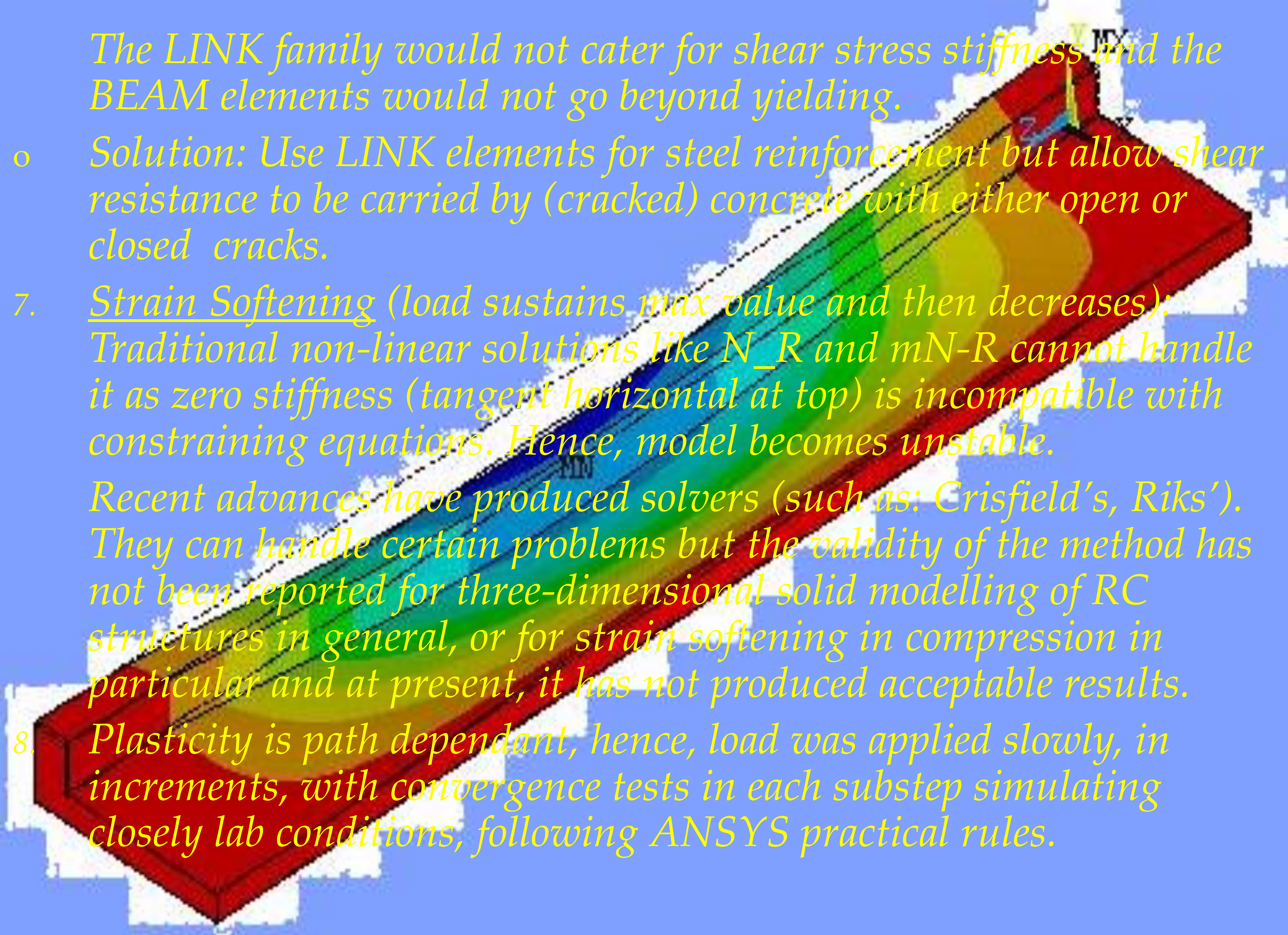
o *<u>Complexities of concrete Failure:</u>*

1. *Under low loading intensity, RC-structural elements (beams, slabs) behave essentially as uncracked elastic members.*
2. *After only few load increments vertical flexural cracks appear at midspan, resulting in a redistribution of stresses and causing increased steel stresses, bond stresses and some bond failure (slip).*
3. *Under more load, cracks spread and increase in number. If shear and diagonal failure is not critical, beam fails by yielding of the longitudinal tension reinforcement (u-reinf'ed section) or, by crushing of the concrete in the compression zone (o-reinf'ed section), or both (balanced section).*
4. *If shear and diagonal tension are critical then diagonal tension cracks evolve. These cracks activate resistance to vertical shear by:*
    - *a) doweling action of the main tension reinforcement*
    - *b) aggregate interlocking along the diagonal crack,*
    - *c) stresses in vertical stirrups, if present,*
    - *d) resistance in the uncracked concrete above the crack (compression zone).*

5. *A sudden increase takes place in the longitudinal steel stresses at the base of the diagonal tension cracks.*
6. *Under increasing load the diagonal cracks propagate towards the loading points causing a shear increase in the dowel bars.*
7. *Final failure occurs when the 'heads' of the diagonal cracks have penetrated the compression block to a point where "shear compression" failure occurs under a combined state of stress.*

Proposed Numerical Model

1. *Based on the previous statements, failure condition for concrete due to multi-axial stress state can be expressed as:* $\frac{F}{f_c} - S \geq 0$
2. *The above relationship must be satisfied for cracking (achieved by modifying stress-strain relationships and introducing a plane of weakness in the σ_{prin}-direction) and crushing . SOLID65 initially behaves in a linear elastic manner; can also simulate non-linear response if one of the applied principal stresses exceeds the tensile or compressive strength of concrete.*
3. *The later will crash, if all principal stresses are compressive and crack, if any of the principal stresses are tensile. For cracking in the tension zone the element includes a 'smeared' crack analogy allowing cracks to be shown in the deformed shape.*
4. *Shear Transfer can be included via the 'concrete material data table', modelling a range of perfectly-smooth-to-fully-rough cracks. also allowing for tensile and compressive strengths of concrete.*
5. *The rebars can be modelled as smeared stiffnesses too. They can resist tension and compression but, surprisingly, not shear. No full cure is achieved by introducing discrete LINK or BEAM elements.*



