

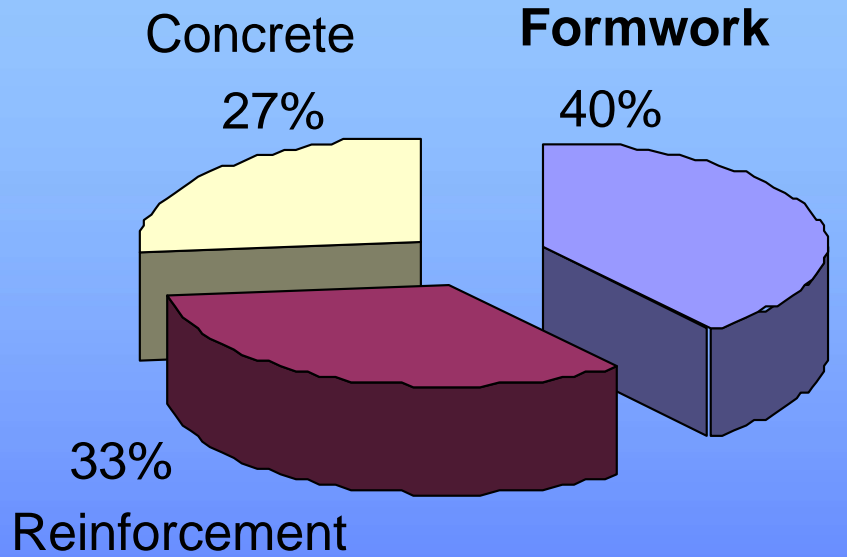
# Applications of FRP/GRC in Permanent Formwork

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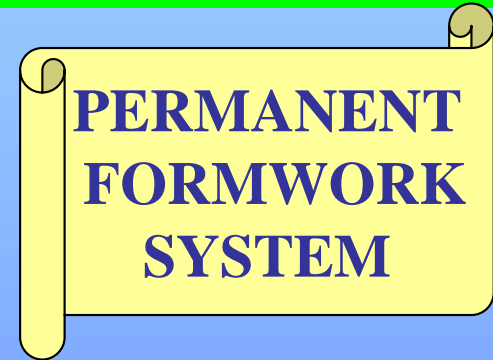
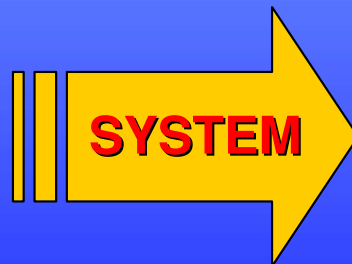
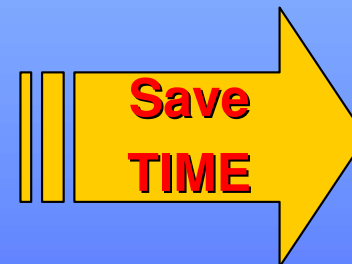
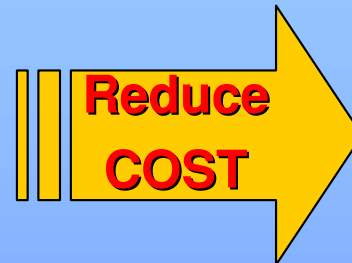
Innovative Materials and Technologies for Construction and Restoration  
Lecce (Italy), June 6-9, 2004

