FRP Café # 1
Strengthening of RC Structures using FRP

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JSPS Postdoctoral Fellow

Today's references

- Principles of Composite Material Mechanics – RF Gibson
- Strengthening of Reinforced Concrete Structures using externally bonded FRP composites in structural and civil engineering – LC Hollaway and MB Leeming
- FRP Strengthened RC Structures
  - JG Teng, JF Chen, ST Smith, L Lam
- Maeda T, Asano Y, Sato Y, Ueda T, Kakuta Y, "A Study on Bond Mechanism of Carbon Fiber Sheet", Non-Metallic (FRP) Reinforcement for Concrete Structures, 1997, Vol. 1 pp 279-286.
- Sato Y, Ueda T, Kakuta Y, Ono S, "Ultimate Shear Capacity of Reinforced Concrete Beams with Carbon Fiber Sheet" Non-Metallic (FRP) Reinforcement for Concrete Structures, 1997, Vol. 1 pp 499-506.

What is FRP?

- Fibers (high strength and stiffness) embedded in a resin matrix.
- A viable alternative to classical types of reinforcement, offering many potentials.
- Externally bonded FRP is used in strengthening of structures

Merits and demerits of FRP

- ✓ High strength
- ✓ Light weight
- ✓ Transport of plates
- ✓ Versatile design of systems
- ✓ Reduced mechanical fixing
- ✓ Durability of strengthening system
- ✓ Reduced risk of freeze/thaw damage
- ✓ Maintenance of strengthening system
- ✓ Reduced construction period
- ✓ Ability to prestress

- ✗ Cost of plates
- ✗ Mechanical damage

Background

- Structural Materials
  - Metals
  - Polymers
  - Ceramics
  - Composites

Composites are used as they have desirable properties which could not be achieved by either of the constituent materials acting alone.

History of composites

- Wood, bone
- Man-made composites
  - Straw reinforced clay bricks used by the Israelis recorded in Old Testament
  - Use of fiber plants in pottery by the early natives of South and Central America
  - Steel-reinforced concrete and polymer reinforced fibers

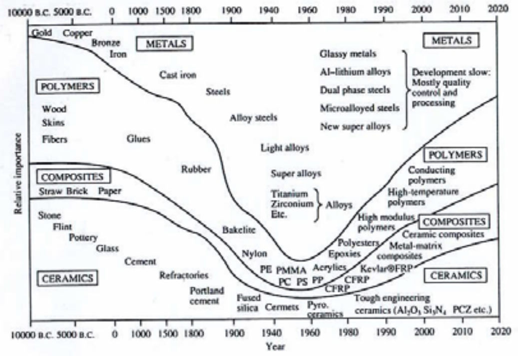


FIGURE 1.1
The relative importance of metals, polymers, composites, and ceramics as a function of time. The diagram is schematic and describes neither tonnage nor value. The time scale is nonlinear. (*From* Ashby [1.1].)

Fibrous Reinforcement

- Advantage: Most materials are much stronger and stiffer in fiber form then they are in bulk form

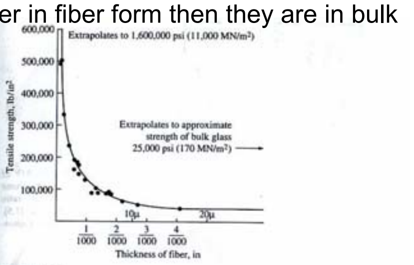


FIGURE 1.2
Griffith's measurements of tensile strength as a function of fiber thickness for glass fibers. (*Data from Griffith* [1.3], *as analyzed by Gordon* [1.4].)

Fibrous Reinforcement

- Disadvantage: Fibers alone cannot support longitudinal compressive loads and their transverse properties are not so good.
- Fibers are generally useless unless held together in a structural unit with a binder or matrix material

Fiber composites

- Geometrical configuration of fibers is very effective in interacting with matrix (binder)
- Matrix protects fibers from external damage and environmental attack.