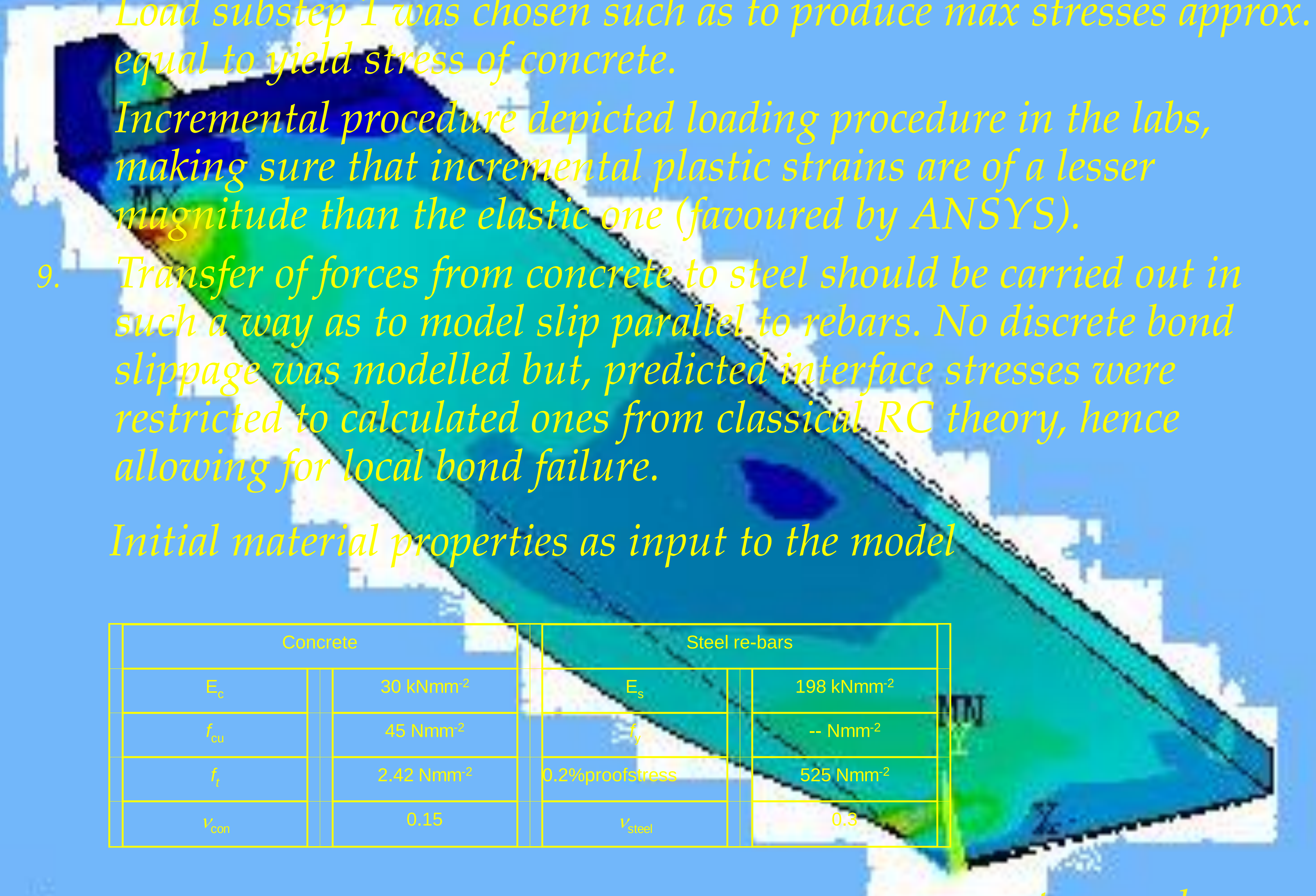
The LINK family would not cater for shear stress stiffness and the BEAM elements would not go beyond yielding.

- Solution: Use LINK elements for steel reinforcement but allow shear resistance to be carried by (cracked) concrete with either open or closed cracks.

7. <u>Strain Softening</u> (load sustains max value and then decreases): Traditional non-linear solutions like N_R and mN-R cannot handle it as zero stiffness (tangent horizontal at top) is incompatible with constraining equations. Hence, model becomes unstable.

   Recent advances have produced solvers (such as: Crisfield's, Riks'). They can handle certain problems but the validity of the method has not been reported for three-dimensional solid modelling of RC structures in general, or for strain softening in compression in particular and at present, it has not produced acceptable results.

8. Plasticity is path dependant, hence, load was applied slowly, in increments, with convergence tests in each substep simulating closely lab conditions, following ANSYS practical rules.



Load substep 1 was chosen such as to produce max stresses approx. equal to yield stress of concrete.

Incremental procedure depicted loading procedure in the labs, making sure that incremental plastic strains are of a lesser magnitude than the elastic one (favoured by ANSYS).

9. *Transfer of forces from concrete to steel should be carried out in such a way as to model slip parallel to rebars. No discrete bond slippage was modelled but, predicted interface stresses were restricted to calculated ones from classical RC theory, hence allowing for local bond failure.*

Initial material properties as input to the model

Concrete		Steel re-bars	
E_c	30 $kNmm^{-2}$	E_s	198 $kNmm^{-2}$
f_{cu}	45 Nmm^{-2}	f_y	-- Nmm^{-2}
f_t	2.42 Nmm^{-2}	0.2%proofstress	525 Nmm^{-2}
ν_{con}	0.15	ν_{steel}	0.3

to round up:….

Tables showing shear transfer coefficients and failure criteria for steel and concrete, as input to the model

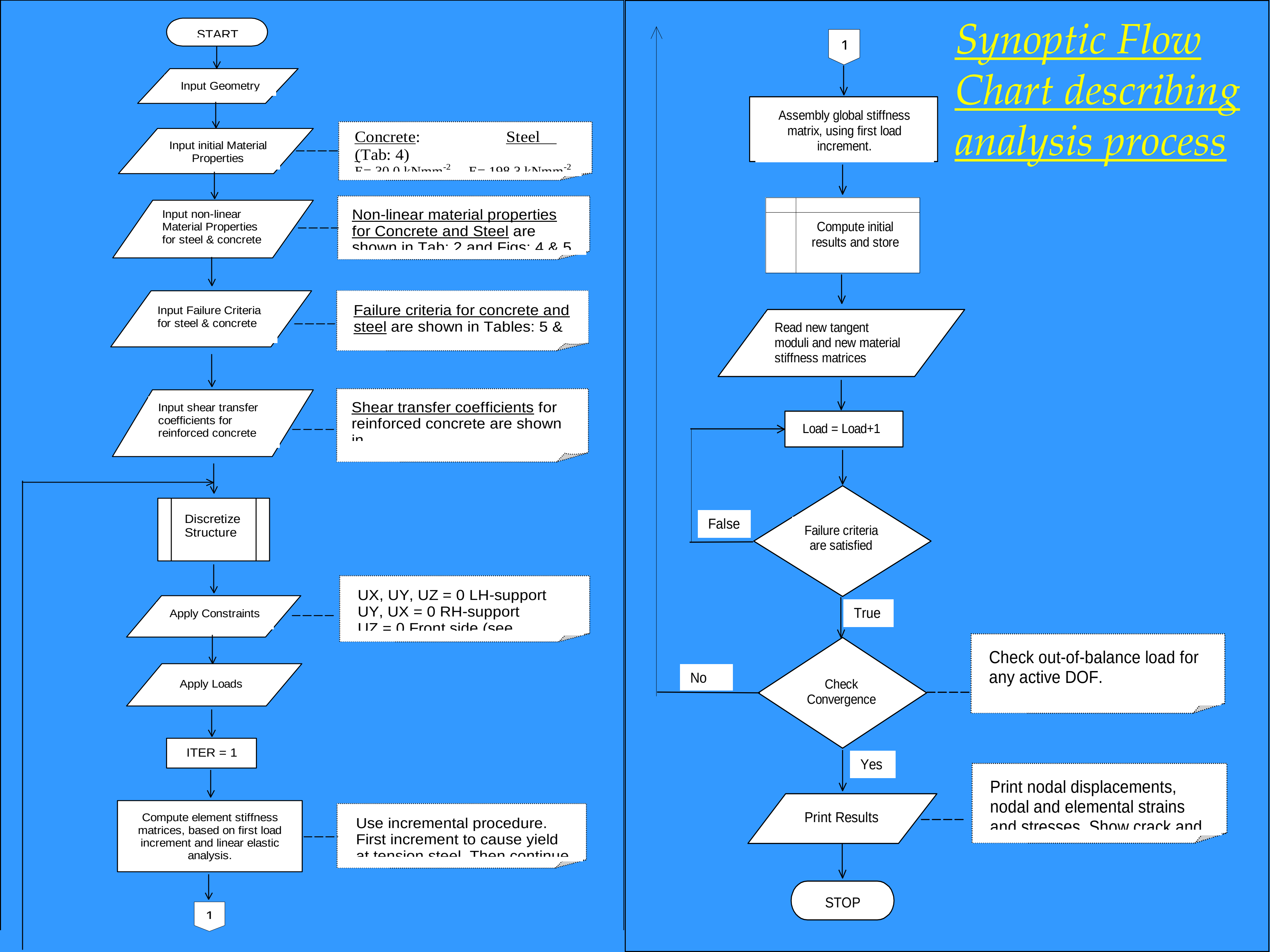
Shear Transfer Contribution as defined by Taylor (%)		For Closed Cracks (%)	For Open Cracks (%)	ANSYS Input. Closed Cracks. (Shear Transf Coef)	ANSYS Input. Open Cracks. (Shear Transf Coef)
Dowel action:	25	25	25	0.25*	0.25*
Aggregate interlock:	45	45	<45	0.40 + 0.25*	0
Compression zone:	30	30	30	0.3	n/a
				Total: 0.95	Total: 0.25