**Presented by: G.B.KIM**

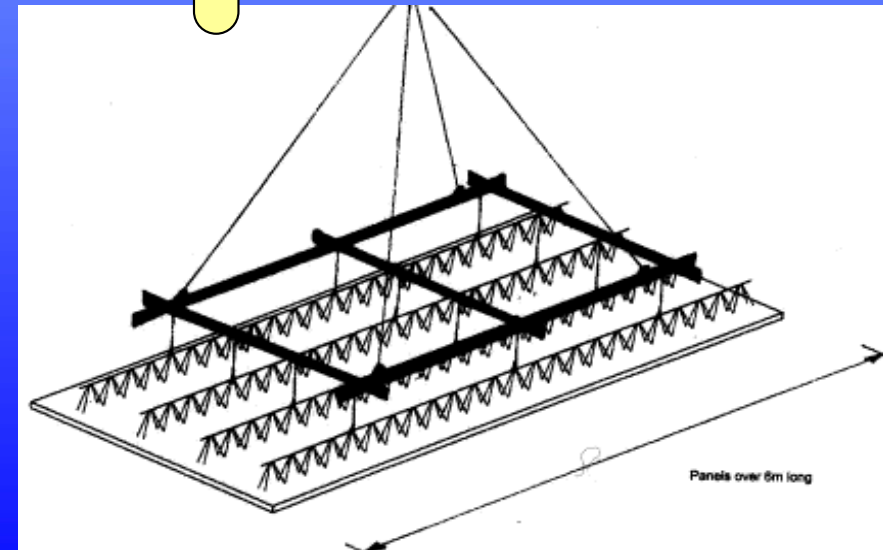
- Permanent Formwork
- GRC and FRP
- Experimental Work Done
- Results
- Optimisation
- Skin and Rib



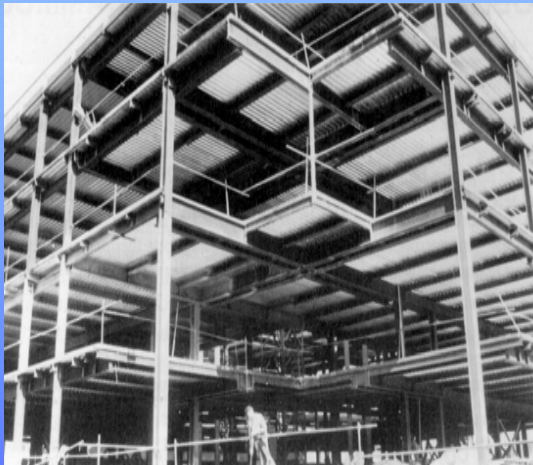
Costs based on typical building



+



# Permanent Formwork Systems



Steel decking

*Speed & Simplicity*

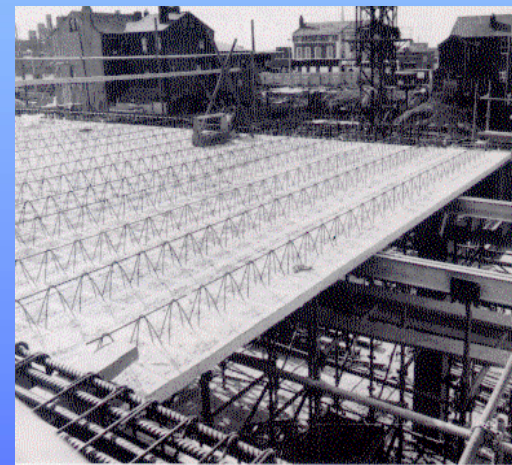
*Corrosion*  
*Fire protection*  
*Constant thickness*  
*One way spanning*  
*Need additional finishes*



