Advances in Hybrid Structures

Precast Concrete Frames and Ductile Steel Connections

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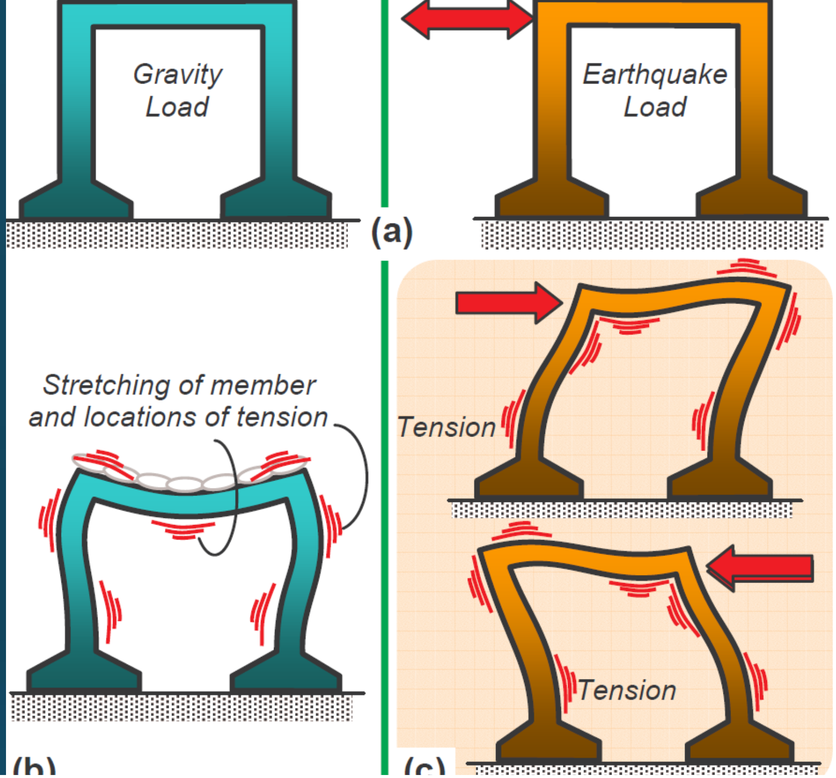
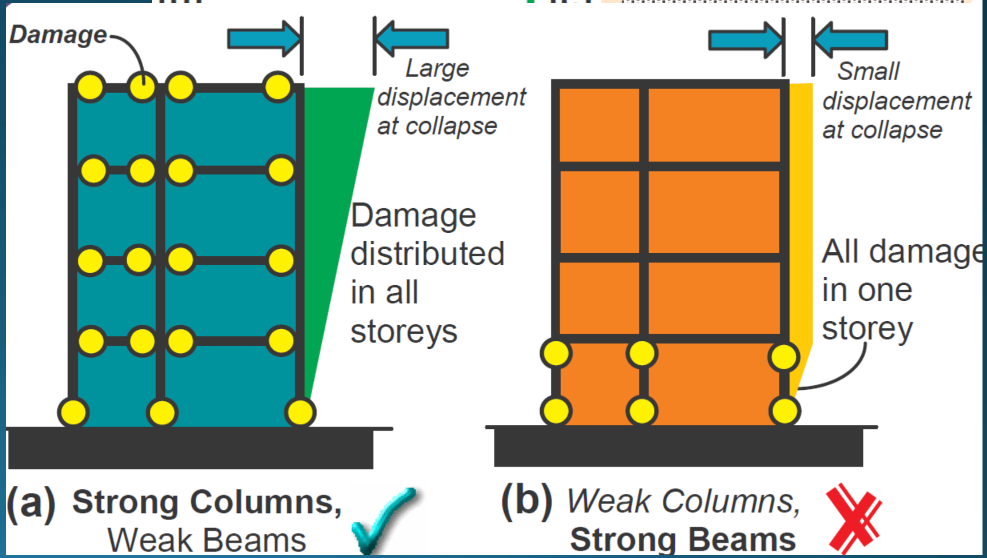
Experience of past earthquake regarding reinforced concrete (RC) frames

In RC frames, the applied seismic energy is dissipated through the ductile behavior of RC moment resisting frames.