** Coefficient 0.25 (contribution of re-bars to shear transfer) is carried over.*

Stress failure criteria for Concrete								
σ_x (tens)	σ_x (comp)	σ_y (tens)	σ_y (comp)	σ_z (tens)	σ_z (comp)	σ_{xy}	σ_{yz}	σ_{zx}
2.42	-45	2.42	-45	2.42	-45	0.45	0.45	0.45
Strain failure criteria for Concrete								
ε_x (ten)	ε_x (comp)	ε_y (ten)	ε_y (comp)	ε_z (ten)	ε_z (comp)	ε_{xy}	ε_{yz}	ε_{zx}
0.0001	-0.00175	0.0001	-0.00175	0.0001	-0.00175			

Stress failure criteria for Steel (N/mm^2)								
σ_x (tens)	σ_x (comp)	σ_y (tens)	σ_y (comp)	σ_z (tens)	σ_z (comp)	σ_{xy}	σ_{yz}	σ_{zx}
660	-660	660	-660	660	-660			
Strain failure criteria for Steel								
ε_x (ten)	ε_x (comp)	ε_y (ten)	ε_y (comp)	ε_z (ten)	ε_z (comp)	ε_{xy}	ε_{yz}	ε_{zx}
0. 09	-0.09	0. 09	-0.09	0.09	-0.09			

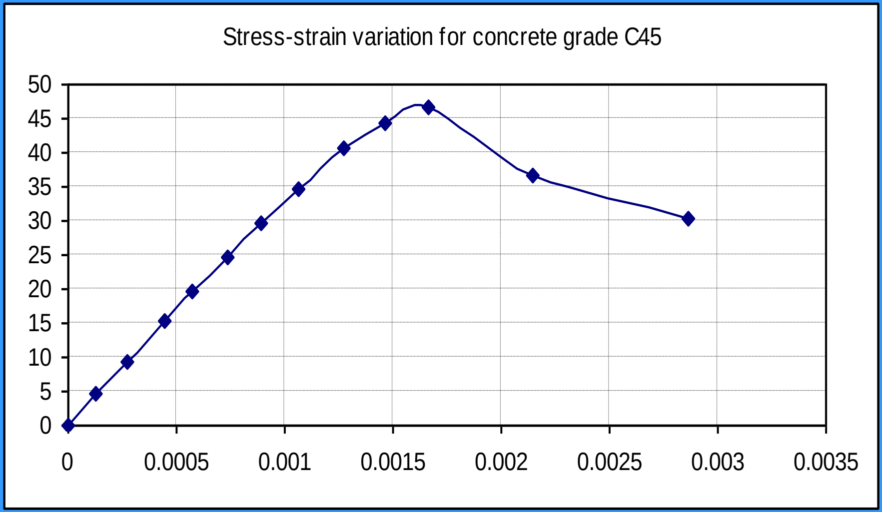
Synoptic Flow Chart describing analysis process



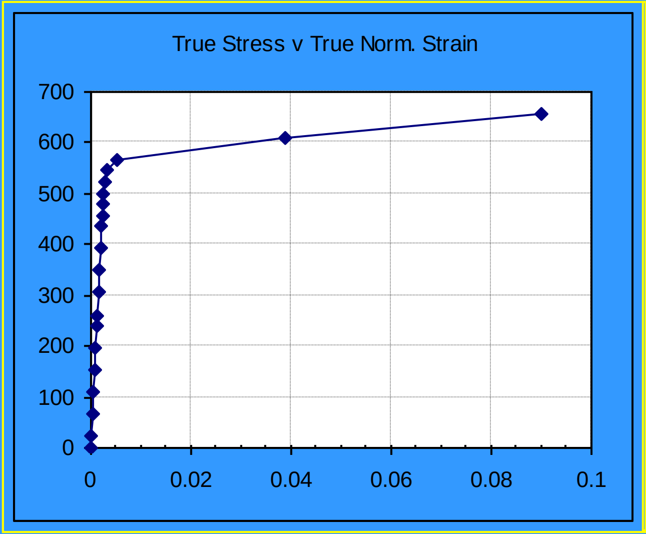
Calibration of the computer model using experimental results

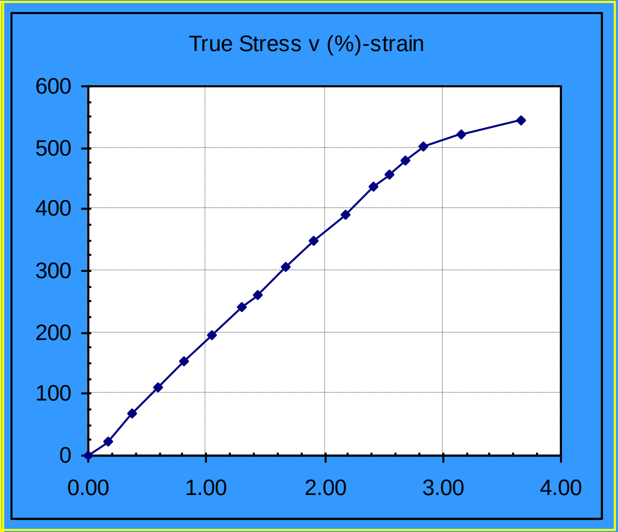
Stress-strain behaviour of concrete cylinders in compression and determination of Static Modulus of Elasticity.

($E= 30.04\ kN/mm^2$)



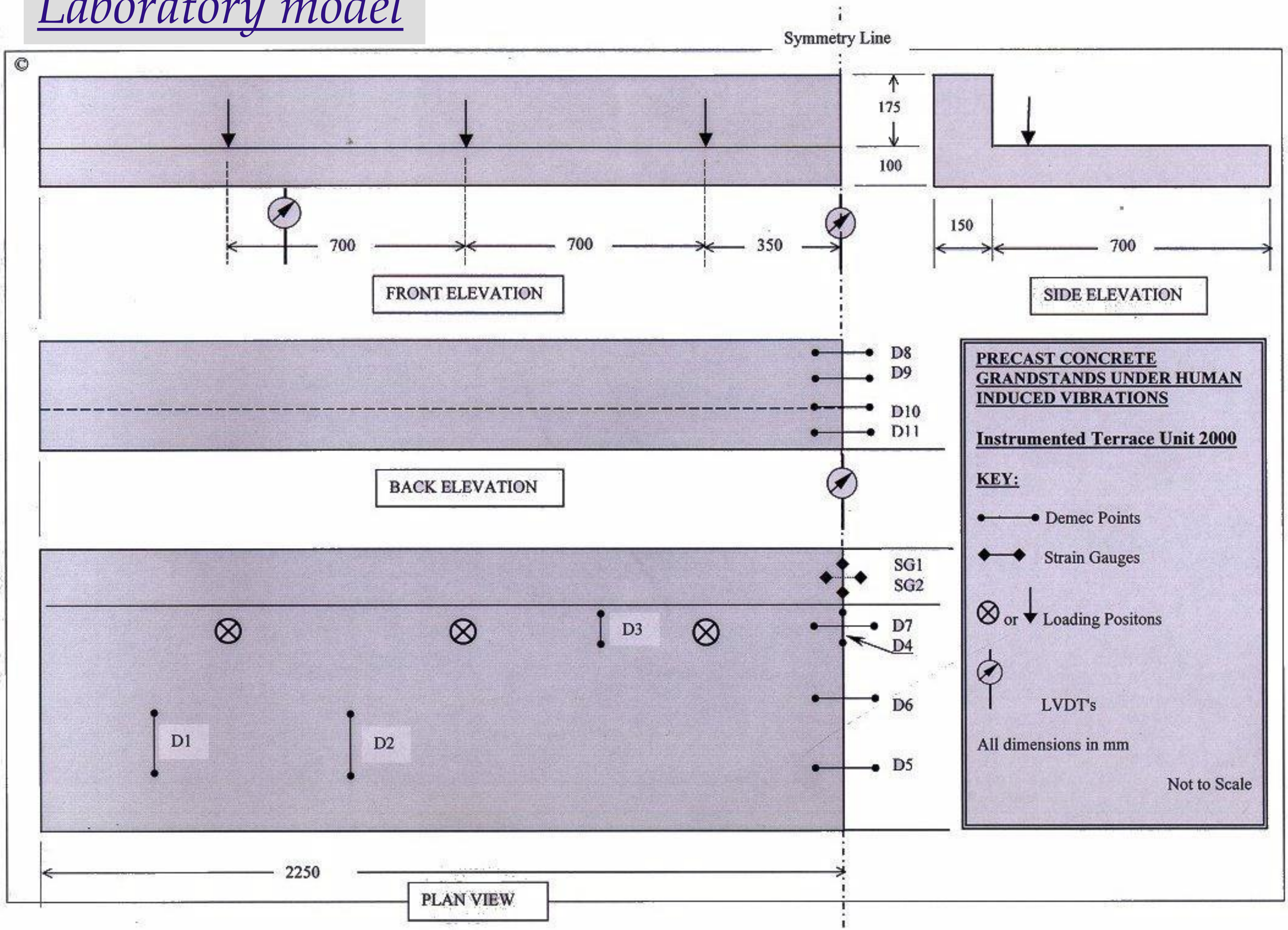
E_{Hughes}	E_{static}	$E_{ultrasonic}$	E_{BS8110}	$E_{FEA\ (agreed)}$
32.367	30.04	28.80	33.5	30.00