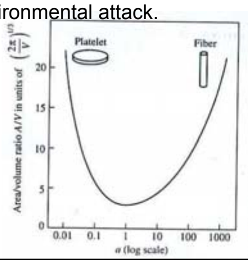
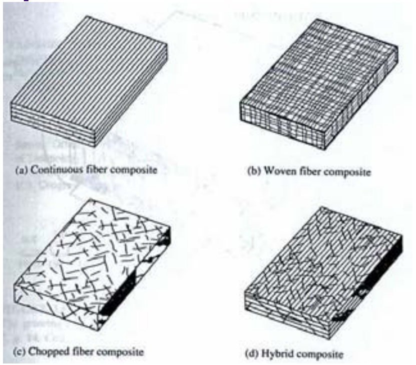


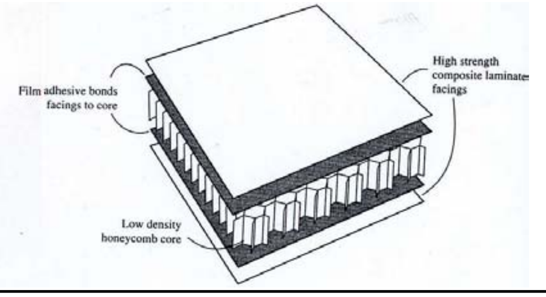
FIGURE 1.3
Surface area-to-volume ratio *A/V* of a cylindrical particle of given volume plotted vs. particle aspect ratio *a* = *l/d*. (*From McCrum et al.* [1.5]. *Copyright* © 1988 *by Oxford University Press.*)

Types of fiber reinforced composites

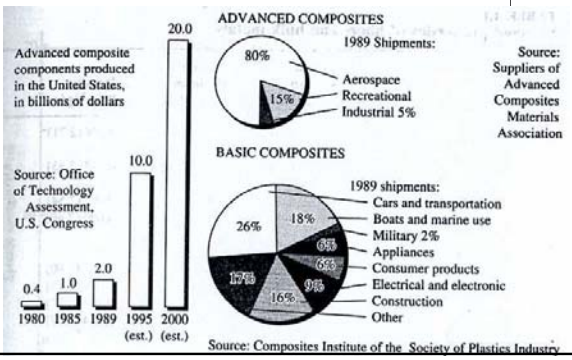


Composite sandwich structures

- High flexural stiffness-to-weight ratio



Growing use of composite materials



Constituent materials for composites

- Fiber materials
  - Glass
  - Carbon
  - Aramid
- Matrix and filler materials

1. Fiber Materials

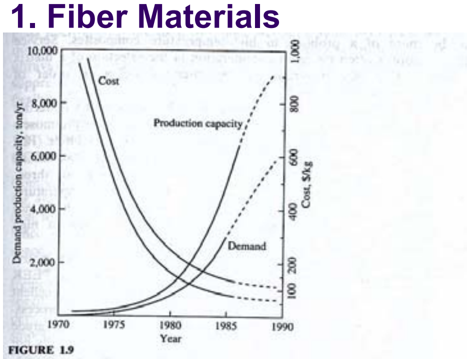


FIGURE 1.9
PAN-base carbon fibers are the major reinforcement used in today's advanced polymer matric composites. Fiber cost has and will continue to drop as production capacity and demand increases. (*From Reinhart*[1.8].)

Matrix and filler materials

- Matrix:
  - Holds the fibers together in a structural unit
  - Protects from external damage
  - Transfers and distributes the applied load to fibers
  - Contributes to ductility, toughness, or electrical insulation
- Filler materials:
  - Reduce weight
  - Reduce cost
  - Protection against ultra-violate rays

Temperature issues

- Epoxy - 150^{o}C
- Advanced thermoplastics - 315-370^{o}C
- Light wt. metals (aluminum) - 1250^{o}C
  - Higher strength, stiffness and ductility
  - Higher density
- Ceramic matrix - 1650^{o}C
  - Poor tensile strength, brittle
- Carbon Matrix - 2760^{o}C

Applications

- Consumer products
  - Skis
  - Golf clubs
  - Tennis rackets
- As structural elements
  - Automotive
  - Aerospace
  - Marine
  - Civil engineering structures

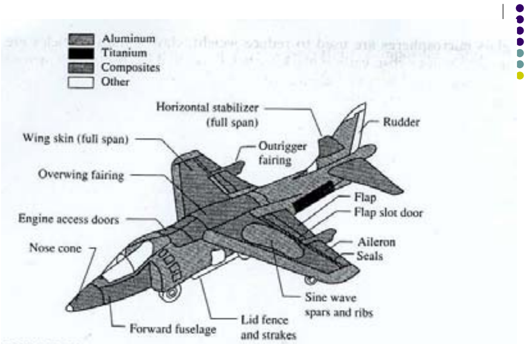


FIGURE 1.10
Composite structures on the AV-8B fighter aircraft. (*From Schwartz* [1.7]. *Copyright* © 1984 *by McGraw-Hill, Inc., Reprinted by permission.*)

