

● CAPACITA' DI ROTAZIONE RISPETTO ALLA CORDA

$$\theta_u = \frac{1}{\gamma_{el}} \cdot \left[ \theta_y + (\phi_u - \phi_y) \cdot L_{pl} \cdot \left( 1 - \frac{L_{pl}}{2 \cdot L_v} \right) \right]$$

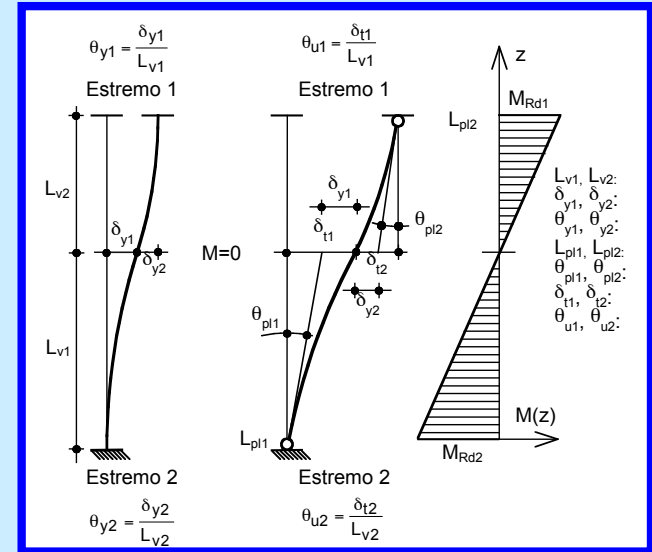
● Curvatura e momento allo snervamento

Non confinato	$\varphi_y = 0.0093 \frac{1}{m}$	Confinato	$\varphi_y = 0.0095 \frac{1}{m}$
	$M_y = 97.29 \text{ kNm}$		$M_y = 96.72 \text{ kNm}$

● Rotazione rispetto alla corda allo snervamento

$$\begin{aligned} \theta_y &= \varphi_y \cdot \frac{L_v}{3} + 0.0013 \cdot \left( 1 + 1.5 \cdot \frac{H}{L_v} \right) + 0.13 \cdot \varphi_y \frac{d_b f_y}{\sqrt{f_c}} = \\ &= 0.0093 \cdot \frac{1.5}{3} + 0.0013 \cdot \left( 1 + 1.5 \cdot \frac{0.4}{1.5} \right) + 0.13 \cdot 0.0093 \cdot \frac{0.016 \cdot 374}{\sqrt{14.4}} = 8.36 \cdot 10^{-3} = 0.48^\circ \quad \text{Confinato} \end{aligned}$$

$$\begin{aligned} \theta_y &= \varphi_y \cdot \frac{L_v}{3} + 0.0013 \cdot \left( 1 + 1.5 \cdot \frac{H}{L_v} \right) + 0.13 \cdot \varphi_y \frac{d_b f_y}{\sqrt{f_c}} = \\ &= 0.0095 \cdot \frac{1.5}{3} + 0.0013 \cdot \left( 1 + 1.5 \cdot \frac{0.4}{1.5} \right) + 0.13 \cdot 0.0095 \cdot \frac{0.016 \cdot 374}{\sqrt{11.3}} = 8.77 \cdot 10^{-3} = 0.50^\circ \quad \text{Non confinato} \end{aligned}$$



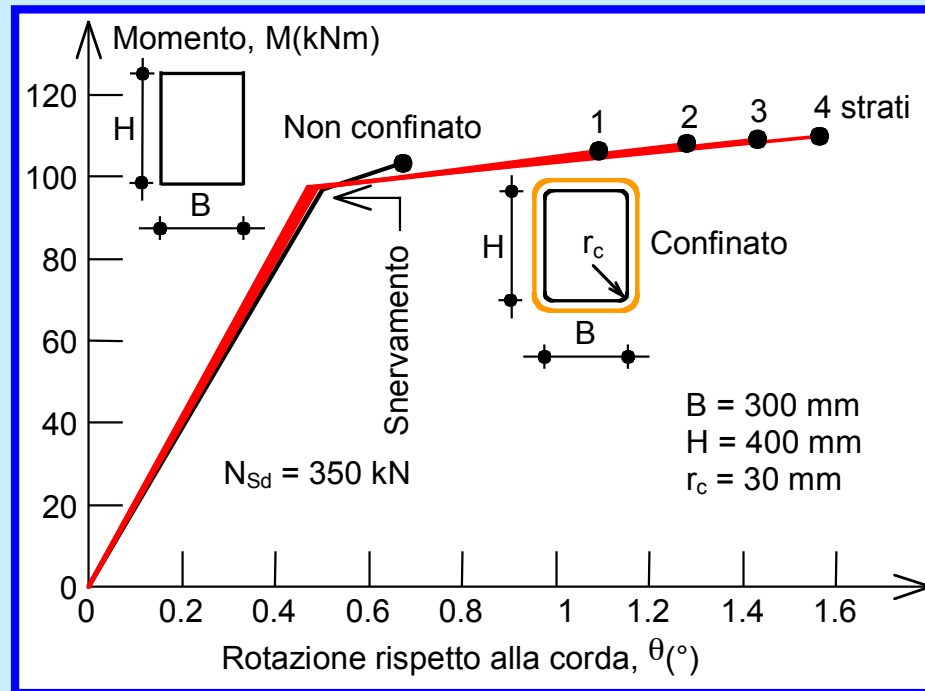
• Capacità di rotazione rispetto alla corda

$$\theta_u = \frac{1}{\gamma_{el}} \cdot \left[ \theta_y + (\varphi_u - \varphi_y) \cdot \left( 1 - \frac{L_{pl}}{2L_V} \right) \cdot L_{pl} \right] =$$

$$= \frac{1}{1.5} \cdot \left[ 8.36 \cdot 10^{-3} + (0.062 - 0.0093) \cdot \left( 1 - \frac{0.6}{2 \cdot 1.5} \right) \cdot 0.6 \right] = 0.022 = 1.28^\circ \quad \text{Confinato}$$

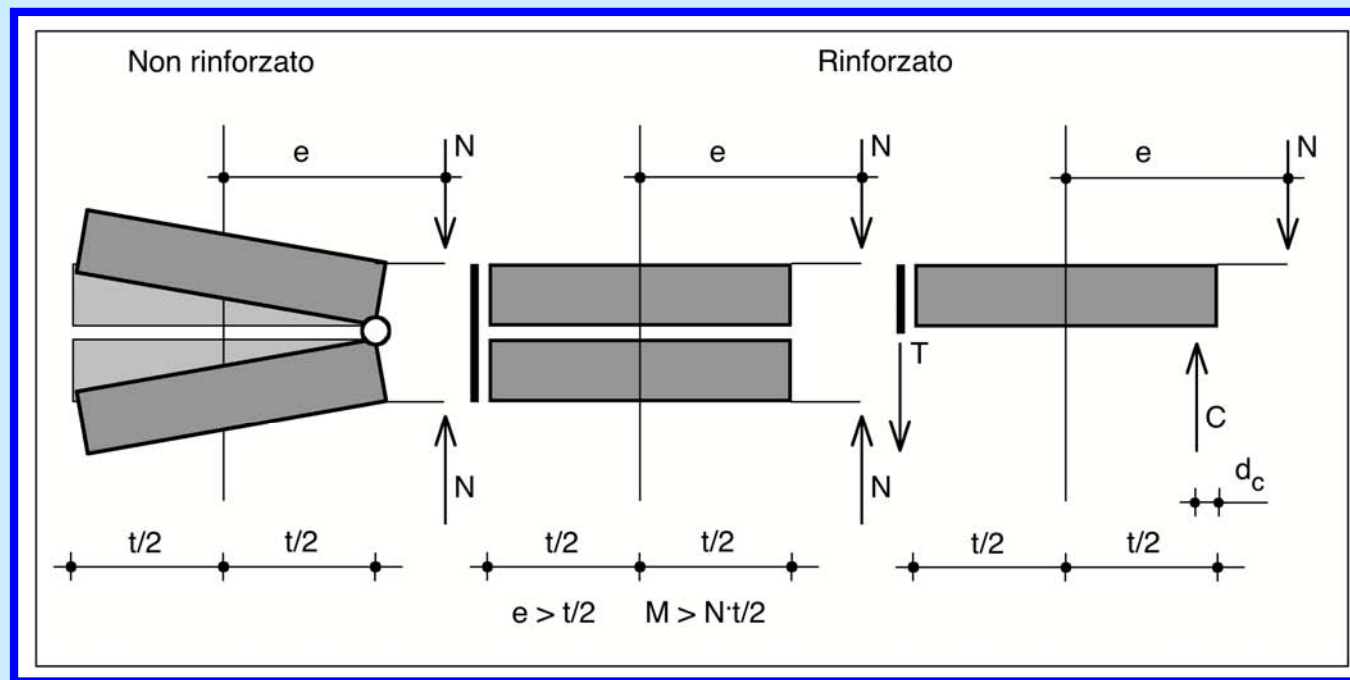
$$\theta_u = \frac{1}{\gamma_{el}} \cdot \left[ \theta_y + (\varphi_u - \varphi_y) \cdot \left( 1 - \frac{L_{pl}}{2L_V} \right) \cdot L_{pl} \right] =$$

$$= \frac{1}{1.5} \cdot \left[ 8.77 \cdot 10^{-3} + (0.027 - 0.0095) \cdot \left( 1 - \frac{0.64}{2 \cdot 1.5} \right) \cdot 0.64 \right] = 0.012 = 0.67^\circ \quad \text{Non confinato}$$



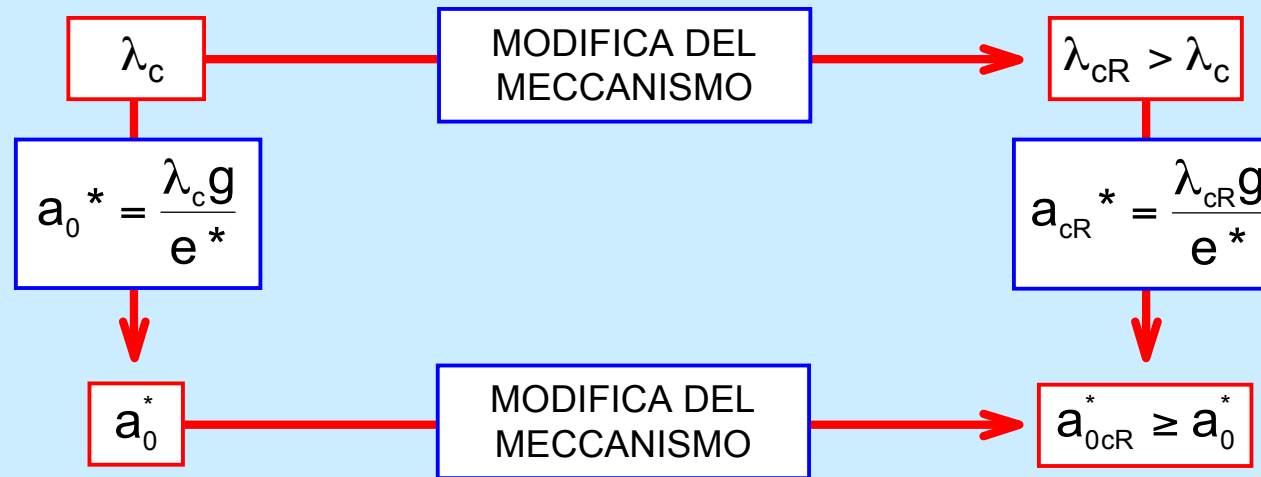
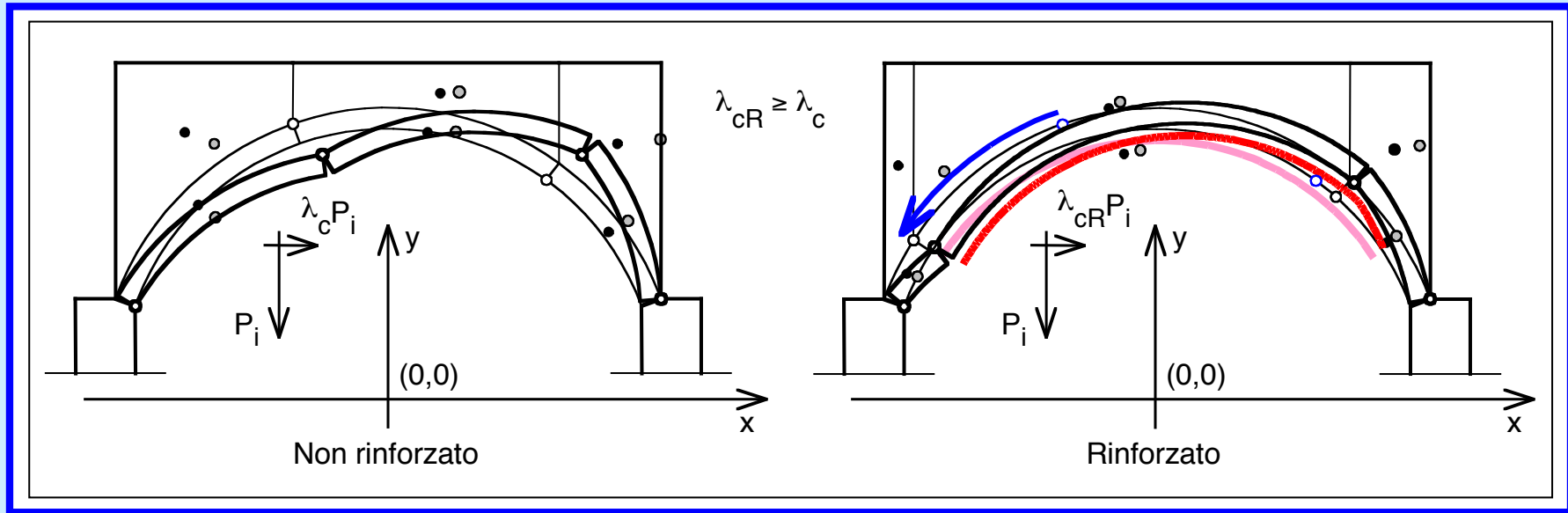
## RINFORZI ADERENTI - ASPETTI GENERALI

- Concio di muratura rinforzato



- Inibizione della formazione della cerniera
- Il centro di pressione può giacere fuori dalla sezione

