Emerging Technologies for Safer Use of FRP in Reinforced Concrete Structures

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Major Developments in Structural Engineering Usually Accompany the Development of New Materials or Advances in Materials Science

Progress in material science advances structural engineering in two ways:

1. Make an existing wild fancy possible/feasible

2. Lead to development of new science/technology

Make an existing wild fancy possible/feasible

Two examples:

1. Development of presstressed concrete design concept (预应力混凝土结构）

2. The concept of space elevator （太空电梯）

Development of presstressed concrete design concept

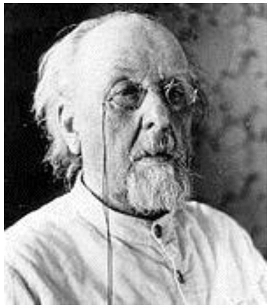
Facts:

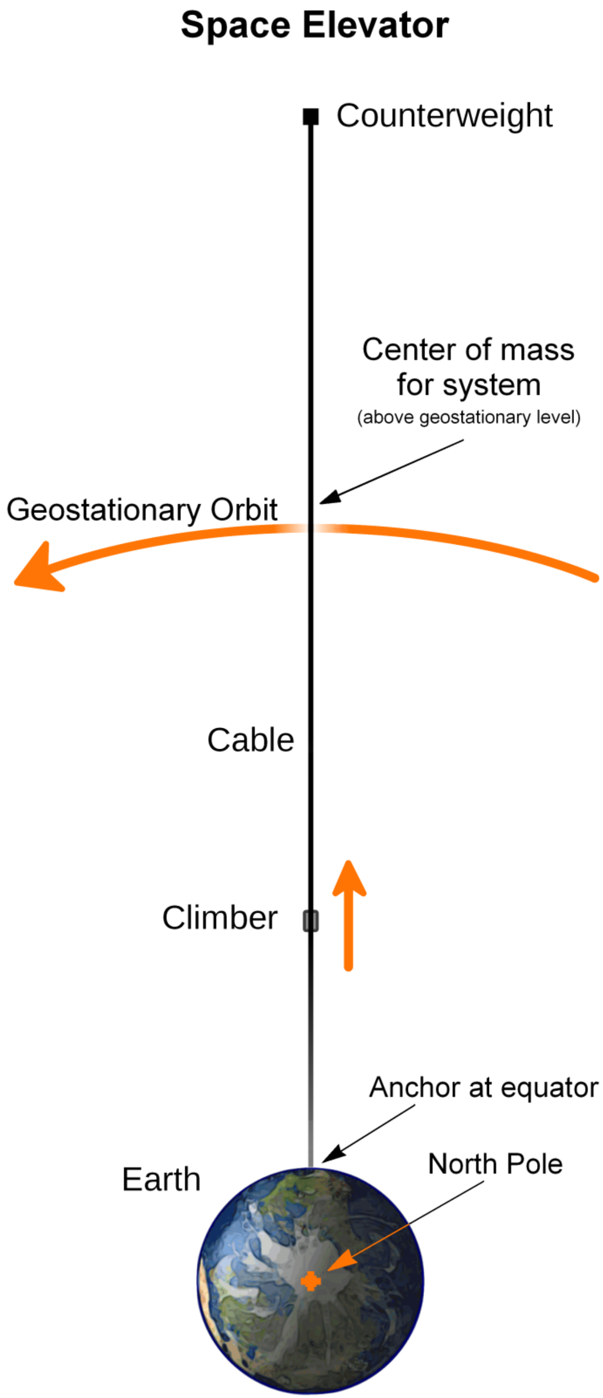
1. "The most significant single new concept in the history of structural engineering"
2. Invented by French engineer Eugene Freyssinet at the turn of 20^{th} century.
3. "The world is waking up to his revolution in the art of building" half a century later.
4. Advances in material science (high strength concrete and steel) make it more practical/feasible.

Space elevator

The concept:

1. key concept proposed in 1895 by Russian scientist Konstantin Tsiolkovsky
2. In 1959 another Russian scientist, Yuri N. Artsutanov, suggested a more feasible proposal: <u>centrifugal force balances gravity load</u>.
3. No existing material sufficiently strong and light.
4. Carbon nanotube (炭纳米管) appears strong enough to make it possible in the future.