- Repairing the beam is difficult because it carry the gravity load **addition to the seismic loads**

- RC frame rely on hinge formation at two end of beams





Strengthening of RC frames

Local

- Jacketing (concrete of steel)
- FRP
- Local repairing

Global

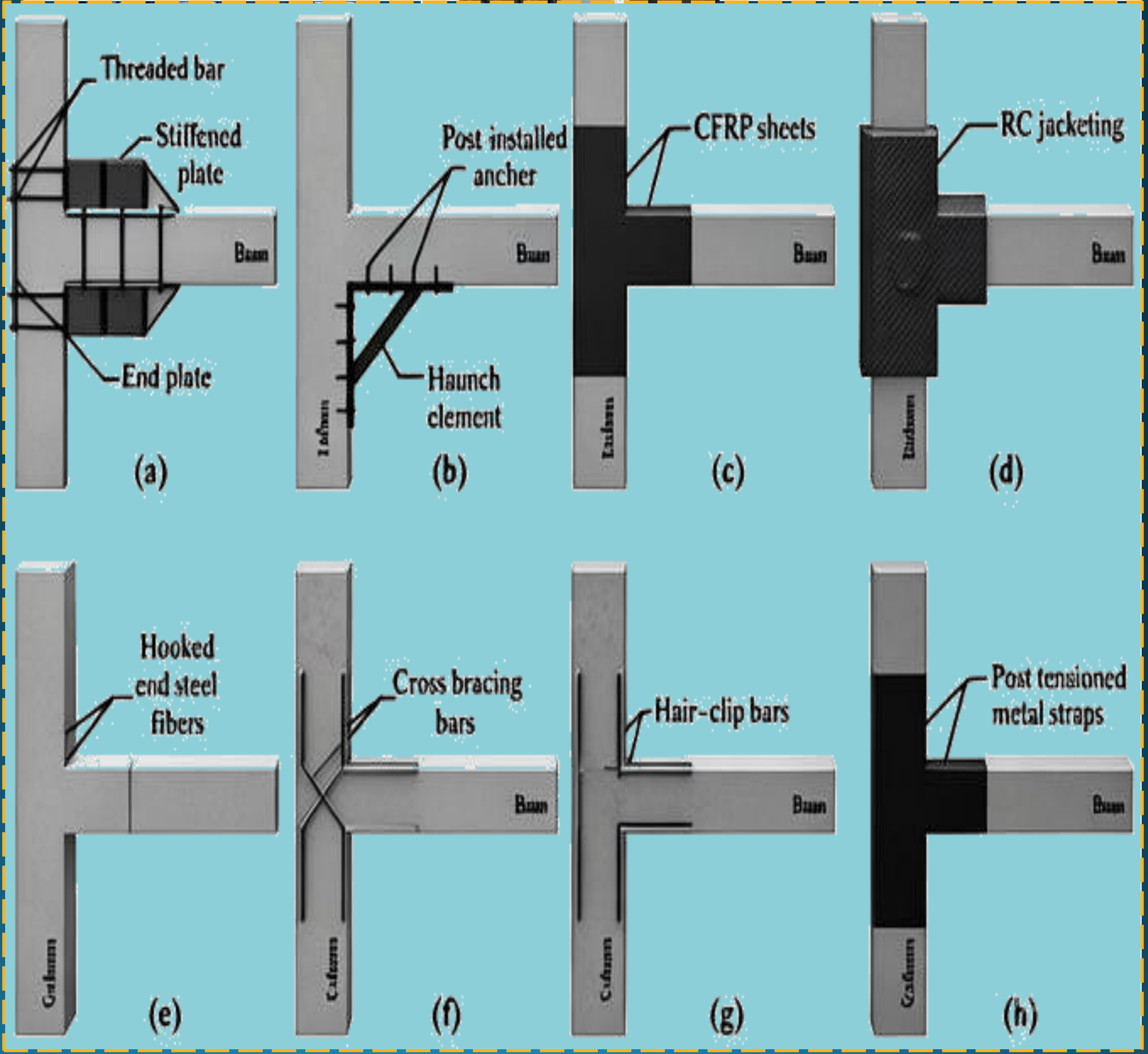
- Concrete shear walls
- Metallic braces (CBF or EBF)
- Steel Plate shear walls
- Metallic dampers
- etc.