# AZIONE SISMICA



## ESEMPIO

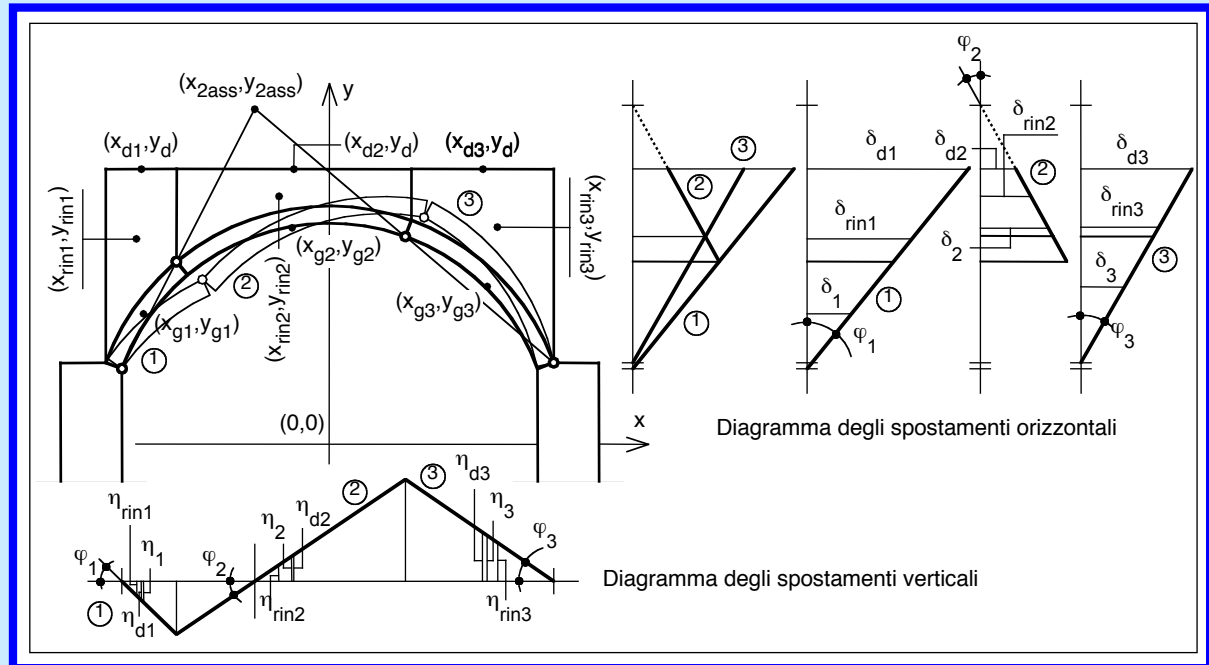
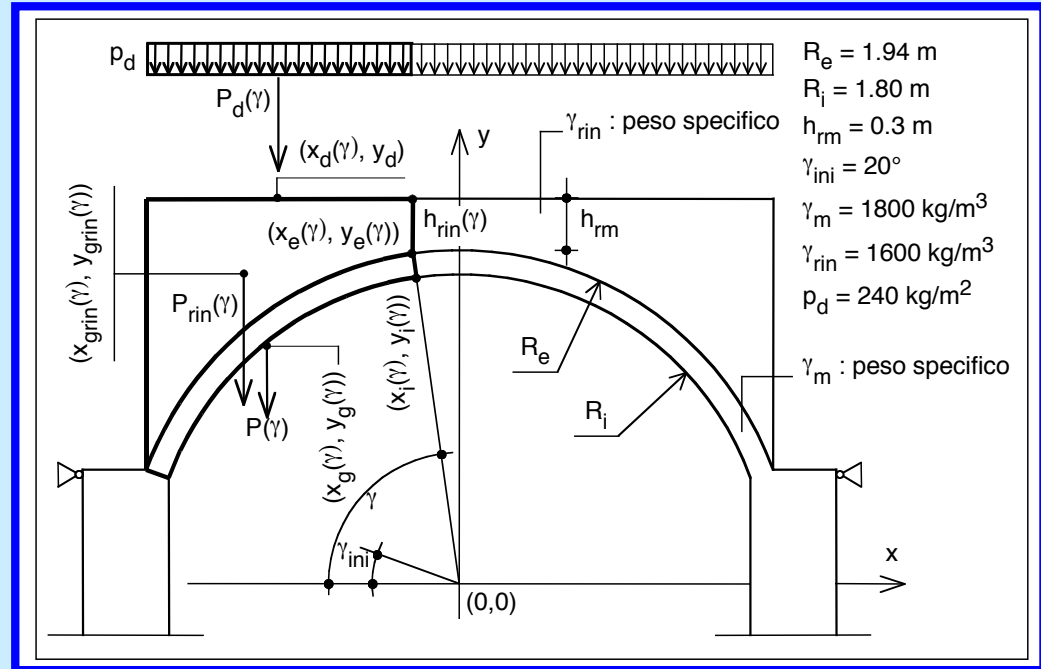
### ● SENZA RINFORZO

➔ Moltiplicatore di collasso

$$\lambda_c = \frac{\sum_{i=1}^3 P_i \cdot \eta_i + \sum_{i=1}^3 P_{rini} \cdot \eta_{rini} + \sum_{i=1}^3 P_{di} \cdot \eta_{di}}{\sum_{i=1}^3 P_i \cdot \delta_i + \sum_{i=1}^3 P_{rini} \cdot \delta_{rini} + \sum_{i=1}^3 P_{di} \cdot \delta_{di}} = 0.1709$$

➔ Accelerazione di attivazione

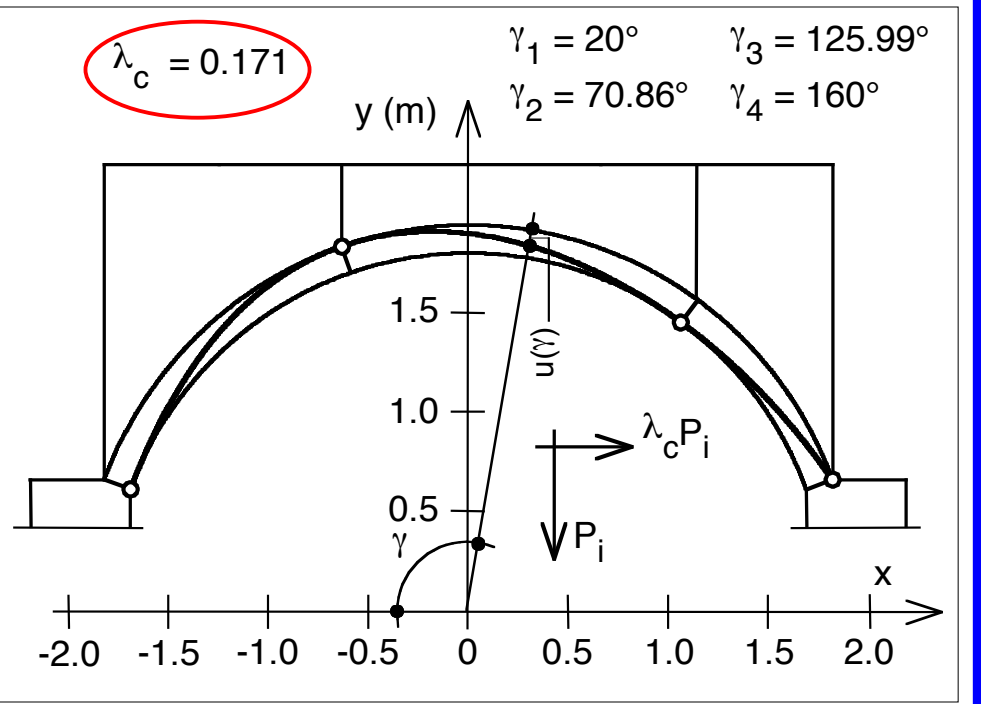
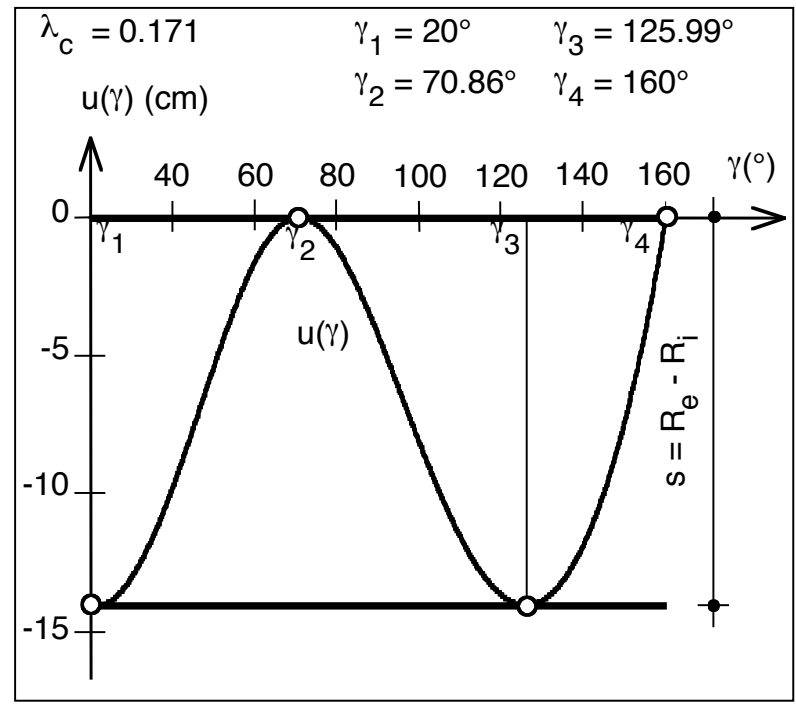
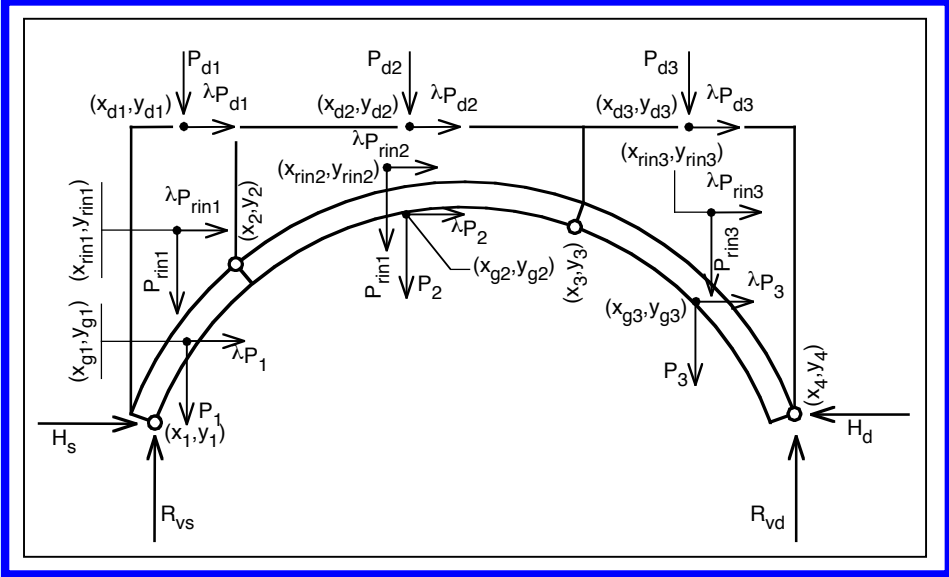
$$a_0^* = \frac{\lambda_c g}{e^*} = 0.218 g$$



# ESEMPIO

## • SENZA RINFORZO

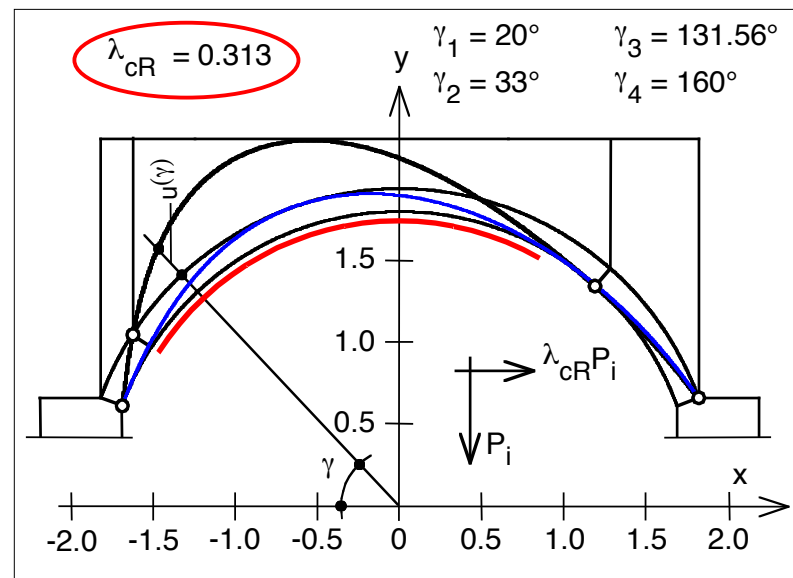
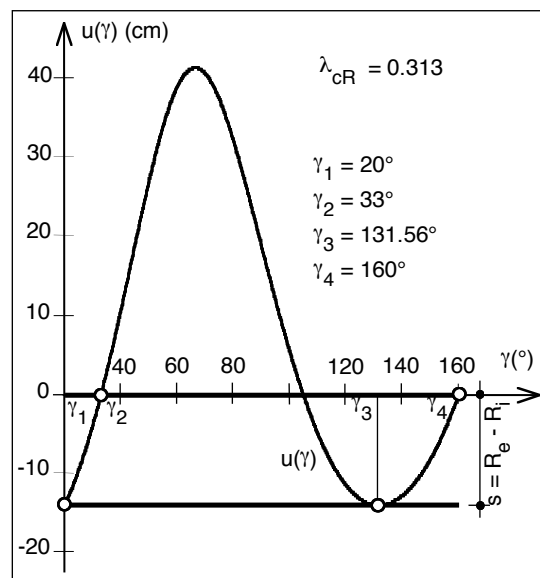
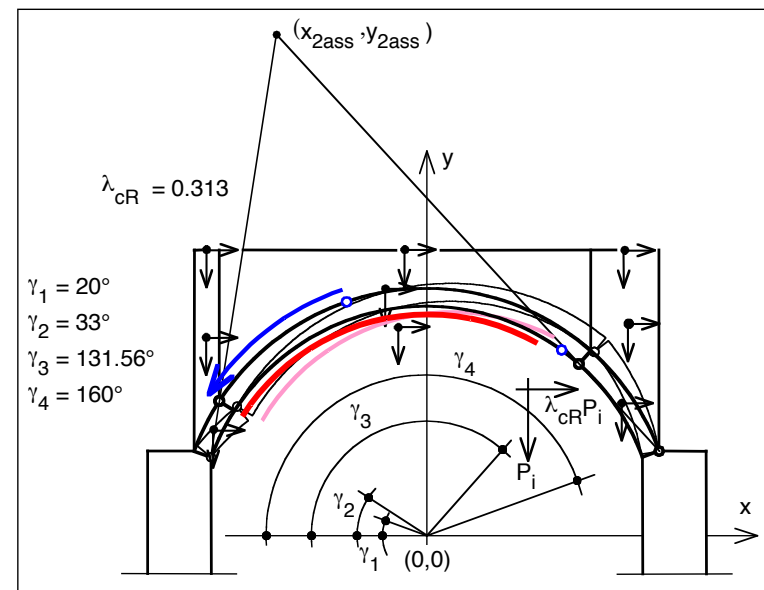
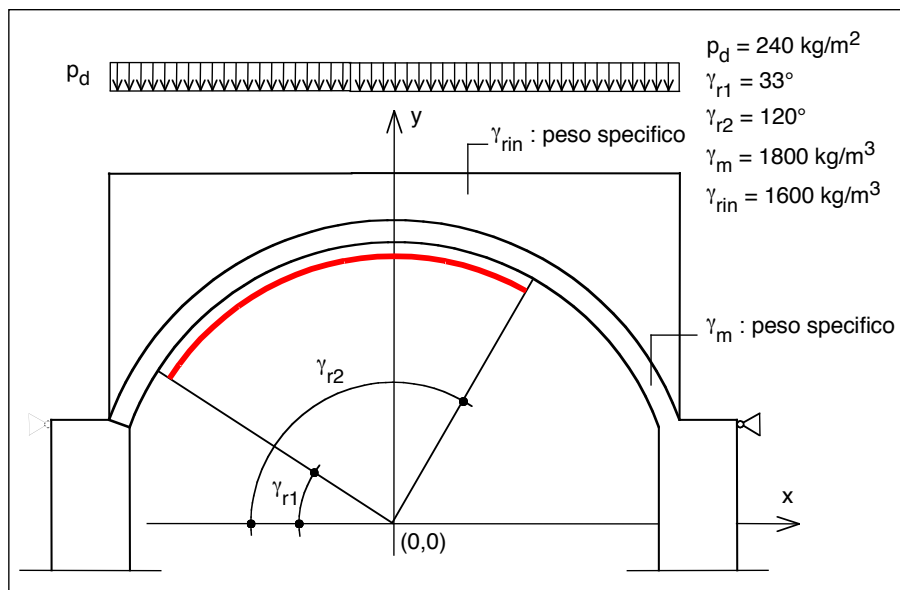
- ➔ Reazioni vincolari
- ➔ Luogo dei centri di pressione



