EXTENDING GFRP REBAR USE TO SEISMIC ZONES: HYBRID RC DESIGN AND CODE MODIFICATIONS

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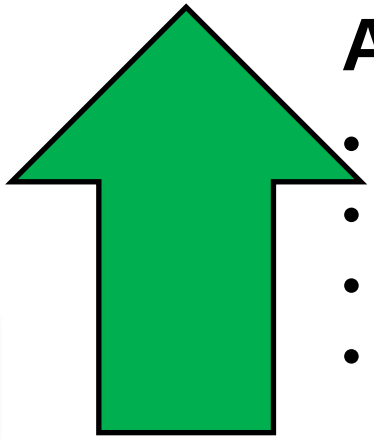
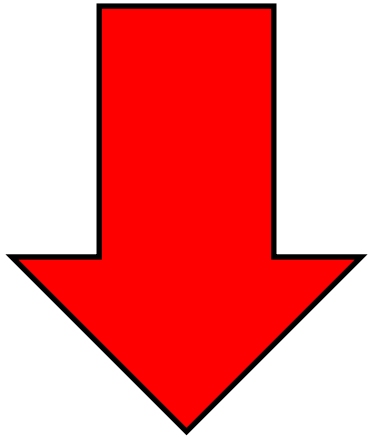
IS GFRP LIMITED TO NON-SEISMIC ZONE?



Advantages:

- high strength
- corrosion resistance
- lightweight
- durability



Limitations:

- brittle behavior
- low stiffness
- lower workability (folding)

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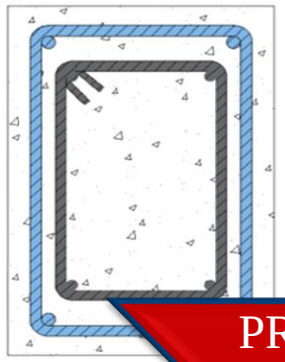
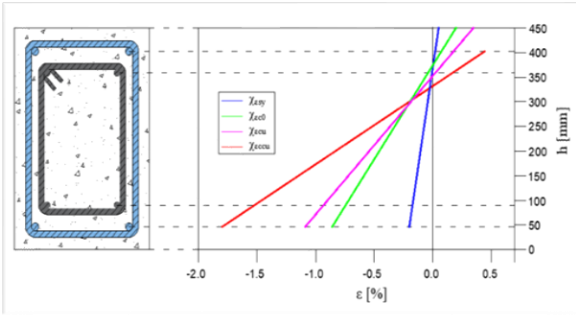
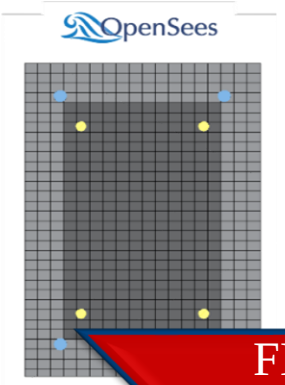
CASE STUDY OVERVIEW



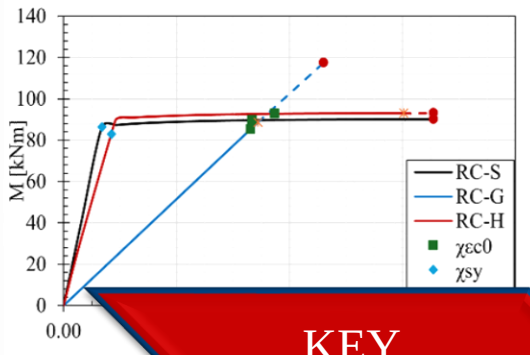
PROPOSED DESIGN APPROACH



ANALYTICAL VALIDATION

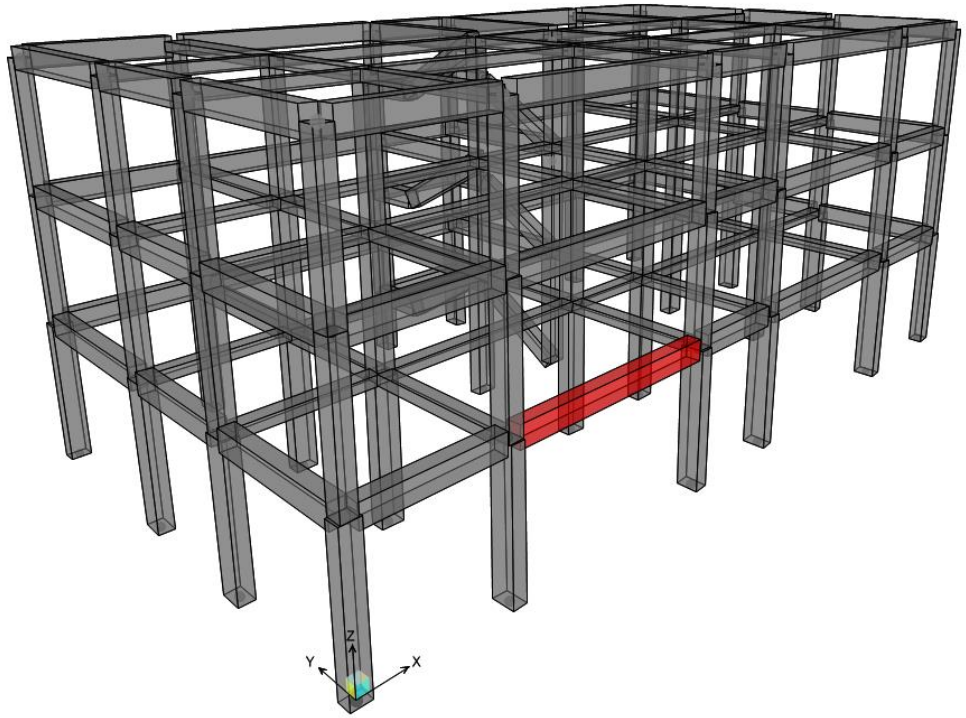


FINITE ELEMENT ANALYSIS



KEY CONCLUSIONS

CASE STUDY OVERVIEW



KEY CHARACTERISTICS

- moment resisting frame
- regular in both plan and elevation
- high seismic hazard site (~S_{DS}= 0.8g)
- code-conforming

