Annual Seminar of Hong Kong Concrete Institute

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Use of Fibre-reinforced Polymer (FRP) Composites for Strengthening Concrete Structures

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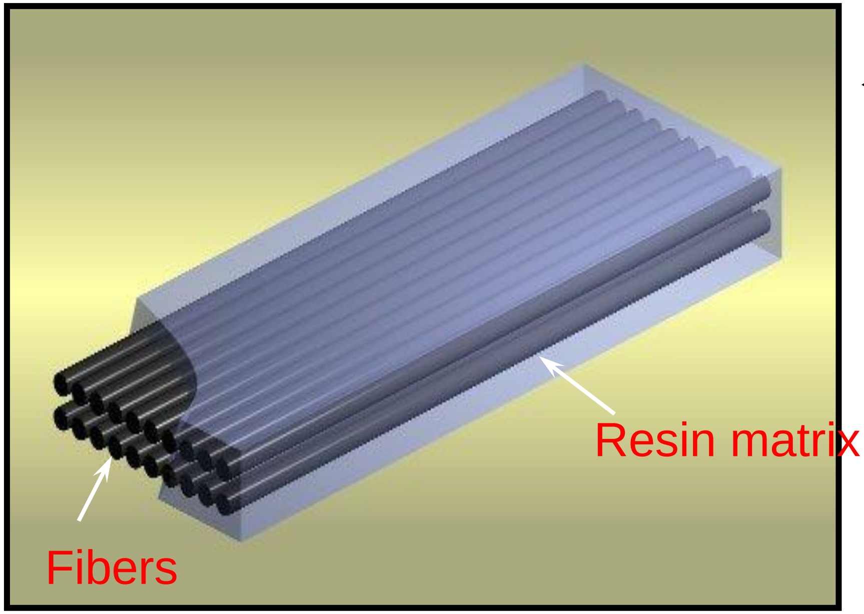
Outline

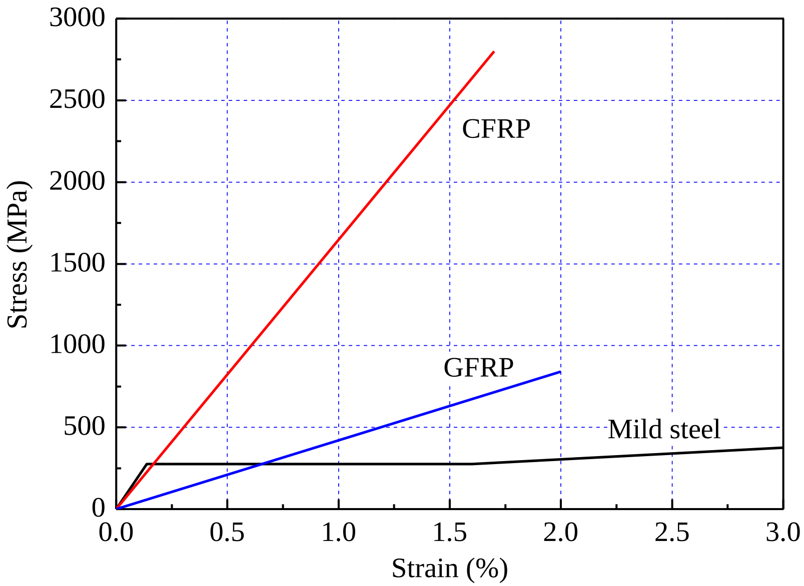
1. Introduction
2. Design of FRP-strengthened concrete structures
3. Practical applications of FRP in strengthening concrete structures
4. Concluding remarks

This PPT file are based mainly on slides developed over the years by Prof. Jin-Guang TENG and Prof. Tao YU.

Fibre-Reinforced Polymer (FRP) Composites

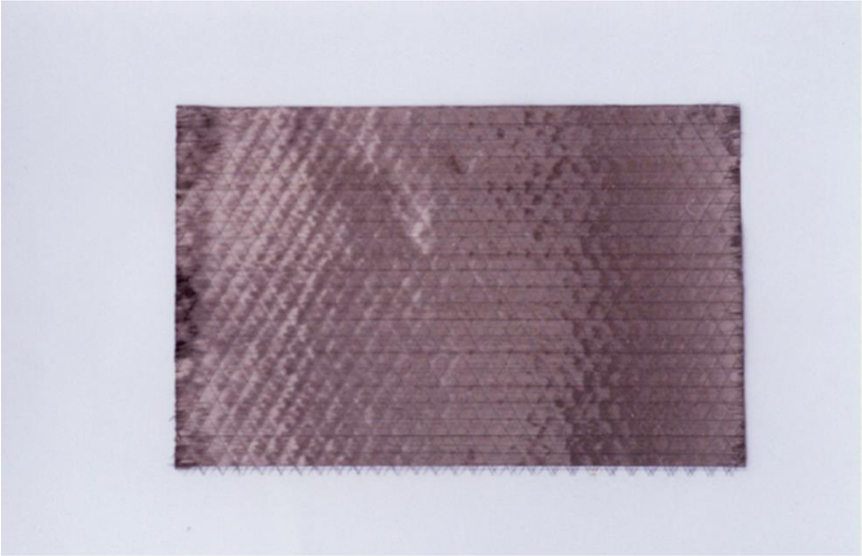


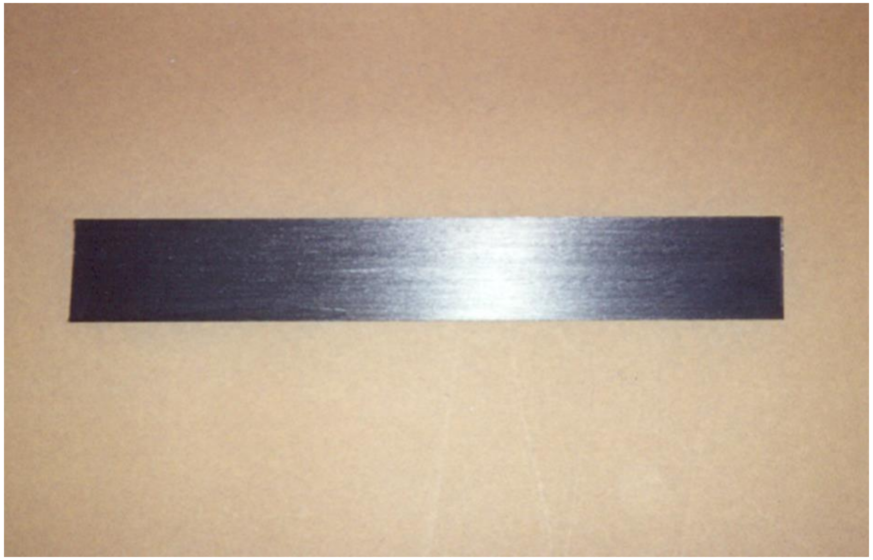
Fiber-reinforced polymer (FRP) composites are formed by embedding continuous fibres in a polymeric resin matrix

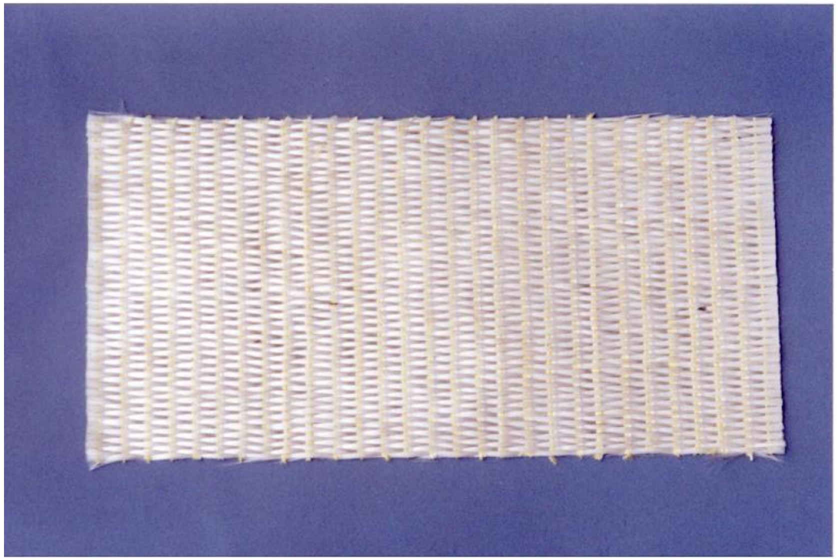


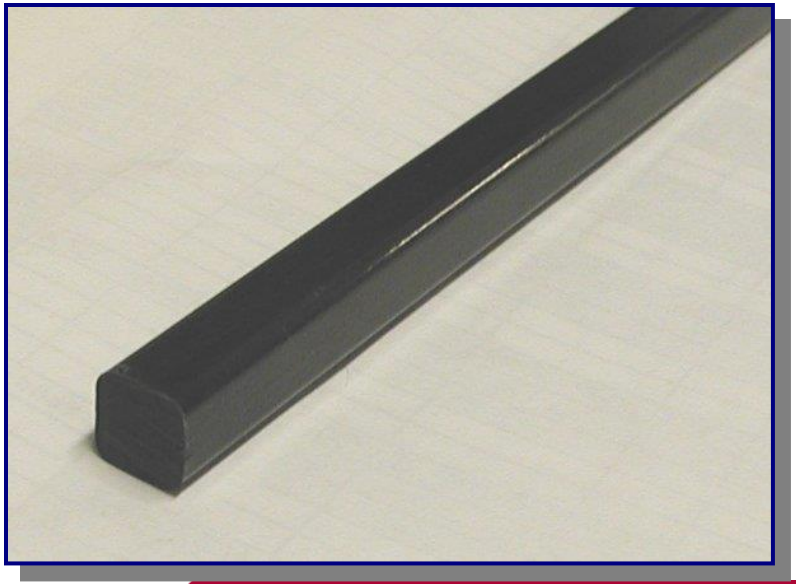
- ✓ AFRP = Aramid FRP
- ✓ BFRP = Basalt FRP
- ✓ CFRP = Carbon FRP
- ✓ GFRP = Glass FRP

FRP Products for Strengthening Applications









Advantages of FRP Strengthening

Have all the advantages of steel plates for plate bonding

Speedy application; Minimal increases in structural weight and size.