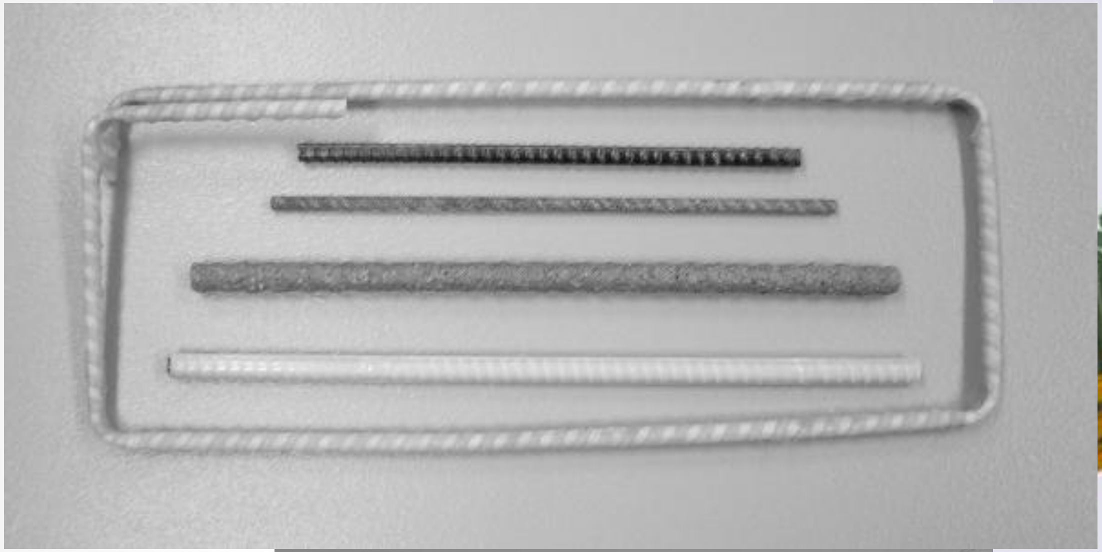


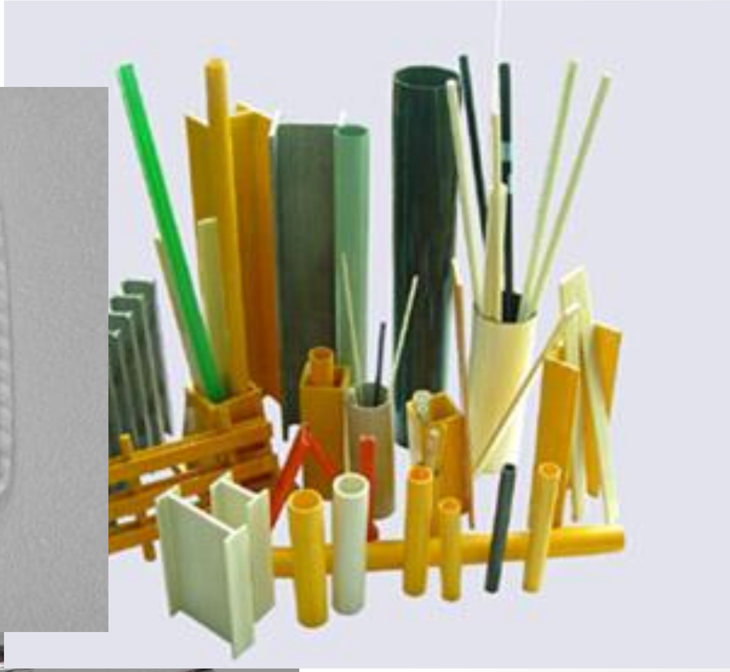
Development of new science/technology

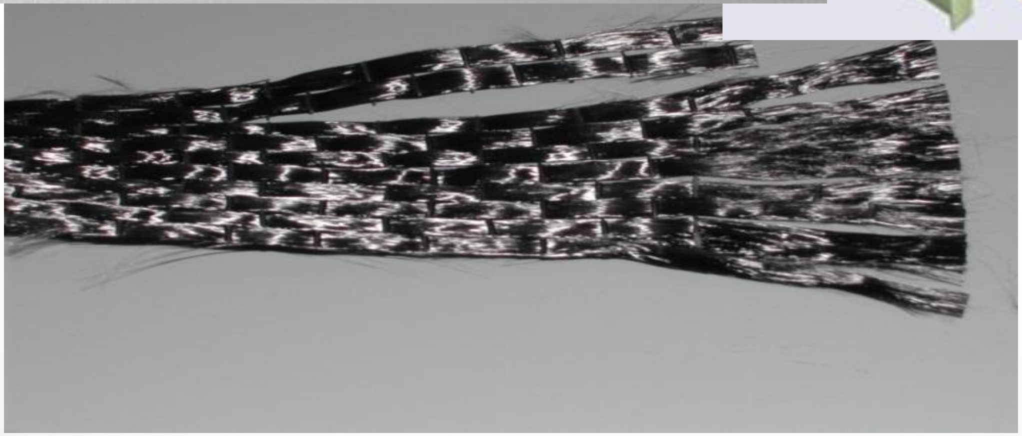
- The introduction of steel and cement at the turn of the 18th and 19th centuries, respectively, formed a solid foundation for modern structural engineering.
- The era of extensive research into steel and normal concrete is ending, because these materials are reaching the limits of their potential.
- A new era of the application of advanced construction materials, such as fiber reinforced polymers (FRPs) and high-performance concrete (HPC), has dawned.

Fiber Reinforced Polymer (FRP) - A new construction material

Advantages: light, strong, durable







Fiber reinforced polymer (FRP) has been in use since the 1940s. At first, composites made with these higher performing fibers were too expensive to make much impact beyond niche applications in the aerospace and defense industries.

FRP has won the attention of civil/structural engineers from 1980s.

As the cost of FRP materials decreases and the need for aggressive infrastructure renewal becomes increasingly evident, FRP materials are now finding wider acceptance in the conservative infrastructure construction industry.

In the construction industry, FRP materials can be used for

(1) rehabilitation (repairing/strengthen-ing/retrofitting) of existing structures, and

(2) construction of new structures, replacing steel reinforcing bars.

There are still serious problems to be resolved for both applications.

This seminar introduces two new efforts in tackling with two major problems in FRP applications:

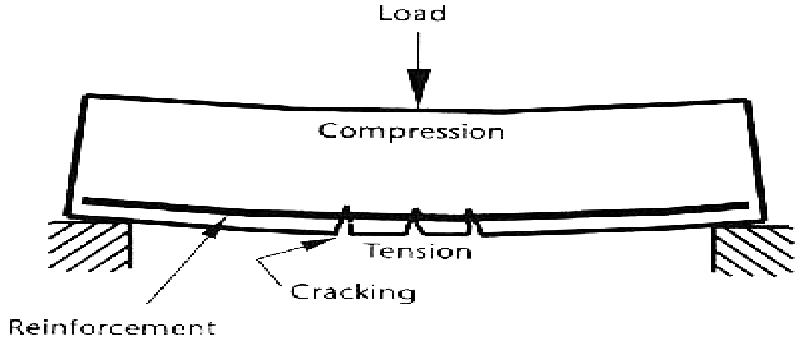
one for structural rehabilitation, and

another for construction of new structures.

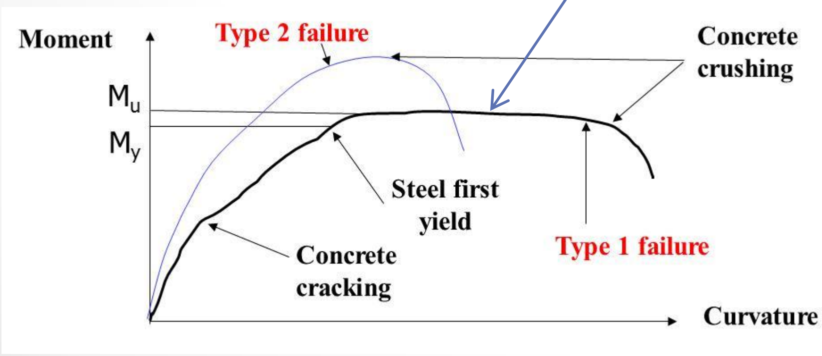
Part I: Improving the Ductility of RC Members through Compression Yielding

Concrete is a brittle material with little ductility

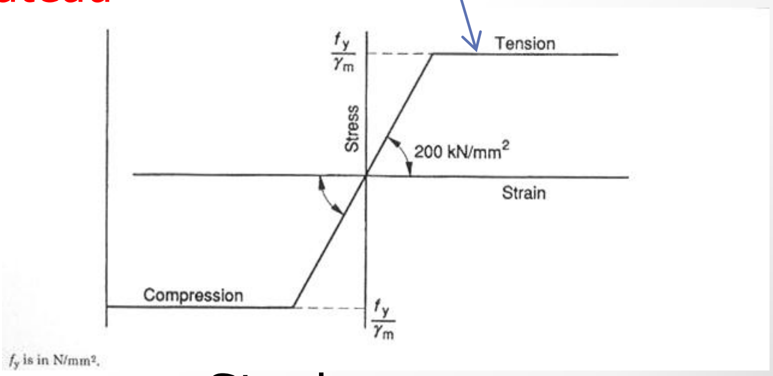
Reinforced concrete members achieve ductility and adequate deformation capacity mainly through the tensile straining or yielding of the reinforcement.



Yield Plateau



Beam response



Steel response

The ductility of RC member is limited *when the tensile straining of the reinforcement is limited*

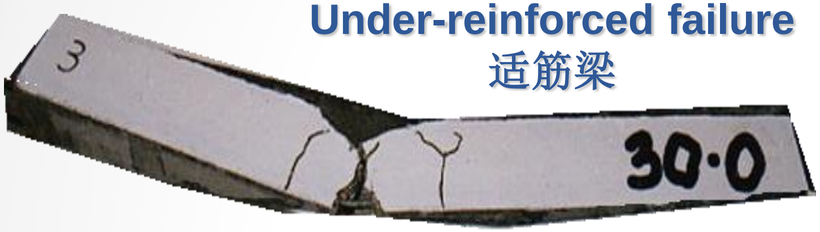
For example in the cases of

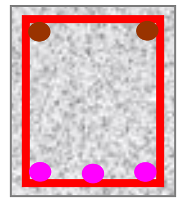
- Over-reinforced RC beams
- RC columns with large axial loads

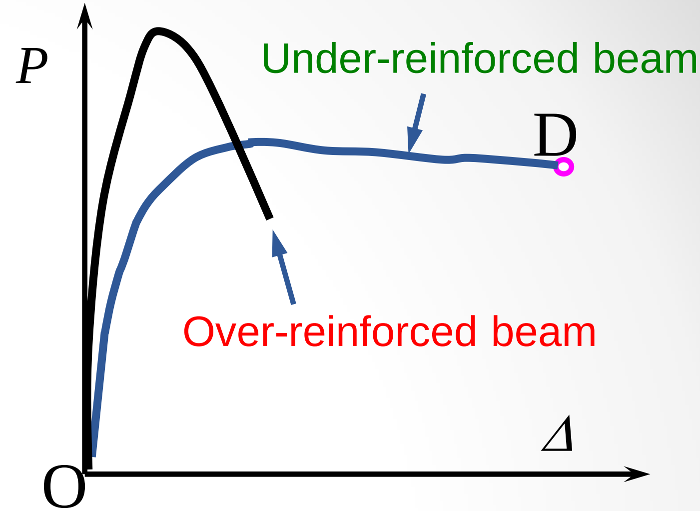
whereby the tensile reinforcement does not yield and the member fails due to concrete crushing