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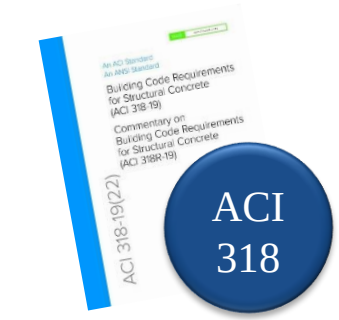
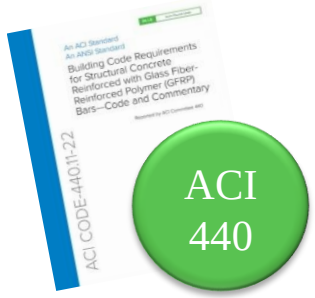
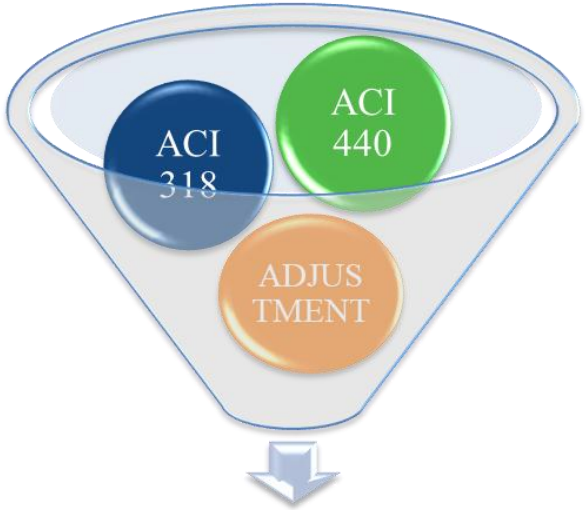
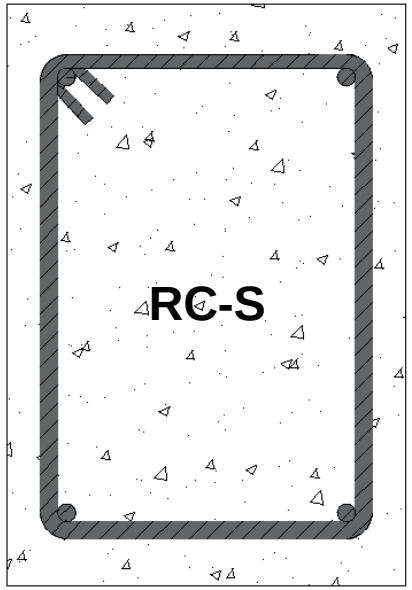
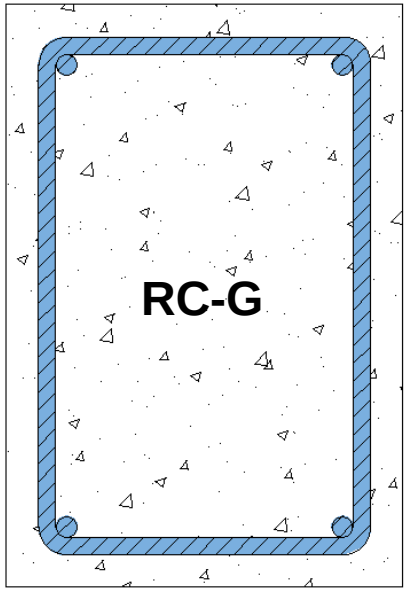
PROPOSED DESIGN APPROACH

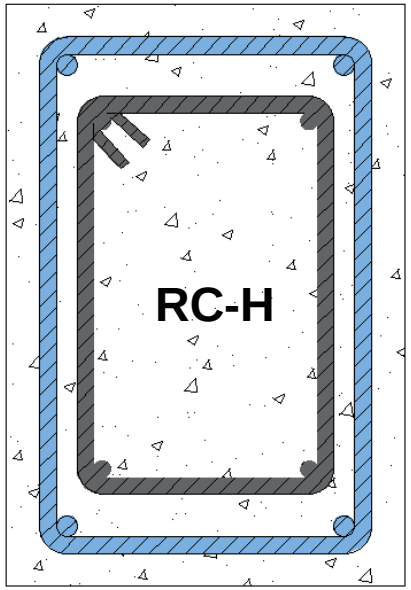












KEY CHARACTERISTICS

- same cross-section
- same bending capacity

STEEL

GFRP

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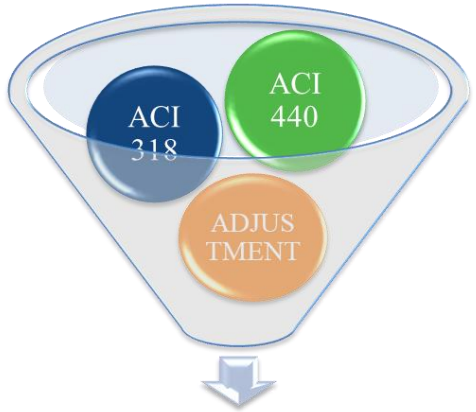
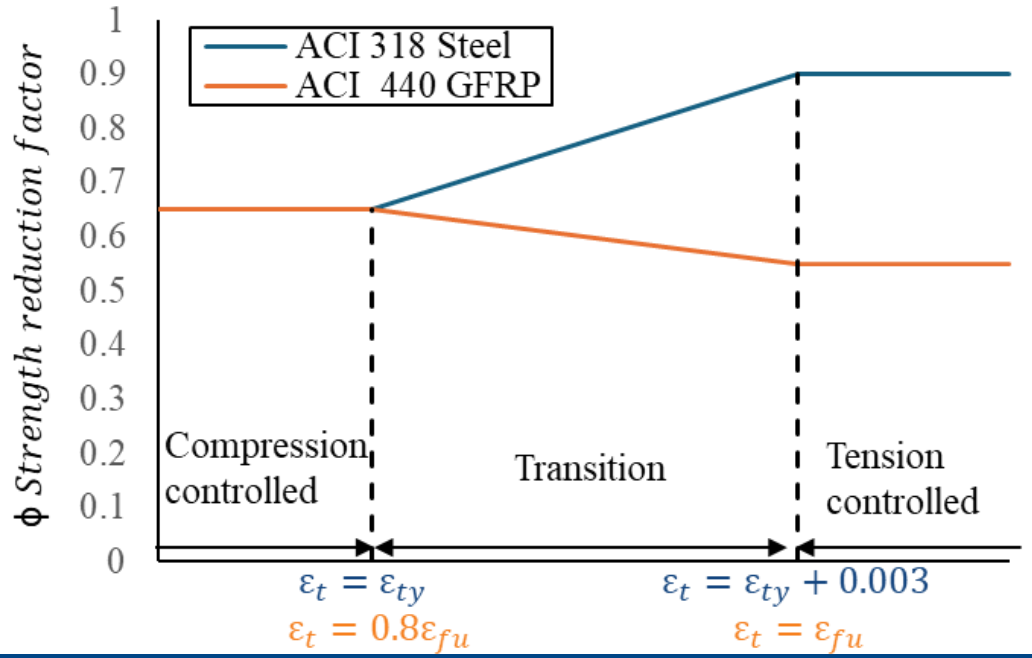
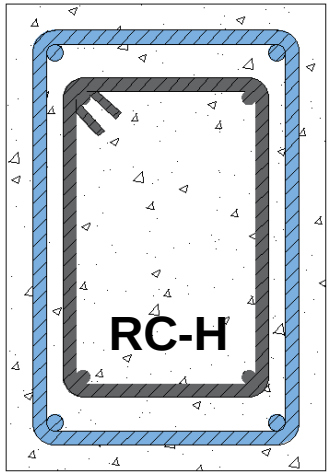
CASE STUDY OVERVIEW