High strength/weight ratio

Lifting equipment eliminated; Reduced labour cost.

Flexibility in shape

Can be handled in rolls; easy for wrapping on curved surfaces and around columns.

Tailorability of material properties

Through fiber orientations and lamination structures

High resistance to corrosion and other chemical attacks

Durable performance.

Ibach bridge 1991

First use of CFRP to strengthen a structure

CFRP strips were going to be prepared

only 6 working hours!

Courtesy of Prof. Urs Meier

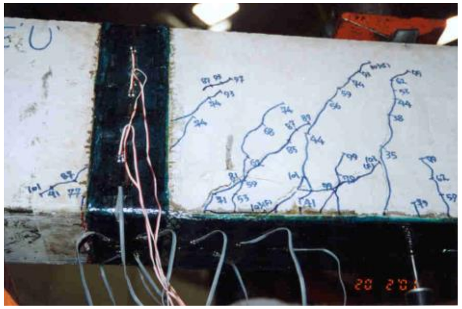
FRP Strengthening of Concrete Structures: Typical Strengthening Scheme

(https://www.structuremag.org/?p=8643)

FRP Strengthening of Concrete Structures

Strengthening of concrete structures with externally-bonded FRP reinforcement

- ❑ Bond-critical applications
  - ✓Debonding failures



- ❑ Contact-critical applications
  - ✓Confined concrete

Debonding Failure

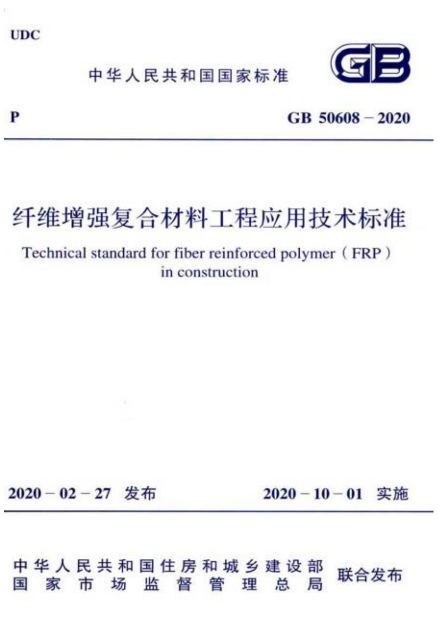
FRP Confinement for Columns

Dynamic collapse test on eccentric reinforced concrete structures with and without seismic retrofit，
Yousok Kima, , , Toshimi Kabeyasawaa, Shunichi Igarashib

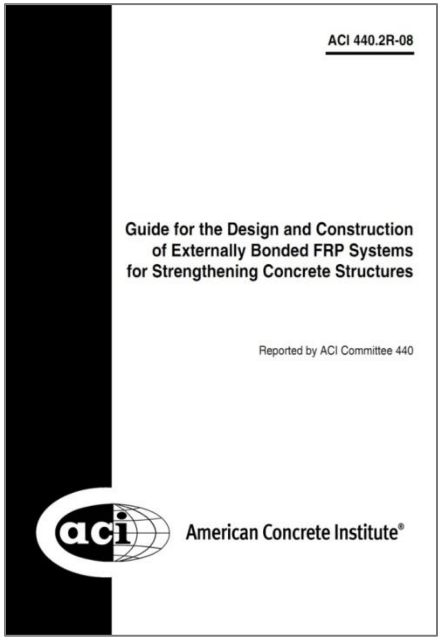
a doi:10.1016/j.engstruct.2011.09.017

FRP Strengthening of Concrete Structures

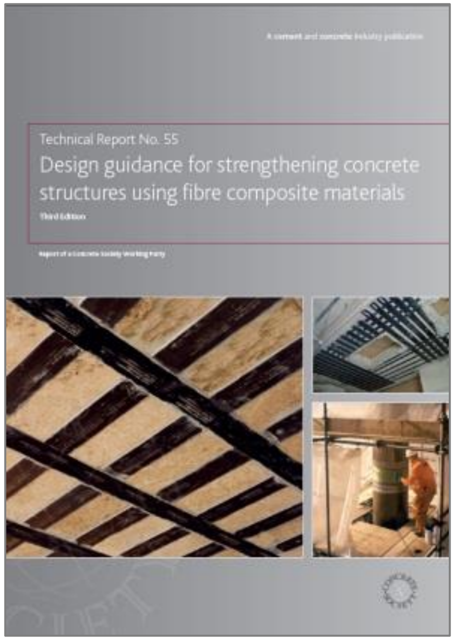
Extensive Research and Design Guidance Exist



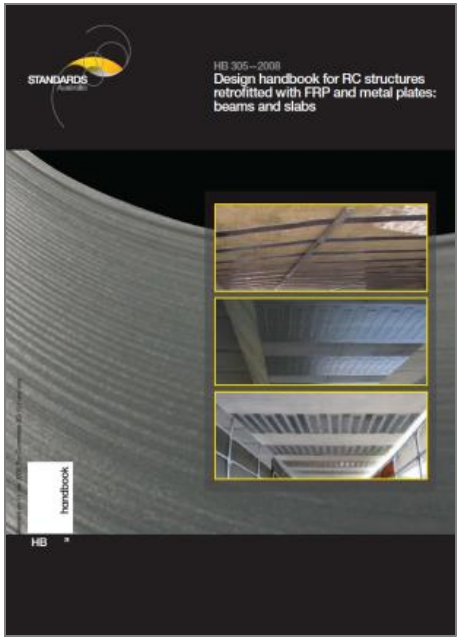
China



USA



UK



Australia

Extensive research has been conducted at PolyU on the theory of FRP-strengthened concrete structures; the research outcomes of PolyU have been widely adopted by design guidance documents around the world.

Design Principles and Requirements

FRP strengthening system

The design of an FRP strengthening system* aims to ensure an acceptable level of probability that the structure or structural member strengthened with the FRP system will perform satisfactorily during the design working life.

With an appropriate degree of safety, the system should:

- ✓ **Sustain all loads and deformations of normal construction and use;**
- ✓ **Remain fit for the purpose of its intended use;**
- ✓ **Have adequate durability for its environment; AND**
- ✓ **Have adequate resistance to the effects of misuse and fire.**

*** An FRP strengthening system is defined to include the FRP material, the bonding adhesive, and the associated primer and putty materials.**

Assessment of Existing Structures

To identify the deficiencies, establish the existing load-carrying capacity, determine the suitability of the FRP strengthening technology, define the performance requirements for the system.

Such an assessment should cover the following:

- A review of existing design calculations and drawings or as-built documents;
- A site investigation; and
- A structural analysis of the existing load-carrying capacity, based on the review of documents and the information gathered from the site investigation.

Basic Principles for FRP Strengthening

- The FRP strengthening system should be so designed that the FRP is only called upon to resist **tensile forces**.
- The strain compatibility between the FRP and the concrete is ensured by **adhesive bonding** (plus mechanical anchoring where appropriate).
- The compressive strength of FRP should be **neglected** in the event that the FRP experiences compression due to moment reversals or load pattern changes.

Basic Principles for FRP Strengthening

- **Long-term performance and durability:** 1) environmental factors including the effects of **moisture**, **temperature**, **freeze and thaw cycles**, and **ultraviolet** (UV) radiations; 2) chemical attacks by **alkaline**, **acidic**, or **salt solutions**; and 3) loading conditions such as **sustained loads** or **cyclic loads** which may cause the creep rupture or fatigue failure of FRP composites.

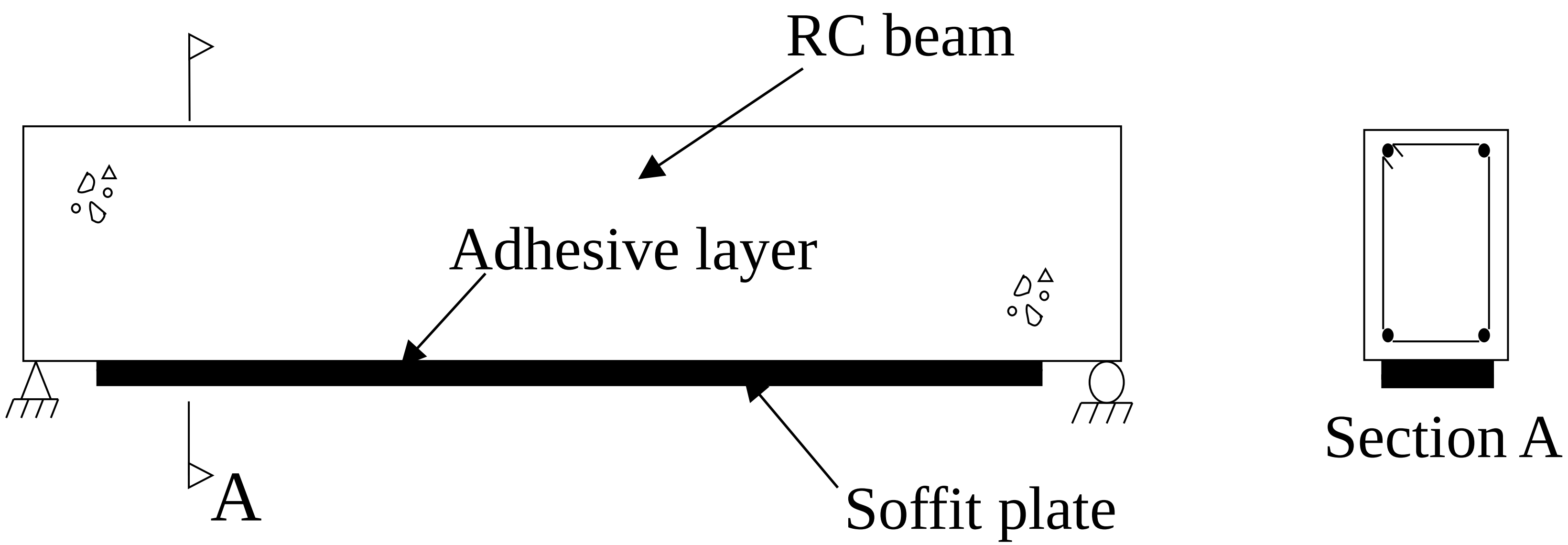
$$\text{Design value} = \frac{1}{\gamma_m} \times \text{characteristic value}$$