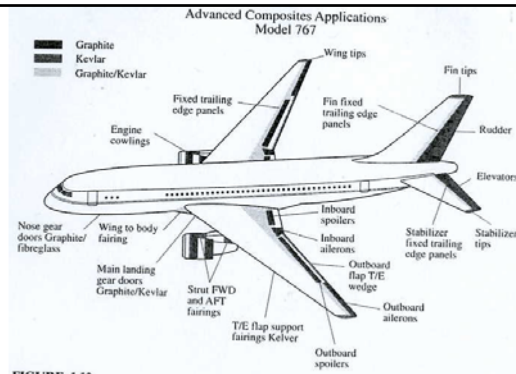


FIGURE 1.12
Composite applications on the Boeing 767 airliner. (*Courtesy of Boeing.*)

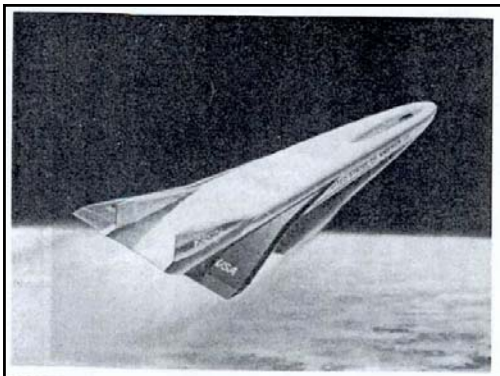


FIGURE 1.15
Conceptual drawing of the proposed National Aero-Space Plane, which would make extensive use of high-temperature composites. (*Courtesy of National Aero-Space Plane Joint Program Office.*)

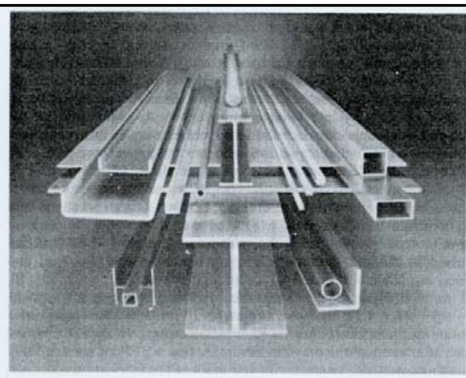


FIGURE 1.18
Fiberglass composite structural elements formed by pultrusion. (*Photo Courtesy of MMFG.*)

Fabrication process

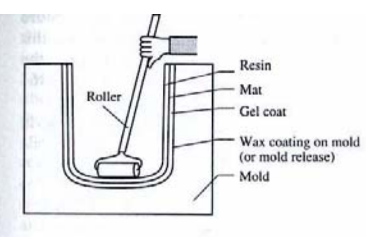


FIGURE 1.20(*a*)
Open mold, hand lay-up composite fabrication.

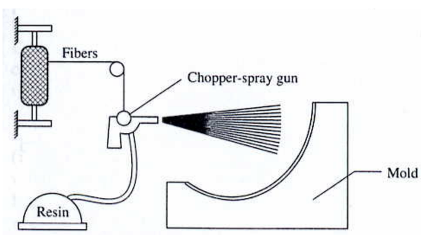


FIGURE 1.20(*b*)
Open mold, spray-up composite fabrication.

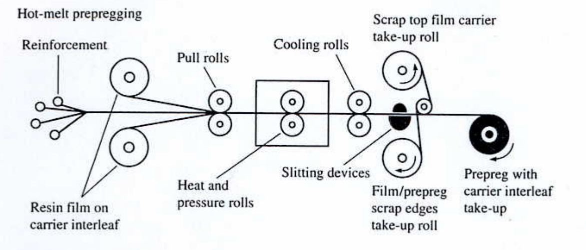


FIGURE 1.21
Hot-melt prepregging process. [*Courtesy of Suppliers of Advanced Composite Materials Association (SACMA).*]

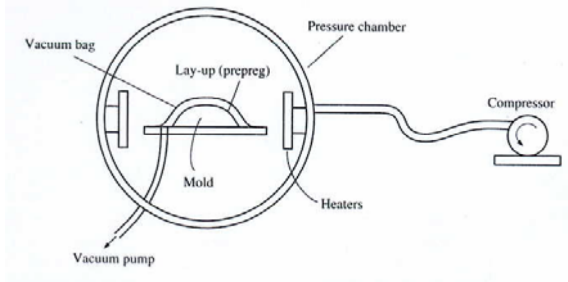


FIGURE 1.22
Autoclave molding.