Failure modes

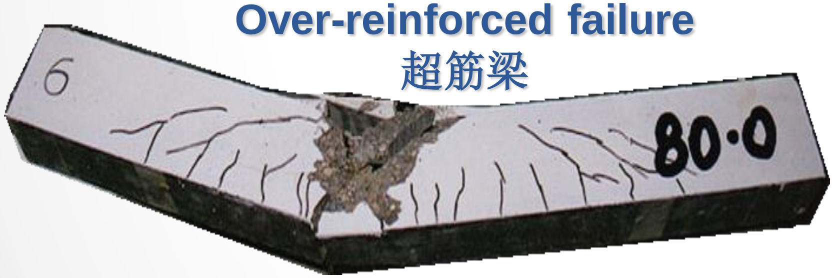
Under-reinforced failure
适筋梁

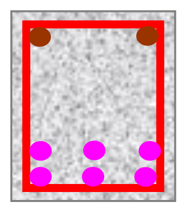


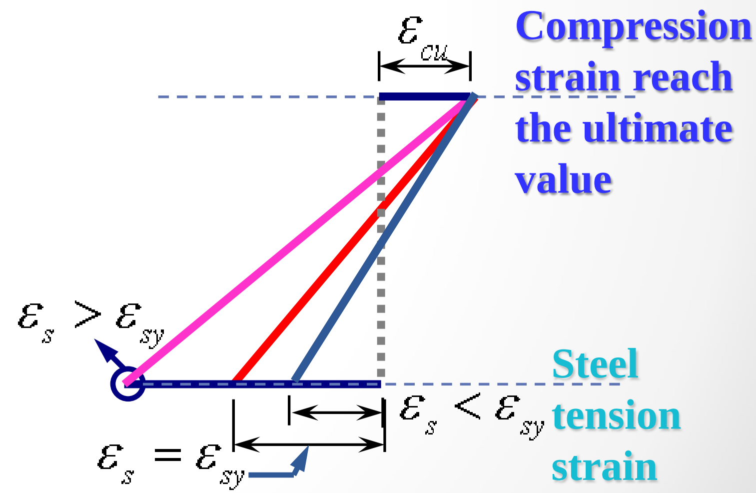




Over-reinforced failure
超筋梁





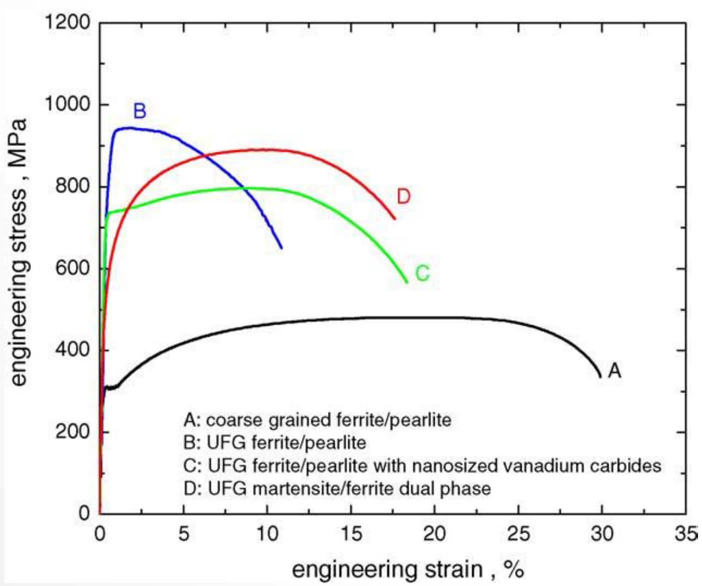


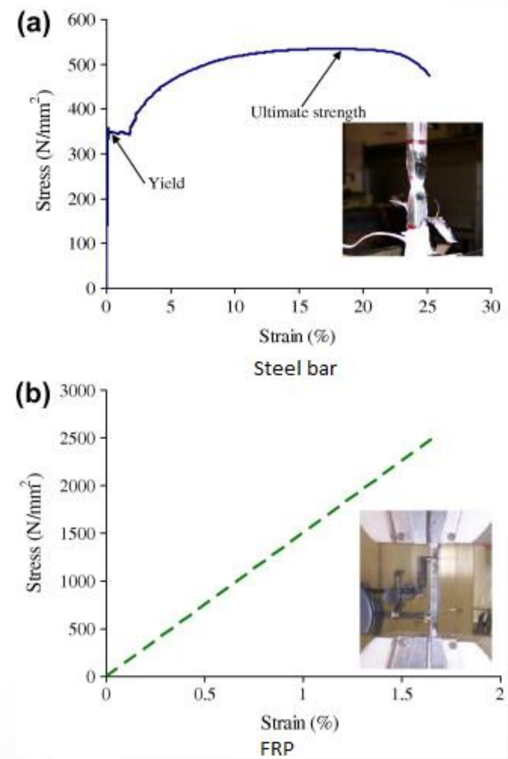
Strain profile

Similarly in the cases of

- application of high-strength bars
- application of fiber-reinforced polymer (FRP) reinforcement

whereby the tensile reinforcement does not have sufficient yield deformation before fracture





Ductility of structures is important

- **To give sufficient warning before structural failure to save lives**
- **The basis of modern structural design approaches, e.g. moment redistribution**
- **Essential and vital in seismic structures**

"*Unless ductility requirements are satisfied, FRP materials cannot be used reliably in structural engineering applications*"

A.E. Naaman (2003)

Existing approaches to improve the ductility of FRP reinforced concrete members (Naaman 2003)

1. Providing confinement to concrete.

   This method cannot avoid FRP rupture for under-reinforced beams. For over-reinforced beams, heavy and excessive confinement reinforcement is usually needed to achieve the ductility requirement.

2. Placing prestressed reinforcement in layers

   Design the effective prestress in each layer to provide a step-by-step progressive failure with increasing deformation.

3. Using partially prestressed concrete

   Where prestressed FRP tendons are combined with conventional steel reinforcement to allow sufficient flexibility to achieve better ductility.

4. Using unbonded tendons

More deformation can be achieved on the tension side as the deformation of the tendons over the whole unbonded length can be utilized. It implies the use of perfect anchorages that can sustain fatigue loading. Moreover, external tendons can be very vulnerable to vandalism.

5. Making use of debonding mechanism

Designing the interface between the FRP reinforcement and the concrete so that a bond failure is triggered when the stress in the tendons reaches a threshold level, thus changing a bonded tendon configuration to an unbonded tendon configuration.

6. Making use of full cross-sectional deformation capacity

Designing the cross-section of a member to proportionate the reinforcement in order to take advantage of the full strain capacity of concrete simultaneously with that of the reinforcement.

Significant efforts have been made worldwide in this research area.

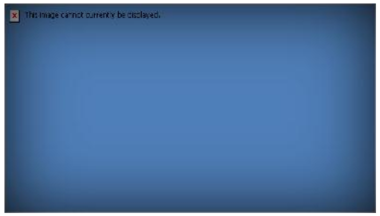
However, they are still considered to be either too complicated, coming at a significant increase in the design and construction costs, or not very effective, with limited increase in the ductility.

A general and satisfactory solution is yet to be found.

Logic thinking leading to scientific inventions

One example:

- How Prestressed Concrete is invented?

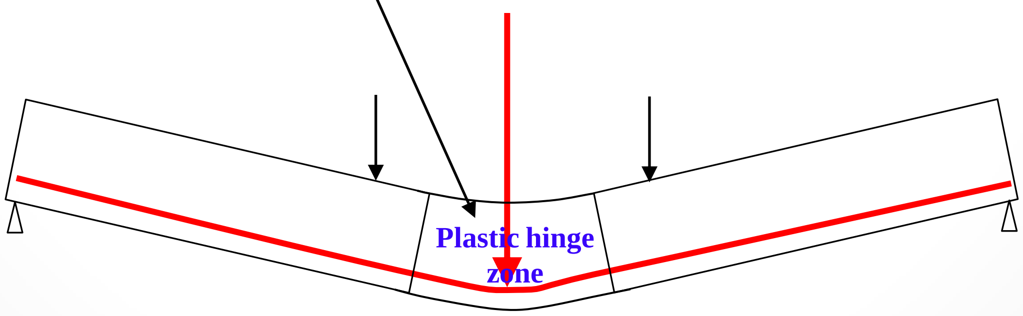


Key of the ductility problem

→ Ductility comes from plastic deformation

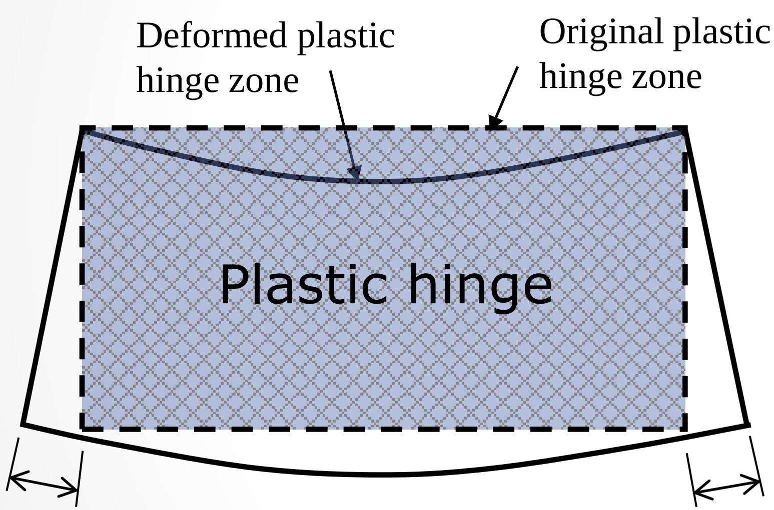
→ Plastic deformation concentrates in the plastic hinge zone