$$\gamma_m = \gamma_{m1}\gamma_{m2}$$

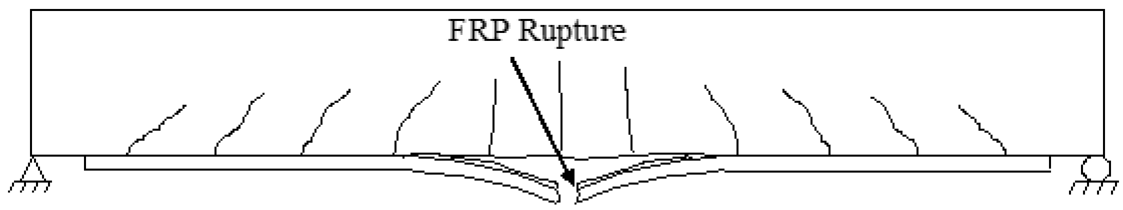
γ_{m1}: Accounts for differences between actual and laboratory values, local weaknesses and inaccuracy in the assessment of resistance

γ_{m2}: Accounts for long-term strength degradations due to environmental exposure including the effects of moisture/solution, alkalinity, elevated temperature and ultraviolet radiations (UV)

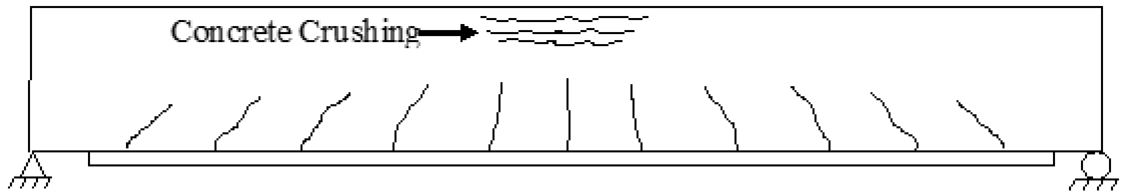
Flexural Strengthening



Conventional Failure Modes

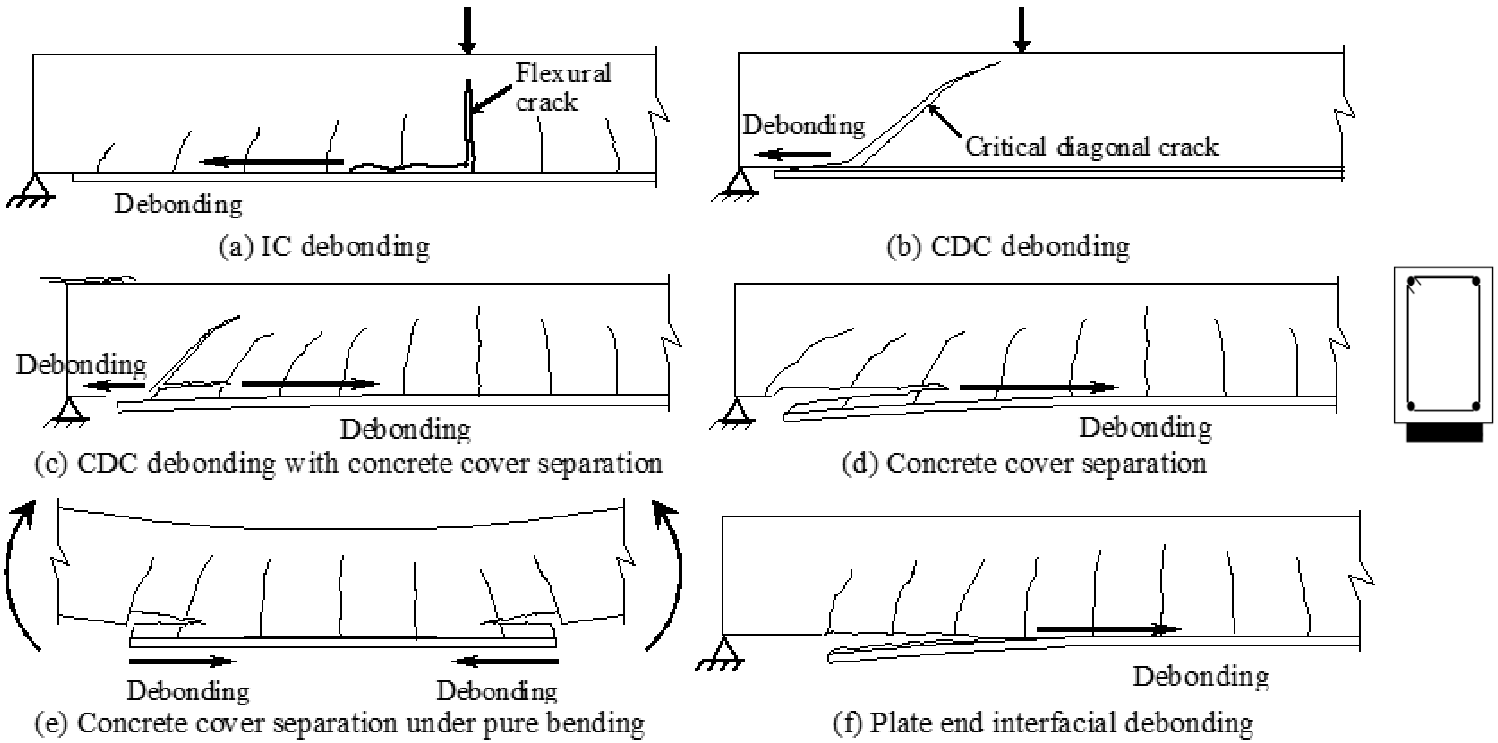


(a) FRP rupture



(b) Crushing of compressive concrete

Debonding Failures of FRP-plated RC Beams

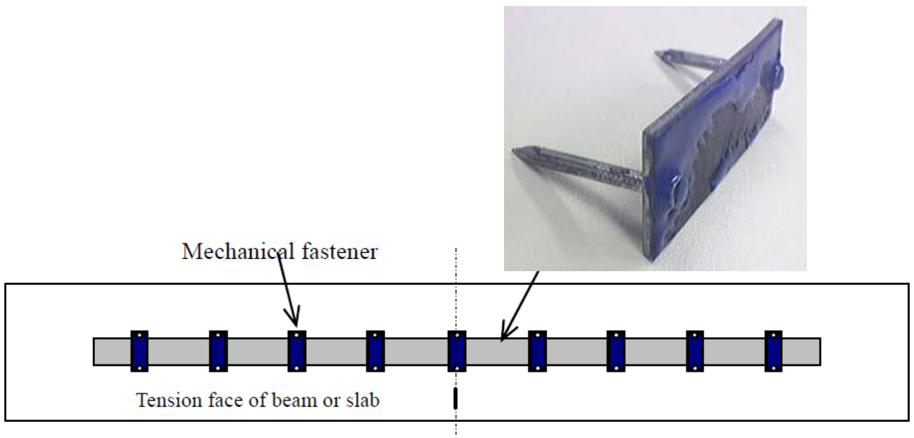


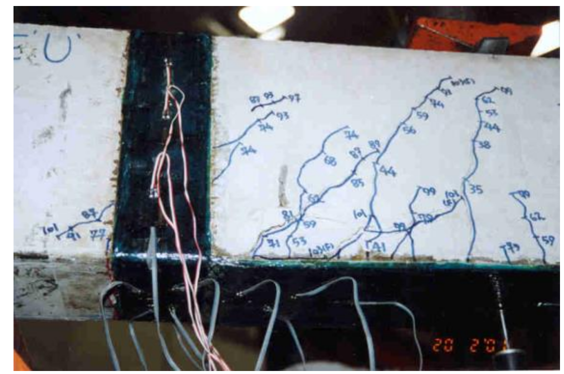
Intermediate crack debonding: (a)