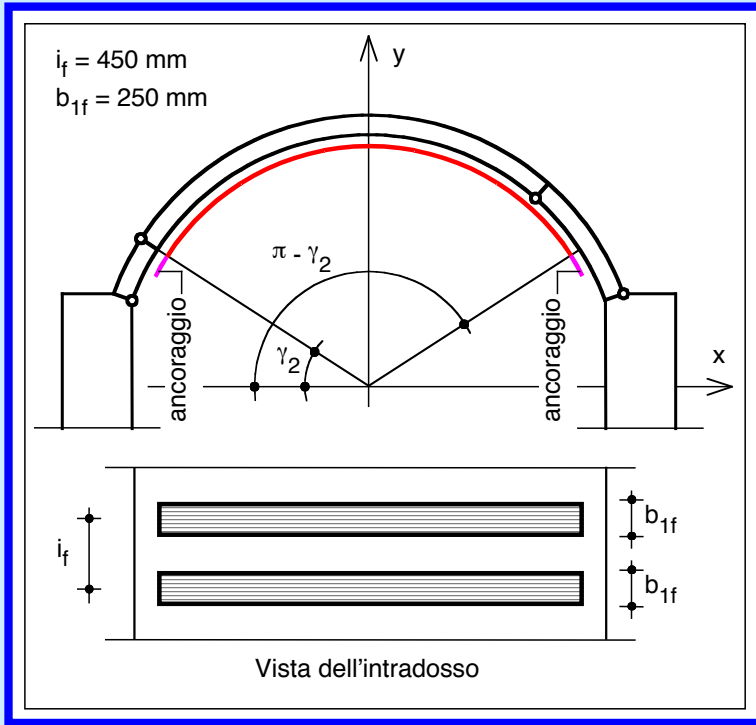
# ESEMPIO

## • CON RINFORZO

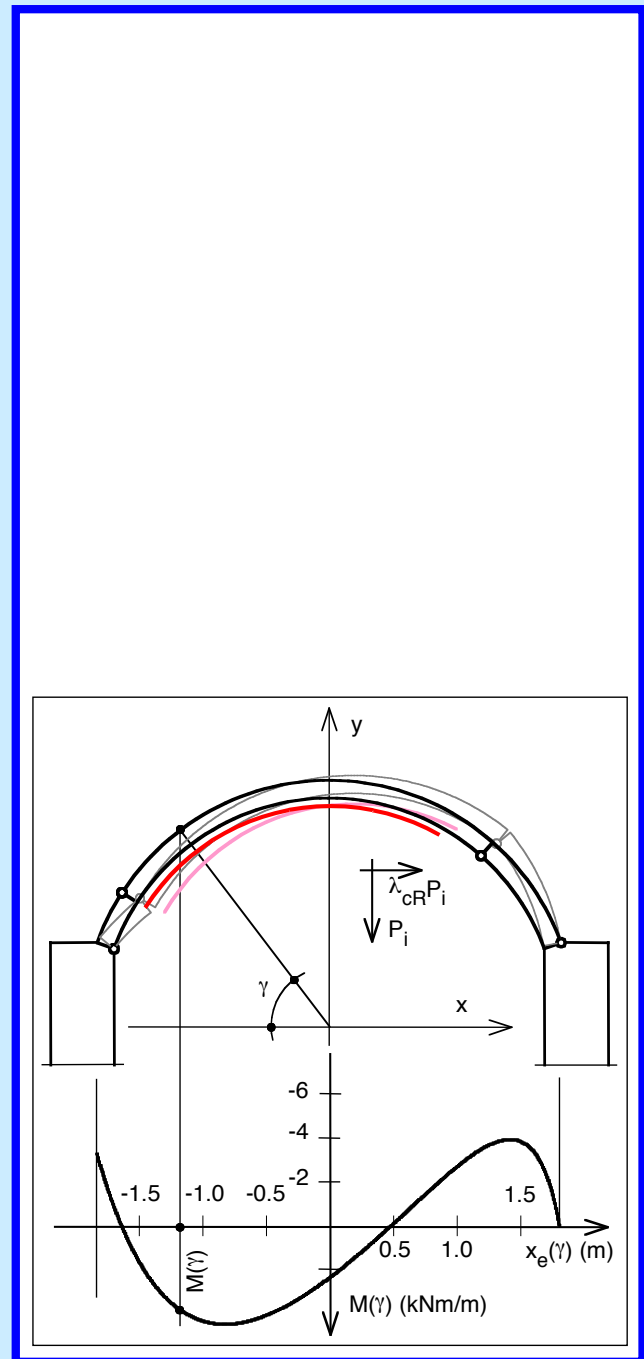
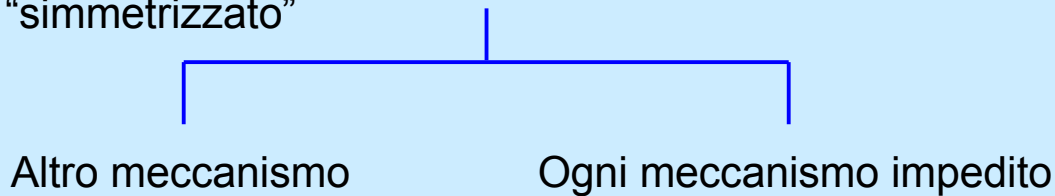
- ➔ Nuovo meccanismo
- ➔ Luogo dei centri di pressione



ESEMPIO



- ➔ Sollecitazioni ➔ Dimensionamento della sezione di rinforzo
- ➔ Azione sismica ➔ "Simmetrizzazione" del rinforzo
- In alcuni casi può accadere che il meccanismo considerato sia effettivamente inibito dal rinforzo "simmetrizzato"





# TAGLIO

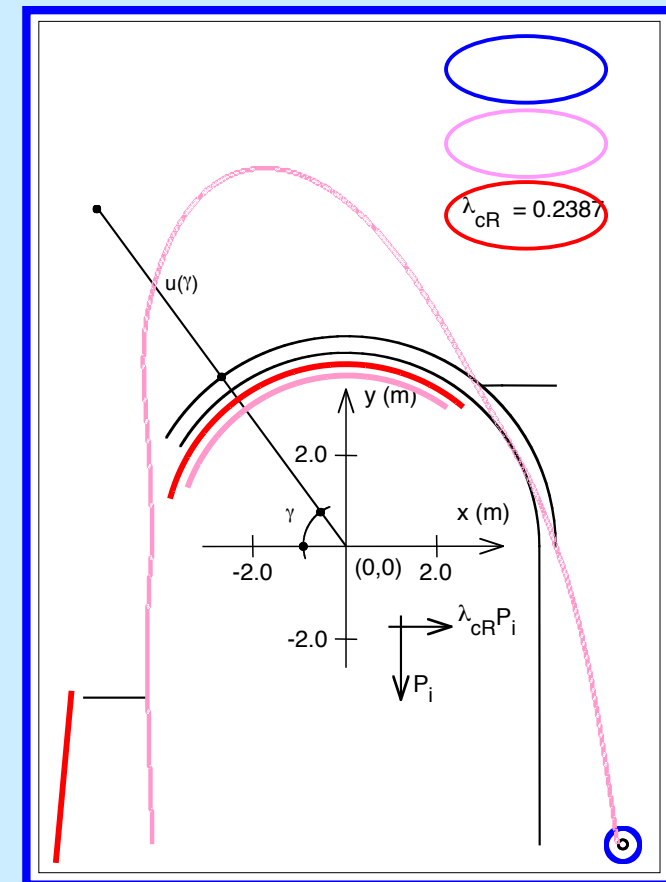
- **SENZA** RINFORZO

➔ In genere non si ha collasso per taglio (risultante poco discosta dall'asse)

- **CON** RINFORZO

➔ Prima del collasso per meccanismo può aversi collasso per taglio (scorrimento tra i giunti)

Esperienze di Bednartz sul rinforzo di archi con FRCM



# TONNARA DI FAVIGNANA

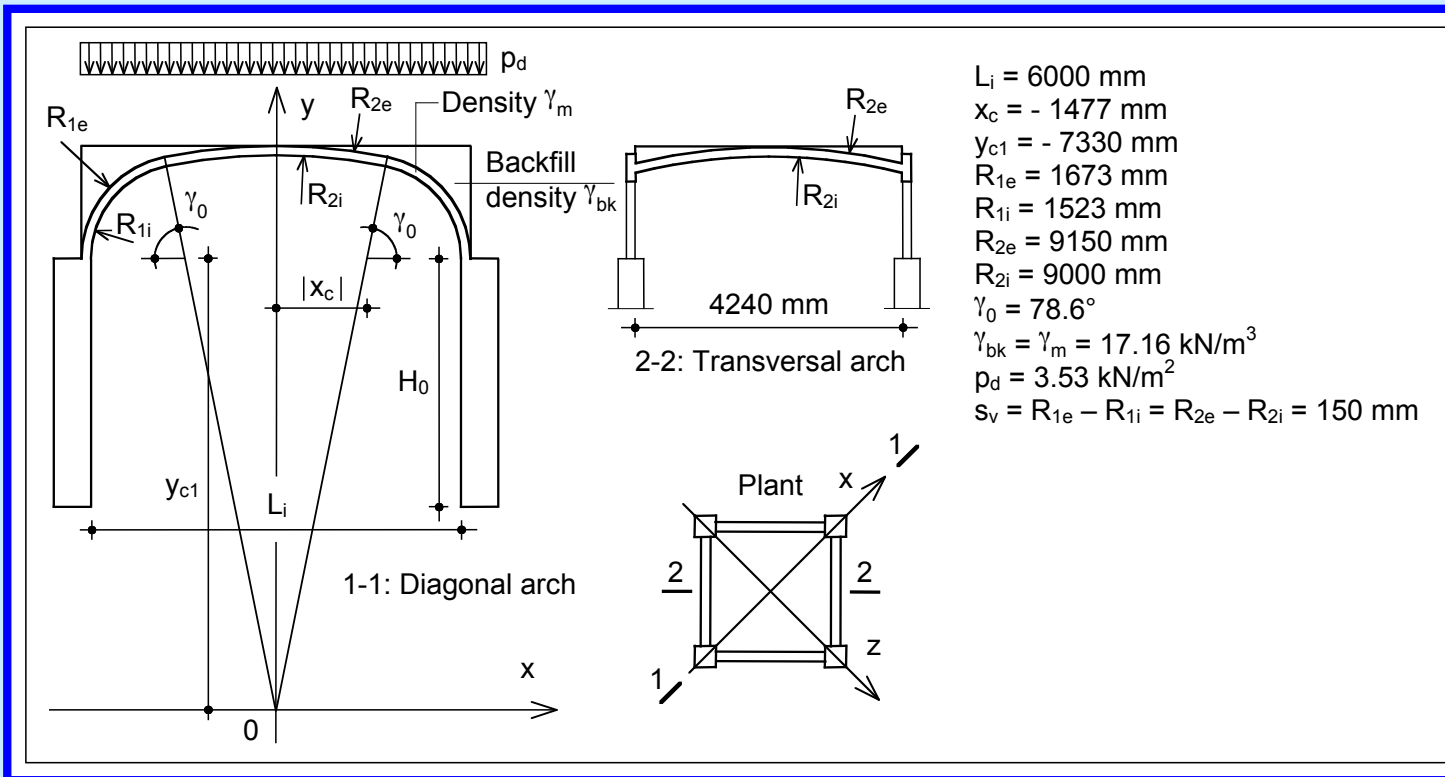


Tonnara "Florio" a Favignana



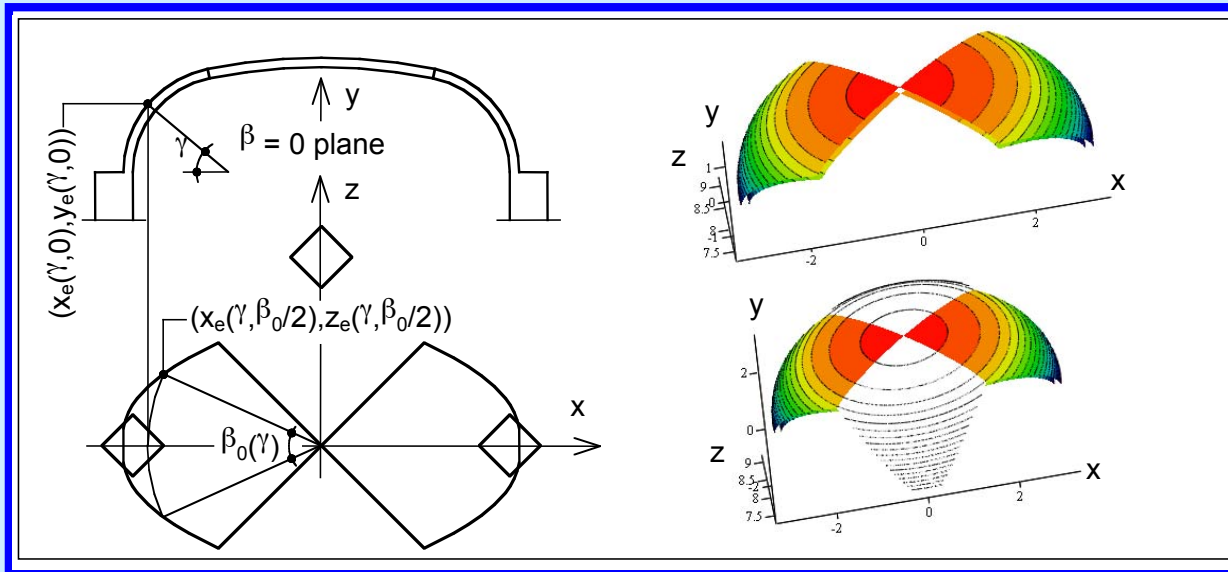
Volte nei "magazzini generali"

# LE VOLTE DELLA TONNARA



# SCHEMATIZZAZIONE

- Parametrizzazione del volume degli "archi"



$$\beta_{ini} = 10^\circ$$

$$\beta_{max} = \frac{\pi}{2}$$

$$\gamma_{bmax} = \frac{\pi}{3}$$

➔ Intradosso ed estradosso

$$x_i(\gamma, \beta) = \begin{cases} x_c - R_{1i} \cos \gamma \cdot \cos \beta \\ -R_{2i} \cos \gamma \cdot \cos \beta \\ -x_c - R_{1i} \cos \gamma \cdot \cos \beta \end{cases} \quad y_i(\gamma, \beta) = \begin{cases} R_{1i} \sin \gamma + y_{c1} \\ R_{2i} \sin \gamma \cdot \cos \beta \\ R_{1i} \sin \gamma \end{cases} \quad z_i(\gamma, \beta) = \begin{cases} x_c - R_{1i} \cos \gamma \cdot \sin \beta & \text{if } 0 \leq \gamma \leq \gamma_0 \\ -R_{2i} \cos \gamma \cdot \sin \beta & \text{if } \gamma_0 < \gamma \leq \pi - \gamma_0 \\ -x_c - R_{1i} \cos \gamma \cdot \sin \beta & \text{if } \pi - \gamma_0 < \gamma \leq \pi \end{cases}$$

$$x_e(\gamma, \beta) = \begin{cases} x_c - R_{1e} \cos \gamma \cdot \cos \beta \\ -R_{2e} \cos \gamma \cdot \cos \beta \\ -x_c - R_{1e} \cos \gamma \cdot \cos \beta \end{cases} \quad y_e(\gamma, \beta) = \begin{cases} R_{1e} \sin \gamma + y_{c1} \\ R_{2e} \sin \gamma \cdot \cos \beta \\ R_{1e} \sin \gamma \end{cases} \quad z_e(\gamma, \beta) = \begin{cases} x_c - R_{1e} \cos \gamma \cdot \sin \beta & \text{if } 0 \leq \gamma \leq \gamma_0 \\ -R_{2e} \cos \gamma \cdot \sin \beta & \text{if } \gamma_0 < \gamma \leq \pi - \gamma_0 \\ -x_c - R_{1e} \cos \gamma \cdot \sin \beta & \text{if } \pi - \gamma_0 < \gamma \leq \pi \end{cases}$$