To improve structure behavior due to improve the:

- strength
- Stiffness
- Ductility (reduce the demand of earthquake)
- Reduction of elements stresses

Experience of past earthquakes

Common approaches for strengthening of connections of RC frames



They are not replaceable after a sever earthquake

Evolution of the connection concept

1960
Conventional RC
Monolithic joint
plastic hinge in beam/column

1990
Precast hybrid
Steel plates / bars / PT
improved constructability

2000
Low-damage PT
Self-centering + mild-steel
energy dissipation

2015
Replaceable fuse
Damage deliberately
concentrated in steel

2026
Current frontier
Externally replaceable
links / CHS dampers + resilience

Precast concrete frames

Main advantages of precast concrete frames

Rapid construction	Structural components are manufactured in a factory while site preparation and foundation work proceed simultaneously. Erection of beams, columns, and slabs is much faster than conventional cast-in-place construction. This can significantly reduce the overall construction schedule.
High and consistent quality	Factory production provides controlled conditions for concrete mixing, casting, curing, and reinforcement placement. Dimensional accuracy and material quality are generally more consistent than site-cast construction. Quality-control procedures can be systematically implemented.
Reduced site labor	Much of the labor-intensive concrete work is transferred from the construction site to the precast plant. This reduces dependence on skilled workers at the construction site.
Reduced construction waste	Factory production allows more accurate control of concrete, reinforcement, and other materials. Formwork can be reused many times, reducing material consumption and waste.
Improved construction safety	A substantial portion of fabrication occurs in a controlled factory environment. Reduced site activities such as formwork erection, reinforcement tying, and concrete casting can improve site safety.

Better durability	Controlled manufacturing and curing conditions can produce dense, high-quality concrete. Properly designed precast elements can provide excellent resistance to environmental exposure, corrosion, and deterioration.
Reduced formwork requirements	Unlike cast-in-place construction, extensive temporary formwork and shoring are generally not required at the construction site. This can reduce both cost and construction time.
Efficient use of materials	Optimized cross-sections can be readily incorporated into precast components. This can allow longer spans, smaller member dimensions, and lower structural weight.
Good dimensional accuracy	Computer-controlled production, reusable molds, and factory quality control provide accurate and repeatable member dimensions. This is particularly beneficial for modular and standardized construction.
Industrialized and modular construction	Precast frames are well suited to **Design for Manufacturing and** Assembly(DfMA) and Building Information Modeling (BIM). Components can be standardized and produced in large quantities.

Cost and Economic Factors

A significant barrier to the use of precast concrete frames is the high initial investment required. This includes costs for factory production, specialized transportation, and equipment . Achieving cost-efficiency is difficult for smaller projects, as it relies heavily on repetition and economies of scale to offset the expensive setup and prototyping phases . In many cases, precast methods remain more costly than traditional cast-in-place (CIP) construction, despite potential savings in labor and time .

Structural and Seismic Performance Concerns

The connections between precast elements, often the weakest link, introduce several engineering challenges.

Complex Seismic Behavior

PC frames can behave fundamentally differently from monolithic cast-in-place structures under seismic loads. The presence of material and geometric discontinuities at connection points can alter how forces are distributed, where plastic hinges form, and how the frame dissipates energy during an earthquake . This can lead to unpredictable failure modes.

Reduced Strength and Stiffness:

Some precast systems have been found to have inferior ultimate load-carrying capacity compared to equivalent cast-in-place frames . A particular concern is the potential for excessive lateral displacement under strong earthquake motions, which is often attributed to low lateral stiffness and limited energy dissipation at the connections . The displacement incompatibility between structural elements and non-structural components like cladding panels can also cause premature failure .

Vulnerability to Collapse:

The connections in a precast frame significantly influence its vulnerability to progressive collapse, where the failure of one component can trigger a chain reaction. Frames with semi-rigid connections, for example, have shown a higher potential for progressive collapse compared to those with rigid connections .

Connection Reliability

The performance of precast connections is highly sensitive to their design, detailing, and construction quality. Unlike the continuous construction of cast-in-place frames, failure often occurs at the joints themselves . For instance, bolted connections can exhibit sudden brittle failure at welds, and the shear strength of interfaces between precast and cast-in-place concrete depends heavily on surface roughness .

Design and Construction Constraints

Precast construction demands a much higher level of precision and planning upfront. If connections are not designed with adequate detail or if elements are not properly modeled and sequenced, the structural integrity can be compromised . Furthermore, reliance on specialized equipment and skilled labor is required for the complex assembly processes, adding to logistical challenges .