→ Plastic hinge zone does not have sufficient tensile deformation capacity

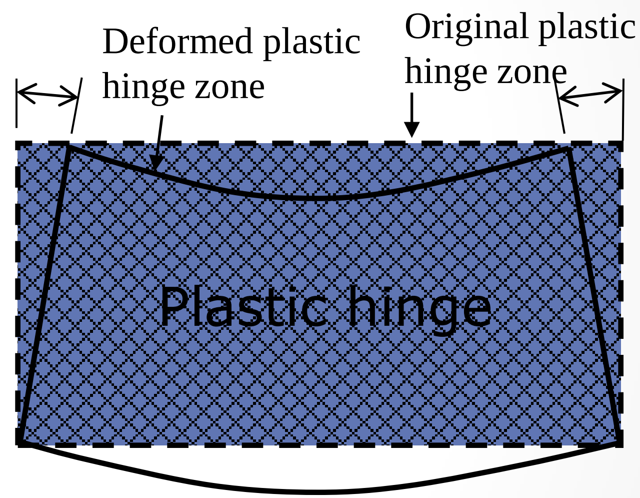


The Only Two Avenues of Achieving Flexural Deformation in Plastic Hinge

Flexural deformation through <u>tensile straining</u>



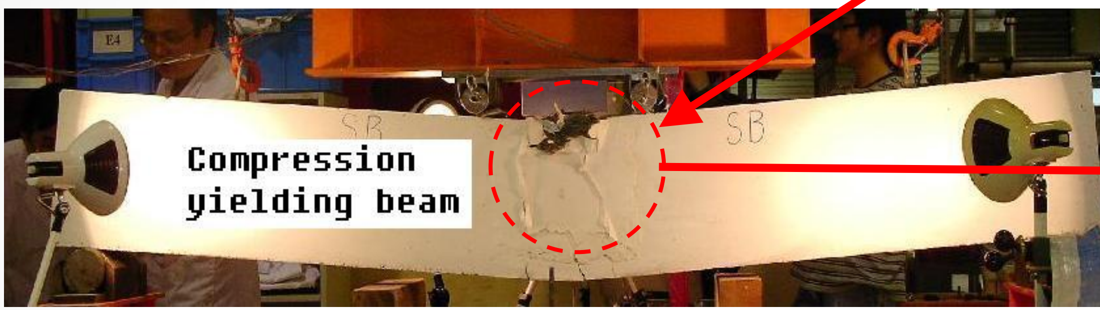
Flexural deformation through <u>compression straining</u>



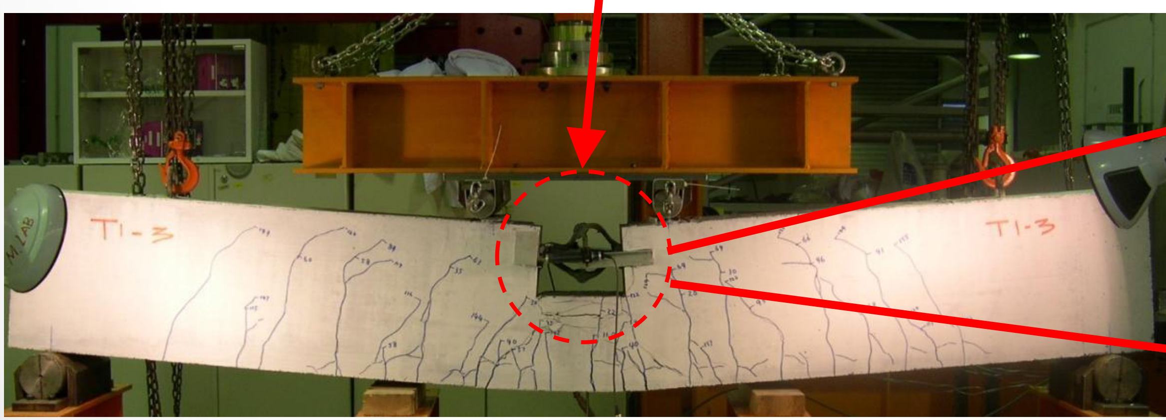
Conclusion: *the only other avenue is by* ***<u>Compression Yielding</u>***

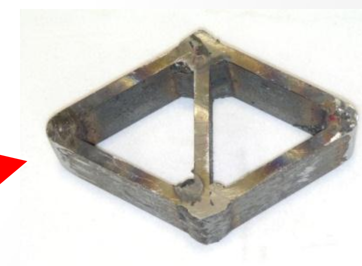
Two approaches to achieving compression yielding in a plastic hinge