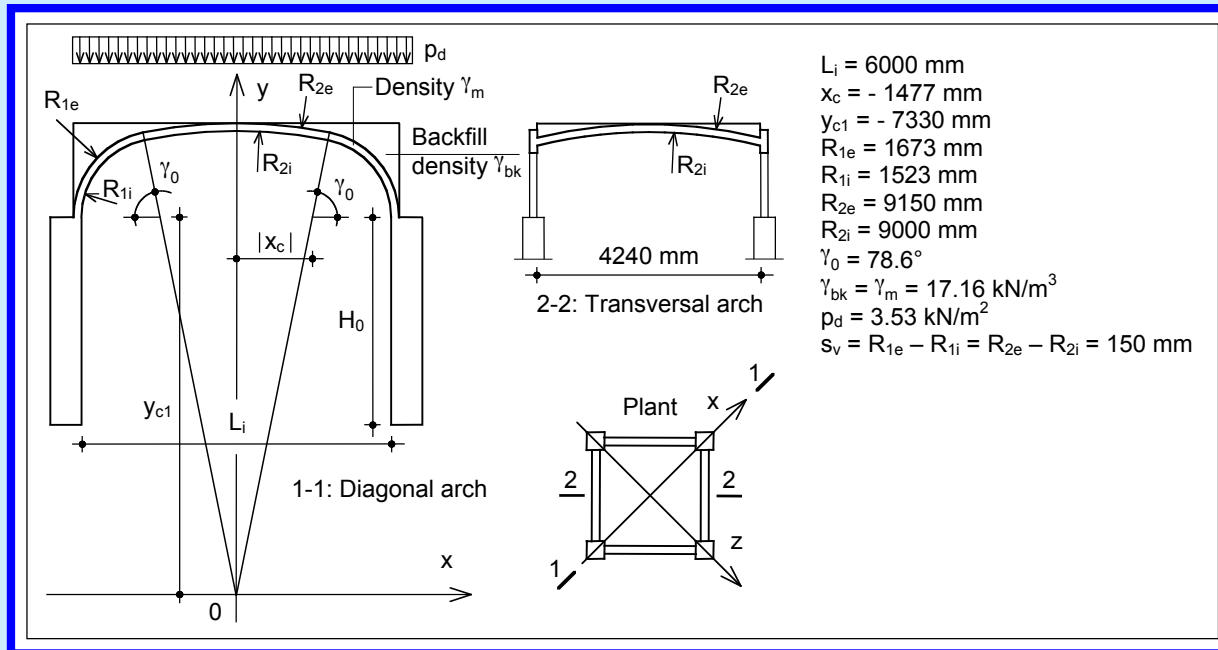
➔ Volume

$$\begin{cases} x(\gamma, \beta, t) = x_i(\gamma, \beta) + t[x_e(\gamma, \beta) - x_i(\gamma, \beta)] \\ y(\gamma, \beta, t) = y_i(\gamma, \beta) + t[y_e(\gamma, \beta) - y_i(\gamma, \beta)] \\ z(\gamma, \beta, t) = z_i(\gamma, \beta) + t[z_e(\gamma, \beta) - z_i(\gamma, \beta)] \end{cases} \quad \begin{cases} \gamma \in [0; \pi] \\ \beta \in \left[-\frac{\beta_0(\gamma)}{2}; \frac{\beta_0(\gamma)}{2}\right] \\ t \in [0; 1] \end{cases} \quad \beta_0(\gamma) = \begin{cases} \beta_{ini} + \frac{\beta_{max} - \beta_{ini}}{\tan \gamma_{bmax}} \cdot \tan \gamma & \text{if } 0 \leq \gamma \leq \gamma_{bmax} \\ \beta_{max} & \text{if } \gamma_0 < \gamma \leq \pi - \gamma_{bmax} \\ \beta_{ini} - \frac{\beta_{max} - \beta_{ini}}{\tan \gamma_{bmax}} \cdot \tan \gamma & \text{if } \pi - \gamma_{bmax} < \gamma \leq \pi \end{cases}$$

# SCHEMATIZZAZIONE

## ● Parametrizzazione del rinfiacco

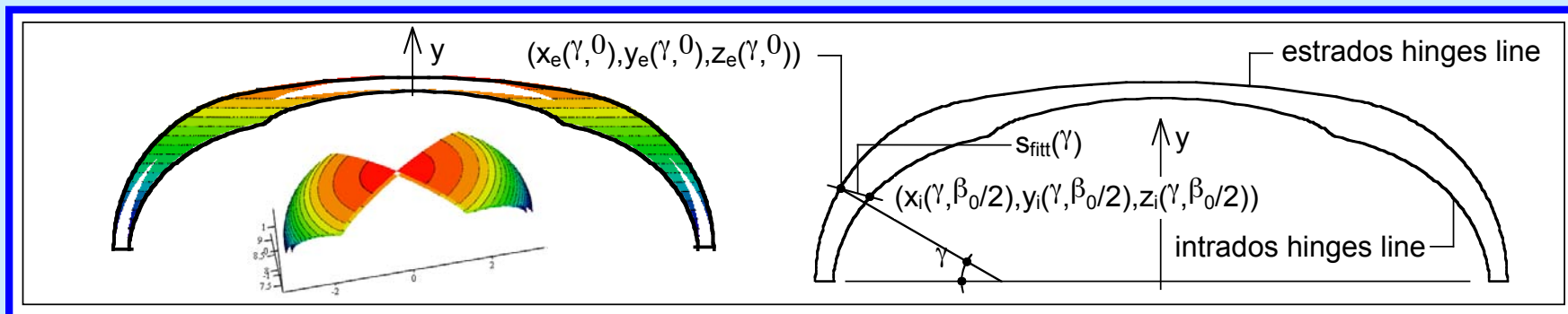
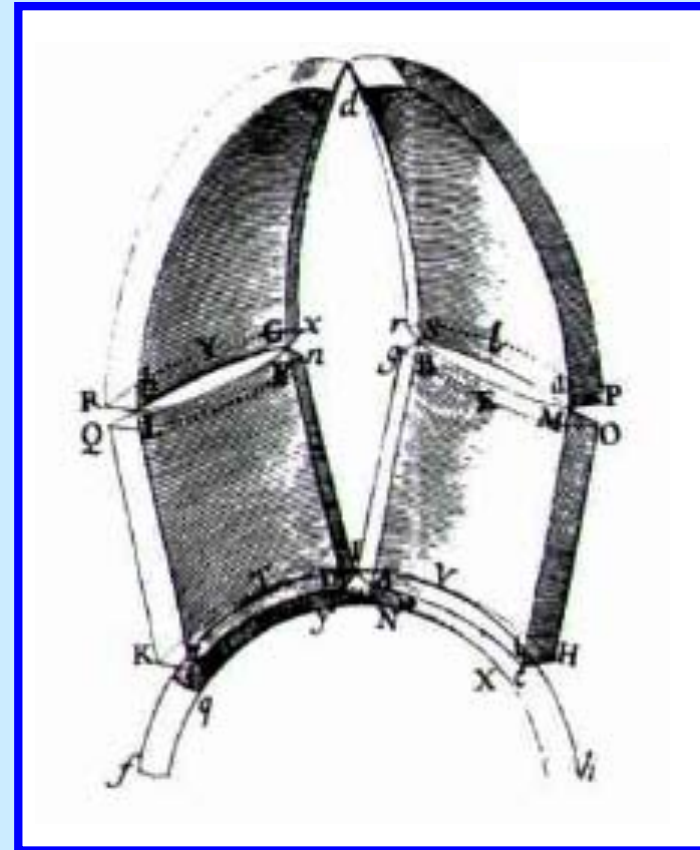
$$\begin{cases} x_{bk}(\gamma, \beta, t) = x_e(\gamma, \beta) \\ y_{bk}(\gamma, \beta, t) = y_e(\gamma, \beta) + t_r [R_{2e} - y_e(\gamma, \beta)] \\ z_{bk}(\gamma, \beta, t) = z_e(\gamma, \beta) \end{cases} \begin{cases} \gamma \in [0; \pi] \\ \beta \in \left[ -\frac{\beta_0(\gamma)}{2}, \frac{\beta_0(\gamma)}{2} \right] \\ t_r \in [0; 1] \end{cases}$$



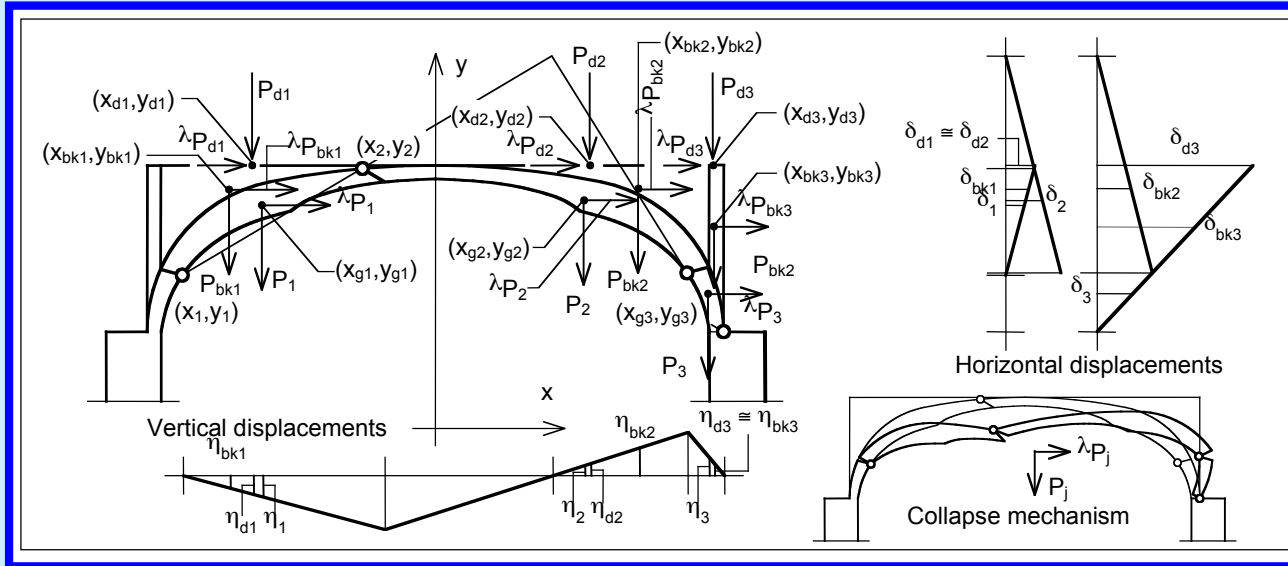
# SCHEMATIZZAZIONE

- In via “semplificata” ci si riconduce ad un “caso piano”

$$S_{fitt}(\gamma) = \sqrt{\left[ x_e(\gamma, 0) - x_i\left(\gamma, \frac{\beta_0}{2}\right) \right]^2 + \left[ y_e(\gamma, 0) - y_i\left(\gamma, \frac{\beta_0}{2}\right) \right]^2}$$



# STRUTTURA NON RINFORZATA: MECCANISMO DI COLLASSO



$$P_{di} = P_d \int_{\gamma_i}^{\gamma_{i+1}} b(\gamma) \cdot \frac{\partial}{\partial \gamma} x_e(\gamma, 0) d\gamma$$

$$x_{di} = \frac{P_d}{P_{di}} \int_{\gamma_i}^{\gamma_{i+1}} x_e(\gamma, 0) b(\gamma) \cdot \frac{\partial}{\partial \gamma} x_e(\gamma, 0) d\gamma$$

$$y_{di} = y_e(\pi, 0) = 9.15 \text{ m}$$

$$\lambda = - \frac{\sum_{i=1}^3 P_i \cdot \eta_{li} + \sum_{i=1}^3 P_{bki} \cdot \eta_{bki} + \sum_{i=1}^3 P_d \cdot \eta_{di}}{\sum_{i=1}^3 P_i \cdot \delta_i + \sum_{i=1}^3 P_{bki} \cdot \delta_{bki} + \sum_{i=1}^3 P_d \cdot \delta_{di}}, \quad i = 1, 2, 3$$

$$\lambda_c = \min \{ \lambda, \gamma_i \in [0, \pi] | i = 1, \dots, 4 \} = 0.008$$

$$a_{Rd} = \lambda_c \cdot g \cdot P_{tot} \frac{\sum_{i=1}^3 P_i \delta_i^2 + \sum_{i=1}^3 P_{bki} \delta_{bki}^2 + \sum_{i=1}^3 P_{di} \delta_{di}^2}{\left( \sum_{i=1}^3 P_i \delta_i + \sum_{i=1}^3 P_{bki} \delta_{bki} + \sum_{i=1}^3 P_{di} \delta_{di} \right)^2} = 0.0105 \text{ g}$$

$$P_i = \gamma_m \int_{\gamma_i}^{\gamma_{i+1}} \int_{-\beta_0 \left( \frac{\gamma}{2} \right)}^{\beta_0 \left( \frac{\gamma}{2} \right)} \int_0^1 \| J_p(\gamma, \beta, t) \| dt d\beta d\gamma$$

$$x_{gi} = \frac{\gamma_m}{P_i} \int_{\gamma_i}^{\gamma_{i+1}} \int_{-\beta_0 \left( \frac{\gamma}{2} \right)}^{\beta_0 \left( \frac{\gamma}{2} \right)} \int_0^1 x(\gamma, \beta, t) \| J_p(\gamma, \beta, t) \| dt d\beta d\gamma$$

$$y_{gi} = \frac{\gamma_m}{P_i} \int_{\gamma_i}^{\gamma_{i+1}} \int_{-\beta_0 \left( \frac{\gamma}{2} \right)}^{\beta_0 \left( \frac{\gamma}{2} \right)} \int_0^1 y(\gamma, \beta, t) \| J_p(\gamma, \beta, t) \| dt d\beta d\gamma$$

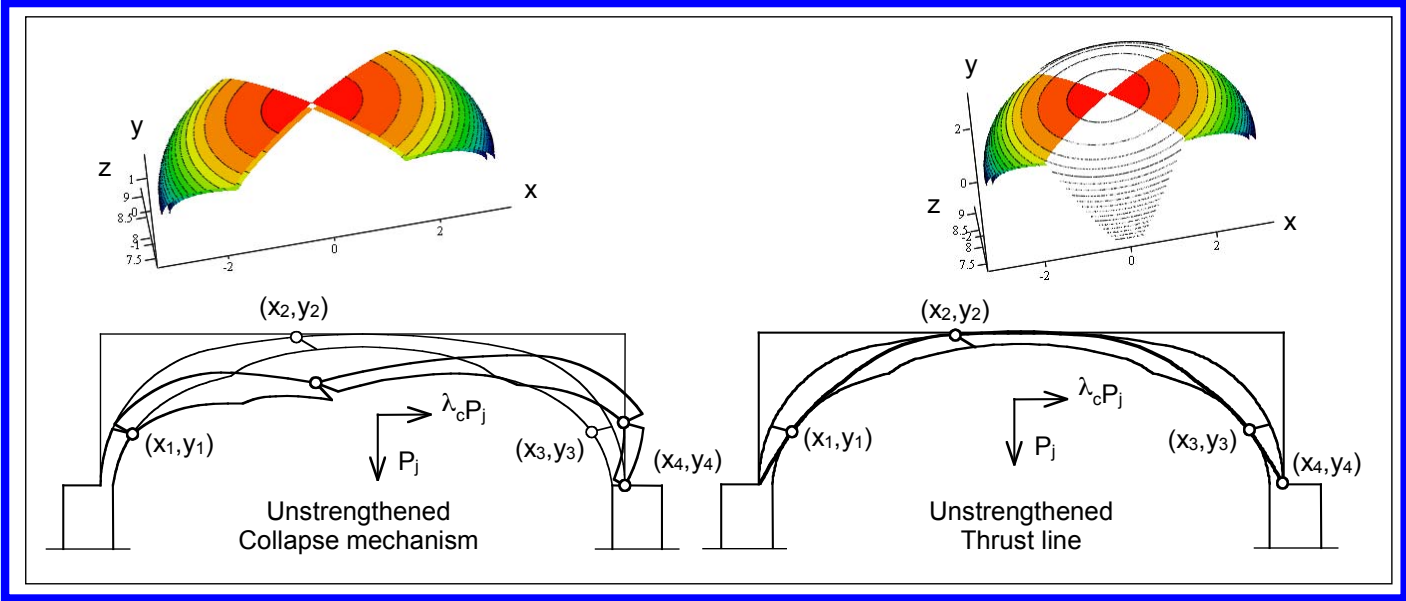
$$b(\gamma) = 2 \cdot \left| z_e \left( \gamma, \frac{\beta_0(\gamma)}{2} \right) \right|$$

$$P_{bki} = \gamma_{bk} \int_{\gamma_i}^{\gamma_{i+1}} \int_{-\beta_0 \left( \frac{\gamma}{2} \right)}^{\beta_0 \left( \frac{\gamma}{2} \right)} \int_0^1 \| J_{bk}(\gamma, \beta, t) \| dt d\beta d\gamma$$

$$x_{bki} = \frac{\gamma_{bk}}{P_{bki}} \int_{\gamma_i}^{\gamma_{i+1}} \int_{-\beta_0 \left( \frac{\gamma}{2} \right)}^{\beta_0 \left( \frac{\gamma}{2} \right)} \int_0^1 x_{bk}(\gamma, \beta, t) \cdot \| J_{bk}(\gamma, \beta, t) \| dt d\beta d\gamma$$

$$y_{bki} = \frac{\gamma_{bk}}{P_{bki}} \int_{\gamma_i}^{\gamma_{i+1}} \int_{-\beta_0 \left( \frac{\gamma}{2} \right)}^{\beta_0 \left( \frac{\gamma}{2} \right)} \int_0^1 y_{bk}(\gamma, \beta, t) \cdot \| J_{bk}(\gamma, \beta, t) \| dt d\beta d\gamma$$