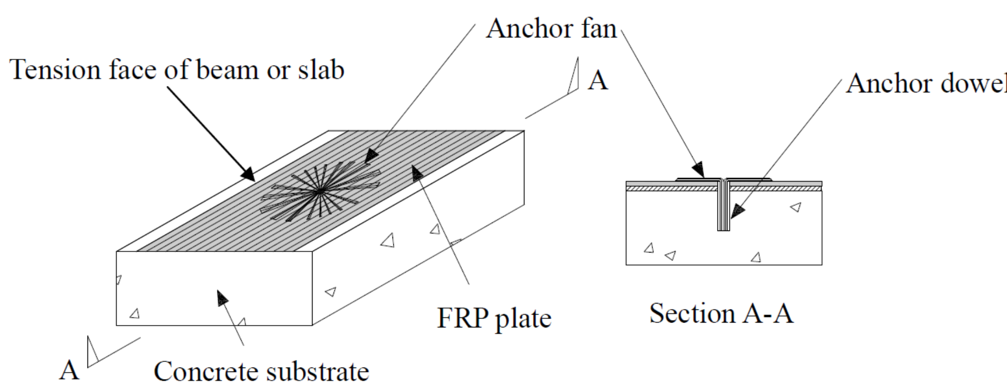
Plate end debonding: (b) to (f)

Plate End Debonding

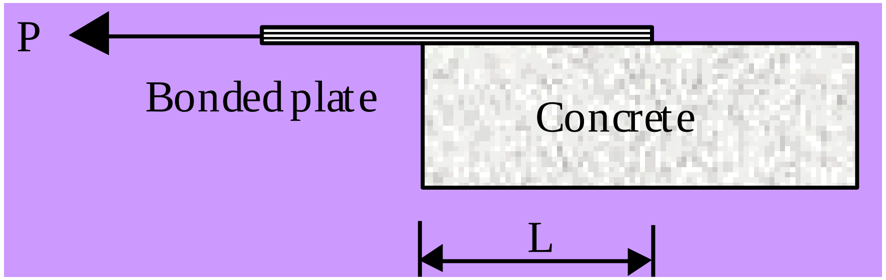
- Due largely to the high interfacial stresses between the FRP plate and the concrete beam near the plate end;
- Should be prevented by additional anchorage at the plate end

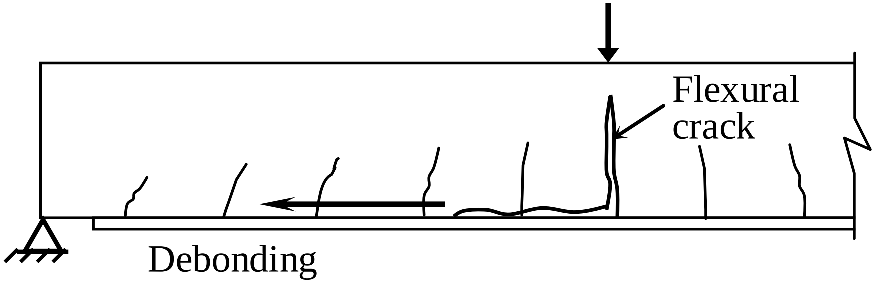


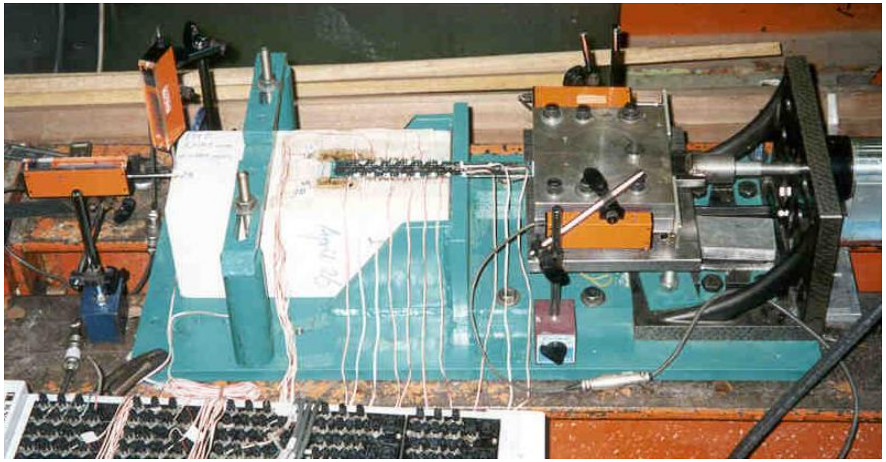




Intermediate Crack Induced (IC) Debonding

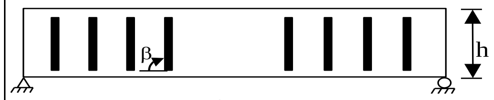
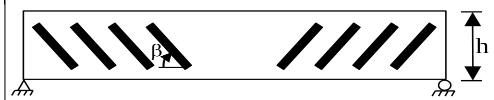
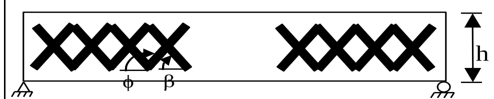
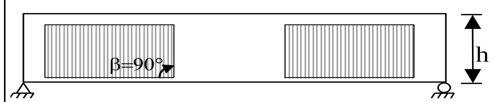
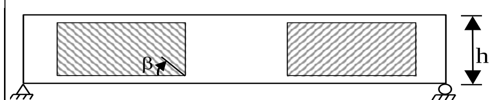
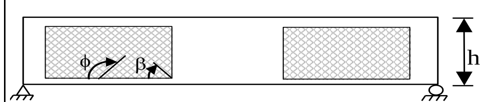






Empirical models have been developed based on results from bonded joint tests for the IC debonding strain.

Concrete Beams Shear Strengthened with FRP

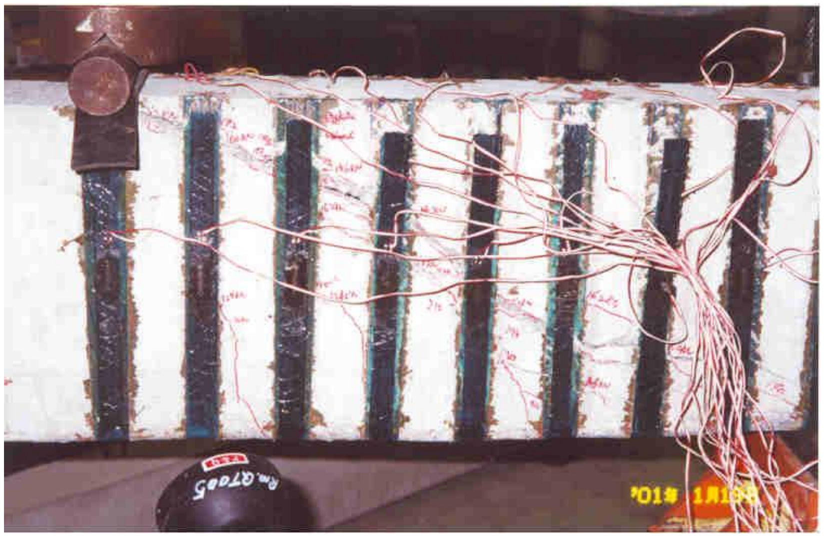
Fibre orientations and distributions	Bonding scheme and notation		
 β = 90°	SS90	US90	WS90
 0 ≤ β < 180°	SSβ	USβ	WSβ
 0 ≤ β < 180°, 0 ≤ ϕ < 180°	SSβ/ϕ	USβ/ϕ	WSβ/ϕ
 β = 90°	SP90	UP90	WP90
 0 ≤ β < 180°	SPβ	UPβ	WPβ
 0 ≤ β < 180°, 0 ≤ ϕ < 180°	SPβ/ϕ	UPβ/ϕ	WPβ/ϕ

Concrete Beams Shear Strengthened with FRP

Factors to be considered in selecting a strengthening scheme:

- Accessibility:
  - Can the whole perimeter of a beam be accessed for wrapping?
- Loading type:
  - Monotonic loading, or reversed cyclic loading?
- Required shear capacity increase; *and*
- Economic considerations.

Concrete Beams Shear Strengthened with FRP



Debonding failure

FRP rupture failure

Shear Capacity

- Shear capacity of shear-strengthened RC beams:

$$V_n = V_c + V_s + V_{frp}$$

  - ✓ V_c = contribution by concrete
  - ✓ V_s = contribution by steel shear reinforcement
  - ✓ V_{frp} = contribution by FRP

- V_c & V_s can be calculated using provisions in an existing code on reinforced concrete structures