1) Replacing the concrete with a ductile material

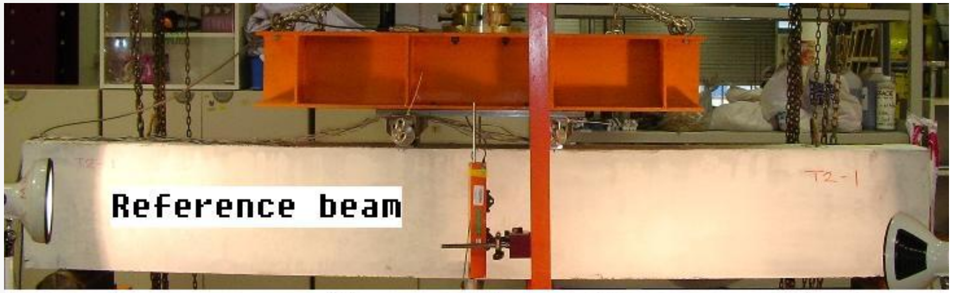


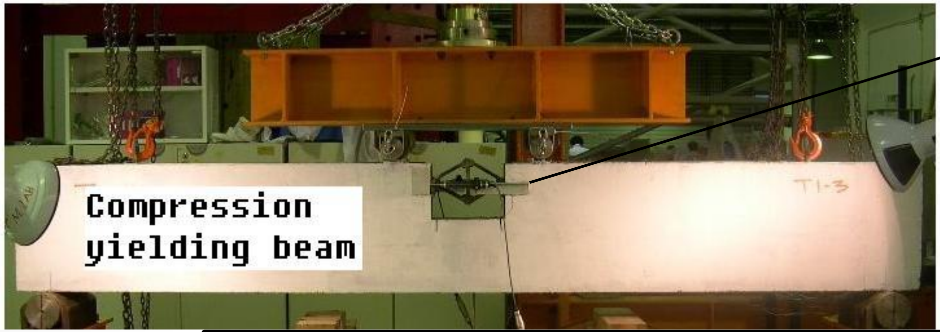
2) Using a ductile mechanism

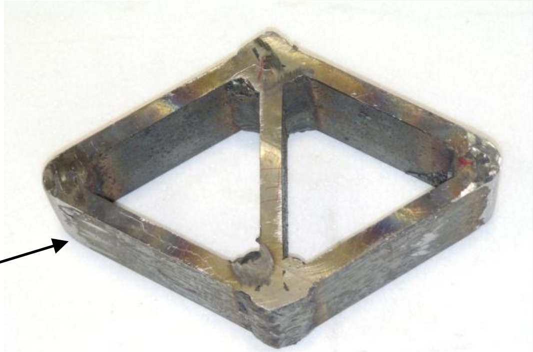




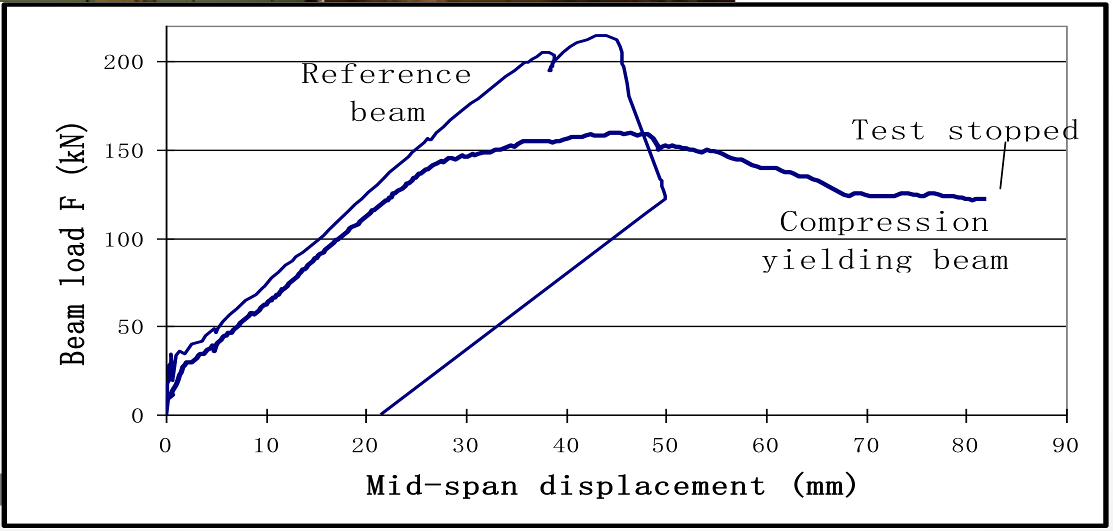
Test result with a diamond steel mechanism



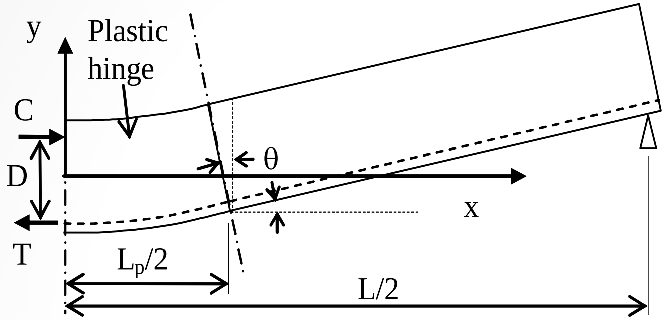


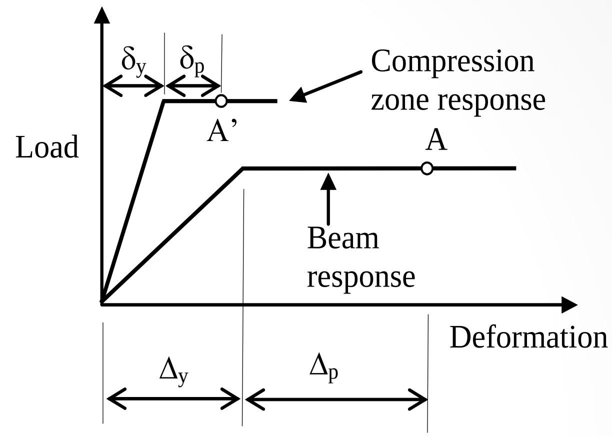


Steel mechanism



Relationship between the ductility demand of the beam and that of the hinge





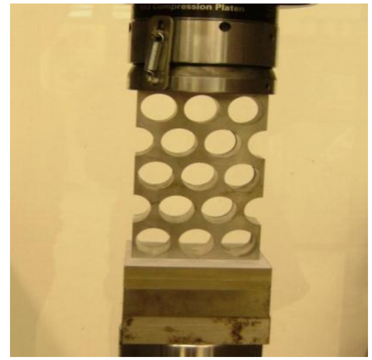
There is a direct relation between the ductility of the compression zone, μ_c, and the ductility factor μ_b of the member.

μ_c is often one order of magnitude greater than μ_b

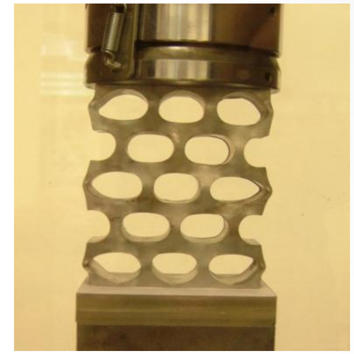
$$\mu_c = 1 + \frac{\Delta_y}{\delta_y} \cdot \frac{4D \cdot (\mu_b - 1)}{\left(L - \frac{L_p}{2} \right)}$$

where D is the distance between the resultants of the compression and tension, δ_y is the yield displacement of the compression zone, Δ_y is the yield displacement of the beam, L_p is the plastic hinge length, L is the span of the beam.

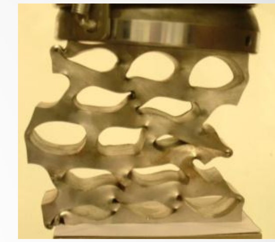
A perfectly elasto-plastic compression yielding mechanism - perforated steel block



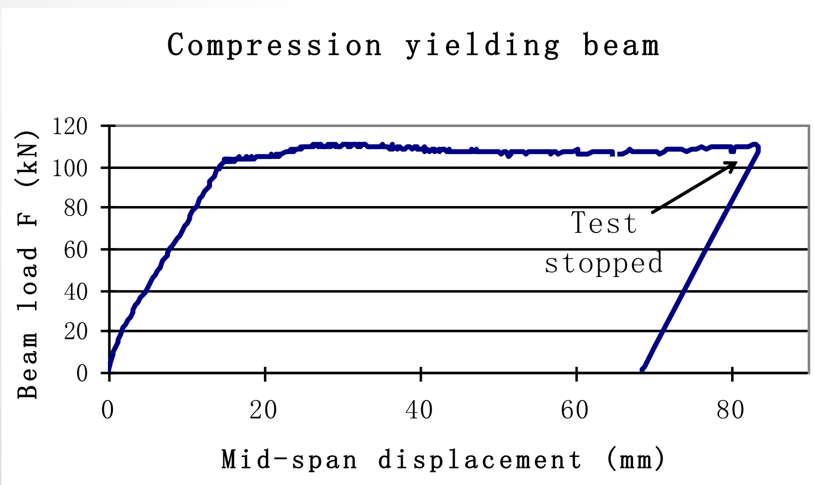
Point A



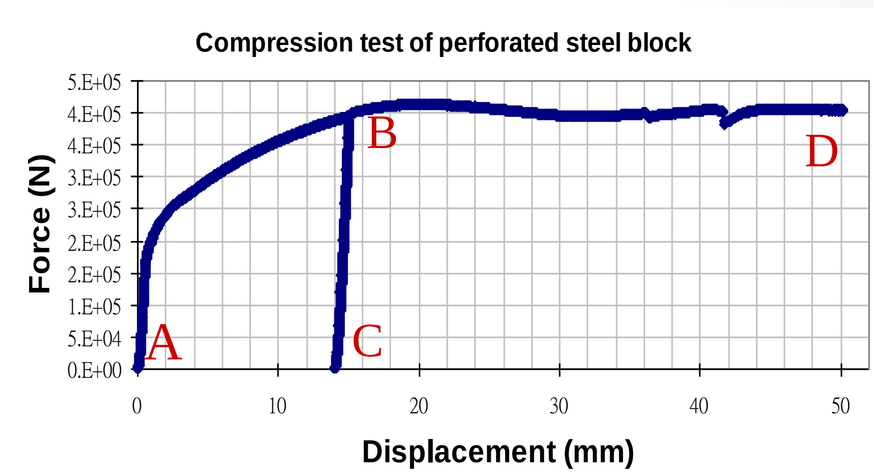
Point B



Point D



Beam response with a P-block



Compression test result

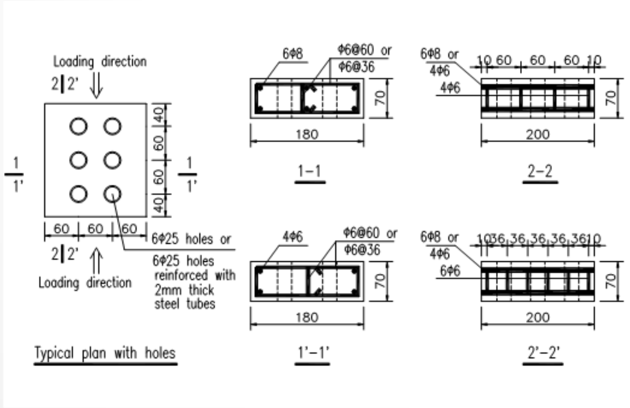
Compression yielding with a ductile material – SIFCON block