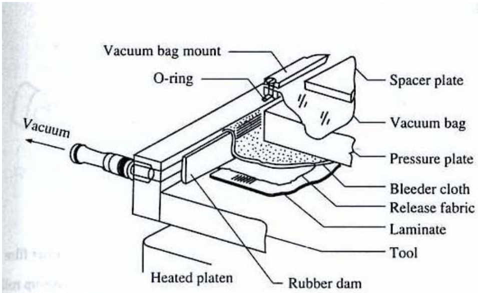


FIGURE 1.23
Lay-up sequence for autoclave-style press molding.

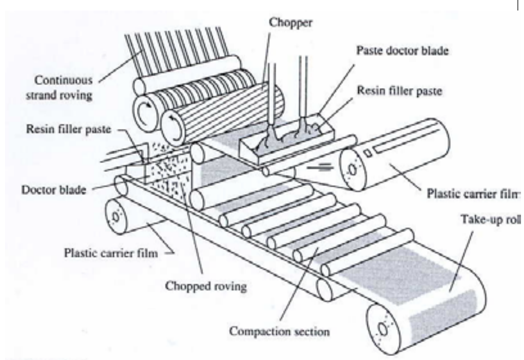


FIGURE 1.24
Machine for producing sheet-molding compound (SMC). (*From Reinhart et al.* [1.12]. *Reprinted by permission of ASM International.*)

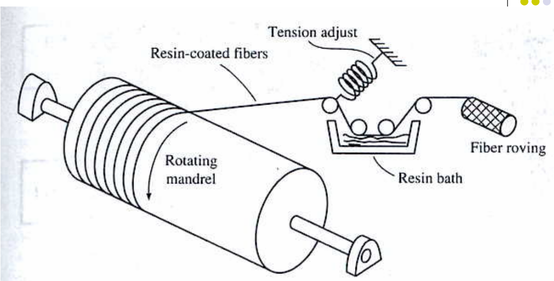


FIGURE 1.26
Filament winding process.

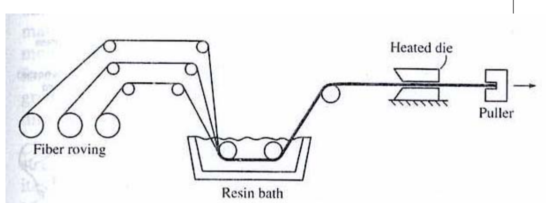
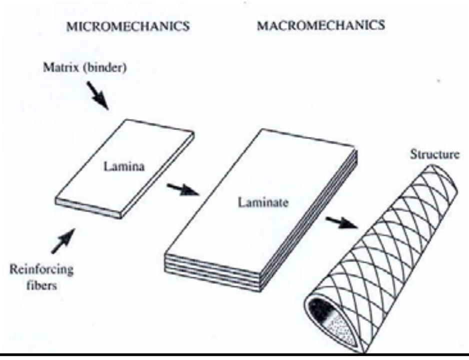


FIGURE 1.29
Pultrusion process.

Mechanical behavior of composites



FRP plates

- Primarily used in retrofitting by bonding it on the surface of structural members.
- Started in 1984 at the Swiss Federal Laboratory

Market of strengthening

- Structures are deteriorating
- Changes in use or imposed loading
- Minimize disruption during repair
- Extend useful life in minimizing capital outlay
- Evaluation of whole life cost of solutions

Table 1.1 Applications for composite plate bonding

Structural need/deficiency	FRP composite plate bonding solution	Comments
Corrosion of reinforcement in reinforced concrete	Replacement of lost reinforcement by plates of equivalent effect	Damaged concrete must be replaced without impairing behaviour of plates
Inadequate flexural capacity of reinforced concrete	Design FRP composite plate bonding solution to add tensile elements	Extent of strengthening limited by capacity of concrete in compression. Plates anchored by bond or mechanically at their ends
Lost prestress due to corrosion in prestressed concrete	Replace prestress that has been lost with stressed composites	Need to ensure no overstress of concrete in the short term
Safety net to cover uncertain durability of prestressed concrete	Add plates, either stressed or unstressed, to ensure safety. Particularly appropriate if corrosion unlikely but possible	Method may be particularly appropriate with segmental construction. May be combined with a monitoring system