Main advantages of precast concrete frames

- Rapid construction
- High and consistent quality
- Reduced site labor
- Reduced construction waste
- Improved construction safety

- Cost and Economic Factors
- Seismic Performance Concerns
- Complex Seismic Behavior
- Reduced Strength and Stiffness:
- Vulnerability to Collapse
- Connection Reliability
- Design and Construction Constraints

While offering benefits in speed and quality control, precast concrete frames require significant upfront investment and careful engineering to overcome challenges related to cost, complex structural behavior, and connection performance, especially in seismic regions.

While precast concrete frames have some notable disadvantages, they also offer a distinct and valuable set of advantages. The "changeless"—or enduring—benefits are what make them a popular choice for many modern construction projects . Here are the key strengths that define their value:

- **Speed and Efficiency**: Manufacturing components off-site happens concurrently with site preparation, which can significantly shorten the overall construction timeline. This leads to fewer weather-related delays and faster project completion.
- **High Quality and Durability**: Factory-controlled production ensures consistent, high-quality results with precise dimensions. This results in strong, durable structures with reduced shrinkage and cracking, and excellent fire resistance .
- **Seismic Resilience**: While seismic performance can be a disadvantage for standard designs, modern precast systems with advanced connections are engineered to perform well in earthquakes, demonstrating minimal damage and self-centering capabilities .
- **Cost and Schedule Certainty**: A fixed manufacturing process and rapid on-site installation provide excellent cost predictability and reduce the risk of expensive delays .
- **Sustainability**: Precision casting generates less waste on-site. The controlled environment also allows for more efficient material use and the potential for lower-carbon concrete mixes .
- **Enhanced Site Safety**: Precast construction reduces the need for extensive formwork, scaffolding, and high-risk on-site activities, contributing to a safer working environment .

Solution for PC frames → Ductile steel connections

Why hybrid precast seismic systems?

Combining prefabrication efficiency with controlled inelastic response

Precast construction

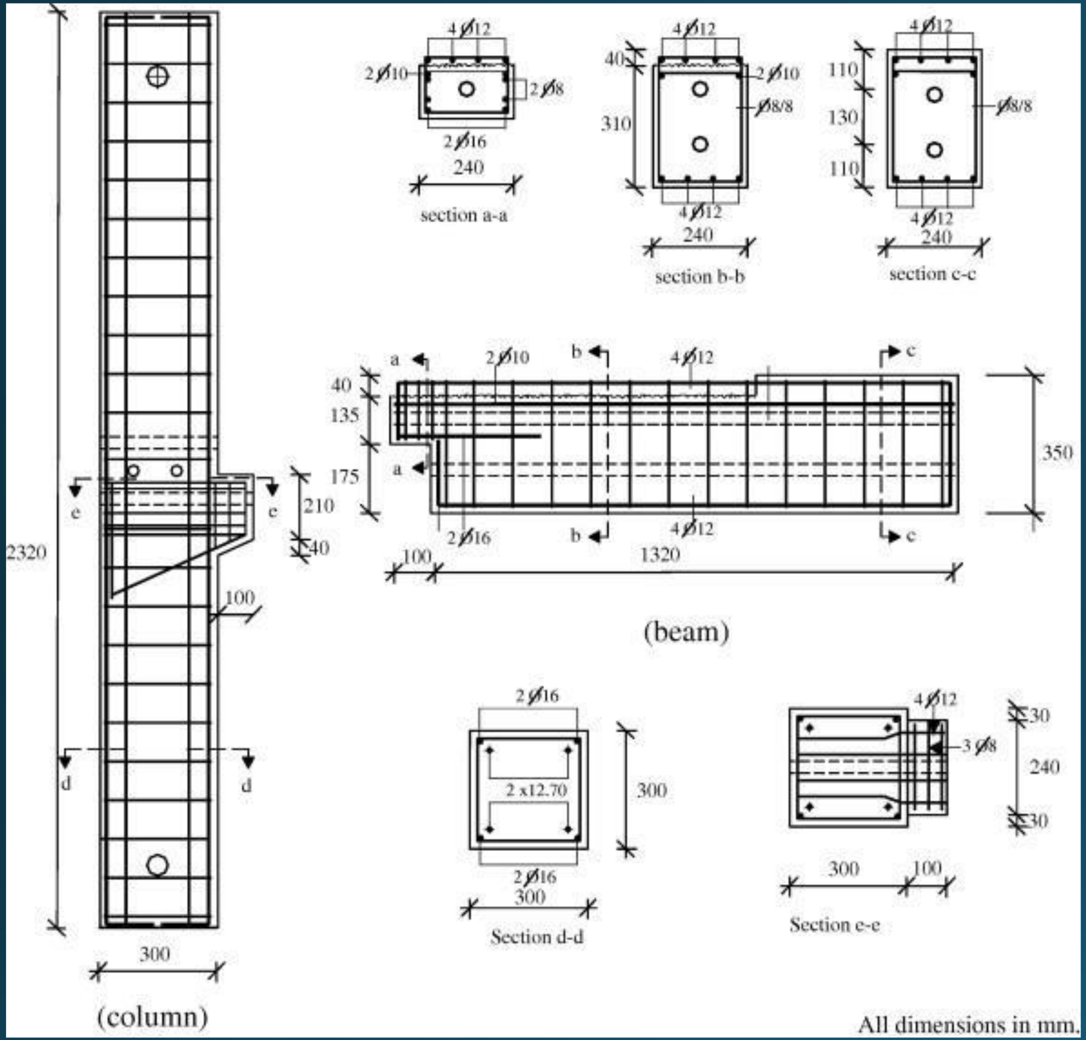
Factory quality control
Rapid erection
Reduced site labor
Modularity and repeatability