Concrete material is brittle

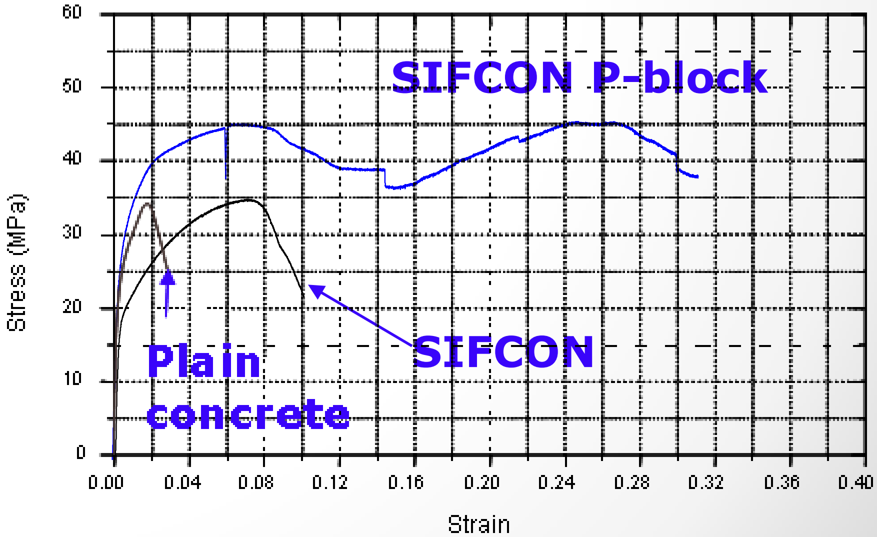
SIFCON (Slurry Infiltrated Fiber Concrete) is a kind of fiber reinforced concrete with enormous ductility

However, SIFCON is still not ductile enough for CY scheme

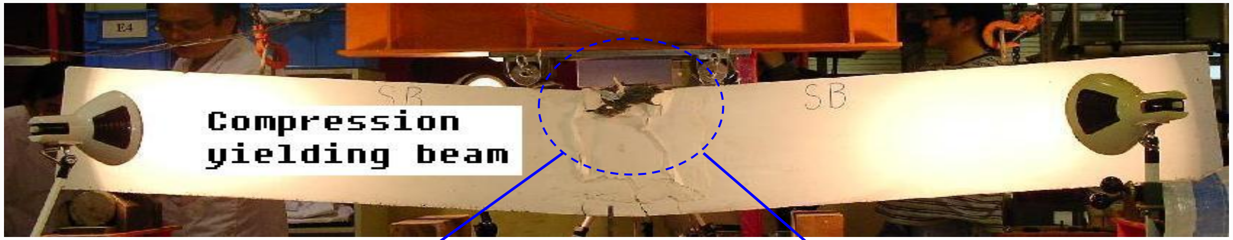
Perforated SIFCON block with confinement is adequate for CY scheme



SIFCON P-block



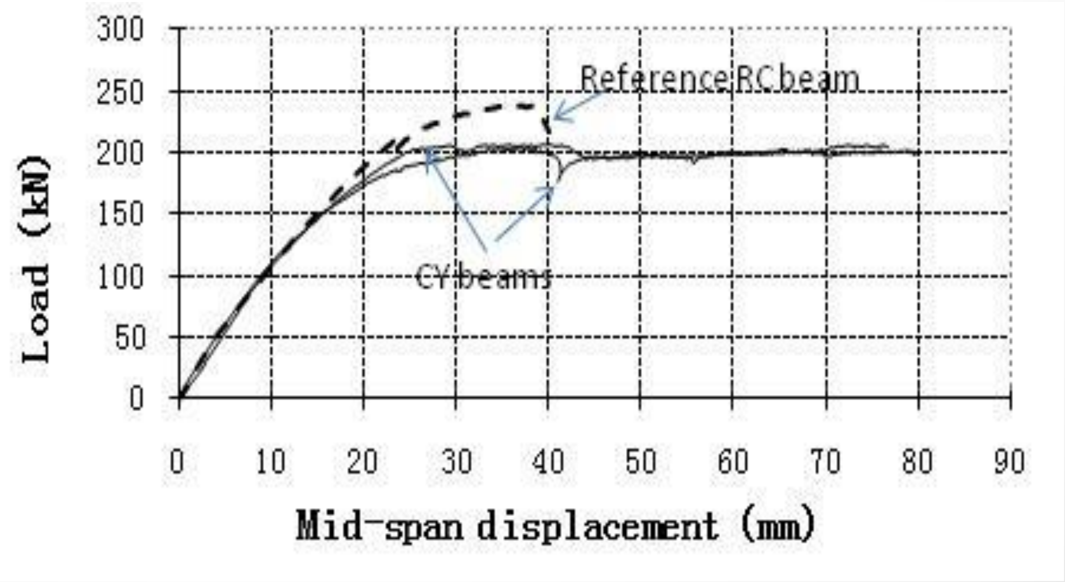
Responses of CY beam with a SIFCON blocks



Before compression yielding

Perforated SIFCON CY block

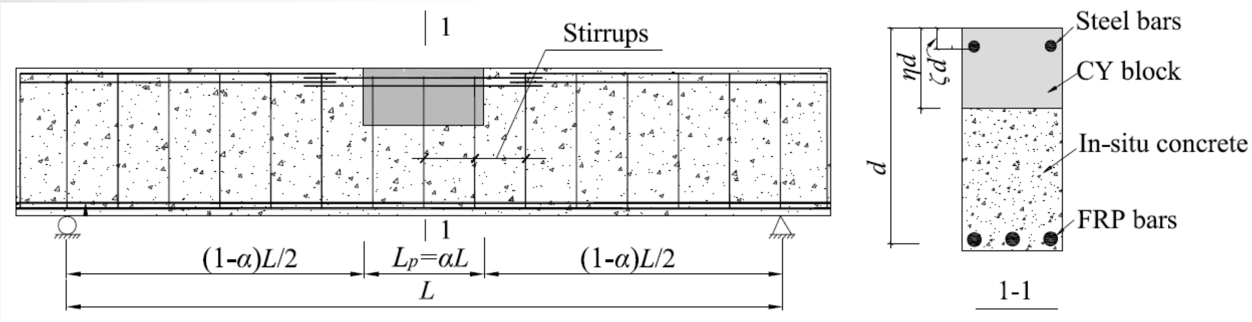
After compression yielding

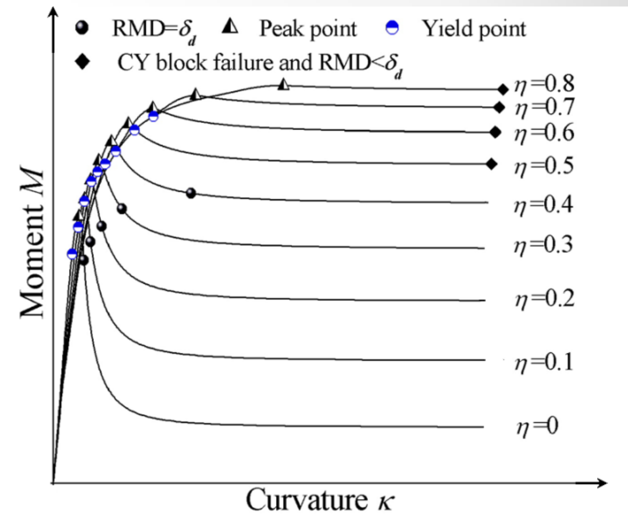


[Test results of FRP bar reinforced concrete beams]