Inadequate stiffness or serviceability of cracked reinforced concrete structure	Add external prestress by means of a stressed composite plate	
Potential overstress due to required structural alteration	Analyse stresses due to alteration, and design composite reinforcement before removing load-bearing members	
Avoidance of sudden failure by cracking of cast iron	Addition of FRP composite plate bonding, either stressed or unstressed, to tensile face	
Increase in structural capacity of timber structures	Increase in stiffness and ultimate capacity by plate bonding	Particularly appropriate with historic structures
Enhancement of shear capacity	Enhanced by external bonding of stressed plates, or by web reinforcement	Web reinforcement techniques little researched

Mechanical properties

Unidirectional composite	Fiber content (% by weight)	Density (kg/m3)	Longitudinal tensile modulus (GPa)	Tensile strength (MPa)
GFRP	50-80	1600-2000	20-55	400-1800
CFRP	65-75	1600-1900	120-250	1200-2250
AFRP	60-70	1050-1250	40-125	1000-1800

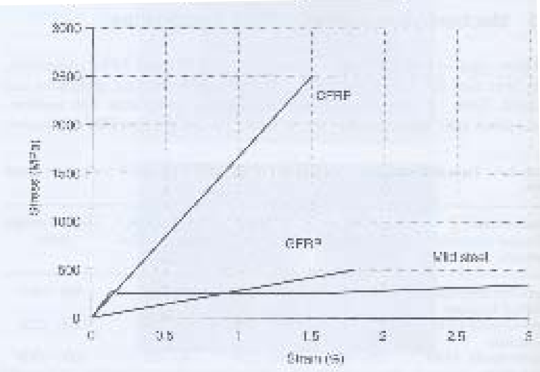


Figure 1.2 Typical FRP and mild steel stress–strain curves

Table 2.1 Comparison of characteristics of FRC sheet produced from different fibres (Meier, 1995)

Characteristics	Carbon	Aramid	E-glass
Tensile strength	Very good	Very good	Very good
Compressive strength	Very good	Inadequate	Good
Stiffness	Very good	Good	Adequate
Long term behaviour	Very good	Good	Adequate
Fatigue behaviour	Excellent	Good	Adequate
Bulk density	Good	Excellent	Adequate
Alkaline resistance	Very good	Good	Inadequate
Cost	Adequate	Adequate	Very good

Shear strengthening

- Selection of strengthening scheme
  - Accessibility of the site
  - Strengthening requirements (monotonic, reversed cyclic)
  - Amount of increase required in the shear capacity
  - Availability of FRP materials
  - Economic considerations

Design philosophy (JSCE)

- Considered similar as an internal shear reinforcement
- Truss analogy with the 45° crack angle is used
- An additional shear reinforcing efficiency 'K' is used in design

$$V_{fyd} = V_{cd} + V_{sd} + V_{fd}$$

$$V_{sd} = \lfloor A_w \cdot f_{wyd} (\sin\alpha_s + \cos\alpha_s) / s_s \rfloor \cdot z / \gamma_b$$

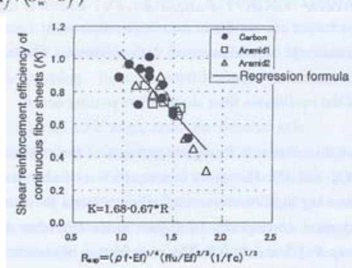
$$V_{fd} = K \cdot [A_f \cdot f_{fud} (\sin\alpha_f + \cos\alpha_f) / s_f] \cdot z / \gamma_b$$

Shear reinforcing efficiency

$K = 1.68 - 0.67R$, however, $0.4 \le K \le 0.8$ ....

$R = (\rho_f \cdot E_f)^{1/4} \left(\frac{f_{fud}}{E_f}\right)^{2/3} \left(\frac{1}{f'_{cd}}\right)^{1/3}$, however, $0.5 \le R \le 2.0$

$\rho_f = A_f / (b_w \cdot s_f)$



- Limitation: Can be used only for full-wrapping
- Why?: for side bonding and U-wrapping, debonding leads to the fractional utilization of FRP strength

What is debonding?