Ductile steel connection

High deformation capacity
Stable energy dissipation
Predictable yielding
Replaceable after severe shaking

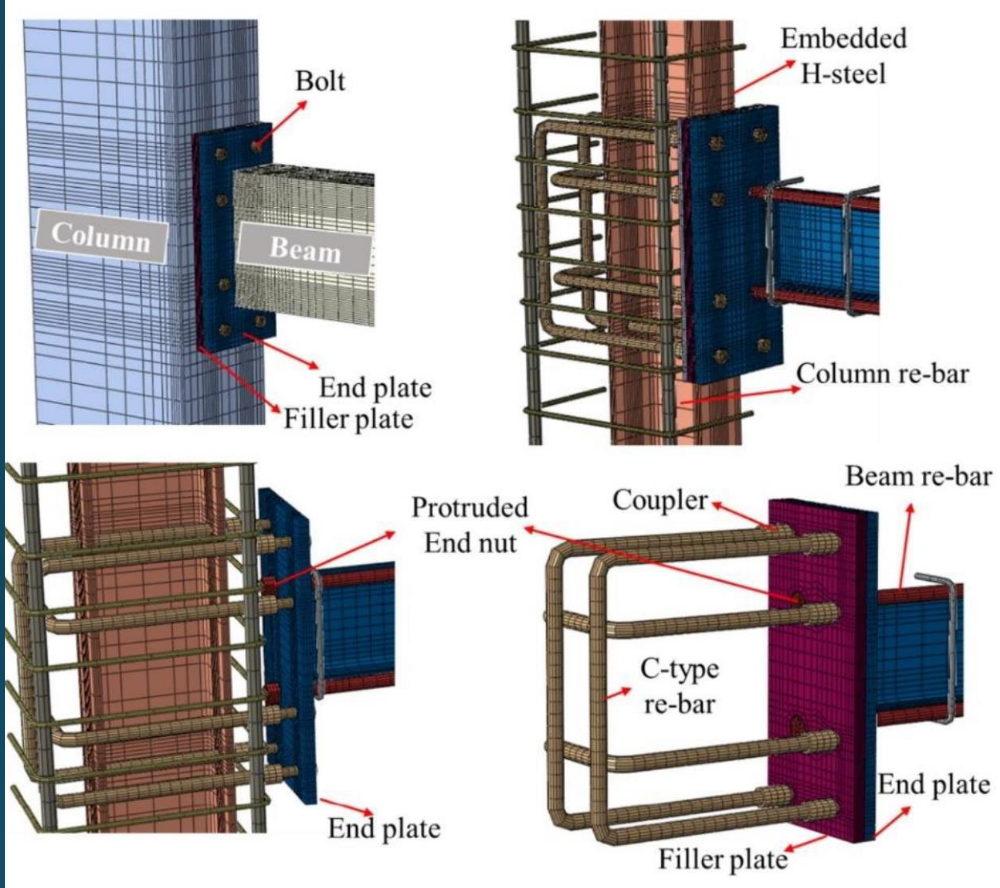
Hybrid objective

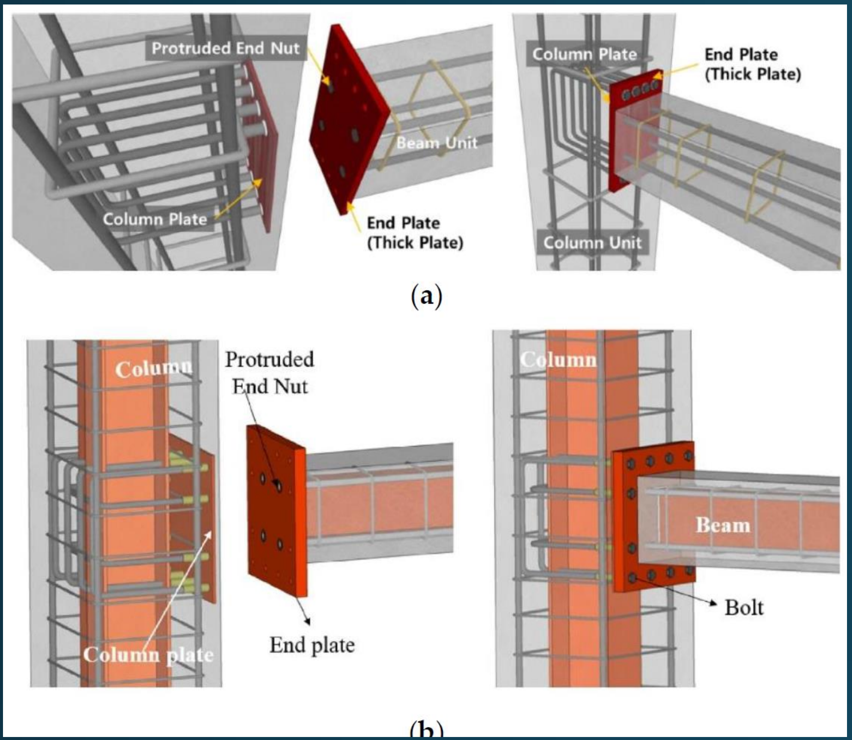
Keep beams/columns and concrete joint damage low
Concentrate damage in a fuse
Restore occupancy rapidly