Method of Column Strengthening

- Wrapping
- Filament Winding
- Prefabricated Shell Jacketing


http://www.norkan.com/

Wet lay-up

Machine winding

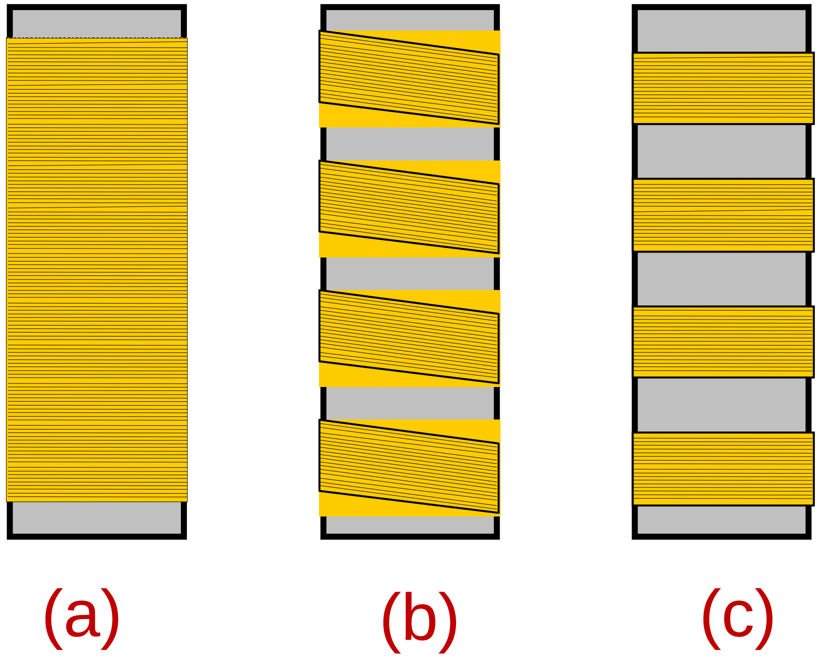
FRP shell

Various Forms of FRP Wrapping

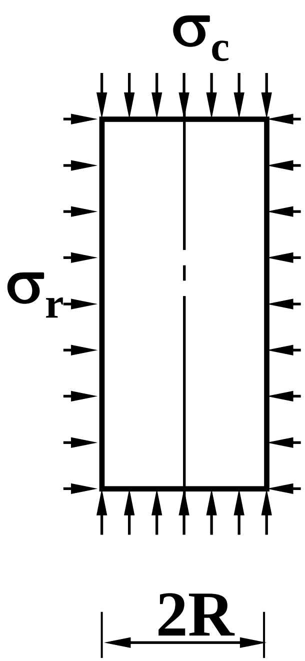
(a) Full Wrapping

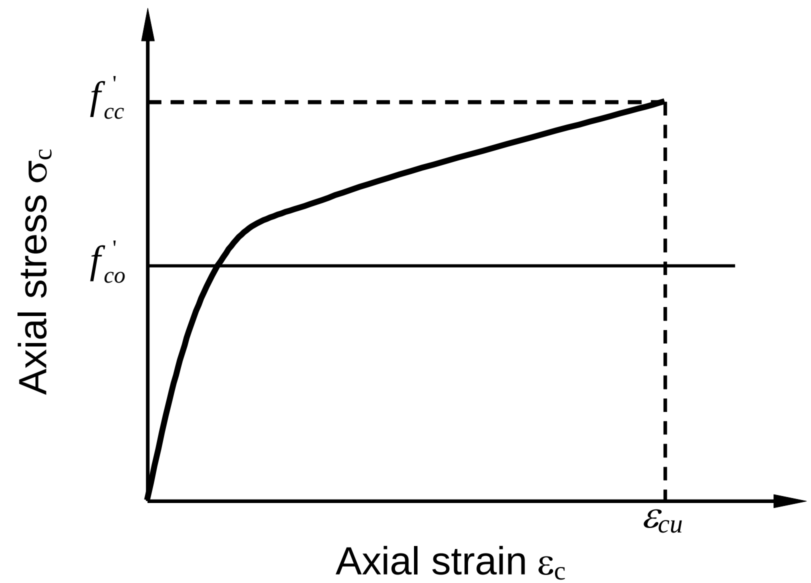
(b) Wrapping with Continuous Spirals

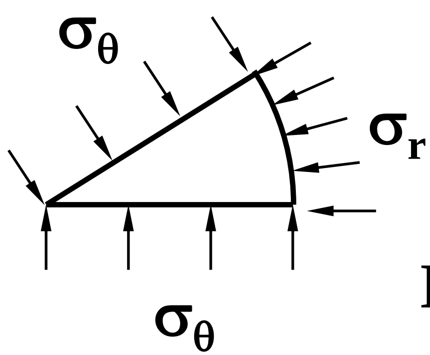
(c) Wrapping with Discrete Rings



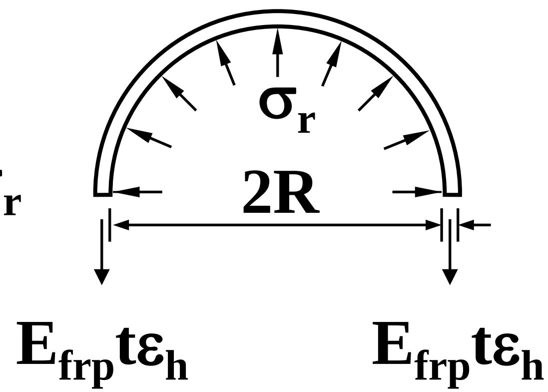
FRP-confined Concrete





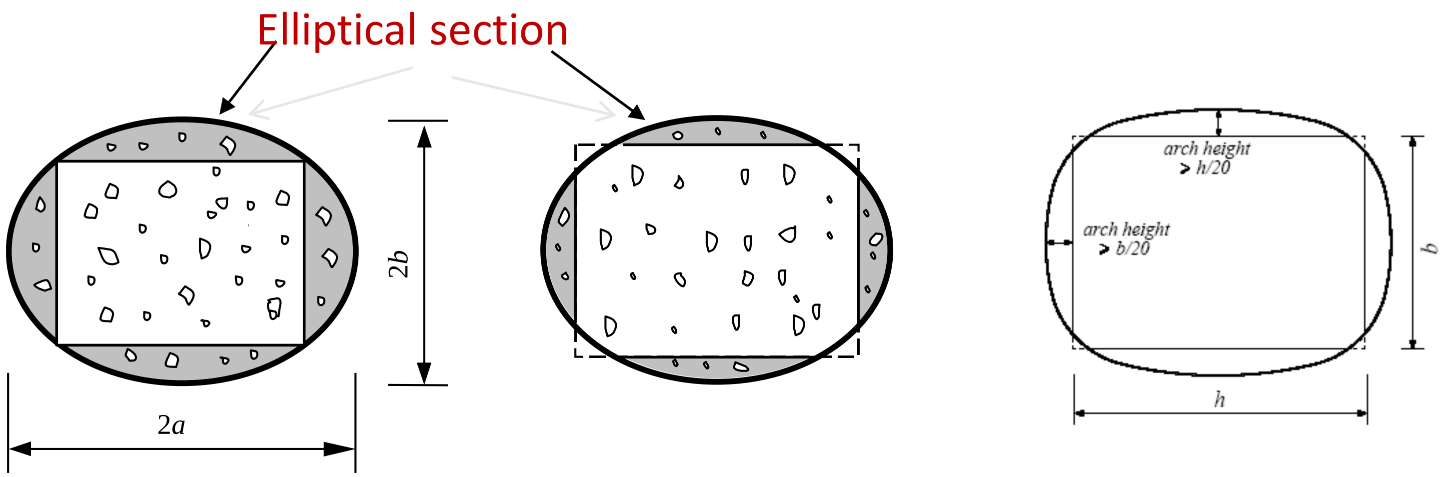


Concrete



FRP jacket

Shape Modification

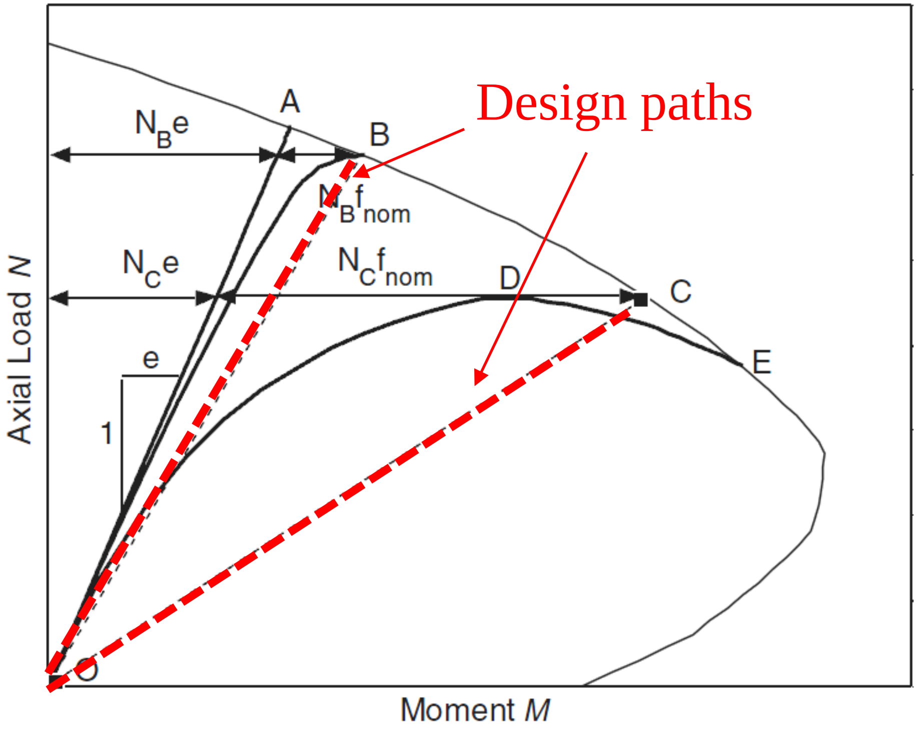


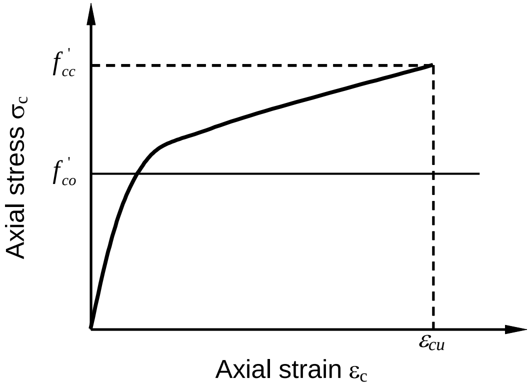
(a) Without rounding

(b) With rounding

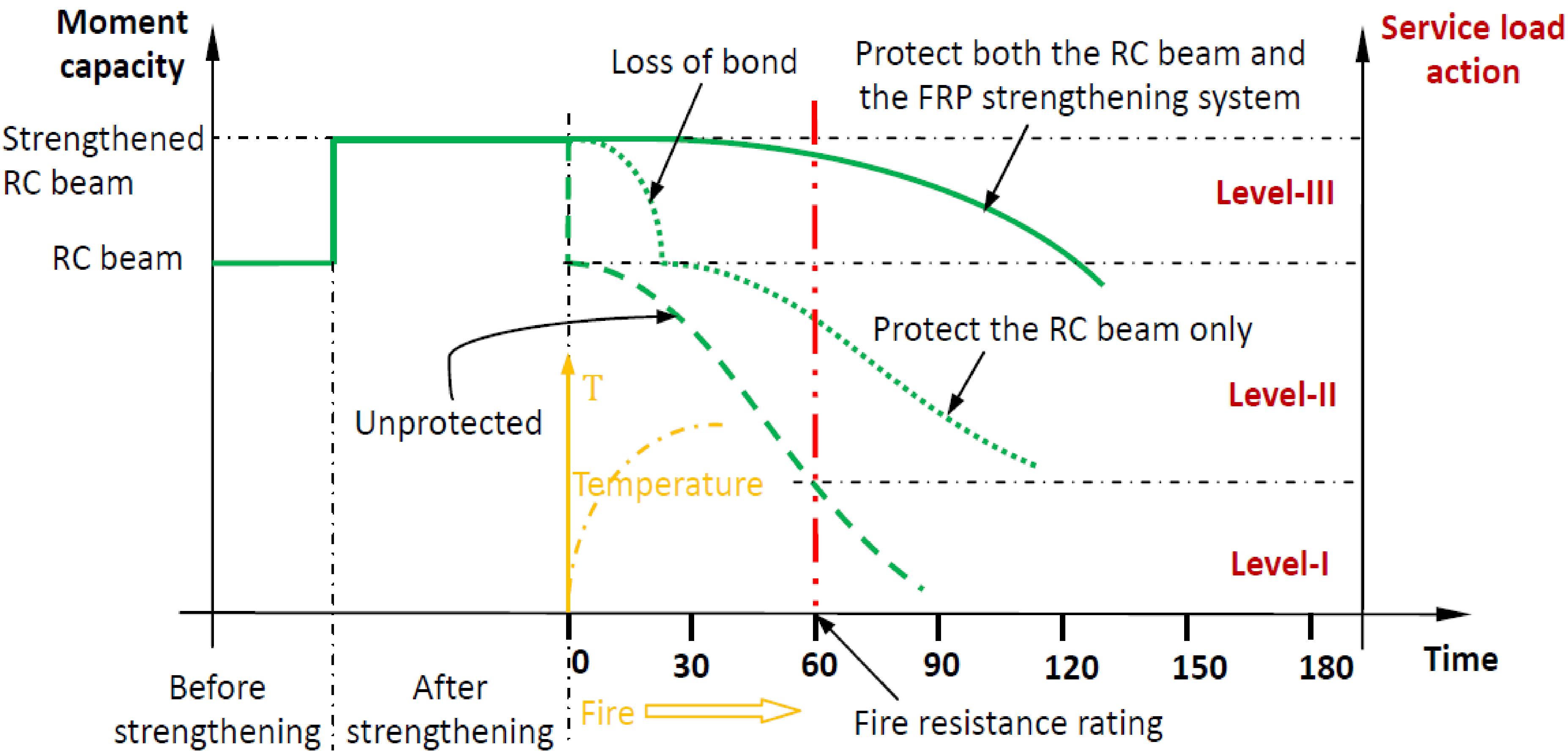
(c) Section curvilinearization

FRP-strengthened Slender Concrete Columns





Three-Level Fire Resistance Design Approaches



Gao, W.Y., Dai, J.G., and Teng, J.G. (2018). "Three-level fire resistance design of FRP-strengthened RC beams." *Journal of Composites for Construction*, ASCE, Vol. 22, No. 3, 05018001.