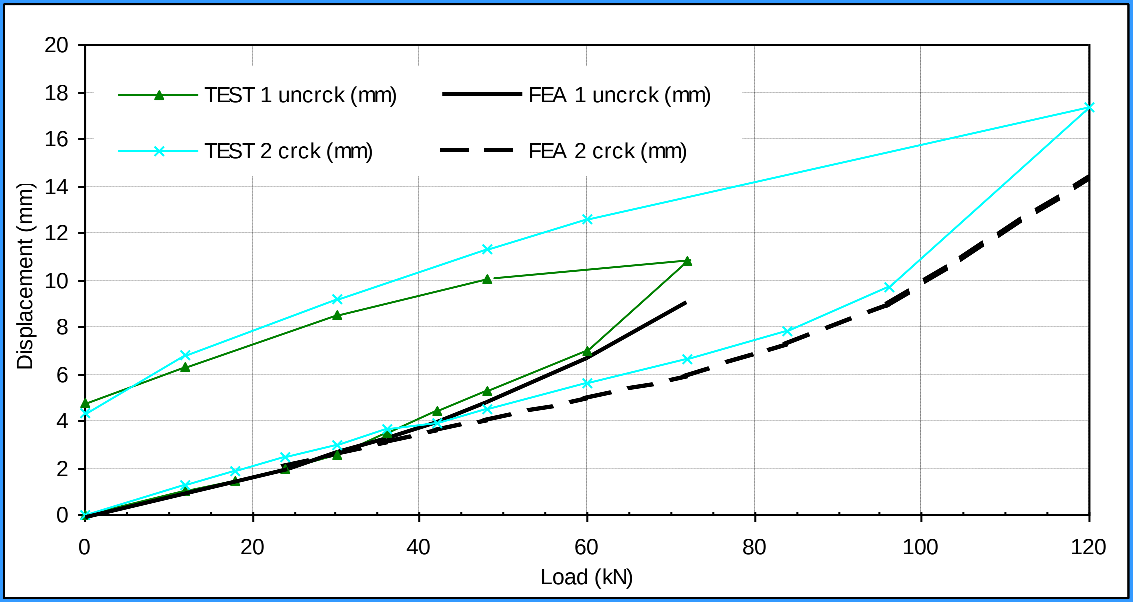


Stress-strain behaviour of Type 2 steel reinforcement and determination of Modulus of Elasticity and Tangent Modulus

Laboratory model



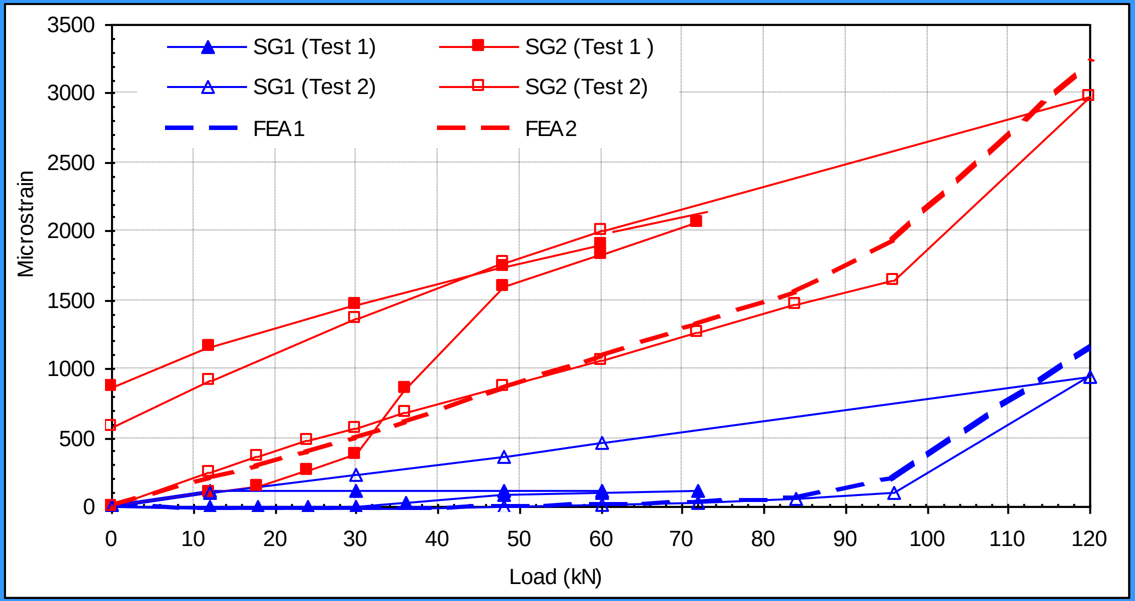
Comparison between measured and predicted maximum displ's



Cracking started at 30 kN. Fully cracked unit has suffered permanent deformation, hence its displacement during the loading process is lower than that of the uncracked unit. This is also depicted by the finite element models.

	Test 1 (uncracked unit)	Test 2 (cracked unit)
Measured (W, δ) : (kN, mm)	(72, 10.7)	(120, 17.2)
Predicted (W, δ) : (kN, mm)	(73, 9.08).	(126, 14.80)

Comparison between measured and predicted strains at the main reinforcement.