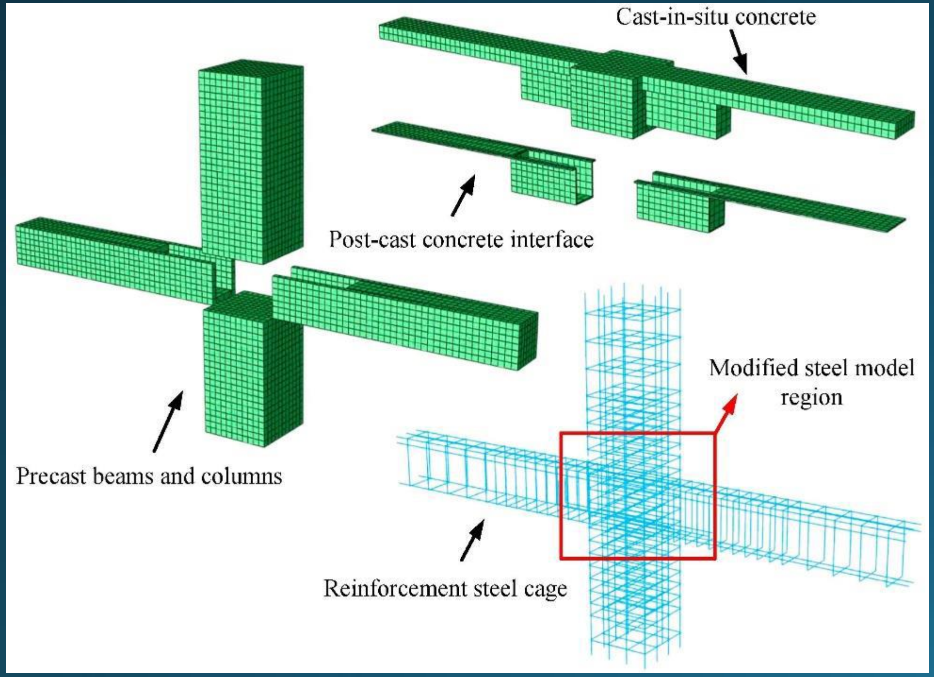
Kaya and Arslan, 2009

Nzabonimpa, 2017