Pre-cast concrete

*Attractive finish*

*Heavy handling*



Omni-plank type

*Effective load transfer*  
*Speedy construction*  
*Controlled finish*

*Crack in tension zone*  
*during casting*

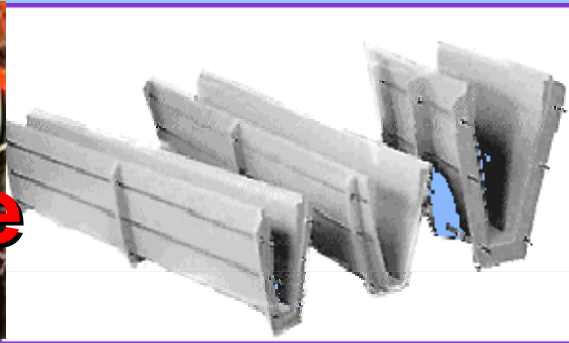


GRC

*Light*  
*Attractive finish*  
*Any shape*

*Low strength*  
*Short spans*

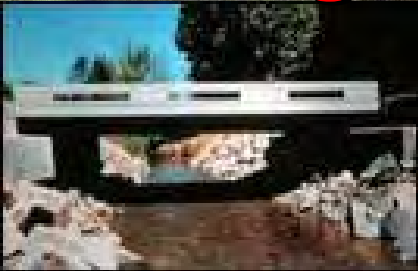
# GRC Applications



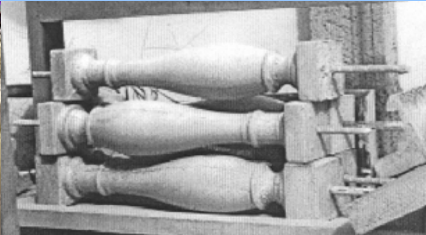
## Drainage



## Bridge



- ✓ Low self-weight
- ✓ Fast to install
- ✓ Easy to create complicated shapes
- ✓ Good Durability of the cover
- ✓ Corrosion protection to the steel reinforcement
- ✓ Attractive finishes

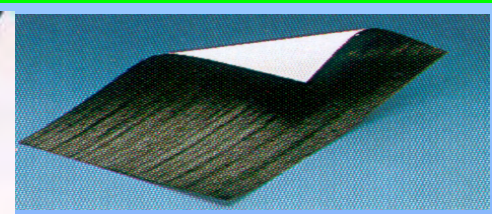
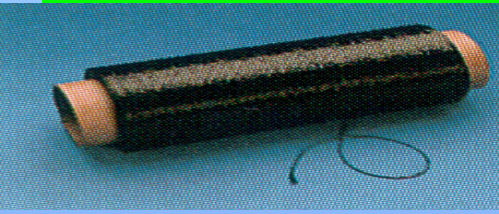


## Architectural



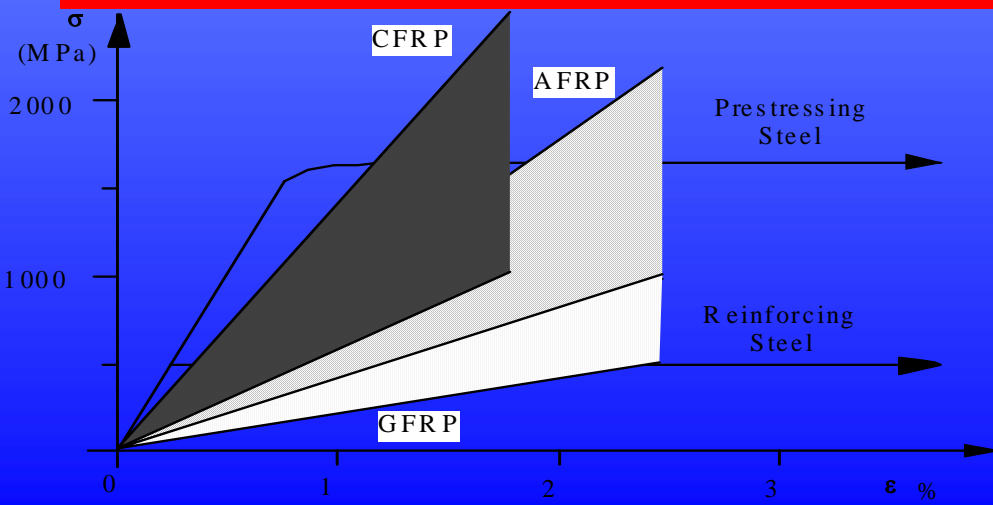
## Tunnel

# FRP PROs & CONs



- **Strength/Specific Gravity (10-15 times that of steel)**
- **Corrosion Resistance**
- **Fatigue Characteristics**
- **Electromagnetic Neutrality**
- **Require minimum cover**

- **High Cost**
- **Low Elastic Modulus**
- **Stress Corrosion**
- **Lack of Ductility**
- **Anisotropic properties**



- Expensive (material costs)
- Additional reinforcement
- Ribs become quite thick