# STRUTTURA NON RINFORZATA: MECCANISMO DI COLLASSO

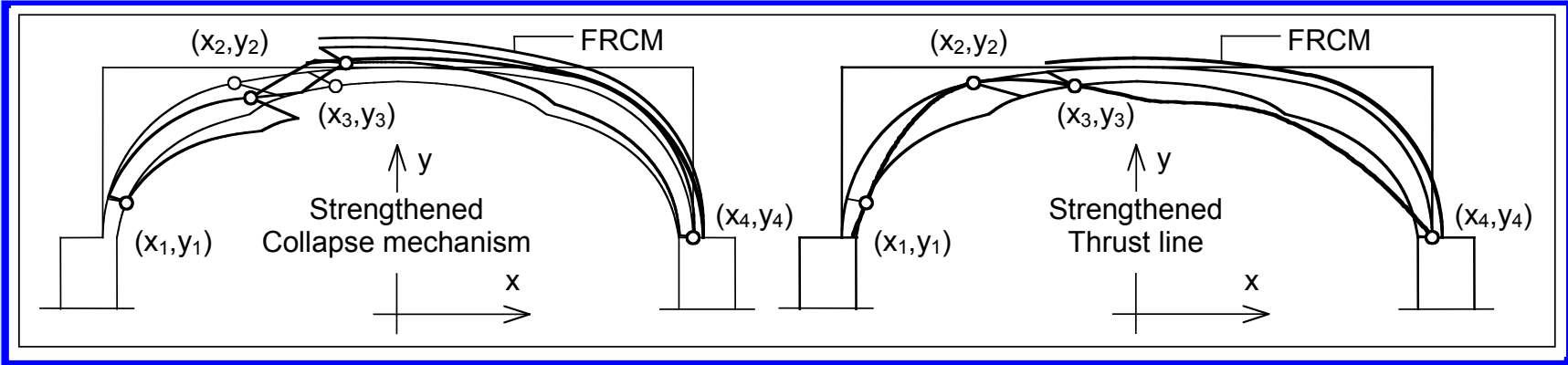
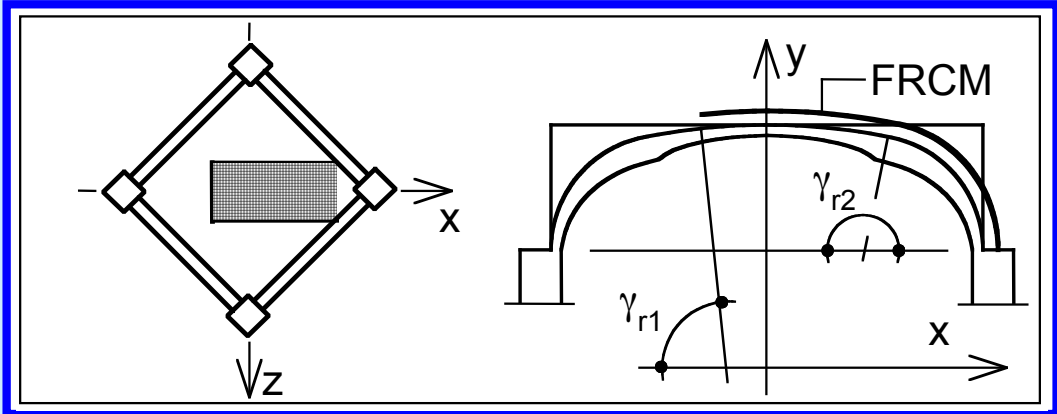


$$\lambda_c = \min \{ \lambda, \gamma_i \in [0, \pi] \mid i = 1, \dots, 4 \} = 0.008$$

$$a_{Rd} = \lambda_c \cdot g \cdot P_{tot} \frac{\sum_{i=1}^3 P_i \delta_i^2 + \sum_{i=1}^3 P_{bki} \delta_{bki}^2 + \sum_{i=1}^3 P_{di} \delta_{di}^2}{\left( \sum_{i=1}^3 P_i \delta_i + \sum_{i=1}^3 P_{bki} \delta_{bki} + \sum_{i=1}^3 P_{di} \delta_{di} \right)^2} = 0.0105 g$$



# STRUTTURA RINFORZATA: MECCANISMO DI COLLASSO

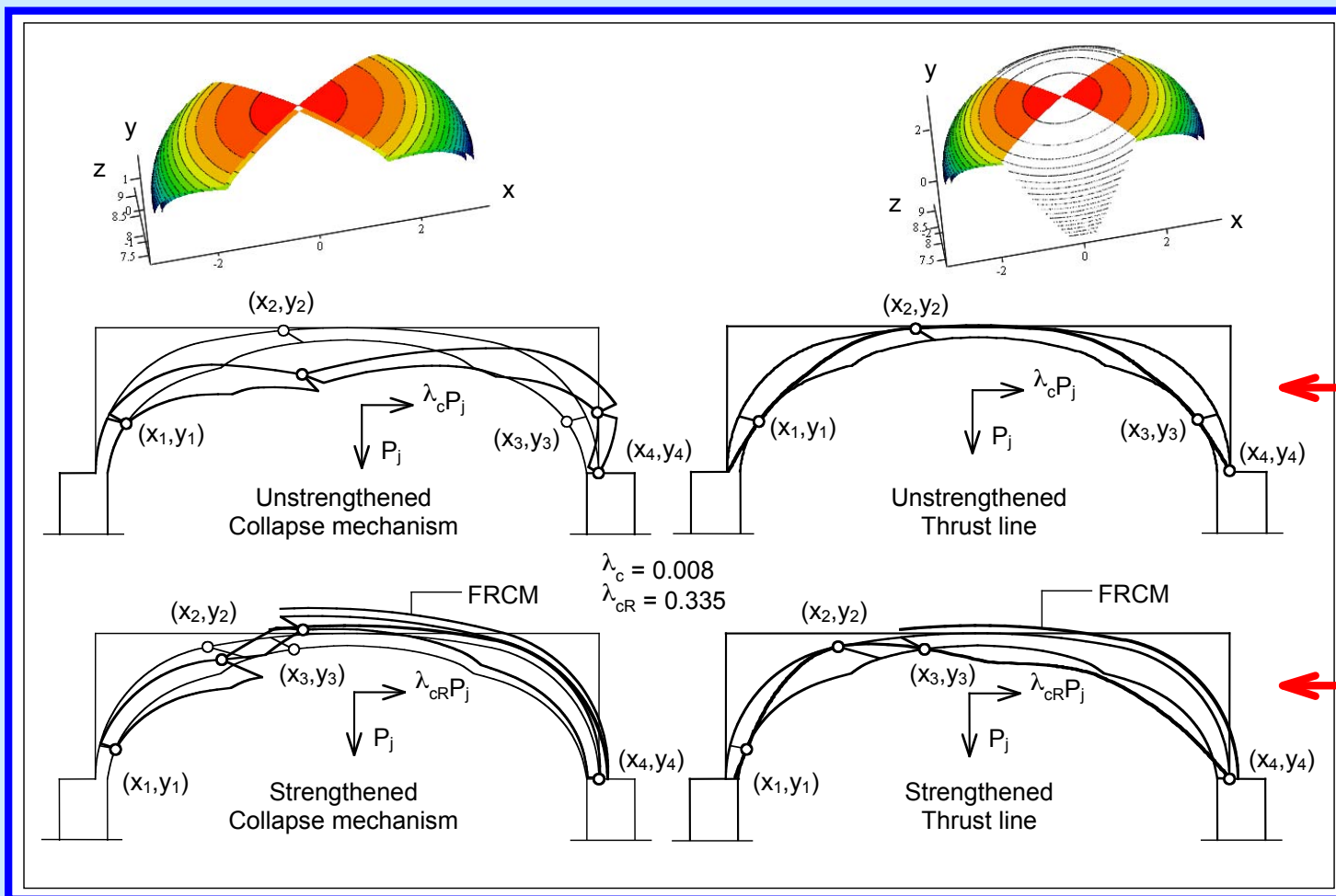


$$\lambda = - \frac{\sum_{i=1}^3 P_i \cdot \eta_i + \sum_{i=1}^3 P_{bki} \cdot \eta_{bki} + \sum_{i=1}^3 P_d \cdot \eta_{di}}{\sum_{i=1}^3 P_i \cdot \delta_i + \sum_{i=1}^3 P_{bki} \cdot \delta_{bki} + \sum_{i=1}^3 P_d \cdot \delta_{di}}, \quad i = 1, 2, 3$$

$$\lambda_{cR} = \min \{ \lambda, \gamma_i \in [0, \pi] \mid i = 2, 4, \gamma_i \in [0, \gamma_{r1}] \mid i = 1, 3 \} = 0.335$$

$$a_{Rd} = \lambda_c \cdot g \cdot P_{tot} \frac{\sum_{i=1}^3 P_i \delta_i^2 + \sum_{i=1}^3 P_{bki} \delta_{bki}^2 + \sum_{i=1}^3 P_{di} \delta_{di}^2}{\left( \sum_{i=1}^3 P_i \delta_i + \sum_{i=1}^3 P_{bki} \delta_{bki} + \sum_{i=1}^3 P_{di} \delta_{di} \right)^2} = 0.348 \text{ g}$$

# CONFRONTO



Non rinforzato

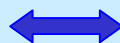
Rinforzato

$$\lambda_c = \min \{ \lambda, \gamma_i \in [0, \pi] | i = 1, \dots, 4 \} = 0.008$$

$$a_{Rd} = 0.0105 \text{ g}$$

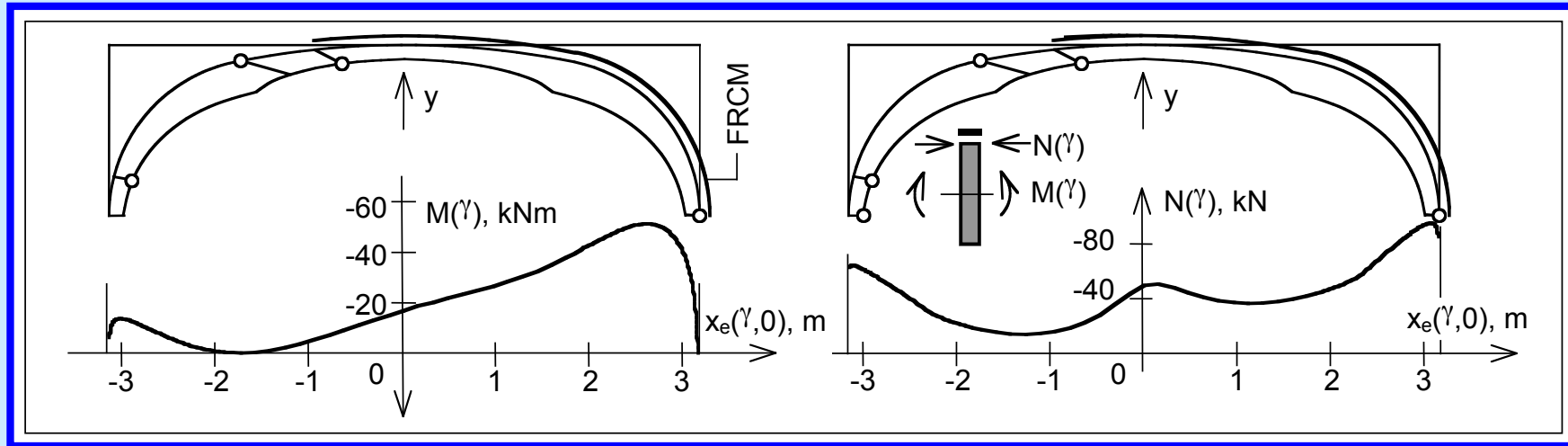
$$\lambda_{cR} = \min \{ \lambda, \gamma_i \in [0, \pi] | i = 2, 4, \gamma_i \in [0, \gamma_{r1}] | i = 1, 3 \} = 0.335$$

$$a_{Rd} = 0.348 \text{ g}$$



# DIMENSIONAMENTO DEL RINFORZO

- Sollecitazioni al collasso della struttura rinforzata



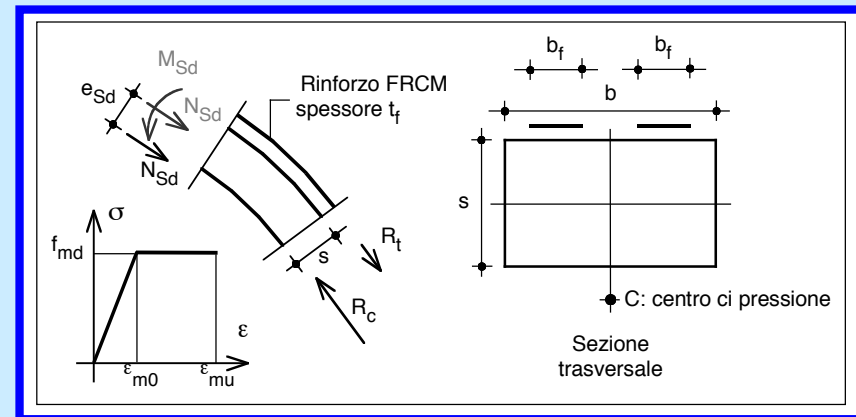
- Resistenza della sezione di muratura rinforzata

$$R_c(x) = \alpha \beta f_{md} t x$$

$$R_t(x) = \varepsilon_{fd} \cdot E_f A_f$$

$$R_t(x) + N_{Sd} = R_c(x) \rightarrow x$$

$$M_{Rd}(N_{Sd}) = \frac{\alpha \beta f_{md} t x}{2} \cdot (L - \beta x) + \varepsilon_{fd} E_f A_f \cdot \left( d - \frac{L}{2} \right)$$



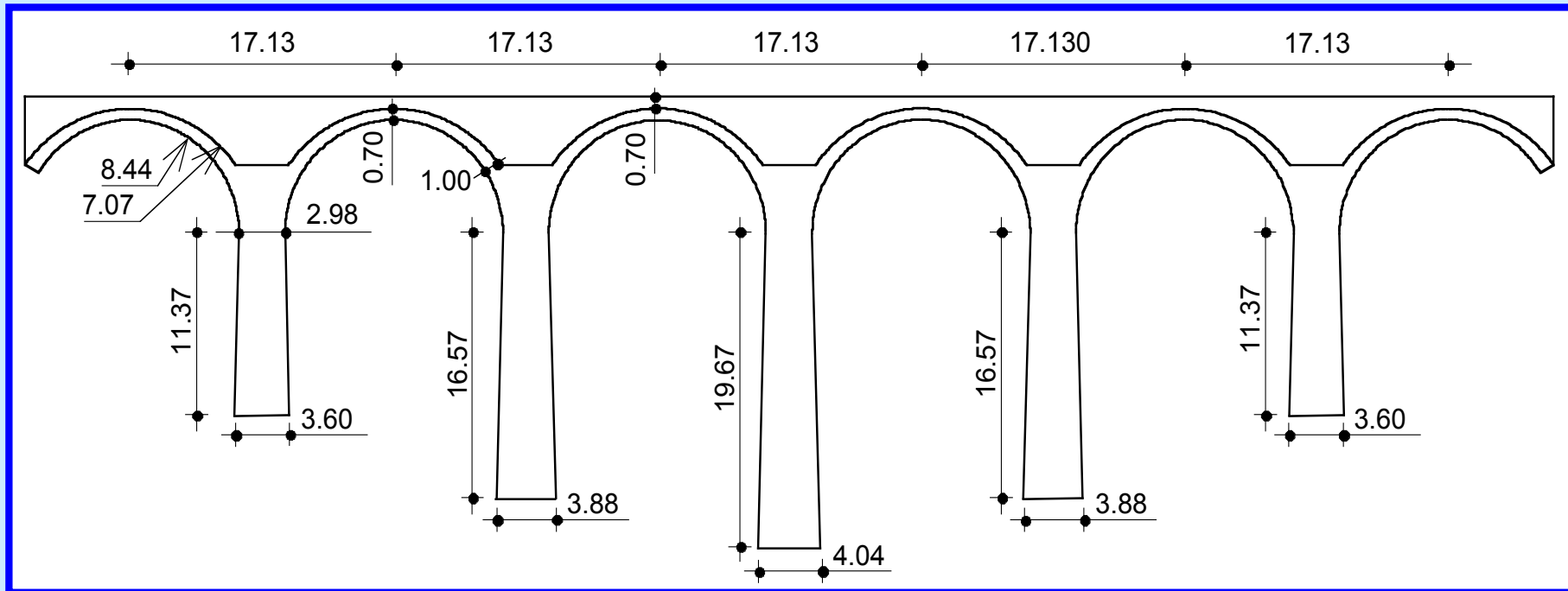
$E_f$ : modulo elastico del rinforzo  
 $A_f$ : sezione di rinforzo