- FRP is highly stressed near crack.
- The stress is transferred to concrete due to bond
- Once the bond stress exceeds the bond strength debonding occurs.
- If there is no proper anchorage (side plates, U-wraps) the strengthening becomes ineffective.
- Bond failure generally occurs in the concrete adjacent to adhesive-concrete interface.

Bond Strength of FRP to Concrete Joints

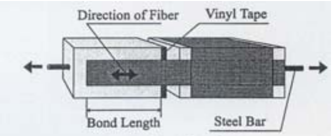


Fig.1 Specimen

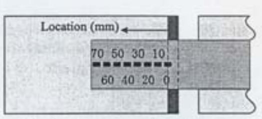


Fig.2 Arrangement of strain gages

Table1 Details of experimental specimens

Specimen	Bond length (mm)	Number of CFS	Compressive strength of concrete (MPa)	Ultimate load (kN)	Failure mode	Average bond strength (MPa)
1	75	1	40.8	11.6	CFS delamination	1.67
2	150	1	40.8	18.4	CFS delamination	1.23
3	300	1	43.3	23.9	CFS delamination	0.80
4	75	1	42.4	20.0	Concrete fracture	2.67
5	150	1	42.4	14.6	CFS breakage	0.97
6	65	2	42.7	19.1	Concrete fracture	2.94
7	150	2	42.7	32.5	CFS delamination	2.17
8	700	1	44.7	20.0	CFS delamination	0.31

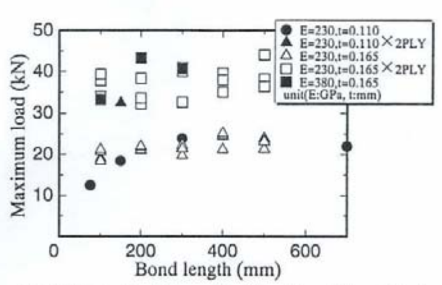


Fig.3 Relationships between bond length and ultimate load

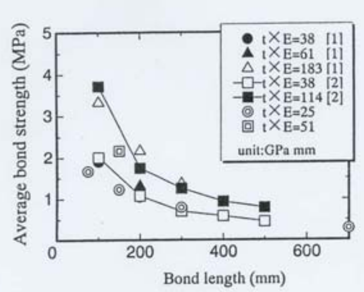


Fig.4 Relationship between bond length and average bond strength

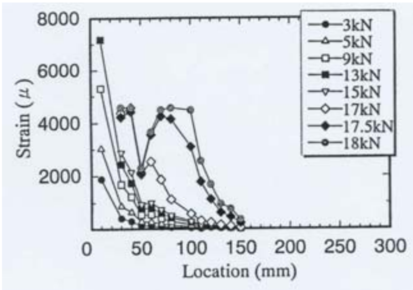


Fig.5 Strain distribution in specimen No.2

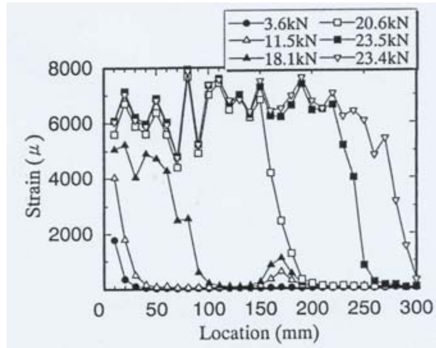


Fig.6 Strain distribution in specimen No.3

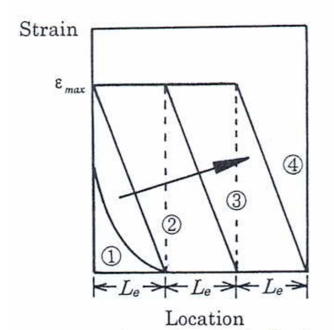


Fig.7 Schematic strain distribution

Mechanical Anchorage

Table 3 Details of bond test specimen

Specimen	Bond length (mm)	Concrete strength (MPa)	Ultimate load (kN)	Failure mode
B1	50	24.8	10.1	Peeling of CFS
B2	100	24.8	13.7	Peeling of CFS
B3	50	24.8	21.9	Concrete splitting
B4	100	24.8	21.9	Breakage of CFS