(b) Load vs. mid-spa
of beams

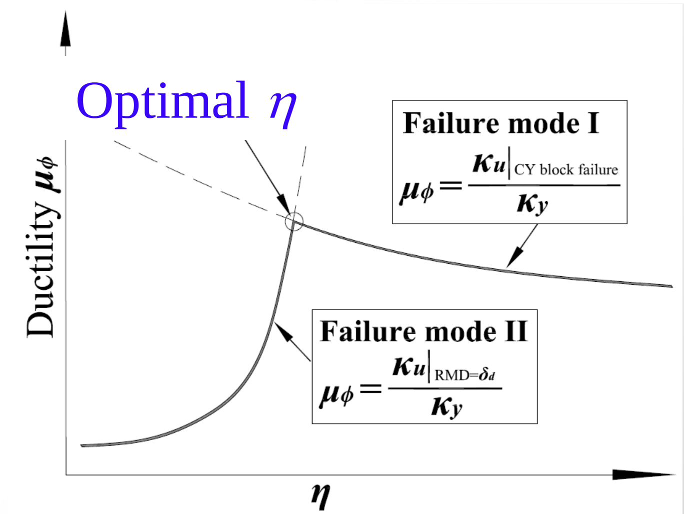
Performanced-based Design of CY beams





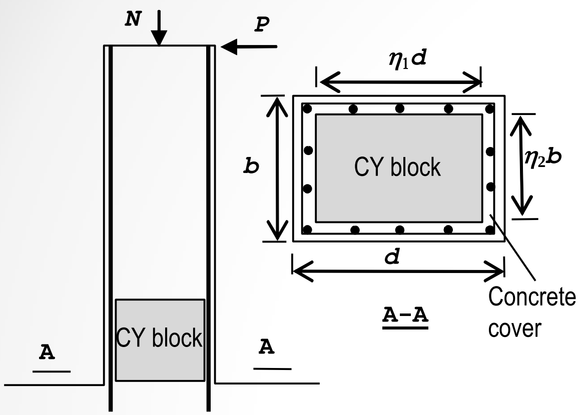
Strength requirement: $M_m \geq M_d$

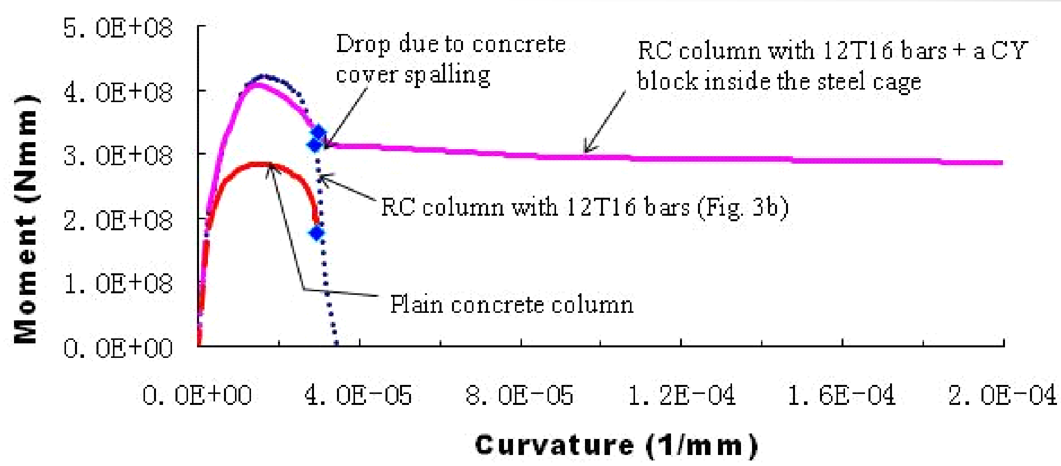
Ductility demand: $$\mu_\Delta = \frac{\alpha(2-\alpha)\mu_\varphi + 8\lambda(1-\alpha)^2 \frac{(EI)_p}{(EI)_e}}{\alpha(2-\alpha) + 8\lambda(1-\alpha)^2 \frac{(EI)_p}{(EI)_e}}$$

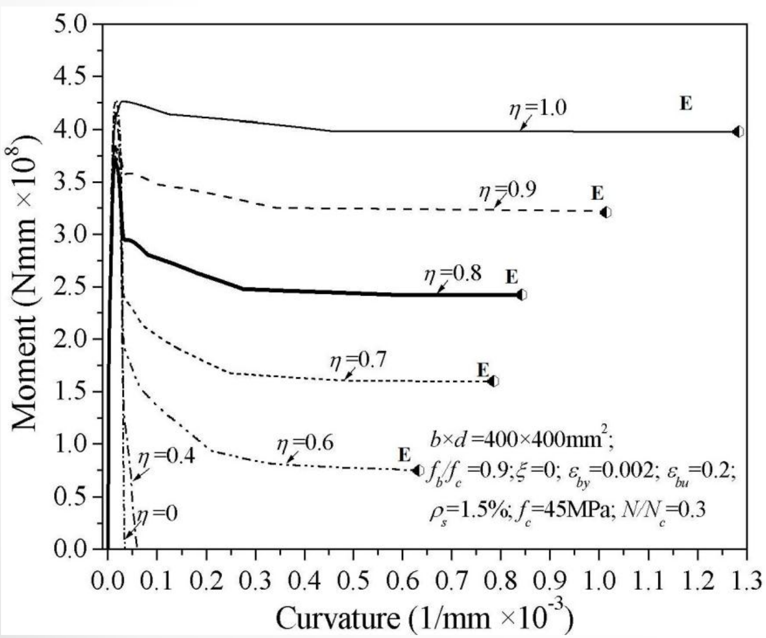


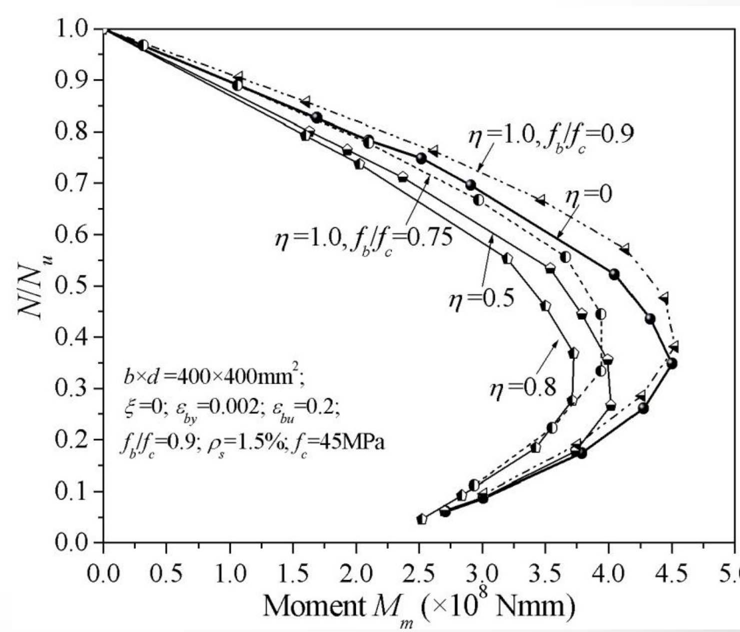
Optimal design: $$\frac{M_m - M_{\min}}{M_m} = \delta_d$$

CY columns


N
P
η1d
b
η2b
CY block
d
A-A
Concrete cover
A
A
CY block


Drop due to concrete cover spalling
RC column with 12T16 bars + a CY block inside the steel cage
RC column with 12T16 bars (Fig. 3b)
Plain concrete column
Moment (Nmm)
Curvature (1/mm)
5. 0E+08
4. 0E+08
3. 0E+08
2. 0E+08
1. 0E+08
0. 0E+00
0. 0E+00
4. 0E-05
8. 0E-05
1. 2E-04
1. 6E-04
2. 0E-04


Moment (Nmm ×10^8)
Curvature (1/mm ×10^-3)
η=1.0
η=0.9
η=0.8
η=0.7
η=0.6
η=0.4
η=0
E
b×d=400×400mm²;
fb/fc=0.9; ξ=0; εby=0.002; εbu=0.2;
ρs=1.5%; fc=45MPa; N/Nc=0.3


N/Nu
Moment Mm (×10^8 Nmm)
η=1.0, fb/fc=0.9
η=0
η=1.0, fb/fc=0.75
η=0.5
η=0.8
b×d=400×400mm²;
ξ=0; εby=0.002; εbu=0.2;
fb/fc=0.9; ρs=1.5%; fc=45MPa

Summary

Apart from increasing ductility, the ductile compression zone *acts as a fuse* in the structural system.

When excessive loading occurs, the fuse will be triggered and force the structural system to deform in a plastic manner to avoid abrupt reinforcement rupture, concrete crushing, or shear failure.