PROPOSED DESIGN APPROACH

Quantity	Equations in the Codes and Proposed		
	RC-G (ACI 440.11)	RC-S (ACI 318-19)	RC-H (Proposed)
Strength reduction factor for tension-controlled section	**0.55**	**0.90**	**0.90**







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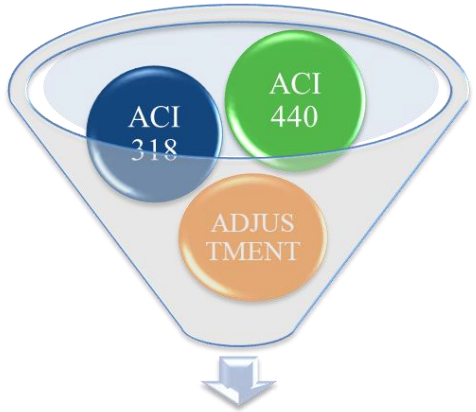
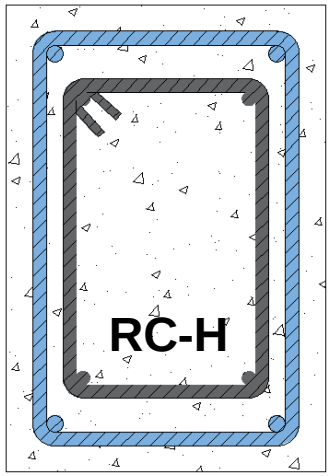
PROPOSED DESIGN APPROACH

Quantity	Equations in the Codes and Proposed		
	RC-G (ACI 440.11)	RC-S (ACI 318-19)	RC-H (Proposed)
Strength reduction factor for tension-controlled section	**0.55**	**0.90**	**0.90**
Strain	$C_{E^*}\varepsilon_{fu}$[1]	0.005	0.005
Minimum reinforcement area	$\frac{0.41\sqrt{f_c'}}{f_{fu}}bd$	$\frac{0.25\sqrt{f_c'}}{f_y}bd$	$\frac{0.25\sqrt{f_c'}}{f_y}bd$
Balanced reinforcement ratio	$\frac{0.85\beta_1 f_c'}{f_{fu}}\left(\frac{E_f\varepsilon_{cu}}{E_f\varepsilon_{cu}+f_{fu}}\right)$	$\frac{0.85\beta_1 f_c'}{f_y}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_y}\right)$	$\frac{0.85\beta_1 f_c'}{f_y}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_y}\right)$





Z. Hussain, F. Tuozzo, G. Magliulo, A. Nanni, Hybrid Reinforced Concrete Cross-section Using Fiber-Reinforced Polymer and Steel Bars. International Journal of Concrete Structures and Materials. 2024 (under review)

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Quantity	Equations in the Codes and Proposed		
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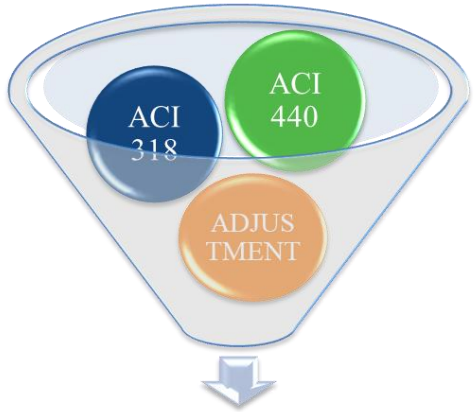
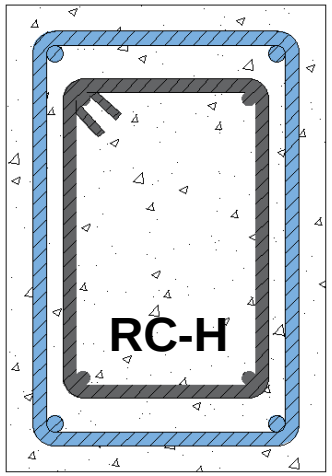
Shear strength	$V_c + V_f$	$V_c + V_s$	$V_c + V_f$
Concrete contribution to shear strength	$max\begin{cases} 0.42\lambda_s k_{cr}\sqrt{f'_c}bd \\ 0.066\lambda_s\sqrt{f'_c}bd \end{cases}$	$0.17\lambda_s\sqrt{f'_c}bd$	$0.17\lambda_s\sqrt{f'_c}bd$