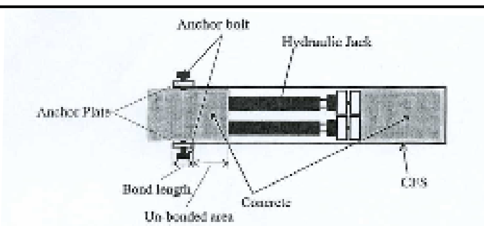


Fig.10 Specimen

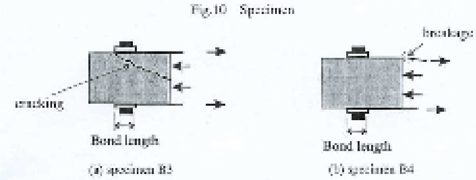


Fig.11 Failure mode in specimens B3 and B4

Shear Strengthening with mechanical anchorage

Table 2 Details of experimental specimens

Specimen	f_c' [1] (MPa)	p_t [2] (%)	p_w [3] (%)		p_{CFS} [4] (%)	Anchor[5]	V_u [6] (kN)	Failure mode [7]
No.1	35.9	3.28	0.35	0.79	0	w/o	199	DT
No.2	35.7	3.28	0.35	0.79	0.15	w/o	223	P
No.3	35.3	3.28	0.35	0.79	0.15	with	264	P

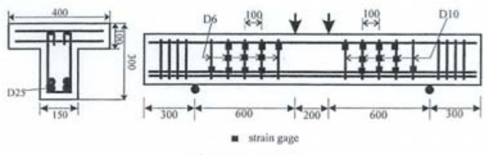


Fig.1 Specimen

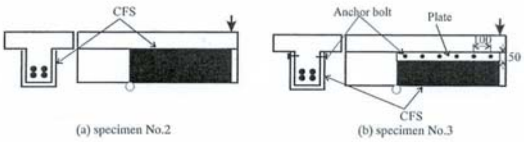


Fig.2 Arrangement of CFS

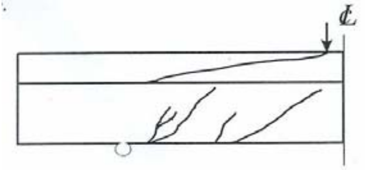


Fig.3 Crack pattern of specimen No.1

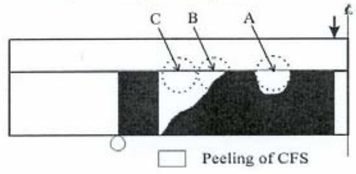


Fig.4 Delamination of CFS in specimens No.2

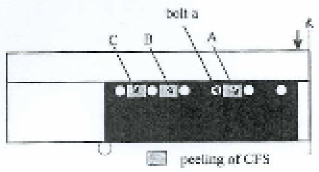


Fig.5 Delamination of CFS in specimen No.3

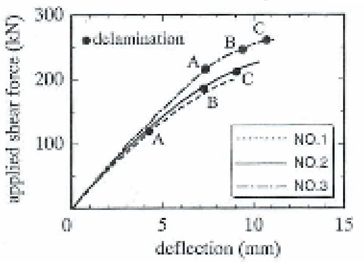


Fig.6 Relationships between shear force and deflection at the center of span

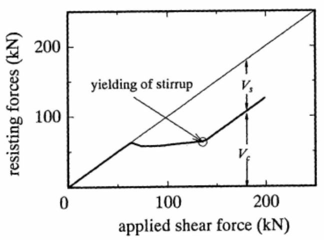


Fig.7 Relationships between applied shear force and shear resisting forces (specimen No.1)

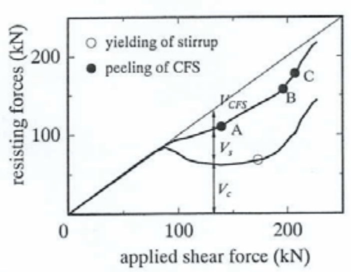


Fig.8 Relationships between applied shear force and shear resisting forces (specimen No.2)

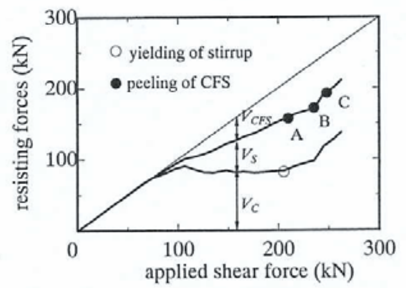


Fig.9 Relationships between applied shear force and shear resisting forces (specimen No.3)