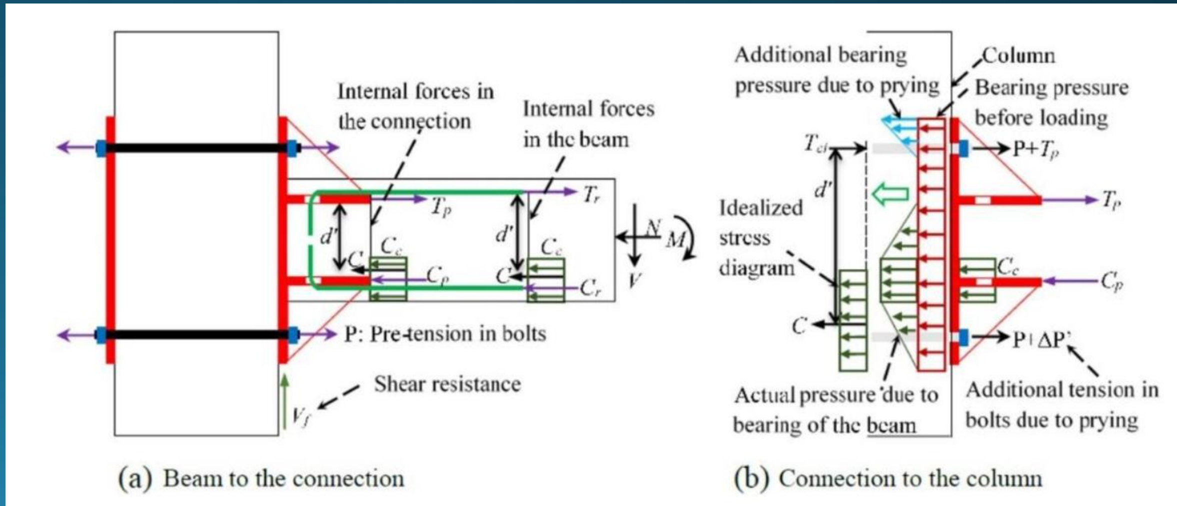


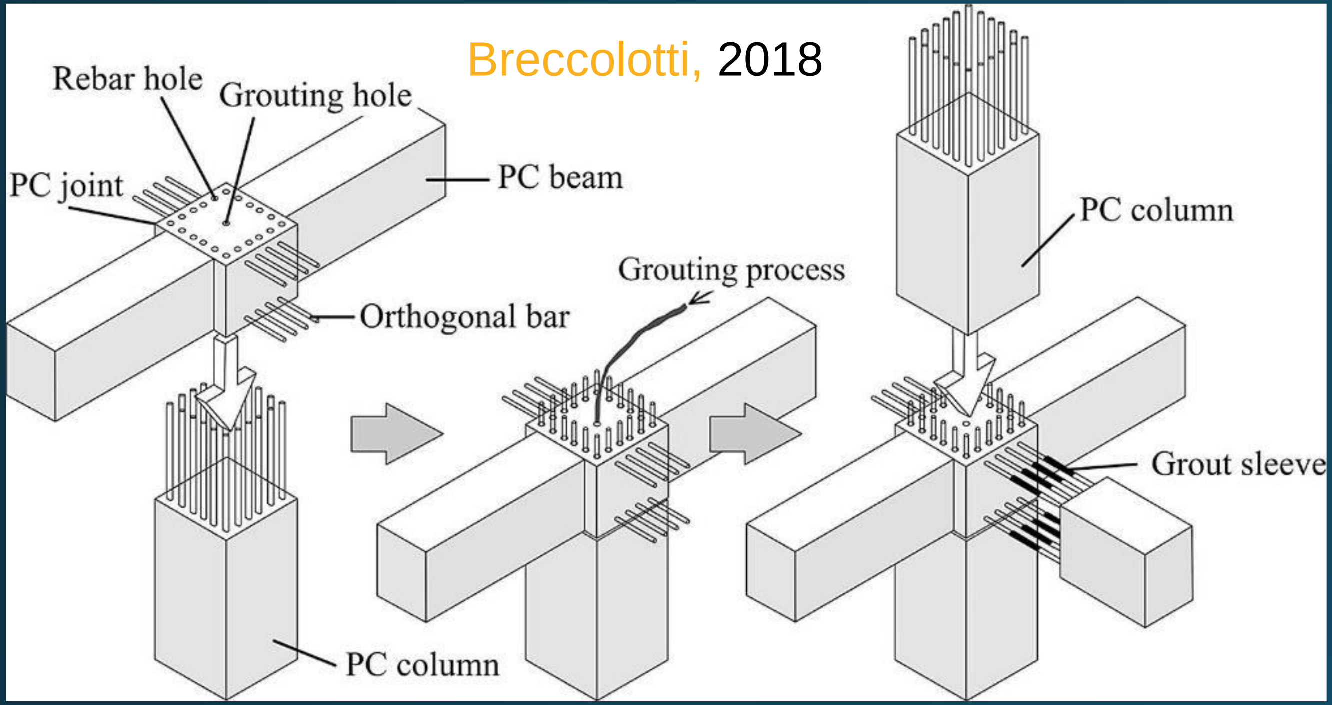
Nzabonimpa, 2017