# VIADOTTO km 32+926, Roma-Formia



• Volte di calcestruzzo non armato

• Pile di muratura



# MATERIALI



- $\delta = 4.94 \text{ MPa}$   
 $R_{ck} = R_{cm} - 1.64 \cdot \delta = 4.64 \text{ MPa}$

- $f_{cd} = \frac{R_{cm}}{FC \cdot \gamma_c} = 6.54 \text{ MPa}$

	VOLTA 1	VOLTA 2	VOLTA 1	VOLTA 1	VOLTA 1
Resistenze valutate con sonda Windsor	11.0	17.1	17.1	20.2	8.1
	7.6	7.0	16.6	13.1	9.7
	8.2	9.9	12.1	12.9	23.4
	14.4	10.1	6.0	10.0	20.2
<b>Resistenze medie volte (MPa)</b>	<b>10.30</b>	<b>11.03</b>	<b>12.95</b>	<b>14.05</b>	<b>15.35</b>
<b>Resistenza media <math>R_{cm}</math> (MPa)</b>	<b>12.74</b>				

# CARICHI VERTICALI

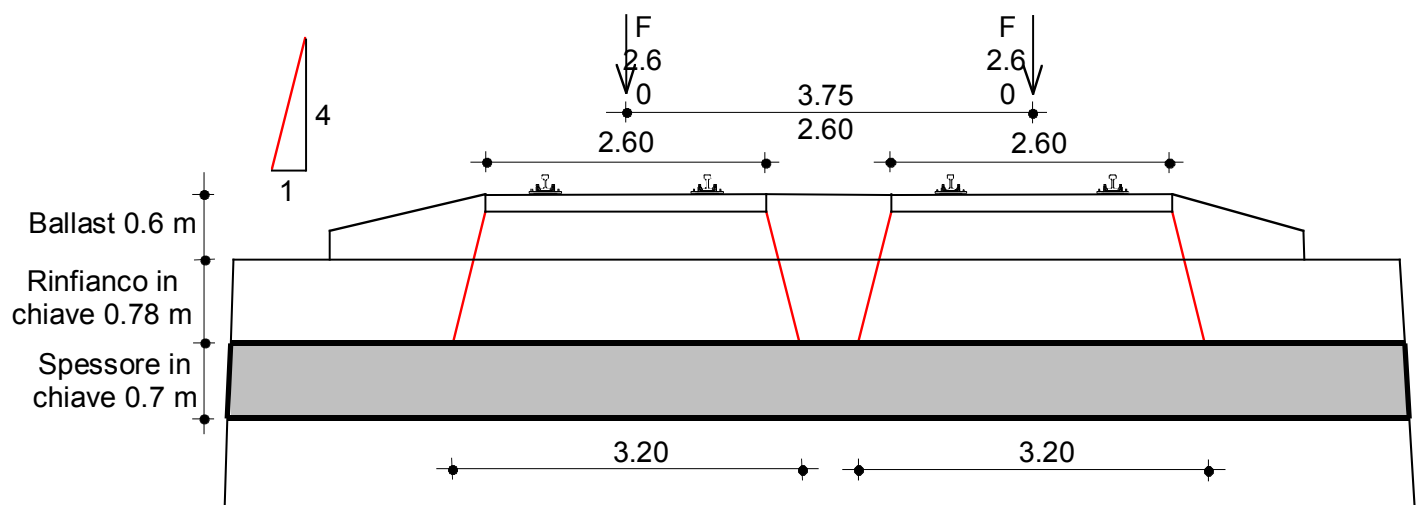
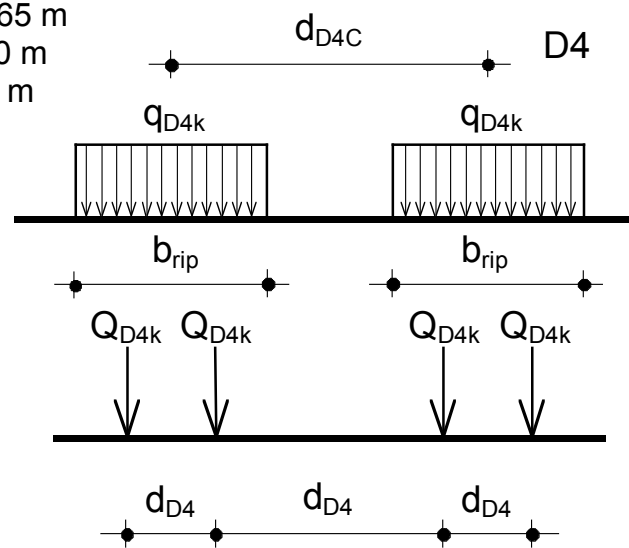
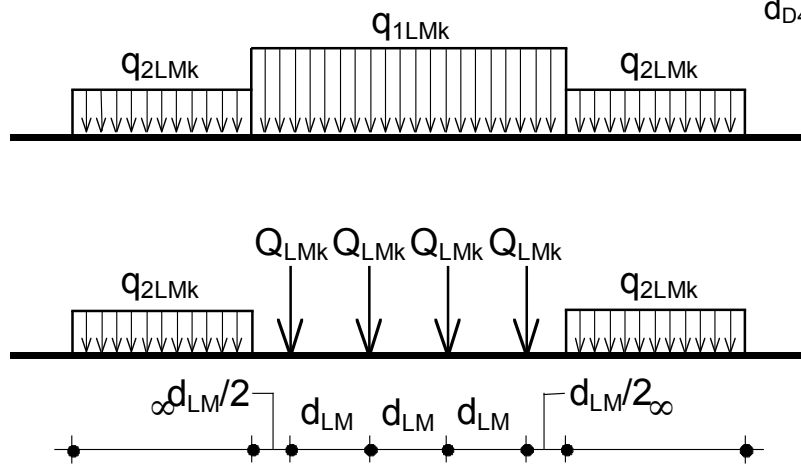
LM71

$d_{LM} = 1.60 \text{ m}$

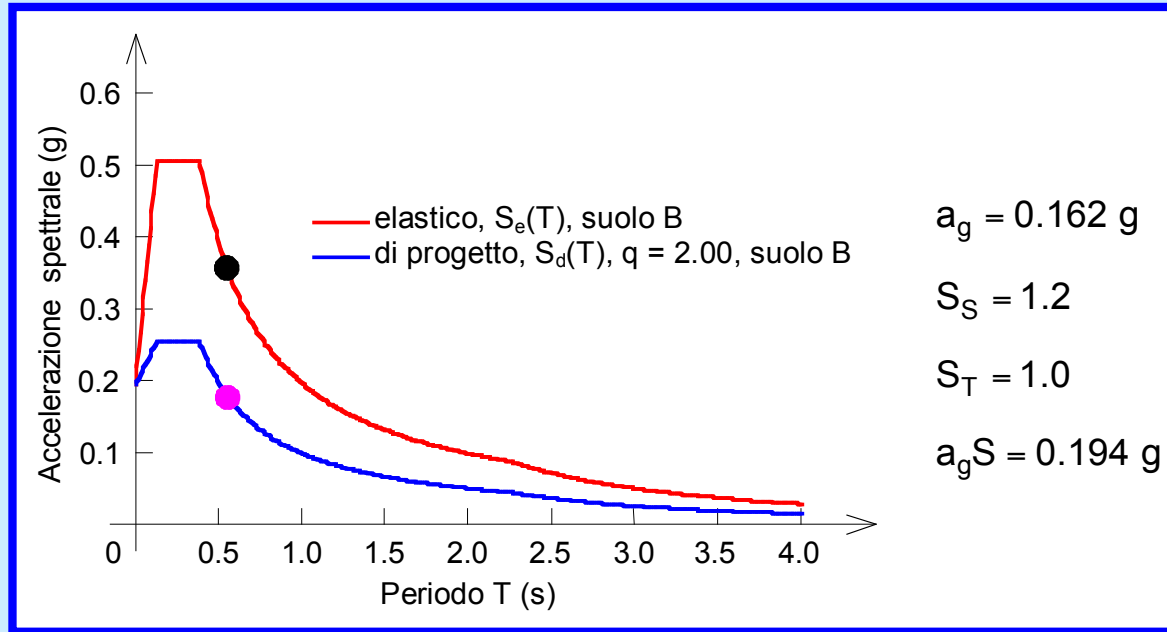
$d_{D4C} = 4.65 \text{ m}$

$b_{rip} = 3.90 \text{ m}$

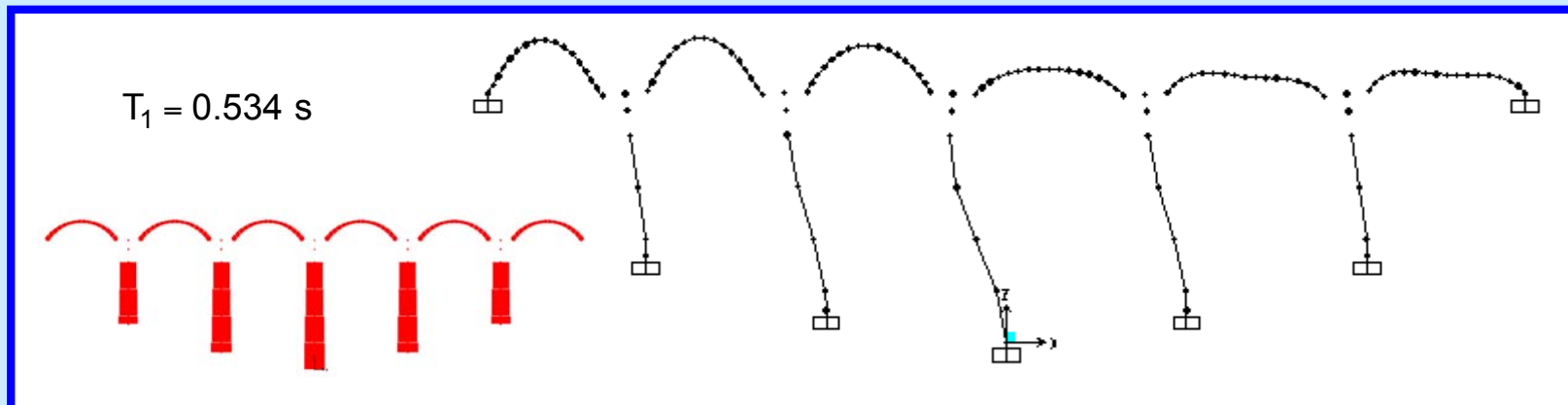
$d_{D4} = 1.8 \text{ m}$



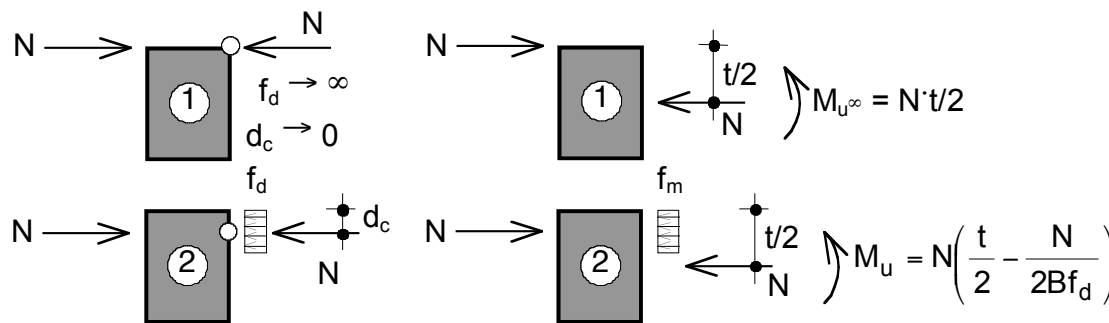
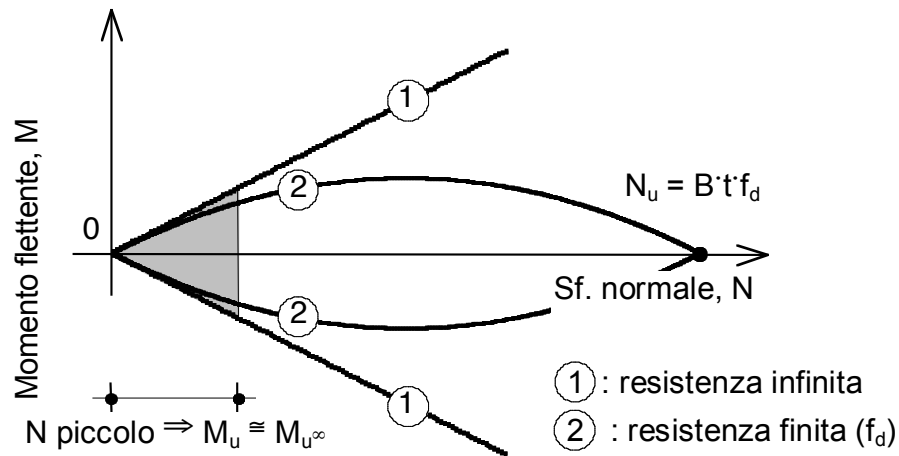
# AZIONE SISMICA LONGITUDINALE



$$S_d(T_1) = 0.183 \text{ g}$$

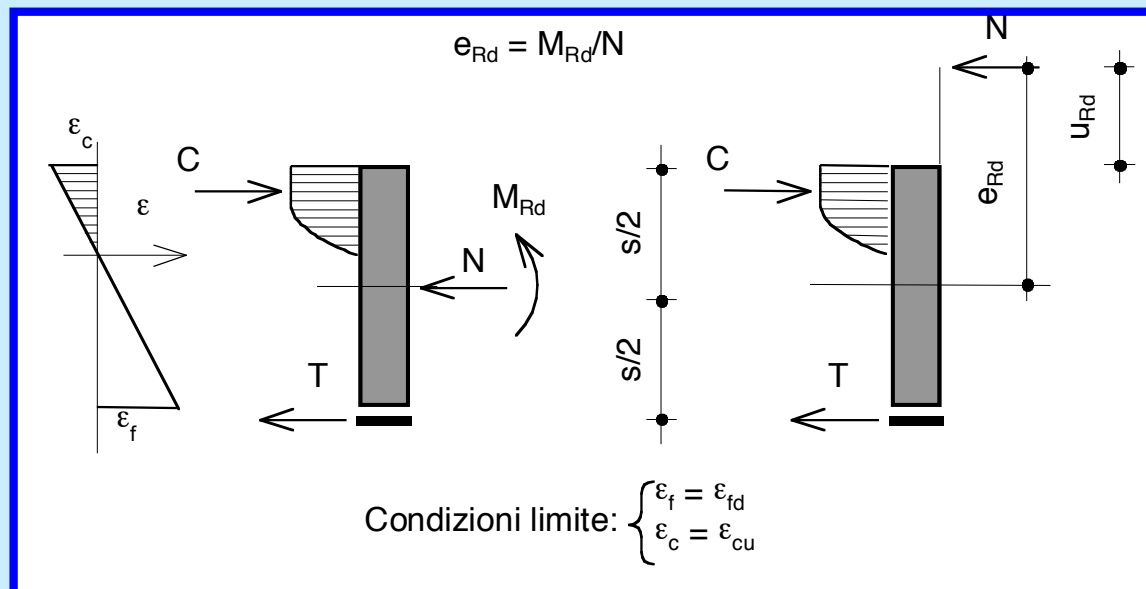
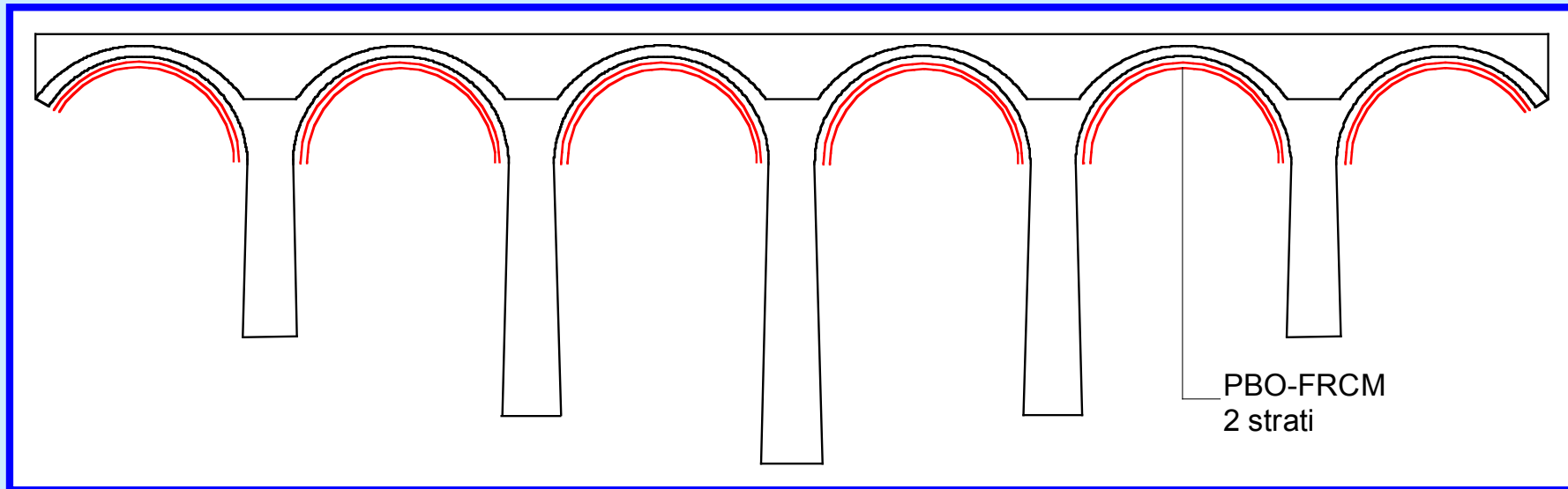