Three-Level Fire Resistance Design Approaches

Level-I design (Unprotected FRP-strengthened RC beams)

- Design formulae

$$R\left(\gamma, c, \rho, \frac{l}{d}, \frac{A_{sc}}{A_{st}}, \mu_{ag}, b\right) = \varphi(\gamma) \times \omega(c, \rho_s) \times \psi\left(\frac{l}{d}, \rho_s\right) \times \xi\left(\frac{A_{sc}}{A_{st}}\right) \times \phi(b)$$

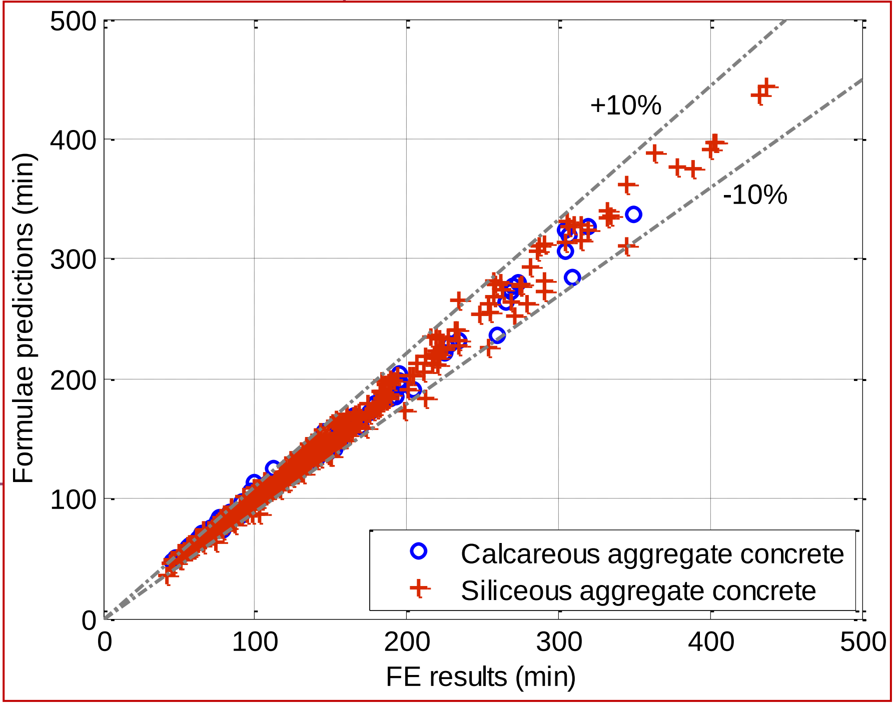
$$\varphi(\gamma) = a_1 + a_2 \cdot \gamma + a_3 \cdot \gamma^2 + a_4 \cdot \gamma^3$$

$$\omega(c, \rho_s) = \omega_0 + \omega_1 \cdot c$$

$$\psi\left(\frac{l}{d}, \rho\right) = \psi_0 + \psi_1 \cdot \rho + \psi_2 \cdot \rho^2$$

$$\xi\left(\frac{A_{sc}}{A_{st}}\right) = \xi_1 + \xi_2 \cdot \left(\frac{A_{sc}}{A_{st}}\right)$$

Total **512** numerical tests



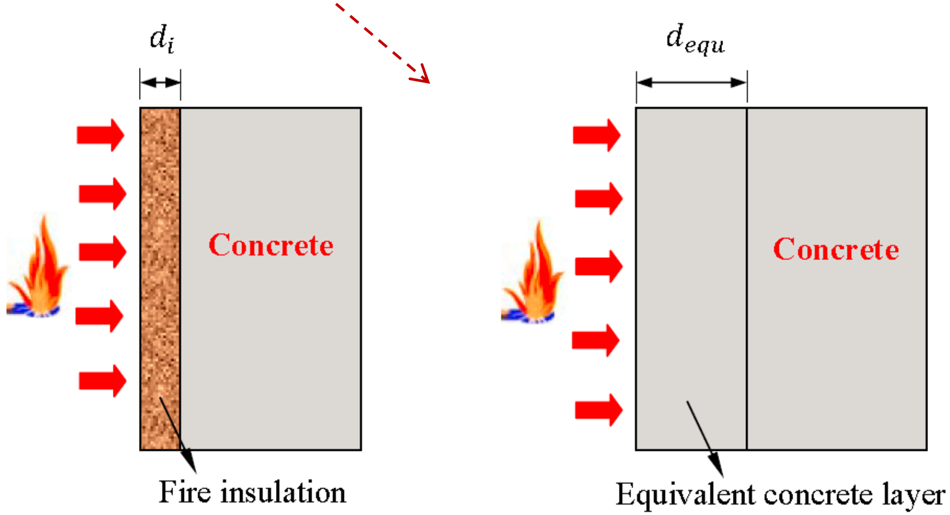
Gao, W.Y., Dai, J.G., and Teng, J.G. (2016). “Fire resistance design of un-protected FRP-strengthened RC beams.” *Materials and Structures*, Vol. 49, No. 12, 5357-5371.