SG1 = lateral reinf't

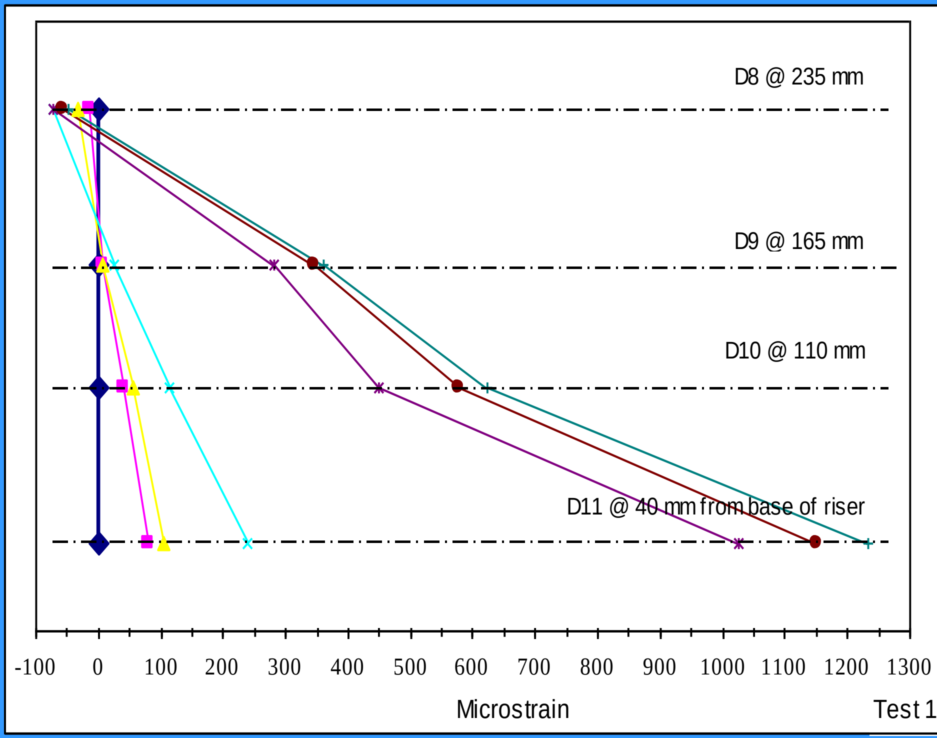
SG2 = longitudinal reinf't

All strain values were below the ultimate value of 3330 μs.

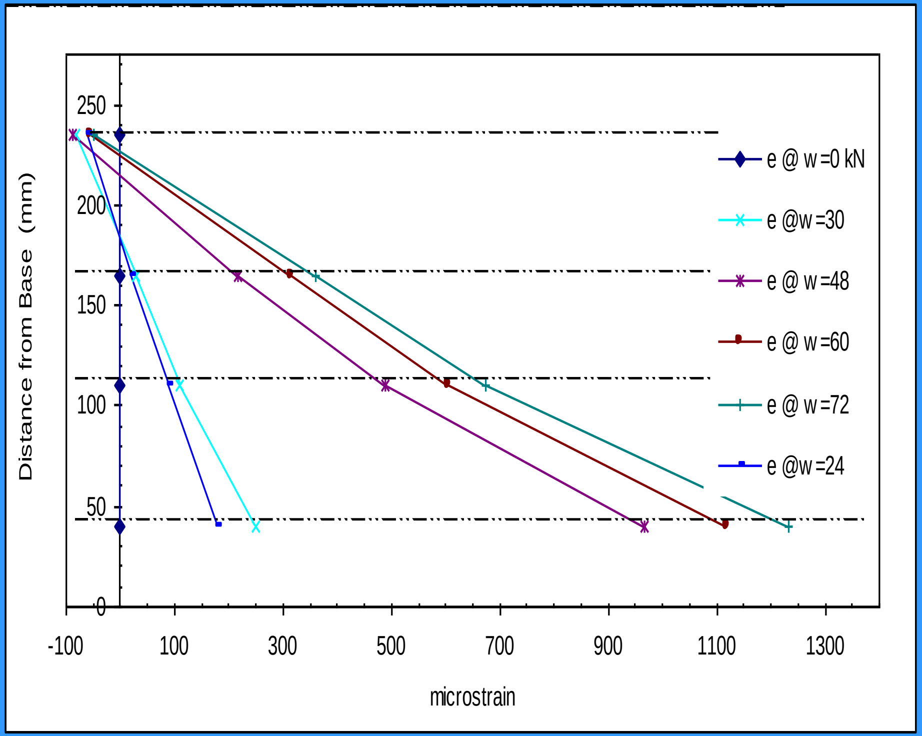
Lateral reinforcement		Longitudinal reinforcement	
Test No:	(kN, μs)	Test No:	(kN, μs)
1	(72, 114)	1	(72, 2058)
2	(120, 940)	2	(120, 2974)
FEA1	(126, 1167)	FEA2	(126, 3238)

No significant residual strains were noticed for SG1, indicating that any cracks formed across transverse reinforcement must have closed.

Strain distribution across the Riser. Test 1, Uncracked unit.