# RESISTENZA A COMPRESSIONE FINITA

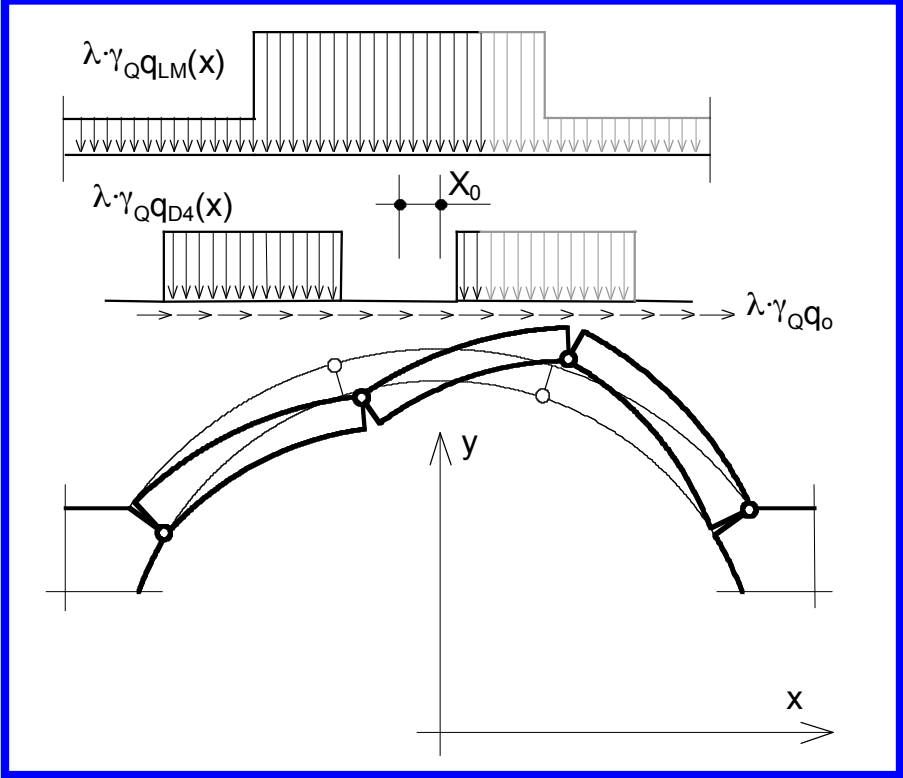




# CONFIGURAZIONE DI RINFORZO

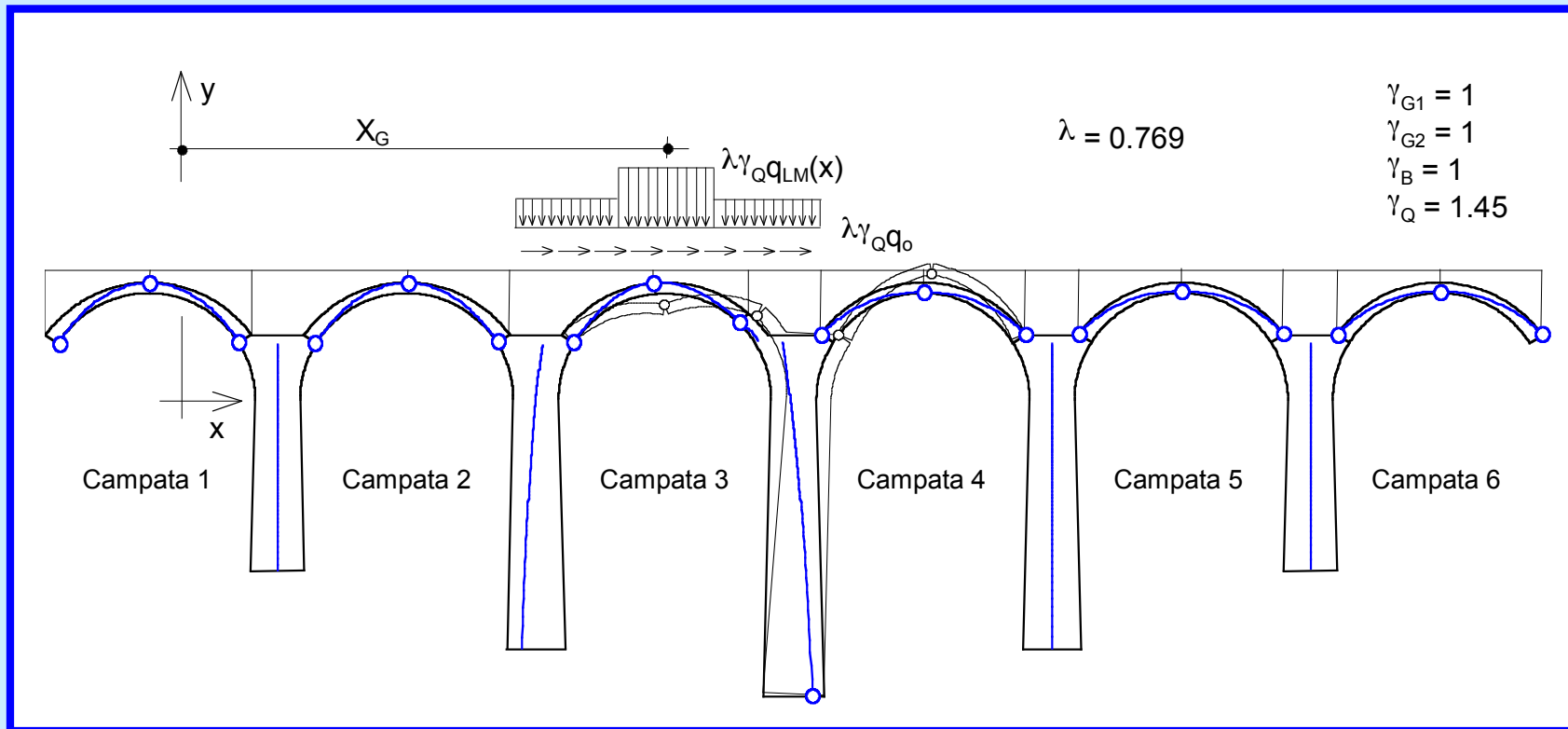


# POSSIBILI MECCANISMI DI COLLASSO



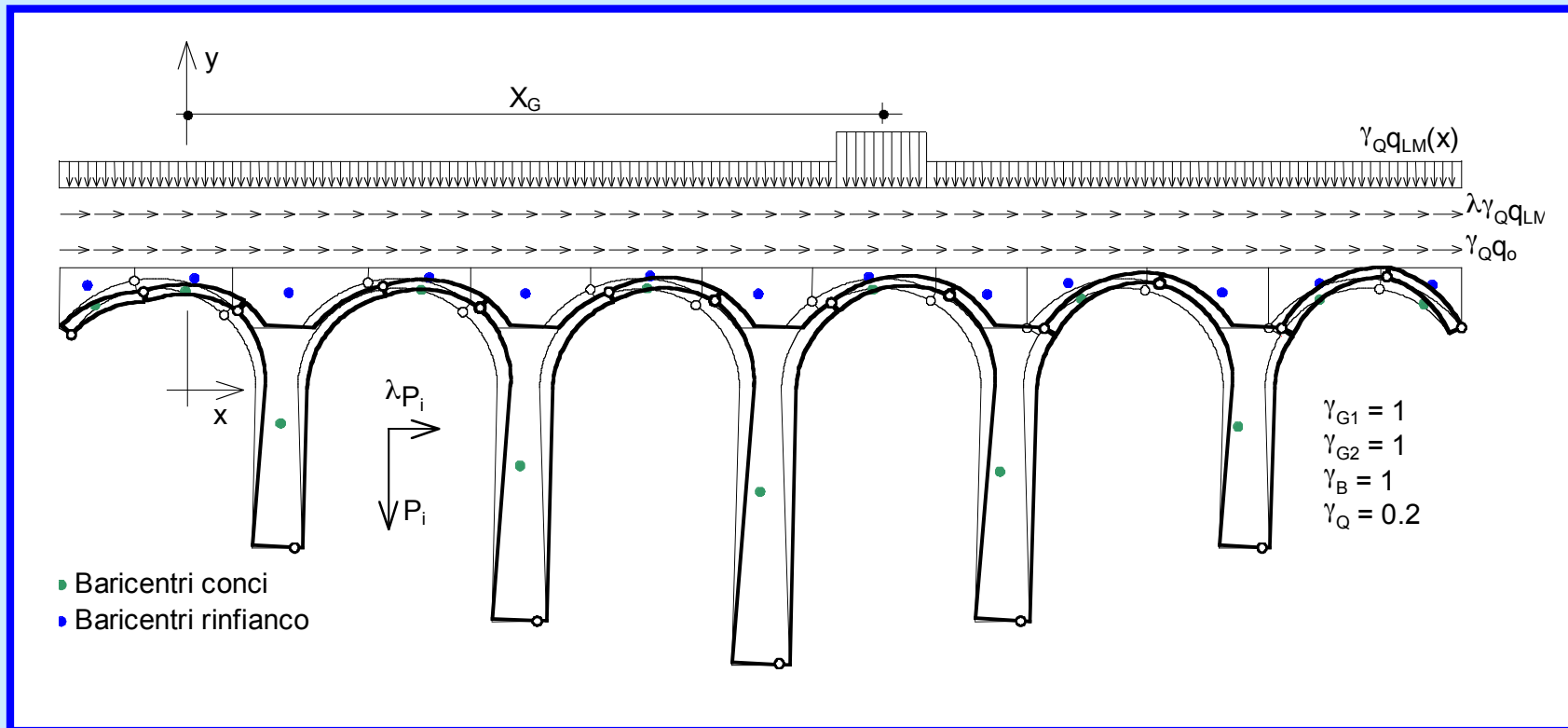
- **MECCANISMO 1: Carichi verticali/Azione sismica**