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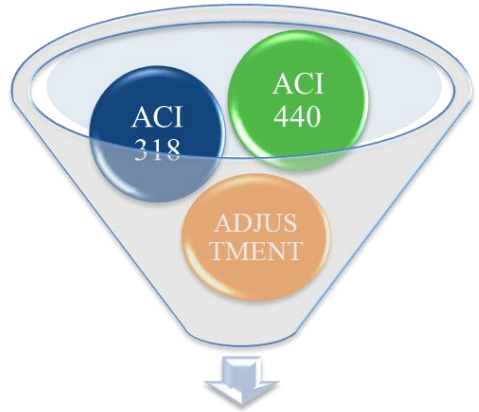
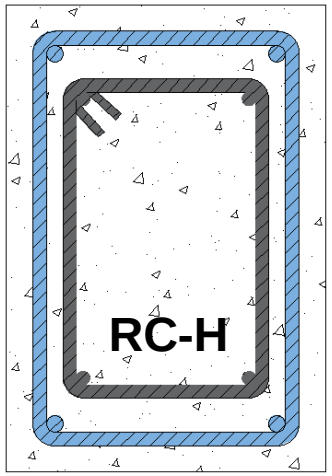
Strain	$C_{E^*}\varepsilon_{fu}$	0.005	**0.005**
Minimum reinforcement area	$\frac{0.41\sqrt{f_c'}}{f_{fu}}bd$	$\frac{0.25\sqrt{f_c'}}{f_y}bd$	$\mathbf{\frac{0.25\sqrt{f_c'}}{f_y}bd}$
Balanced reinforcement ratio	$\frac{0.85\beta_1 f_c'}{f_{fu}}\left(\frac{E_f\varepsilon_{cu}}{E_f\varepsilon_{cu}+f_{fu}}\right)$	$\frac{0.85\beta_1 f_c'}{f_y}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_y}\right)$	$\mathbf{\frac{0.85\beta_1 f_c'}{f_y}\left(\frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_y}\right)}$
Shear strength	$V_c + V_f$	$V_c + V_s$	$\mathbf{V_c + V_f}$
Concrete shear strength	$\max\begin{cases}0.42\lambda_s k_{cr}\sqrt{f'_c}bd \\ 0.066\lambda_s\sqrt{f'_c}bd\end{cases}$	$0.17\lambda_s\sqrt{f'_c}bd$	$\mathbf{0.17\lambda_s\sqrt{f'_c}bd}$





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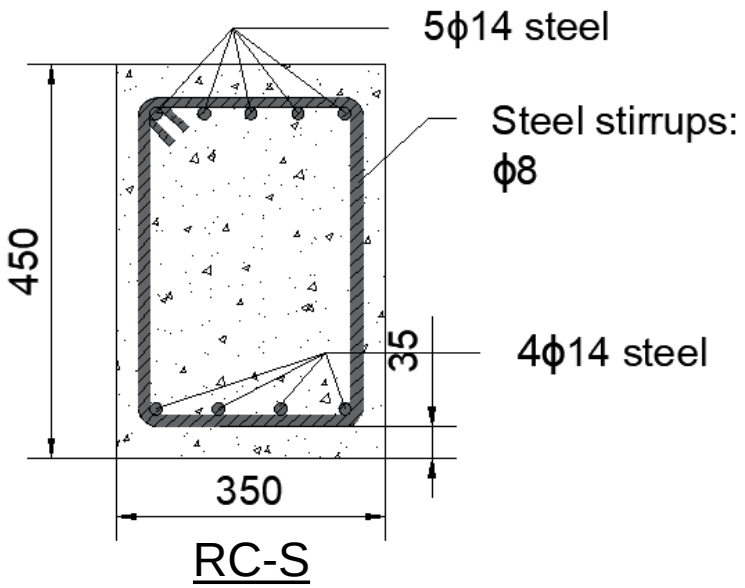
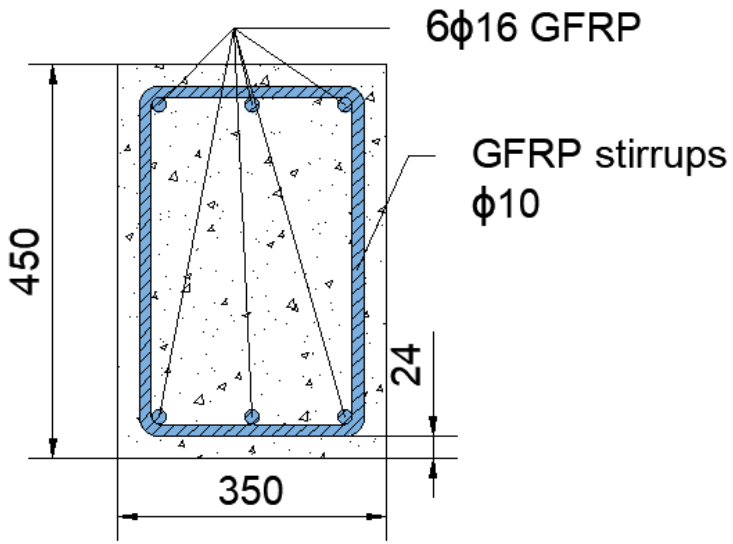
CASE STUDY OVERVIEW

PROPOSED DESIGN APPROACH

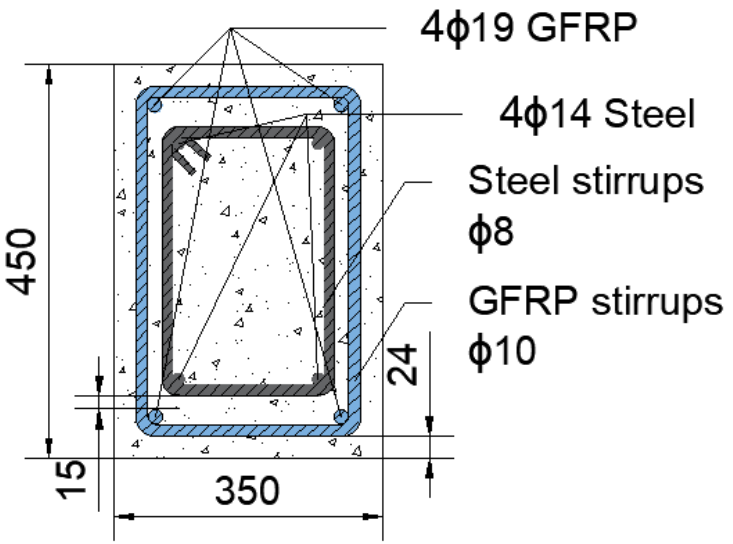
DESIGNED SECTIONS



RC-S



RC-G



RC-H

STEEL GFRP

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CASE STUDY OVERVIEW | PROPOSED DESIGN APPROACH | **ANALYTICAL VALIDATION**