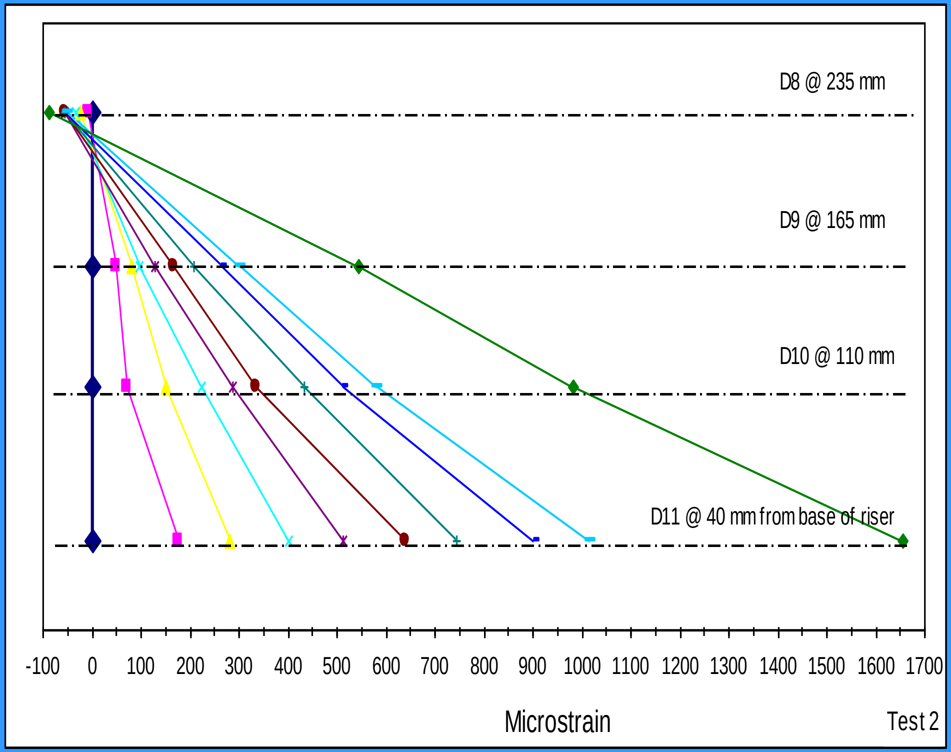
Experimental behaviour

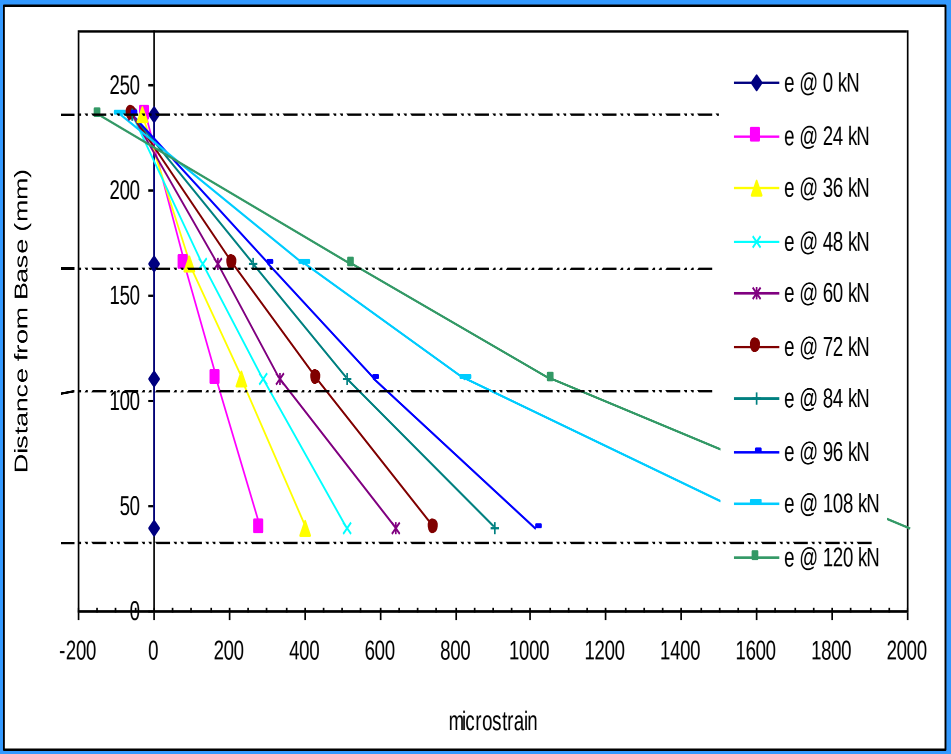


Theoretical behaviour

Notice linear behaviour up to 30 kN. Applied loads resisted by both, concrete and reinforcement. Tension gradually transferred to reinforcement as first cracks appear at bottom. Equilibrium is maintained by gradual movement of the N_A upwards, that is, by reducing the area in compression.

Strain distribution across the Riser. Test 2, Cracked unit



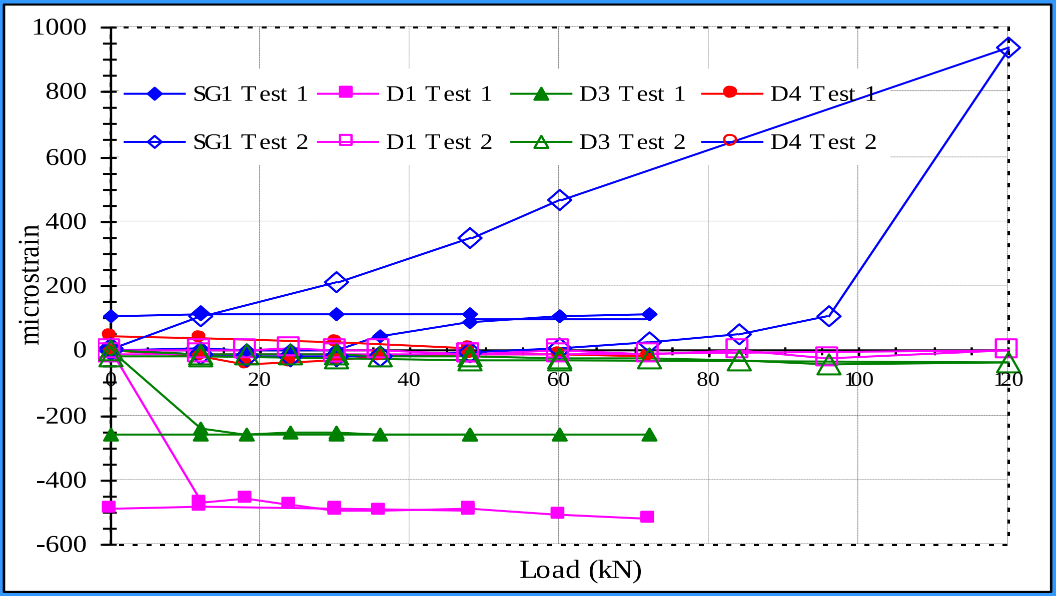


Experimental behaviour

Theoretical behaviour

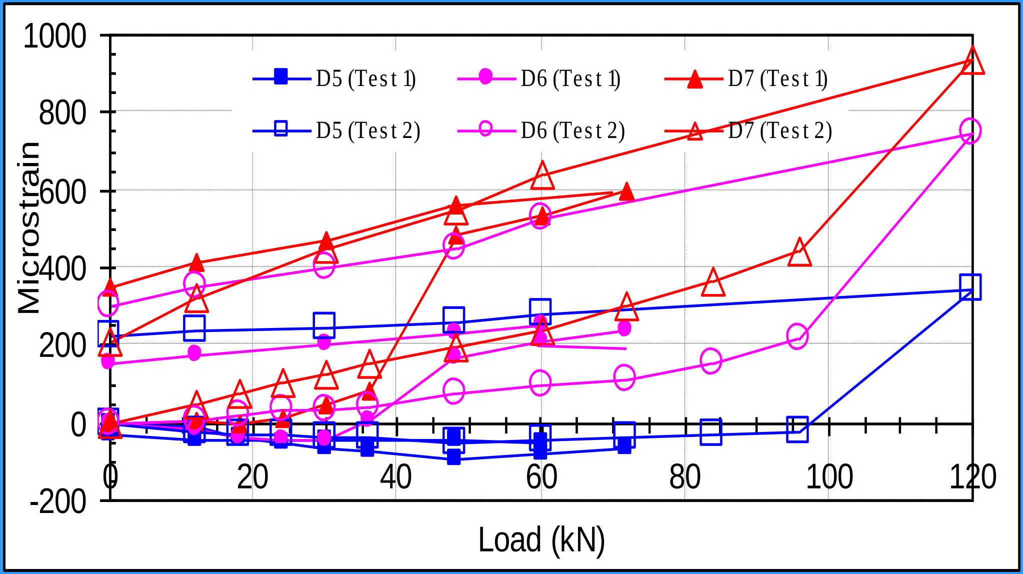
Once cracks are developed, no sudden changes of strain are present during reloading and the strain path is smoother. Strain readings reach higher values as cracks open wider causing the reinforcement to undergo yielding.

Strain at some other positions

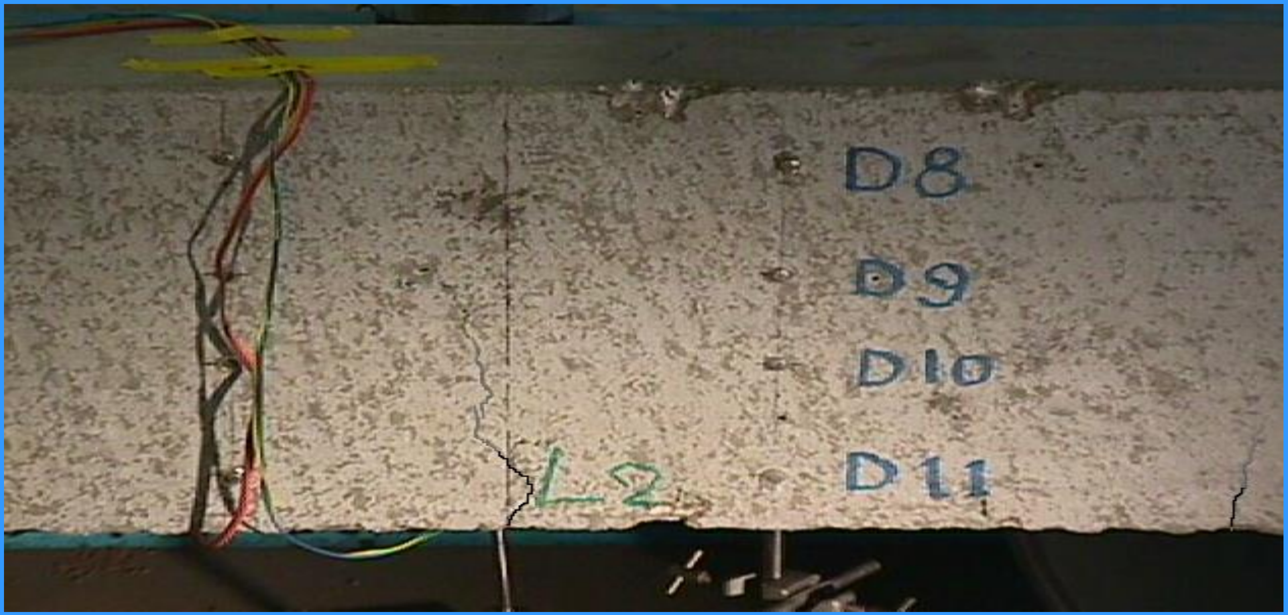


Terrace unit 1. Tests 1 & 2. Comparison between strains @ SG1, D1, D3, D4 (on tread).