The fuse would slightly weaken the CY member. However, the safe design strength can be higher than the original member due to the safe failure mode and hence a much smaller safety factor.

Reference papers

1. Wu, Y.-F. New avenue of achieving ductility for reinforced concrete members. *Journal of Structural Engineering ASCE* 2006, 132(9): 1502-1506.
2. Wu YF. Ductility demand of compression yielding fiber-reinforced polymer-reinforced concrete beams. *ACI structural Journal* 2008; 105(1):104-110.
3. Zhou YW, Wu YF, Teng JG, Leung AYT. Parametric space for the optimal design of compression-yielding FRP-reinforced concrete beams. *Materials and Structures*, 2010; 43(1-2): 81-97.
4. Zhou YW, Wu YF, Teng JG, Leung AYT, Ductility analysis of compression-yielding FRP-reinforced composite beams, Cement and Concrete Composites, 2009 October, 31(9): 682–691.
5. Wu YF, Zhou YW, He XQ. Performance-based optimal design of compression-yielding FRP-reinforced concrete beams. *Composite Structures* 2010; 93(1): 113-123.
6. Wu YF, Jiang JF, Liu K. Perforated SIFCON blocks – An extraordinarily ductile material ideal for use in compression yielding structural systems, *Construction and Building Materials*, 2010; 24(12): 2454-2465
7. Wu YF, Zhou YW. Controlling the Damage of Concrete Columns through Compression Yielding, *Structural Control and Health Monitoring*, in press

Patent

A US patent filed for this new technology

Part II: HB FRP - A New Technology to Avoid Debonding between FRP and Concrete

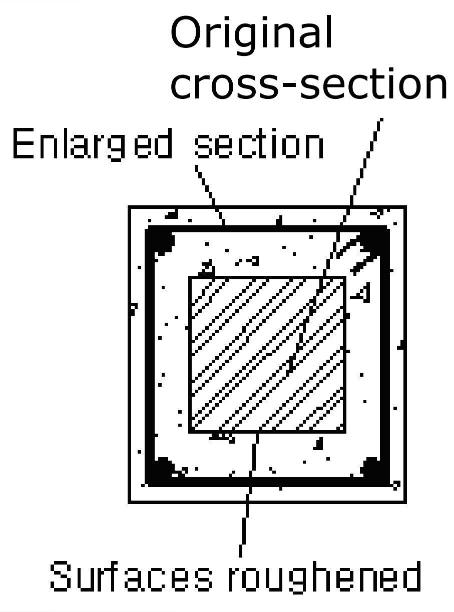
- Rehabilitation (repair/strengthening/retrofitting) of old structures - a major task in civil engineering in developed countries, accounting for more than 50% of total spending in the construction industry.

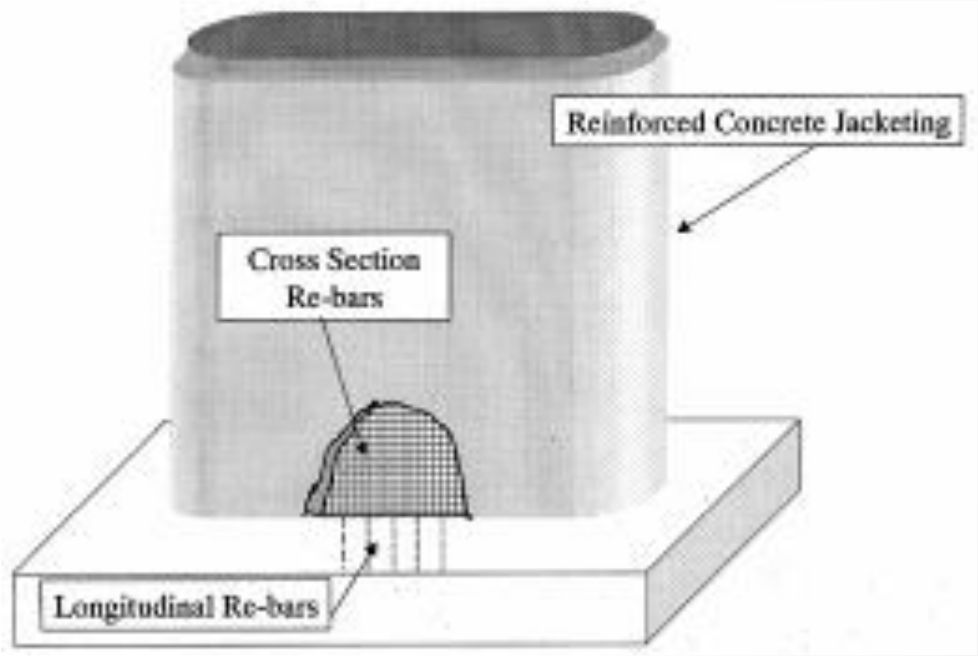
- An emerging problem in developing countries - due to poor design and construction or inadequate maintenance, particularly in China.

- Hong Kong has a similar need – particularly when seismic design becomes a requirement in the near future. The retrofitting of buildings and bridges will become a massive undertaking because existing structures were not constructed to resist seismic action.

Traditional methods for rehabilitation (strengthening/retrofitting/repairing) of RC members

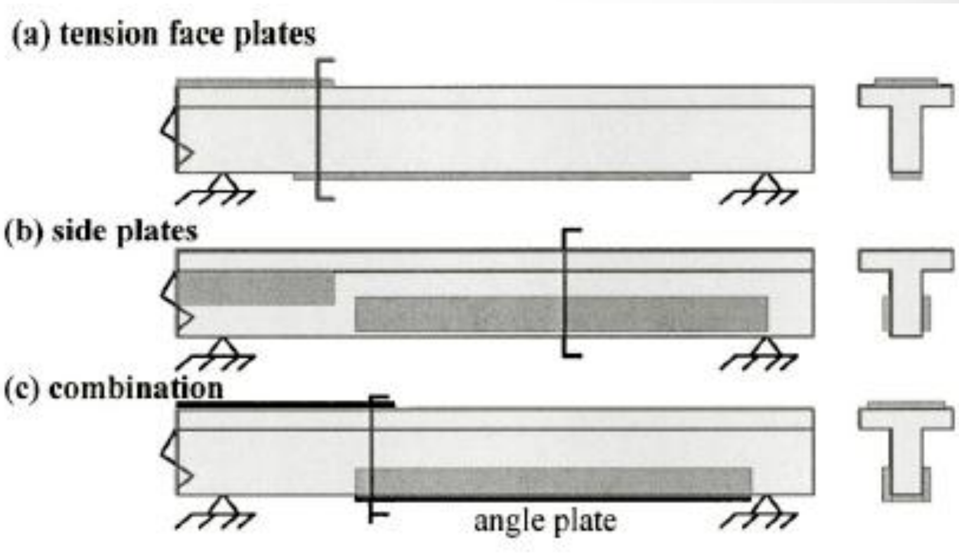
RC jacketing

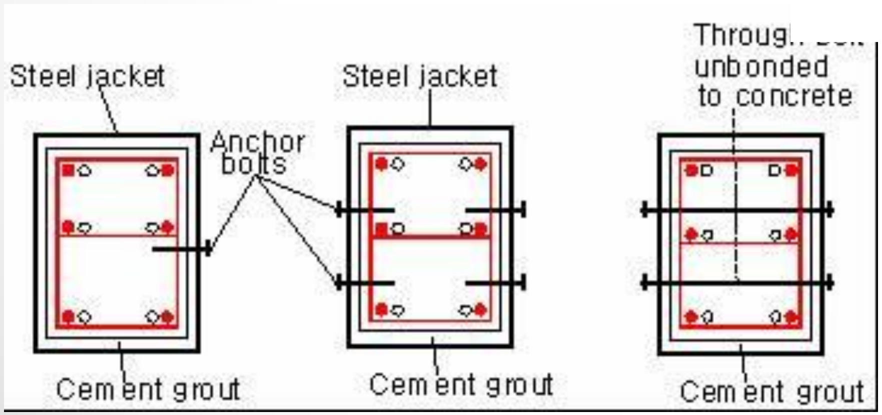




Traditional methods for rehabilitation (strengthening/retrofitting/repairing) of RC members

<u>Steel jacketing/plating</u>





FRP – an ideal material for structural rehabilitation

- FRP materials can be conveniently applied onto the external faces of concrete structures for structural rehabilitation.