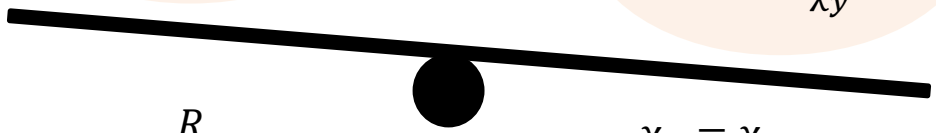
CURVATURE DUCTILITY

DEMAND

$$\mu_{\chi,D} = 2\,q_0 - 1$$

CAPACITY

$$\mu_{\chi,C} = \frac{\chi_u}{\chi_y}$$



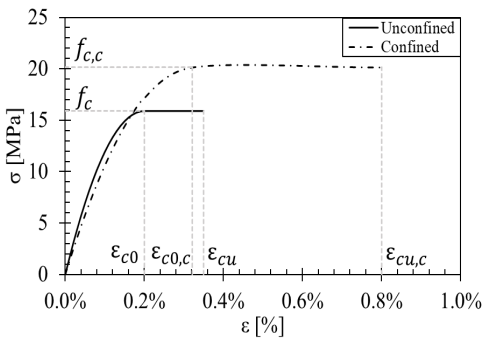
$$q_0 \approx \frac{R}{I_e}$$

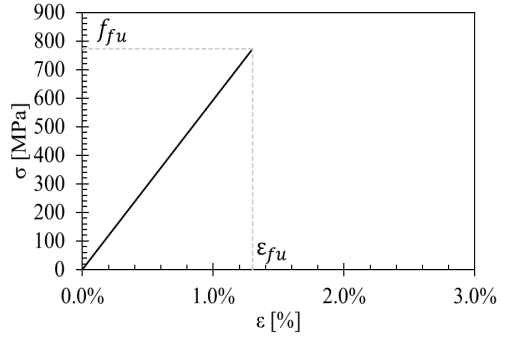
$$\chi_y = \chi_{\varepsilon sy}$$

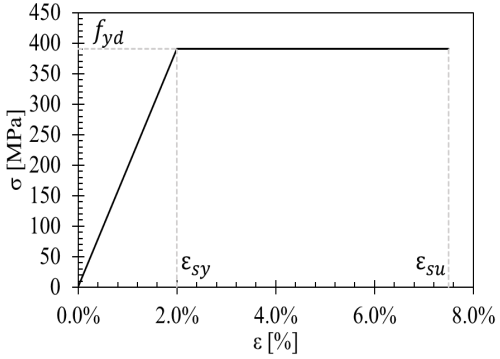
$$\chi_u = \min(\chi_{\varepsilon su}, \chi_{\varepsilon cu,c}, \boldsymbol{\chi_{\varepsilon fu}})$$

q_0 behavior factor (EC8);
R response modification coefficient (ASCE7);
I_e importance factor (ASCE7).