 Longer span, Thinner, stronger structural elements

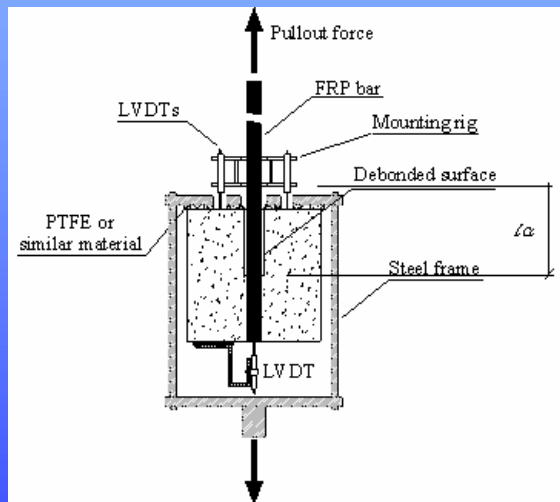
## Permanent formwork

- ① Optimal utilisation of the material
- ② Achieving longer unsupported spans

- ◆ A preliminary experimental study (Pullout & Splitting)
- ◆ Bond behaviour of GRC containing embedded reinforcing bars

## □ EXPERIMENTAL SET-UP

- ✓ Four / Five LVDT are used



## □ MATERIALS

- Mechanical properties of GRC & rebars
  - W/C = 0.35, S/C = 1.0   -  $f_c = 54$  and  $66$  MPa   -  $f_{ct} = 6$  and  $7$  MPa (by Brazilian Test )
  - $f_{t\_steel} = 500$  MPa,  $f_{t\_GFRP} = 900$  MPa   -  $E_{GFRP} = 45$  GPa,    $E_{steel} = 205$  GPa

## □ SLIP

Actual slip of the bar with respect to the concrete,  $\delta_{le}$

Average slip measurements of three LVDTs,  $\delta_{av}$

Elastic elongation of the unbonded portion of the bar,  $\Delta l$

$$\delta_{le} = \delta_{av} - \Delta l = (\delta_1 + \delta_2 + \delta_3) / 3 - Fl_a / (EA)$$