Three-Level Fire Resistance Design Approaches

Level-II design (Partially protected FRP-strengthened RC beams)

- Simple design method

Temperature field analysis of insulated RC beams + "500 °C" isotherm method



(a) Insulated concrete member (b) Equivalent bare concrete member

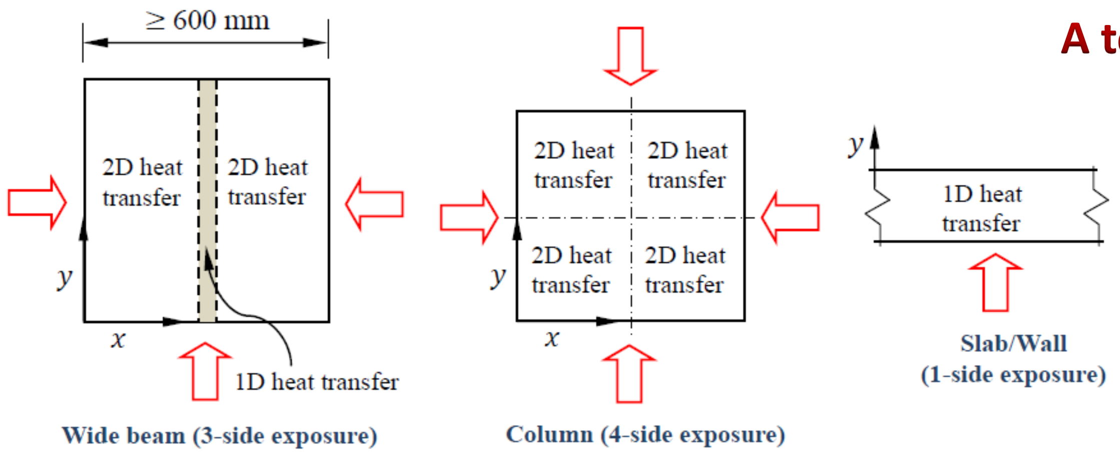
Fire insulation layer = Equivalent concrete layer

$$d_{equ} = d_a \, k_\lambda \, k_{\rho c}$$

Gao, W.Y., Dai, J.G., and Teng, J.G. (2015). "Simple method for predicting temperatures in insulated, FRP-strengthened RC members exposed to a standard fire." *Journal of Composites for Construction*, ASCE, Vol. 19, No. 6, 04015013.

Three-Level Fire Resistance Design Approaches

Level-III design (Fully protected FRP-strengthened RC beams)



A temperature analysis problem

One-dimensional heat transfer

$$\Delta T = \theta_{d,120}\, k_t\, k_b$$

$$\theta_{d,120} = a_0 \cdot \exp(a_1 d) + a_2$$

$$k_t = \frac{t_1 t_2 + t_3\, t^{t_4}}{t_2 + t^{t_4}}$$

$$k_b = \exp\left[b_0 + \frac{b_1}{b/200} + b_2\, ln(b/200)\right]$$

Two-dimensional heat transfer

$$\Delta T = \left\{\left[\ln\left(\frac{\theta_x}{\theta_y} + 1\right) + 1\right] \cdot \theta_y \cdot m(y) \cdot n\left(\frac{y}{x}\right)\right\} k_t\, k_b$$

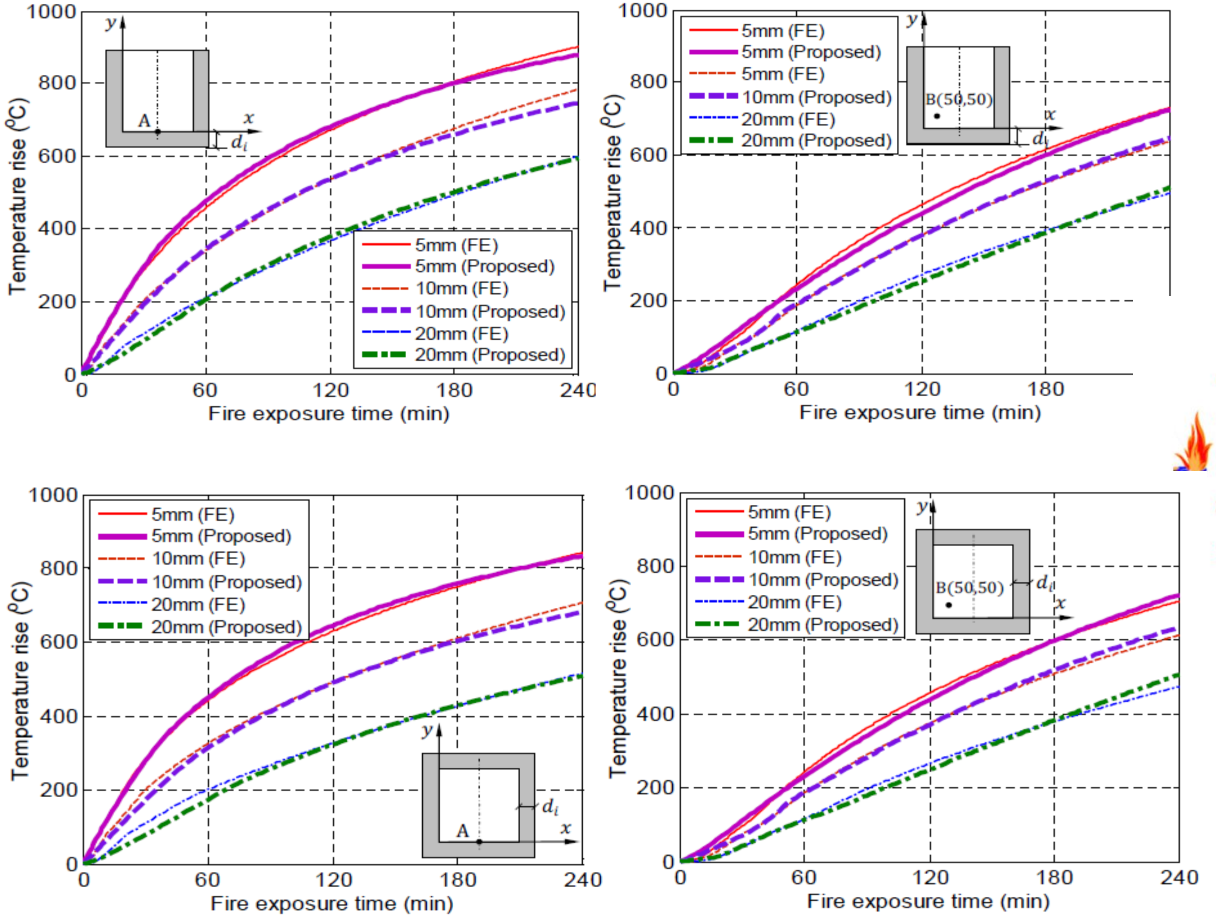
$$m(y) = 0.759 + 4.37 \times 10^{-3} y - 1.71 \times 10^{-5} y^2$$

$$n\left(\frac{y}{x}\right) = 1.26 - 1.32\left(\frac{y}{x}\right) + 0.881\left(\frac{y}{x}\right)^2$$

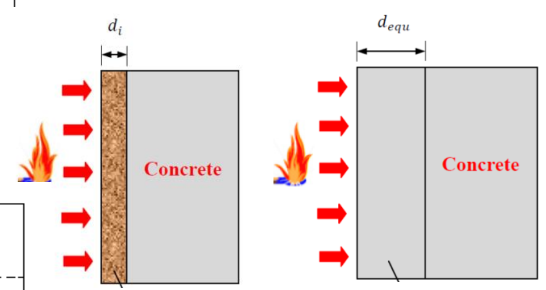
Gao, W.Y., Dai, J.G., and Teng, J.G. (2014). “Simple method for predicting temperatures in reinforced concrete beams exposed to a standard fire.” *Advances in Structural Engineering*, Vol. 17, No. 4, 573-589.

Three-Level Fire Resistance Design Approaches

Level-III design (Fully protected FRP-strengthened RC beams)



Insulated beam sections



Insulated column sections

Gao, W.Y., Dai, J.G., and Teng, J.G. (2015). "Simple method for predicting temperatures in insulated, FRP-strengthened RC members exposed to a standard fire." *Journal of Composites for Construction*, ASCE, No. 19, No. 6, 04015013.

Fire resistance design of FRP-strengthened RC structures

UDC

中华人民共和国国家标准 GB

P GB 50608－2020

纤维增强复合材料工程应用技术标准

Technical standard for fiber reinforced polymer (FRP) in construction

2020－02－27 发布 2020－10－01 实施

中华人民共和国住房和城乡建设部
国家市场监督管理总局 联合发布

目 次

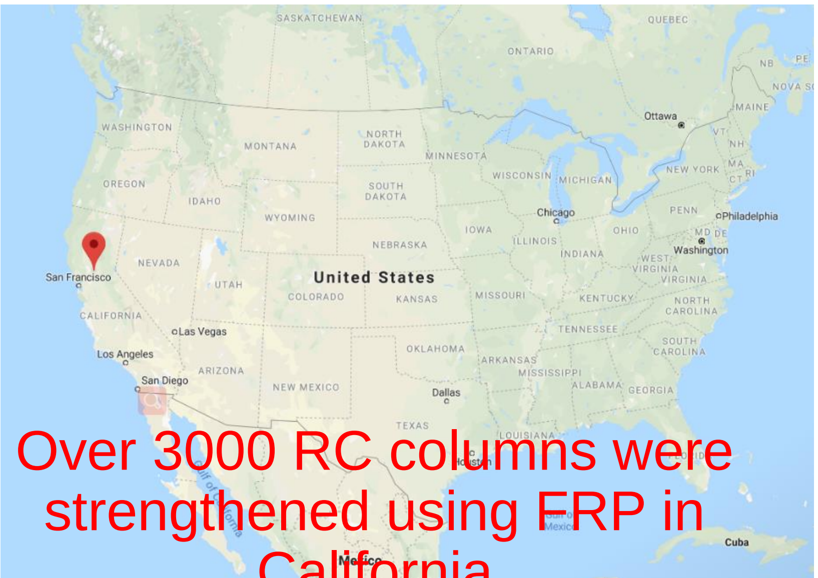
· 1 ·

表 5.7.5 复材加固构件的三等级耐火设计方法

等级	选用条件	防火保护措施
Ⅰ	$S_{mT} \leqslant R_{dT}$	宜在表面粉刷一层不少于 1cm 厚的水泥砂浆用于阻燃，无须采取其他的防火保护措施
Ⅱ	$R_{dT} < S_{mT} \leqslant R_d$	对原有构件采取防火保护措施，使 $S_{mT} \leqslant R_{dT}$ 或 $t_{fire} \geqslant [t_{fire}]$
Ⅲ	$R_d \leqslant S_{mT}$	采取防火保护措施保护原有构件及复材，应确保复材的温度在规定的耐火时间内 $[t_{fire}]$ 低于其玻璃化转变温度 T_g