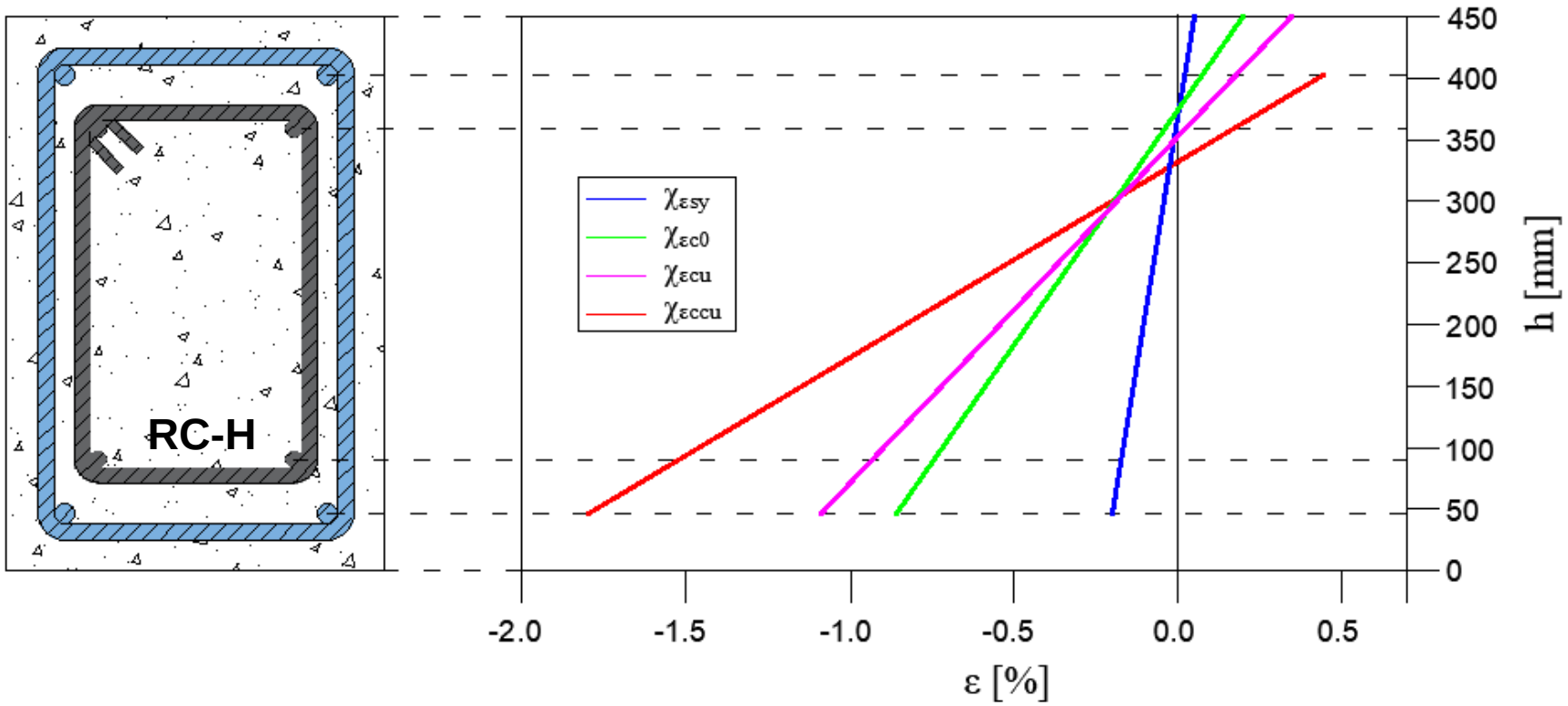
MATERIAL PROPERTIES







SECTIONAL ANALYSIS



CAPACITY

$$\mu_{\chi,C} = \frac{\chi_u}{\chi_y}$$

$$\chi_y = \chi_{\varepsilon sy}$$

$$\chi_u = \min(\chi_{\varepsilon su}, \chi_{\varepsilon cu,c}, \chi_{\varepsilon fu})$$

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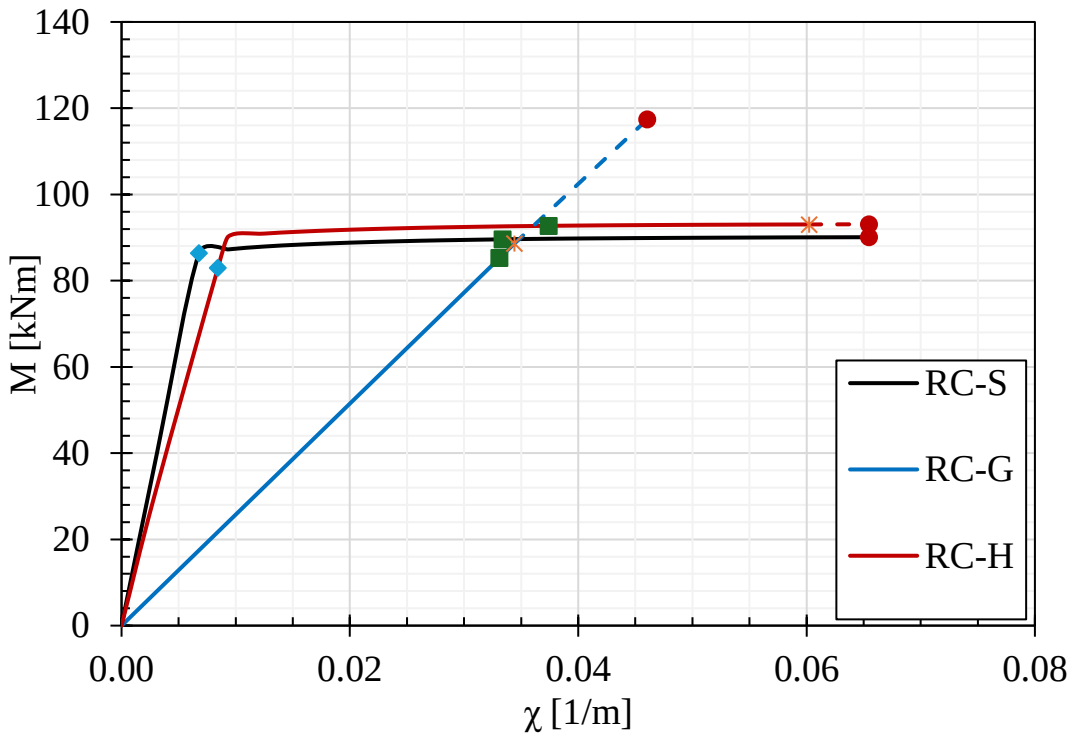
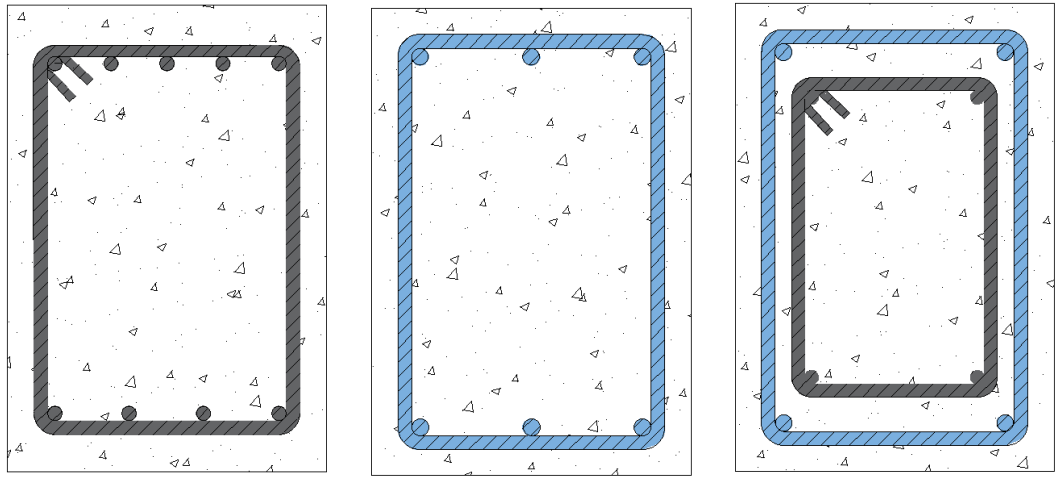
CASE STUDY OVERVIEW | PROPOSED DESIGN APPROACH | **ANALYTICAL VALIDATION**

SECTIONAL ANALYSIS RESULTS



$$\chi_u = \min(\chi_{\varepsilon su}, \chi_{\varepsilon cu,c}, \chi_{\varepsilon fu})$$

RC-S RC-G RC-H



$\mu_{\chi,c}$			$\mu_{\chi,D}$
RC-S	**RC-G**	**RC-H**	**6.2**
9.3	1.1	8.2	

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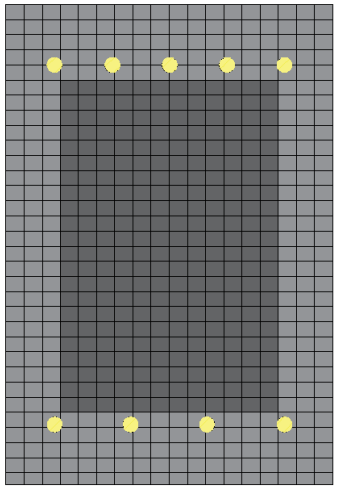
CASE STUDY OVERVIEW | PROPOSED DESIGN APPROACH | ANALYTICAL VALIDATION | **FINITE ELEMENT ANALYSIS**