where,  $\delta_1, \delta_2, \delta_3$  = slip measurements of the three LVDTs

## □ BOND STRESS

$$\tau = \frac{F}{\pi dL}$$

where,  $F$  = applied pullout load

$d$  = diameter

$L$  = bond length of the bar

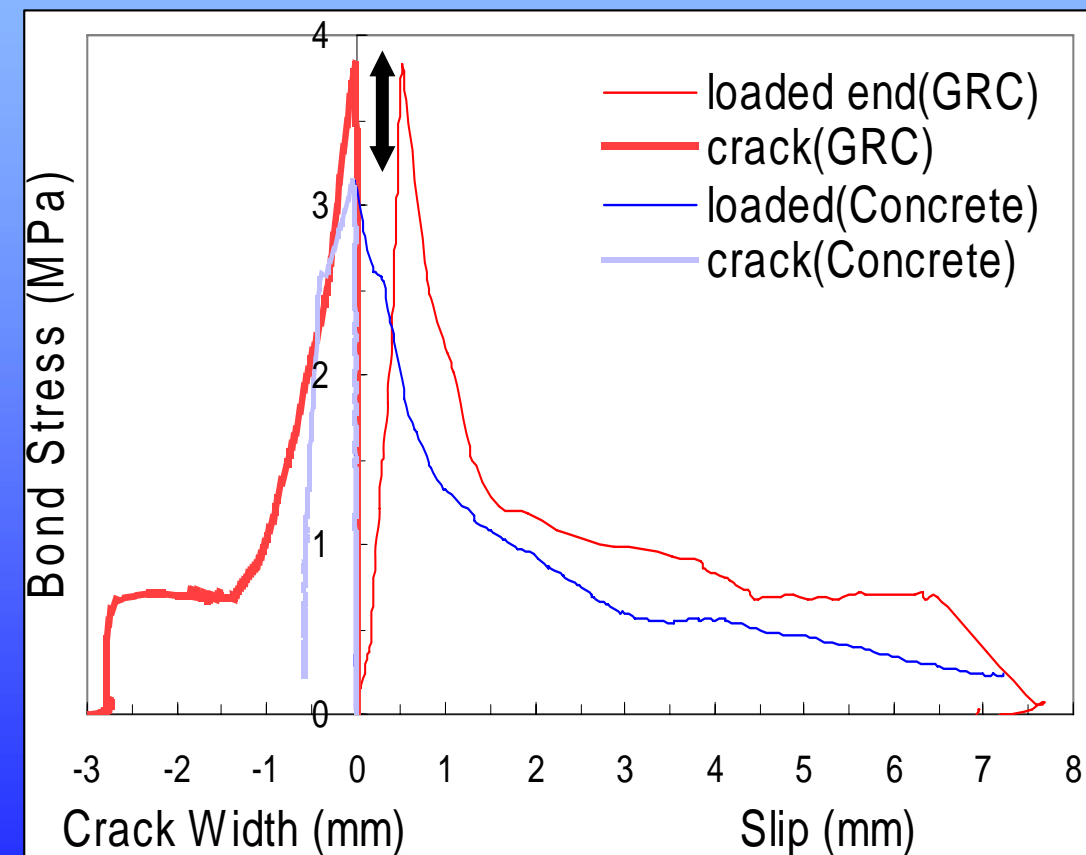
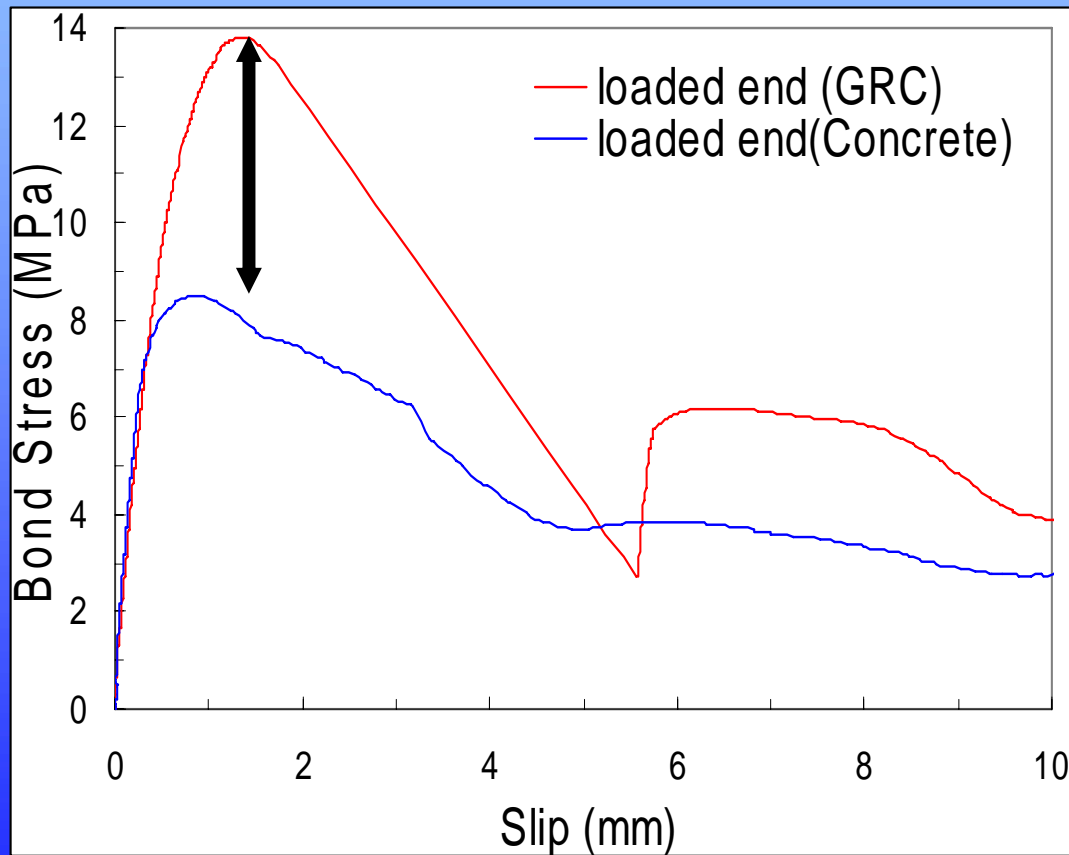
$l_a$  = unloaded length