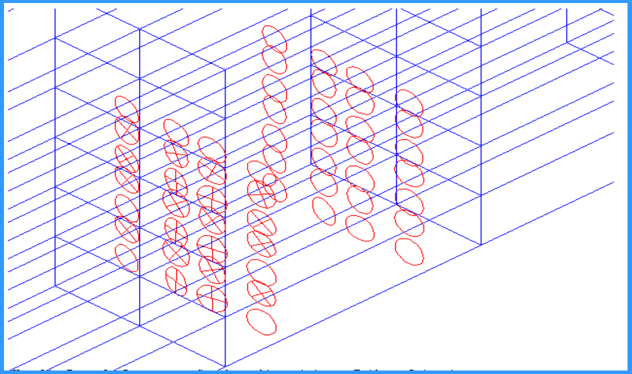
Terrace unit 1. Tests 1 & 2. Comparison between strains @ D5, D6, D7 (on tread).

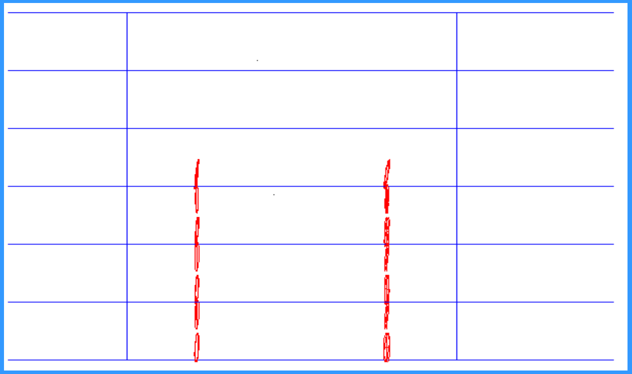


Cracking of concrete at the tension zone.



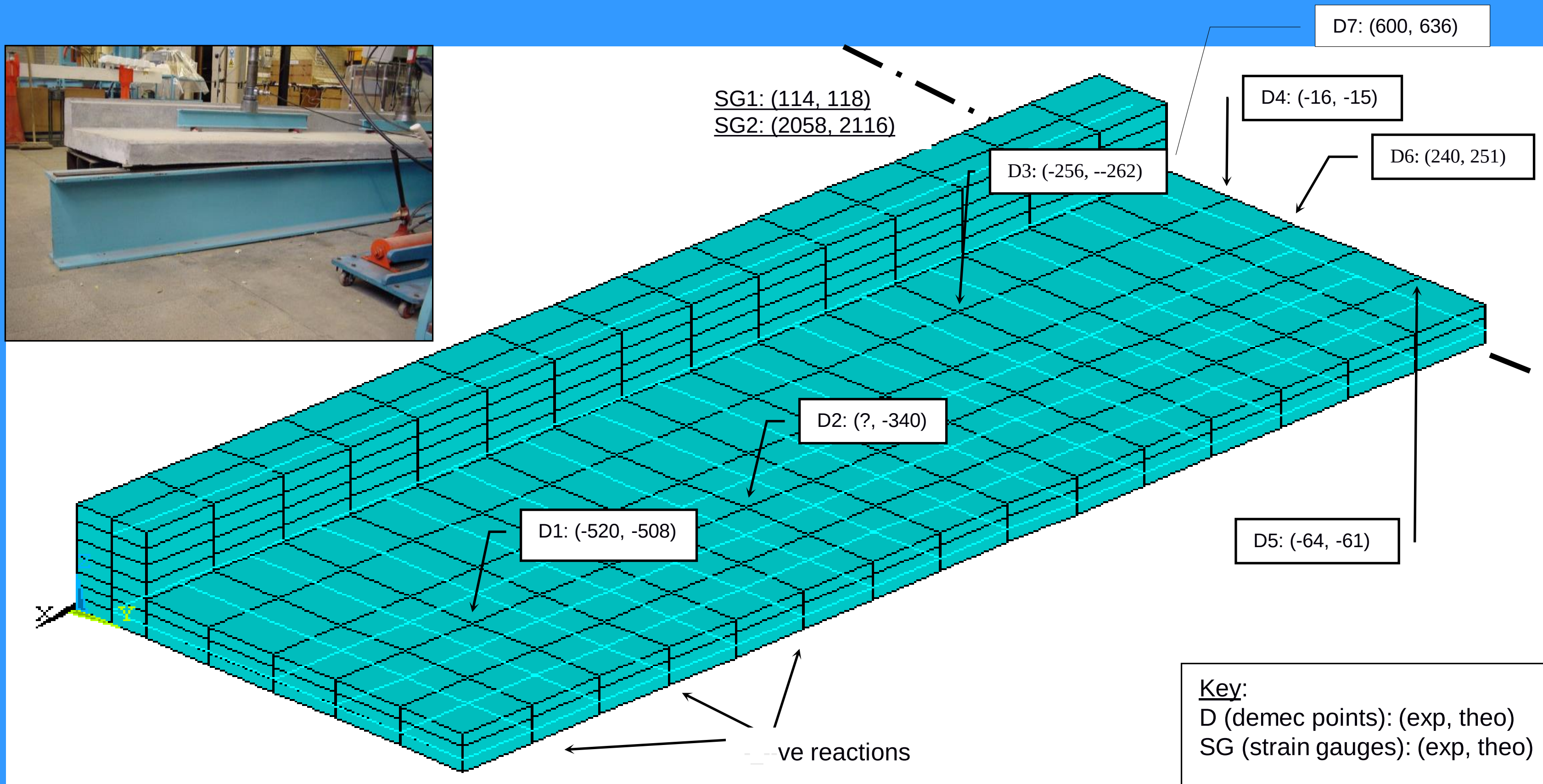
Front view detail of riser at midspan, showing cracks detected in the laboratory.