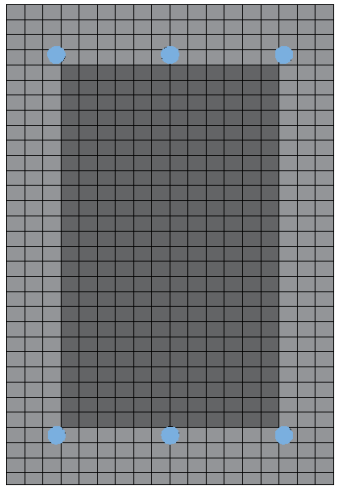
FEM MODEL

OpenSees

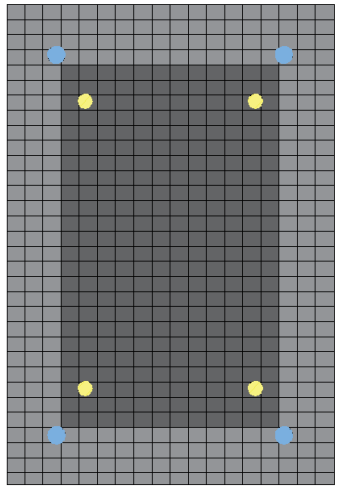
RC-S



RC-G

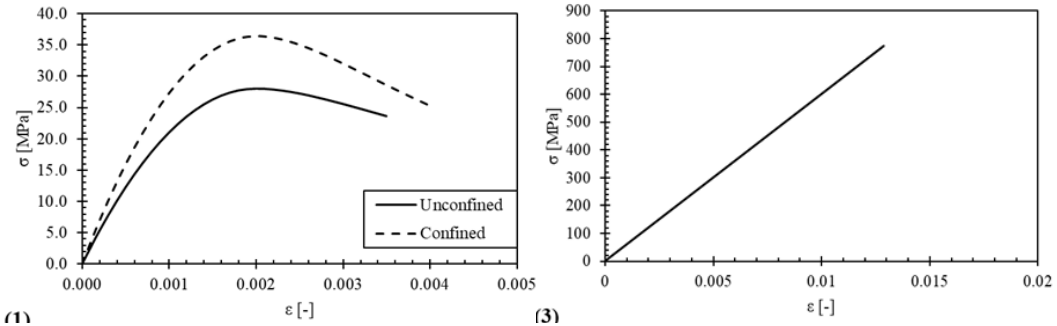


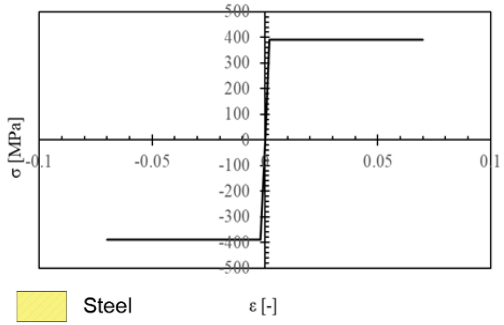
RC-H



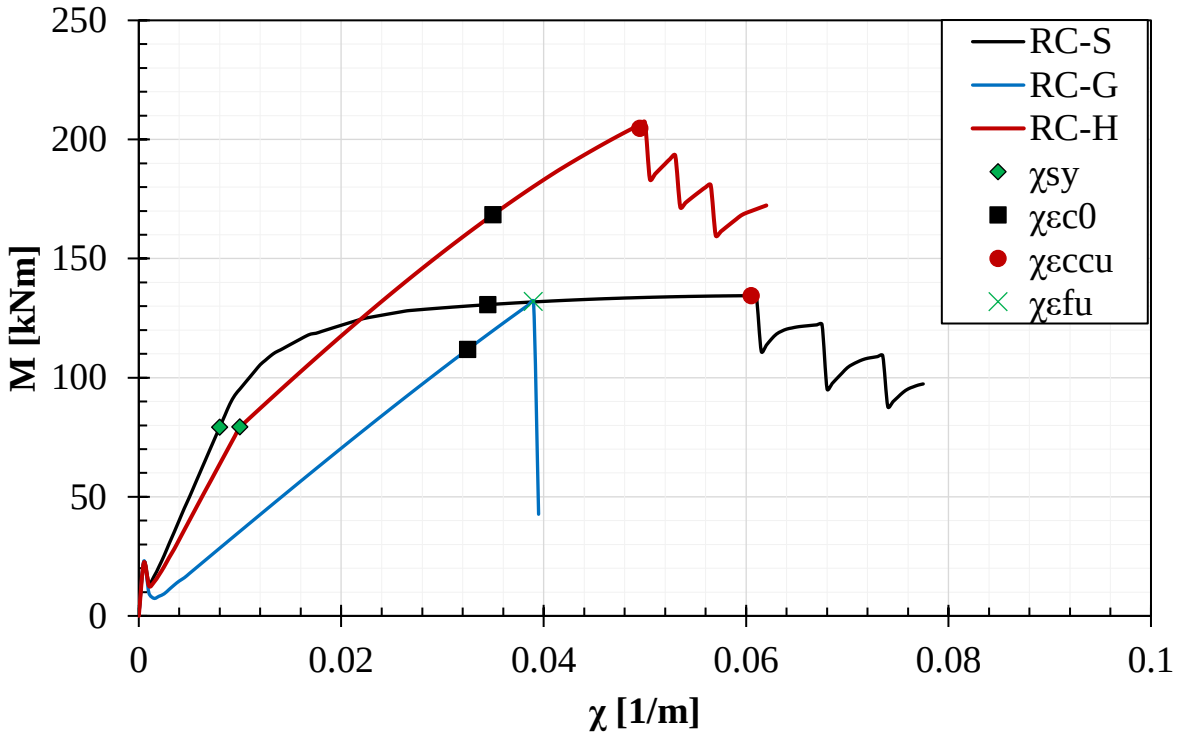
Confined Concrete | Unconfined Concrete | Steel | GFRP