$F$  = applied pullout load

$E$  = elastic modulus of the bar

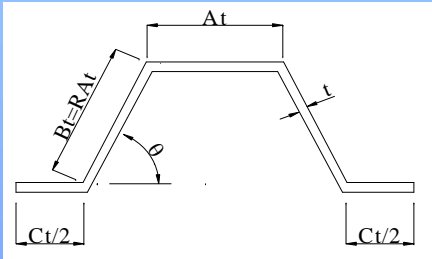
$A$  = cross-sectional area of the bar

- Similar failure mechanism
- GRC provides higher initial and residual strength than Concrete
- Bond stress in GRC : 60% (pullout) & 26% (splitting) higher than in Concrete



<Bond Stress - Slip curves ; 8mm GFRP bars>

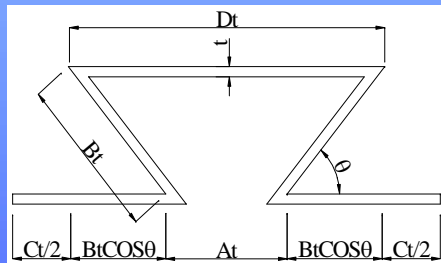
## Trapezoidal section



$$I = \frac{At^4}{6} + \frac{At^4}{2} [B \sin \theta - 1]^2 + \frac{t^4 B^3 \sin^2 \theta}{6}$$

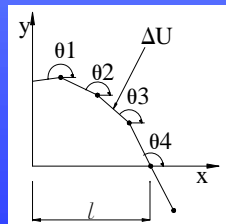
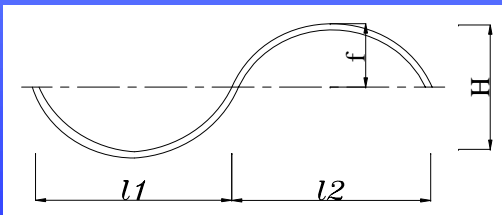
$$W_{ua} = \frac{(A + B)\rho t}{(A + B \cos \theta)} \quad Z'_w = \frac{(I / y_m)}{W_{ua}}$$

## Re-entrant section



$$I = \frac{At^4}{6} + \frac{At^4}{2} [B \sin \theta - 1]^2 + \frac{t^4 B^3 \sin^2 \theta}{6} + B^3 t^4 \sin^2 \theta \cos \theta$$

## Sinusoidal section



$$I_x = \sum_{n=1}^m \Delta I_{xn}$$

$$\Delta I_{xn} = \frac{t_c (\Delta u)^3}{12} \sin^2 \theta_n + t_c (\Delta u) y^2$$

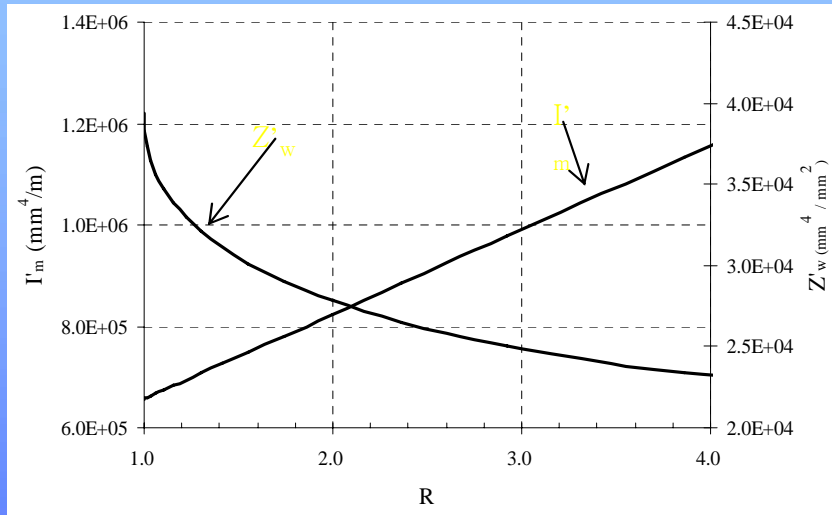
$$\bar{y} = \frac{y_n + y_{n+1}}{2}$$

where,  $At$  is the width of the top plate,  $\theta$  is the inclination of the sloping plate,  $W_{ua}$  is the weight of material per unit area,  $Z'_w$  is section modulus per unit weight,  $\rho$  is the density,  $y_m$  is distance from bottom fibre to neutral axis of section,  $t$  is the thickness,  $m$  is the total number of segments,  $\Delta u$  is the constant segment length, and  $\Delta I_{xn}$  is the moment of inertia of a segment above the centroidal axis.