注：1 R_d 为常温下原有构件的极限承载力。
2 R_{dT} 为达到耐火极限状态时原有构件极限承载力。
3 $[t_{fire}]$ 为《建筑设计防火规范》GB 50016 规定的耐火极限。

FRP Strengthening of RC Structures



Over 3000 RC columns were strengthened using FRP in California

(a)

(b)

(c)

(a)

(b)

(c)

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Emergency Strengthening with FRP
应急加固

成都机场机库震后应急加固

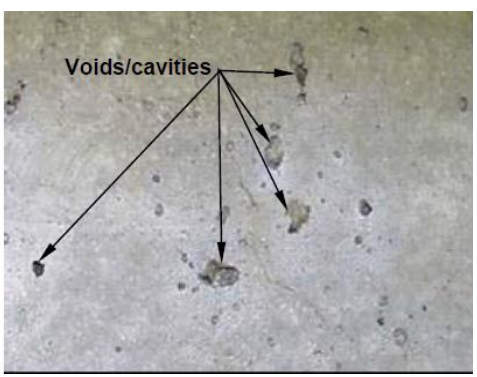
(图片由冶建院提供)

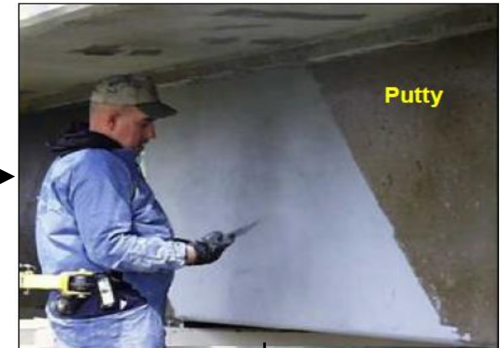
厦门大嶝大桥火灾后加固

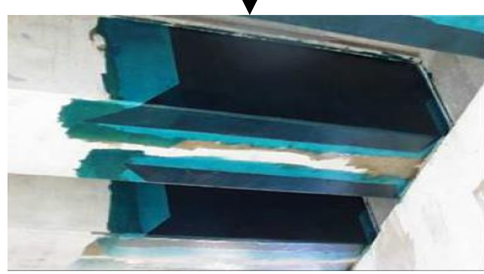
(图片由南京海拓提供)

Example of FRP Strengthening

Bridge Girders







Simpson, JW, Harik, IE and Chiaw, CC (2006). Shear Repair of P/C Box Beams using Carbon Fiber Reinforced Polymer (CFRP) Fabric, *Research Report*, University of Kentucky.

Example of FRP Strengthening
Marine Infrastructure

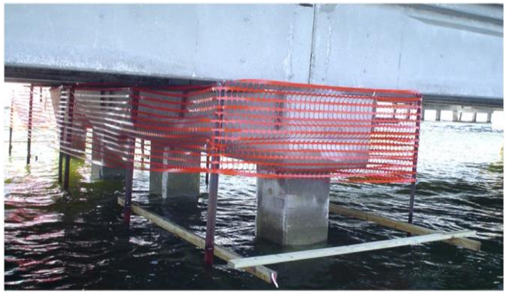
The Friendship Trail Bridge


(a)


(b)


(c)

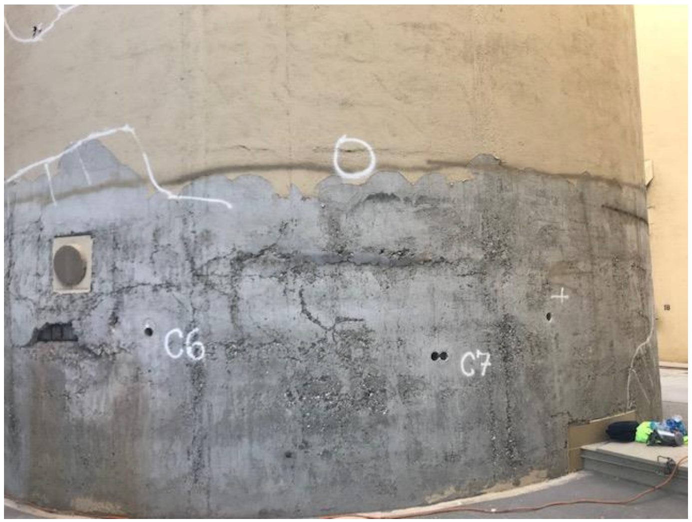

(d)

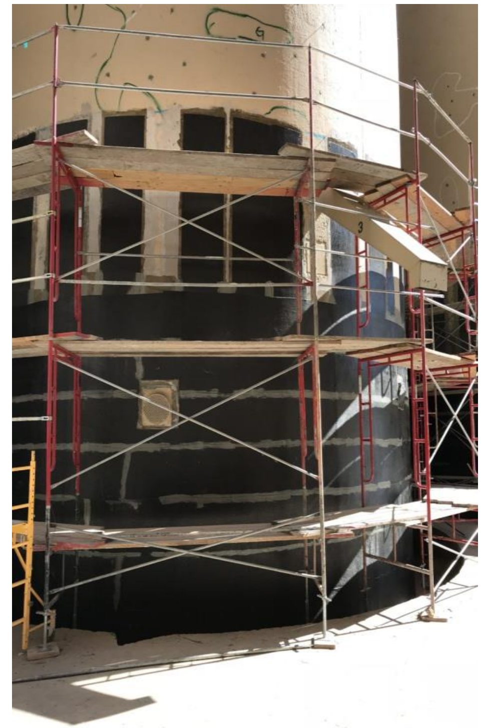


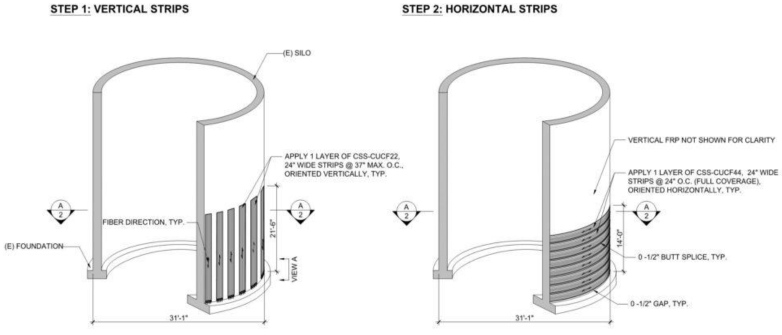
https://en.wikipedia.org/wiki/Gandy_Bridge
Winters, D., Mullins, G., Sen, R., Schrader, A., & Stokes, M. (2008). Bond enhancement for FRP pile repair in tidal waters. *Journal of Composites for Construction*, *12*(3), 334-343.
Al Azzawi, M., Hopkins, P., Mullins, G., & Sen, R. (2018). FRP–Concrete Bond after 12-Year Exposure in Tidal Waters. *Journal of Composites for Construction*, *22*(5), 04018031.

Example of FRP Strengthening

Storage Silos







https://seblog.strongtie.com/2019/10/case-study-shoring-up-aging-concrete-grain-silos-with-fiber-reinforced-polymer/

Local Projects

FRP-strengthened cantilever slabs with fibre anchors

Local Projects

成報 SING PAO DAILY NEWS 創刊1939 SINCE 1939

即时新闻 视频新闻 要闻港闻 社评 国际两岸 财经 娱乐 体育 马经

专家「会诊」 復修拟引进新物料 中环街市「伤重见骨」

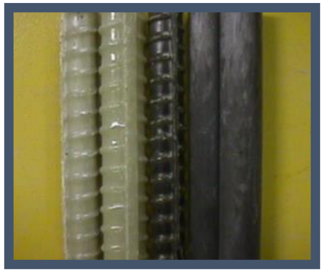
发佈日期：2017-10-23

（右起）麦中杰、韦志成、关建祺及滕锦光教授，到中

工程顧問建議引用「纖維增強聚合物復合材料」(FRP)進行復修

滕博士指，雖然內地和外國已應用FRP多年，不過針對加固後結構的耐火性研究則不多，因此香港在審批業界使用FRP時仍抱審慎態度。不過理大研究小組已就FRP加固後混凝土結構的耐火設計方法進行研究，並提出設計方法，能夠確保物料可安全應用在香港這種高密度城市的樓宇建築中。

FRP for New Construction



Reconstruction Project

Pak KoK Pier on Lamma Island, Hong Kong

Demonstration: **FRP-Reinforced Concrete Slab**

Source:https://www.wenweipo.com/a/202211/14/AP63718e7de4b09044e5126c1b.html

Concluding Remarks

- ✓ FRP strengthening has become accepted as a mainstream technology worldwide.

- ✓ FRP strengthening systems are particularly advantageous for their speedy installation, corrosion-resistance, flexibility in shape and light weight nature and may be used in various structural applications.

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
土木及環境工程學系

Thank you for your attention！

Opening Minds • Shaping the Future
啟迪思維 • 成就未來