MATERIAL PROPERTIES



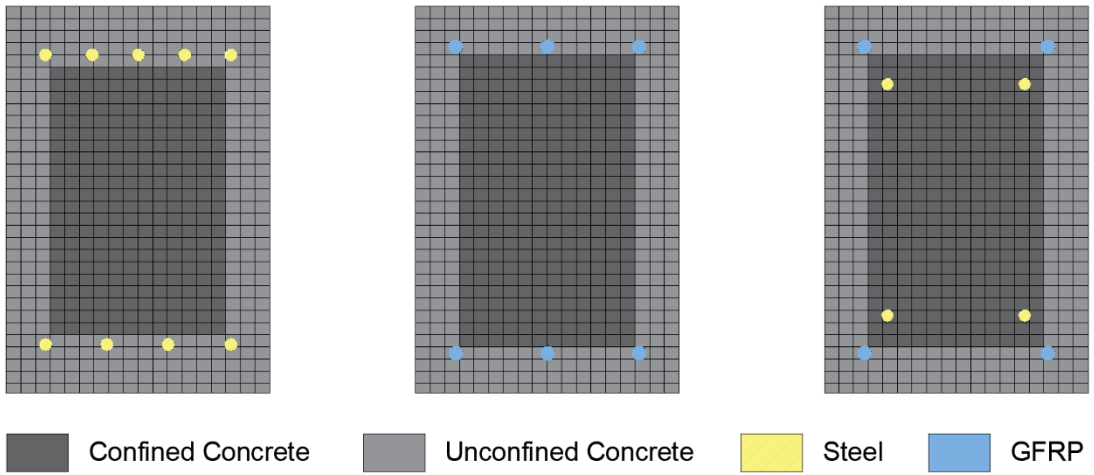


FEM RESULTS



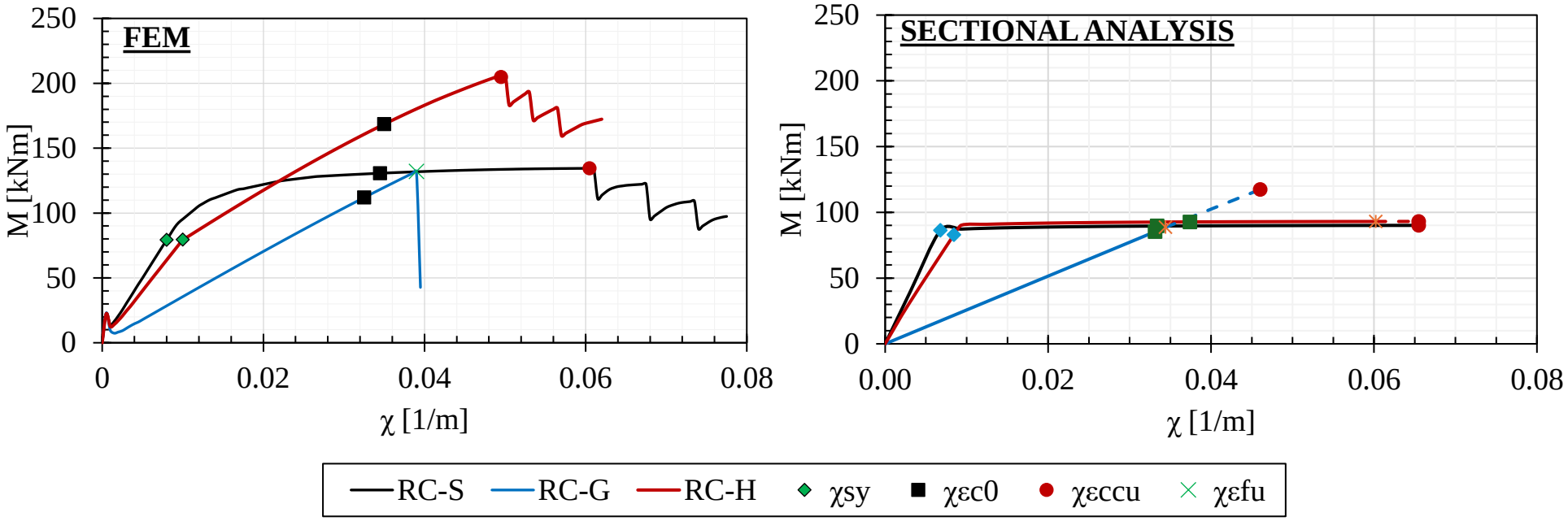
$$\chi_u = \min(\chi_{\varepsilon su}, \chi_{\varepsilon cu,c}, \chi_{\varepsilon fu})$$

RC-S RC-G RC-H



$\mu_{\chi,c}$			$\mu_{\chi,D}$
RC-S	**RC-G**	**RC-H**	**6.2**
8.2	1.2	7.6	

COMPARISON RESULTS



$\mu_{\chi,c}$ FEM			$\mu_{\chi,c}$ SECTIONAL			$\mu_{\chi,D}$
RC-S	**RC-G**	**RC-H**	**RC-S**	**RC-G**	**RC-H**	**6.2**
8.2	1.2	7.6	9.3	1.1	8.2	

- Both sectional analysis and finite element models indicate that the hybrid section is suitable for use in seismic regions.
- The inclusion of steel reinforcement significantly enhances the ductility of the section compared to GFRP-only reinforcement.
- While the curvature ductility of the steel-only section remains higher than that of the hybrid sections, the performance of the latter is still comparable.
- Differences between the sectional analysis and finite element results are primarily due to the distinct material properties considered in each approach.

IS GFRP LIMITED TO NON-SEISMIC ZONE?

FINITE ELEMENT ANALYSIS			DEMAND	SECTIONAL ANALYSIS		
$\mu_{\chi,C}$ FEM			$\mu_{\chi,D}$	$\mu_{\chi,C}$ SECTIONAL		
RC-S	**RC-G**	**RC-H**	**6.2**	**RC-S**	**RC-G**	**RC-H**
8.2	1.2	7.6		9.3	1.1	8.2

REFERENCES:

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THANKS FOR YOUR ATTENTION