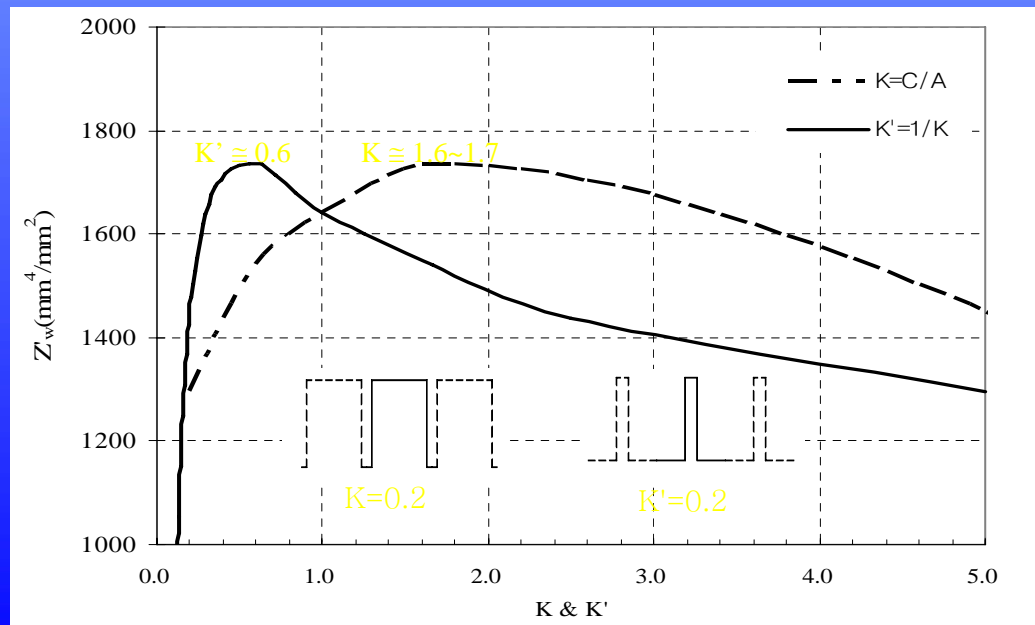
# Relationship of profile variables

$R = \text{Inclined chord} / \text{Top chord}$ ,

$K = \text{Bottom chord} / \text{Top chord}$

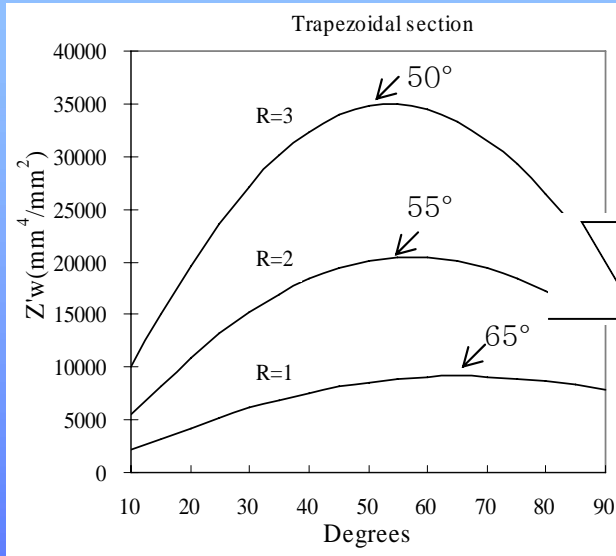


- $I$  &  $W_{ua}$  ↗ with  $\theta$
- for a constant depth and when  $K = 1$ ,  $\theta$  decreases as  $R$  increases
- Trapezoidal section (per metre width);  
 $I'_m$  ↗ with  $R$ , but  $Z'_w$  ↘
- Controlling factor =  $\delta$ ,  $\theta=90$ , but buckling,  
 $R=1.51$
- When  $\theta=90$  & constant depth,  $K=1.6\sim 1.7$
- $K=0.2$  &  $K'=0.2$ ; (exactly same  $I$ )  
construction stage ( $K=0.2$ )  
composite stage ( $K'=0.2$ )