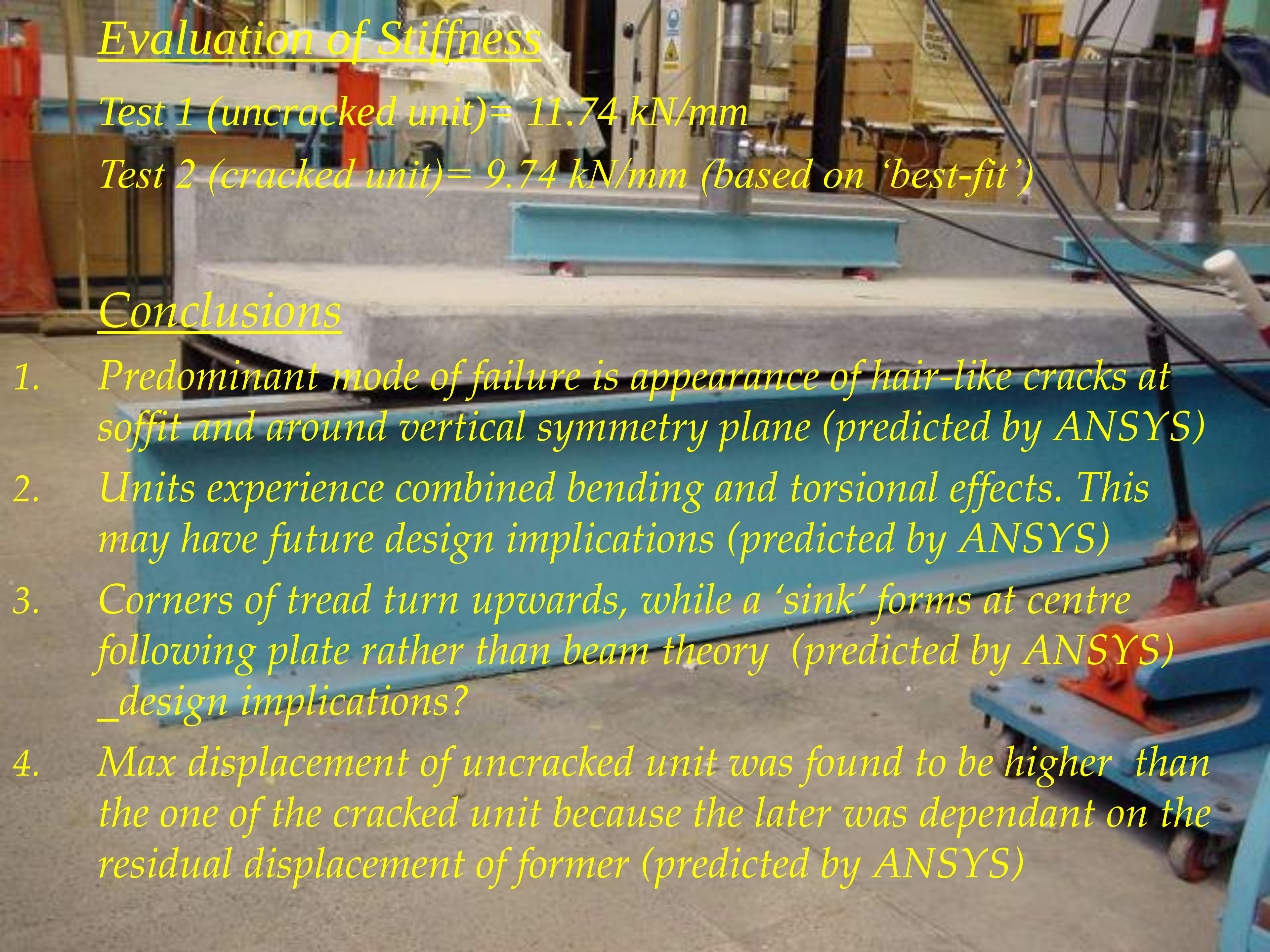
Isometric and front elevation (translucent view) details of the riser at midspan, showing predicted cracks by ANSYS

Comparison between experimental and theoretical strains



Total Load = *72 kN.*

D1, D2, D3, D4 are strains in the lateral, Y-direction and D5, D6, D7 are strains in the longitudinal, X-direction. SG1 and SG2, are lateral and longitudinal strains on the reinforcement. Negative reactions predicted by the FE model are also shown in the inset, as lifting at the corners.



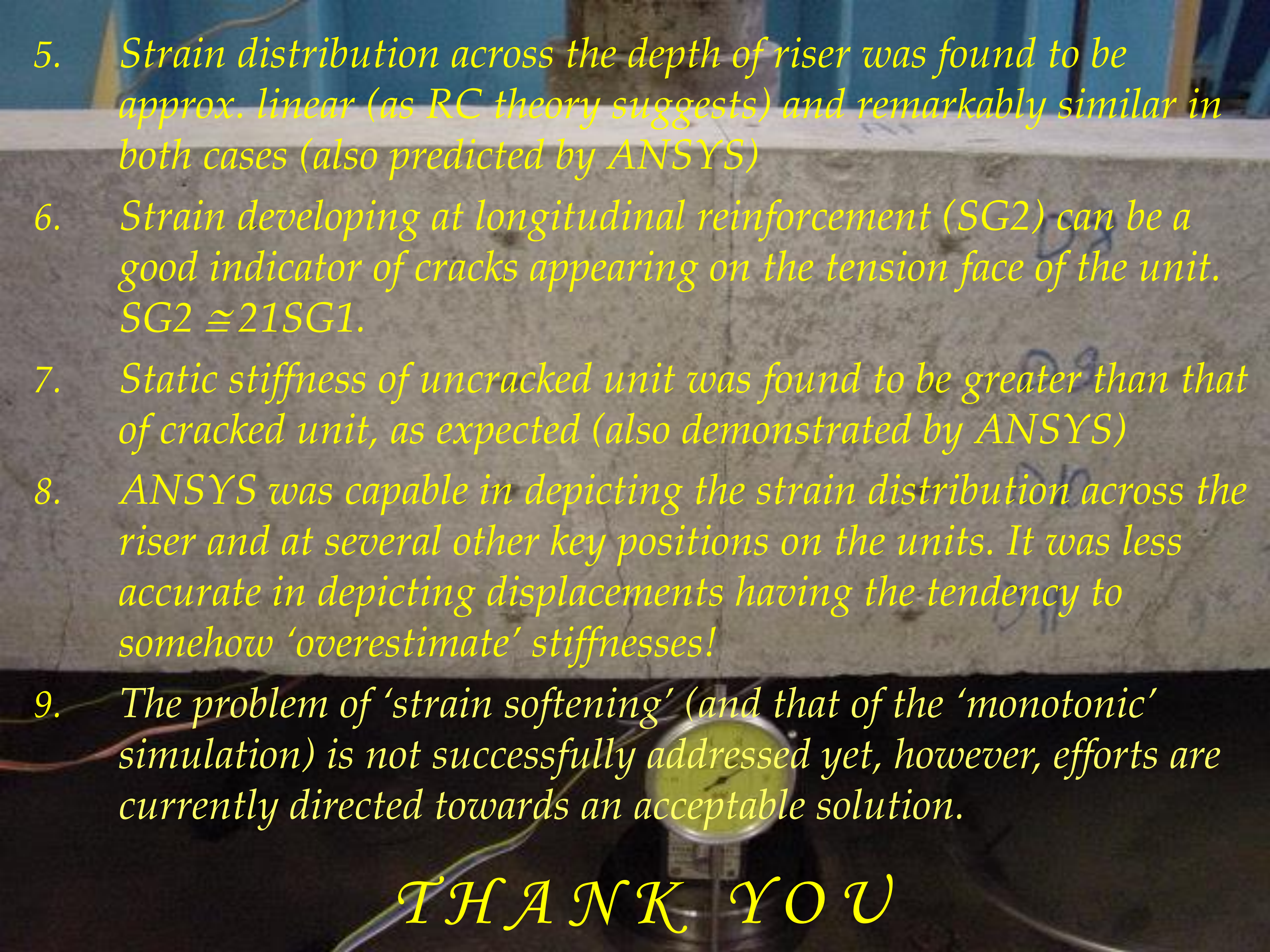
Evaluation of Stiffness

Test 1 (uncracked unit)= 11.74 kN/mm

Test 2 (cracked unit)= 9.74 kN/mm (based on 'best-fit')

Conclusions

1. *Predominant mode of failure is appearance of hair-like cracks at soffit and around vertical symmetry plane (predicted by ANSYS)*
2. *Units experience combined bending and torsional effects. This may have future design implications (predicted by ANSYS)*
3. *Corners of tread turn upwards, while a 'sink' forms at centre following plate rather than beam theory (predicted by ANSYS) _design implications?*
4. *Max displacement of uncracked unit was found to be higher than the one of the cracked unit because the later was dependant on the residual displacement of former (predicted by ANSYS)*



5. *Strain distribution across the depth of riser was found to be approx. linear (as RC theory suggests) and remarkably similar in both cases (also predicted by ANSYS)*
6. *Strain developing at longitudinal reinforcement (SG2) can be a good indicator of cracks appearing on the tension face of the unit. $SG2 \cong 21SG1$.*
7. *Static stiffness of uncracked unit was found to be greater than that of cracked unit, as expected (also demonstrated by ANSYS)*
8. *ANSYS was capable in depicting the strain distribution across the riser and at several other key positions on the units. It was less accurate in depicting displacements having the tendency to somehow 'overestimate' stiffnesses!*
9. *The problem of 'strain softening' (and that of the 'monotonic' simulation) is not successfully addressed yet, however, efforts are currently directed towards an acceptable solution.*

THANK YOU