## POSSIBILI MECCANISMI DI COLLASSO



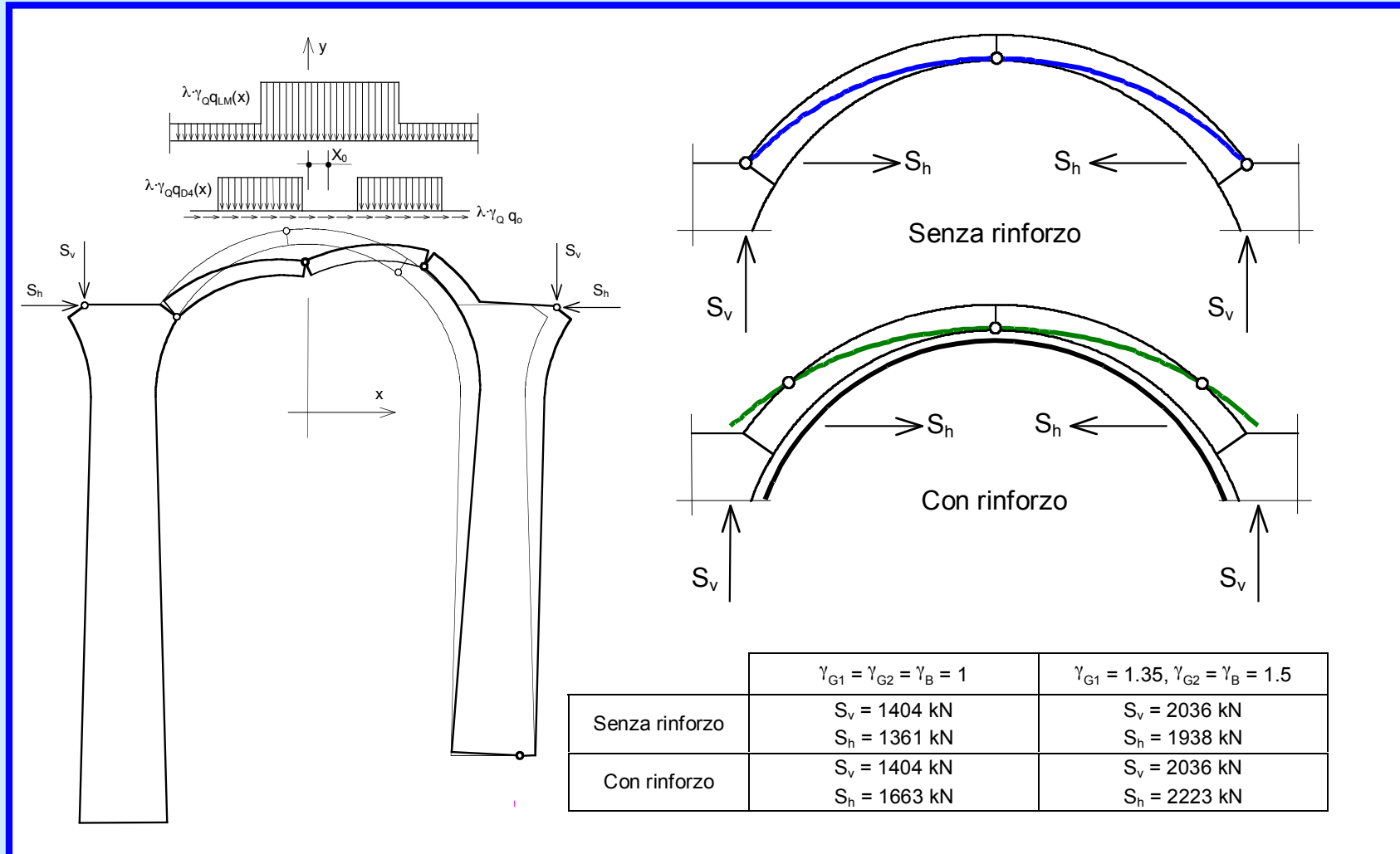
- **MECCANISMO 2: Carichi verticali**

# POSSIBILI MECCANISMI DI COLLASSO

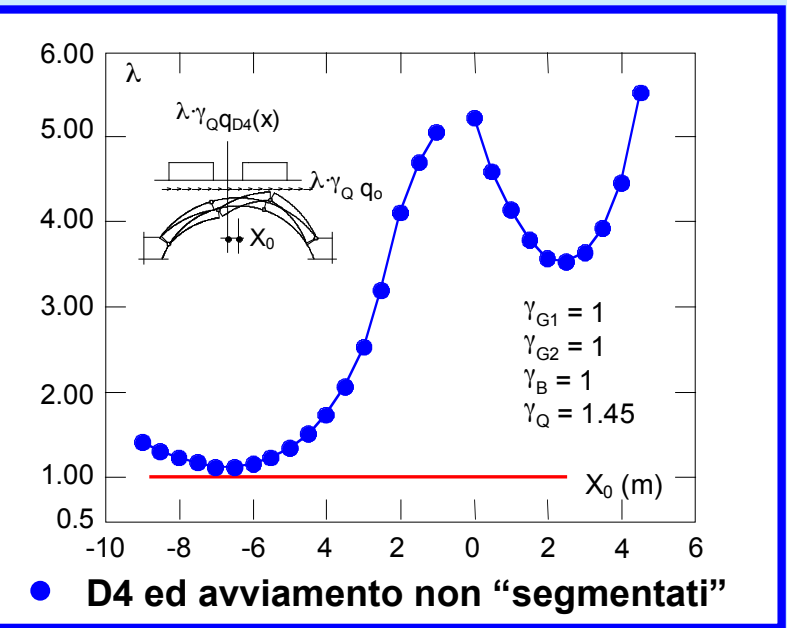
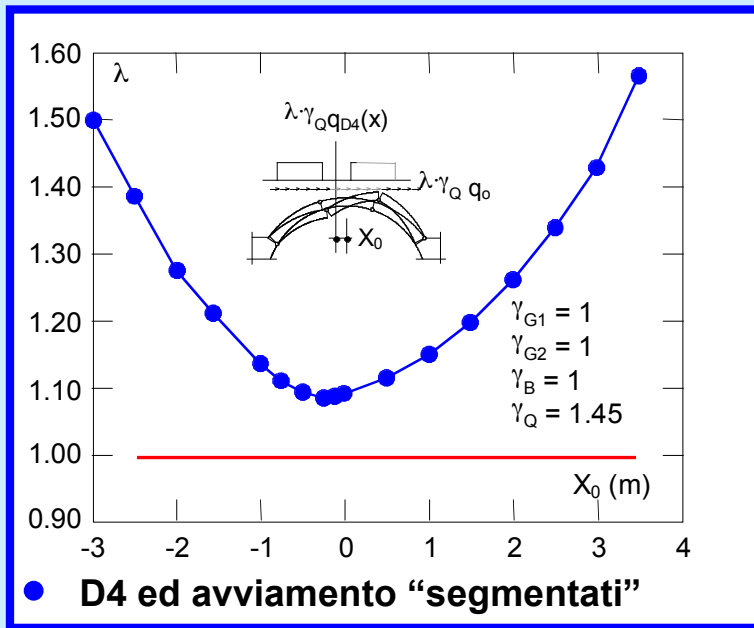
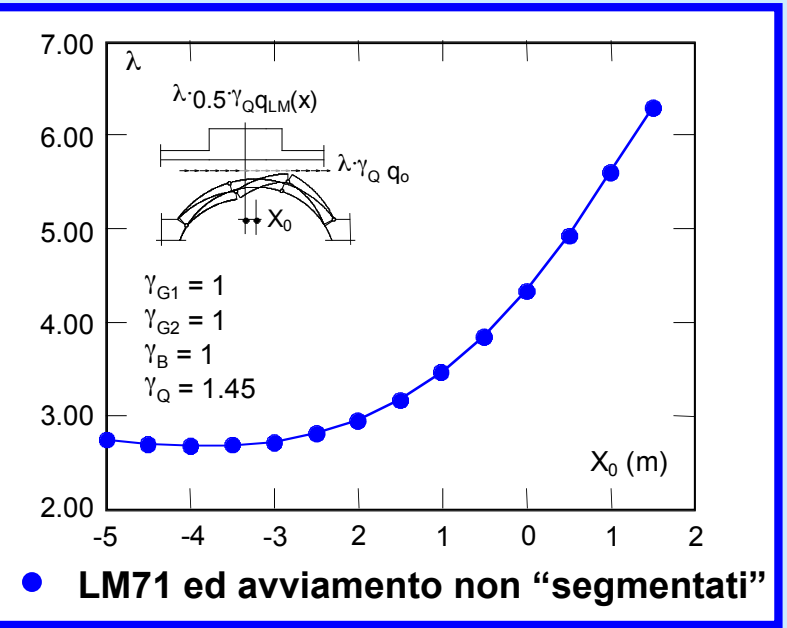
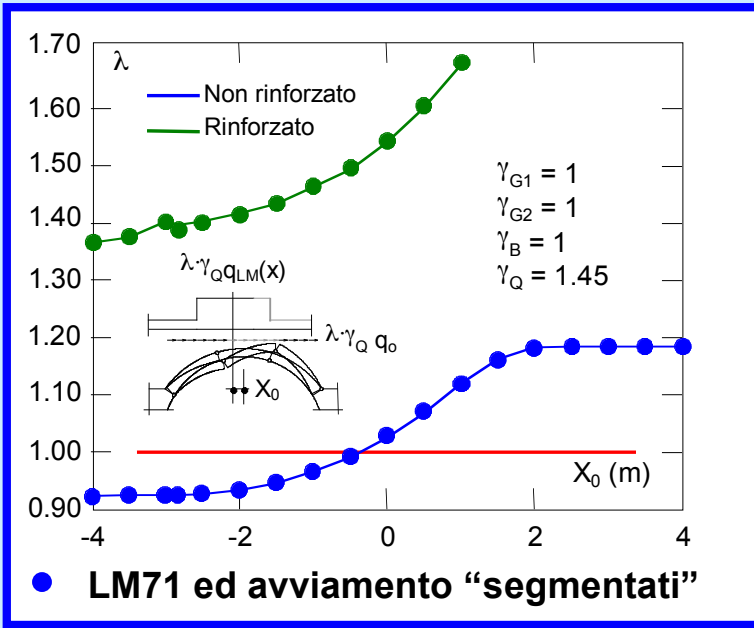


## • MECCANISMO 3: Azione sismica

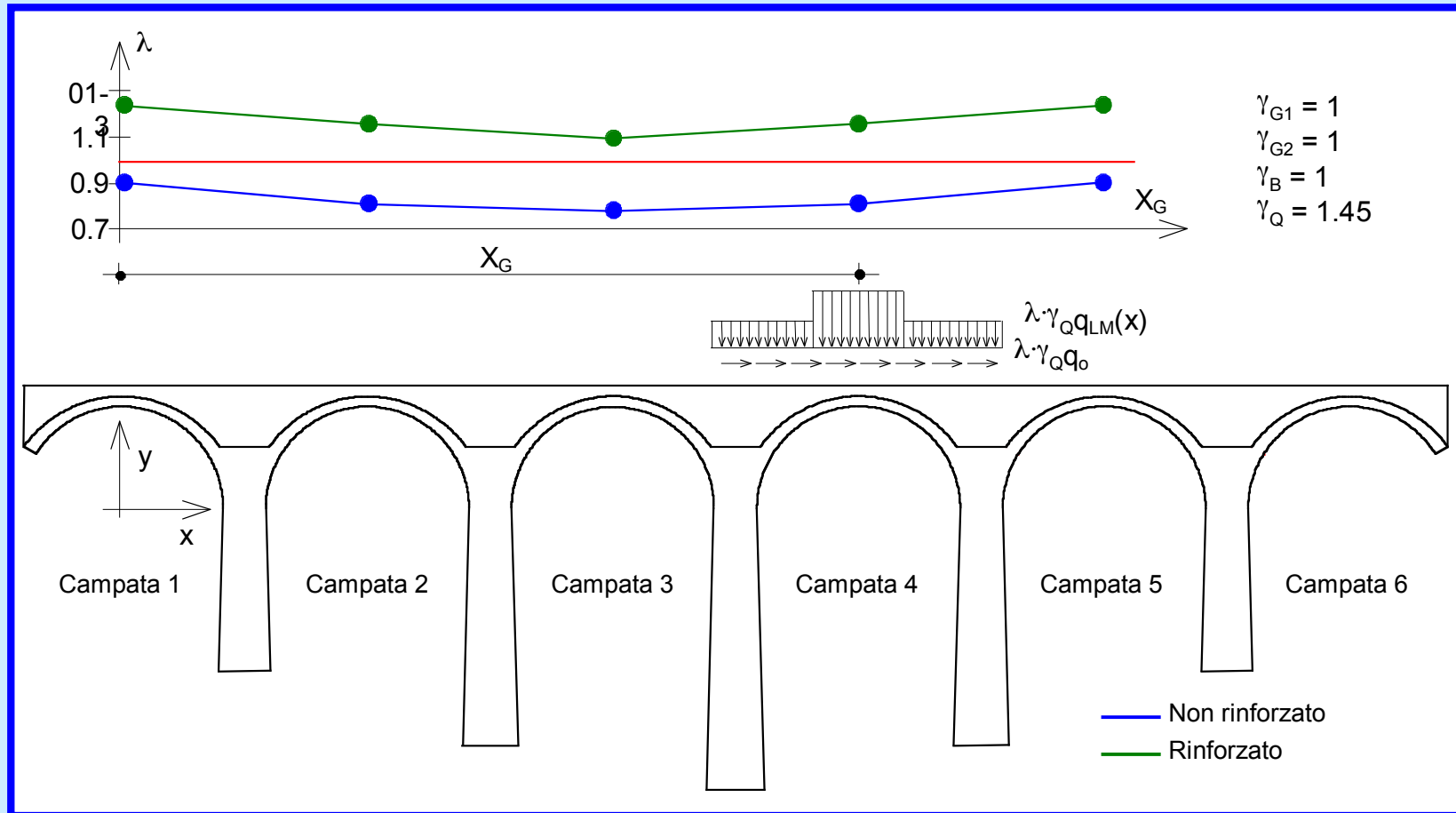
- MECCANISMO 2: Sistemi singoli



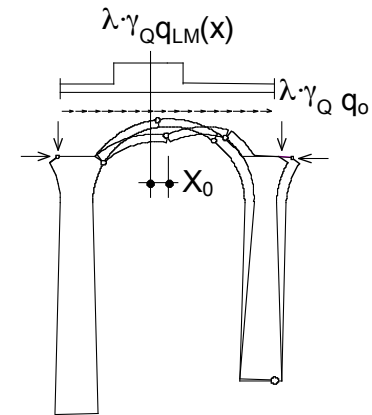
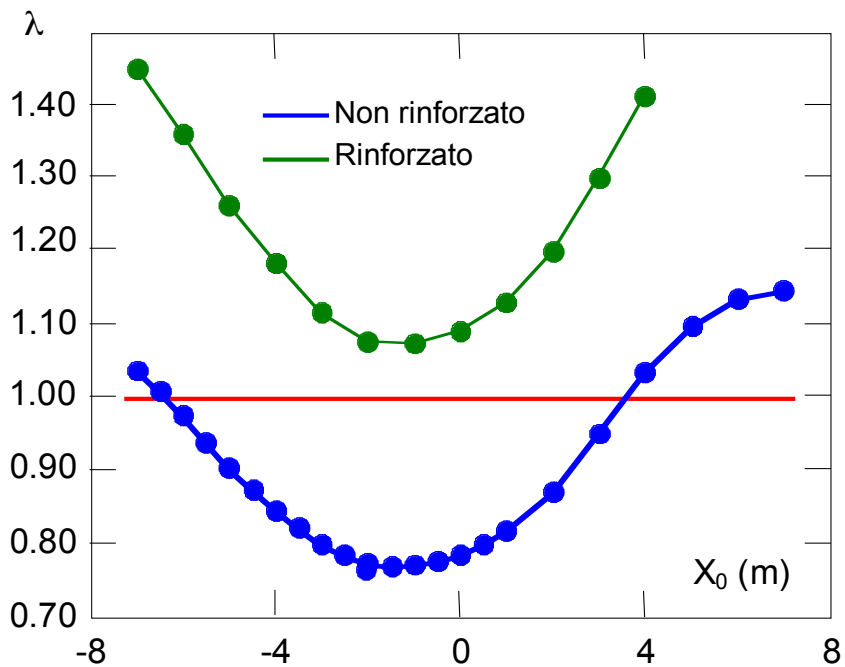
## RISULTATI: Meccanismo 1, senza sisma



## RISULTATI: Meccanismo 2, senza sisma



## RISULTATI: Meccanismo 2, senza sisma

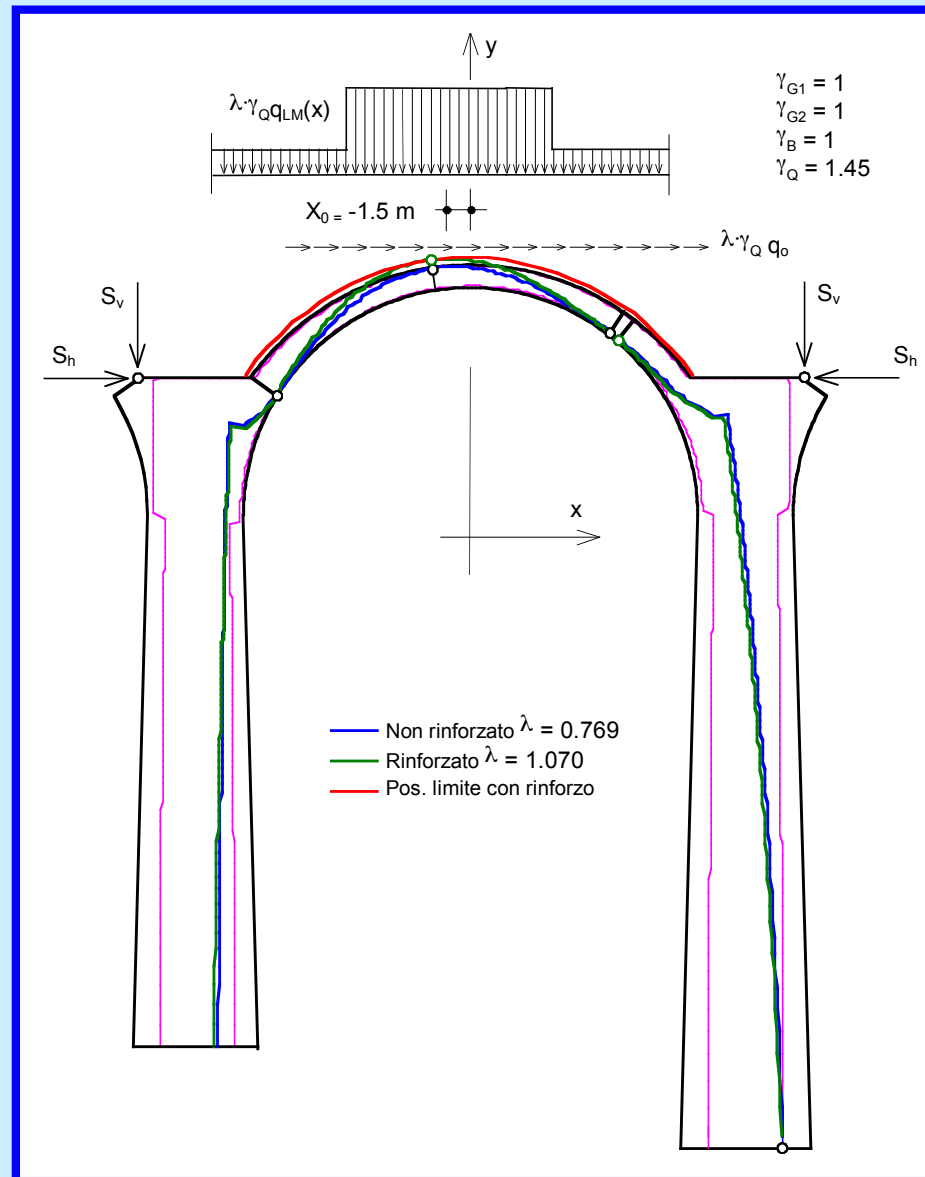


$$\begin{aligned} \gamma_{G1} &= 1 \\ \gamma_{G2} &= 1 \\ B &= 1 \\ \gamma_Q &= 1.45 \end{aligned}$$

● LM71 ed avviamento non “segmentati”



# RISULTATI: Meccanismo 2, senza sisma



# RISULTATI: Meccanismo 3, con sisma