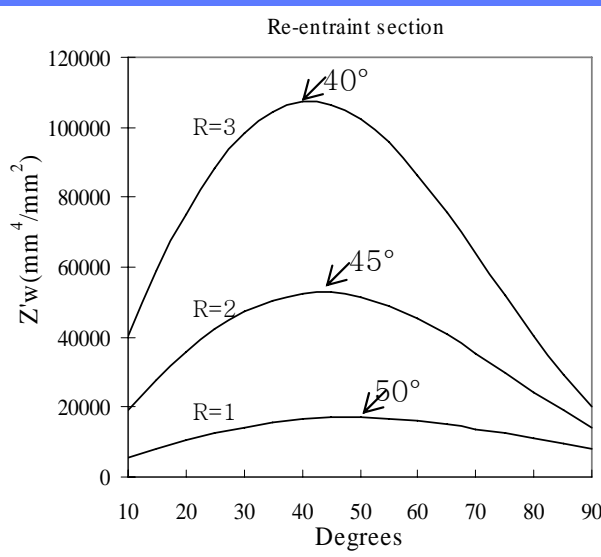


# Optimum angle & Cross section

$K = 1.0$



No.	$\theta^\circ$	$R=B/A$	$K=C/A$	$P=D/A$	$I(\text{cm}^4)$	$I_m(\text{cm}^4/\text{m})$	$Z'_w$	Shape
1	90	1.0	1.0	1.0	66.671	333.354	166.261	
2	-	( $l_1=1.0$ )	( $l_2=1.0$ )	-	39.276	196.382	124.615	
3	90	1.0	1.6	1.0	79.846	307.098	173.201	
4	90	1.0	1.0	1.0	44.710	171.960	125.402	
5	90	1.0	1.0	1.0	41.920	349.330	130.590	
6	-	( $l_1=0.2$ )	( $l_2=1.0$ )	-	39.660	330.500	136.309	
7	90	1.0	0.2	1.0	41.420	345.163	129.033	
8	-	( $l_1=0.2$ )	( $l_2=1.0$ )	-	39.948	332.903	136.374	
9	65	1.103	1.0	1.93	68.394	233.219	162.196	
10	-	( $l_1=1.1$ )	( $l_2=1.0$ )	-	48.505	165.397	128.289	
11	65	1.103	1.6	1.93	81.602	230.996	169.413	
12	-	( $l_1=1.1$ )	( $l_2=1.6$ )	-	54.636	154.662	127.976	
13	50	0.5	0.37	0.37	155.675	423.029	195.149	
14		(as 13 – rounded corners)			147.726	401.430	<b>218.363</b>	
15	50	0.5	0.6	0.37	169.775	396.671	197.938	
16		(as 15 – rounded corners)			161.827	378.100	219.719	

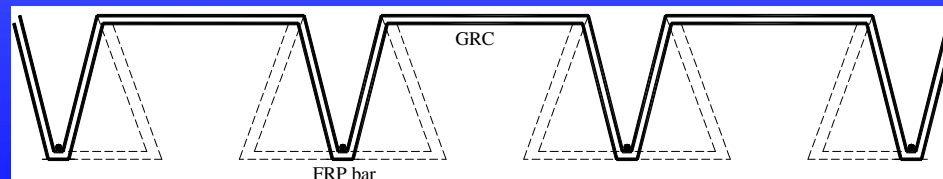


# “Skin” and “rib” approach

Thin GRC structural elements  
Thickness does not have to be constant  
Compressive strength much higher

## GRC PF incorporating FRP reinforcement

Provide much of tensile capacity  
Little Cover  
Crack width limit relaxed up to 0.5mm



- **Combination of new materials (superior durability)**
- **Bond Strength Good**  
( $\tau_{\text{FRP rebar and GRC}} \approx 1.6 \times \tau_{\text{FRP rebar and concrete}}$ )
- **Development of integrated permanent formwork solutions**
- **Develop ; connection, support system & further study ; load-carrying capacity of completed slab**
- **Case studies**
- **Design guidelines**