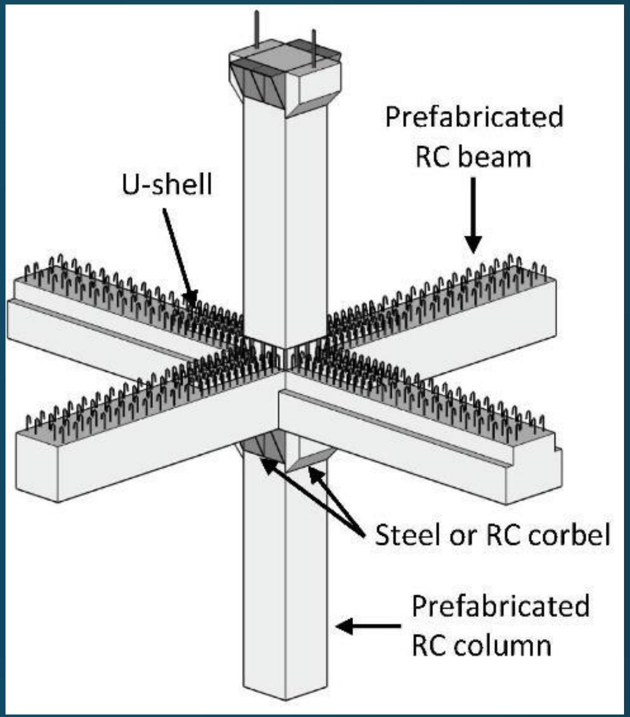


Feng, 2018

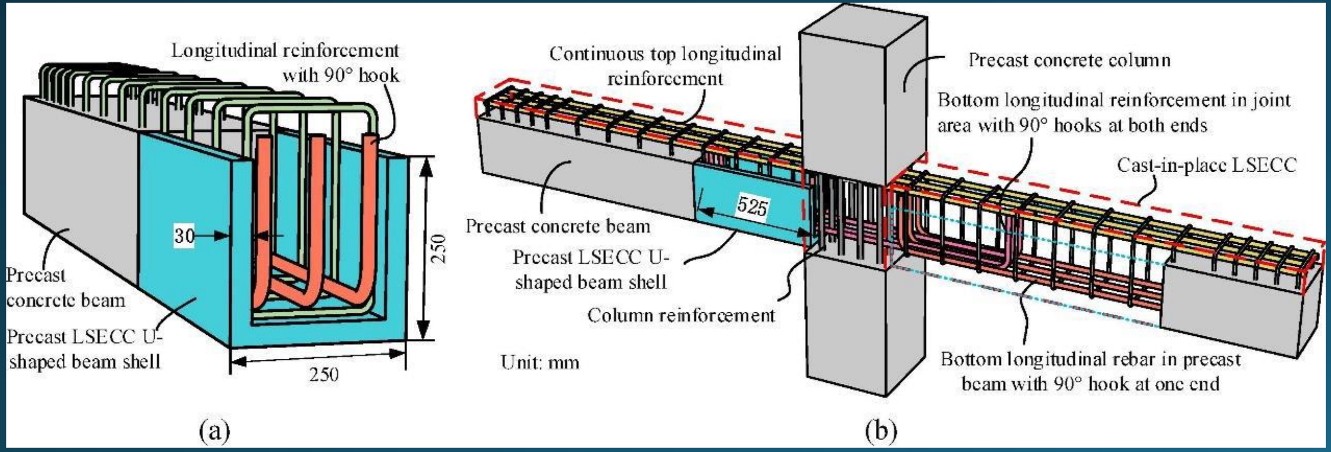
Aninthaneni, 2018



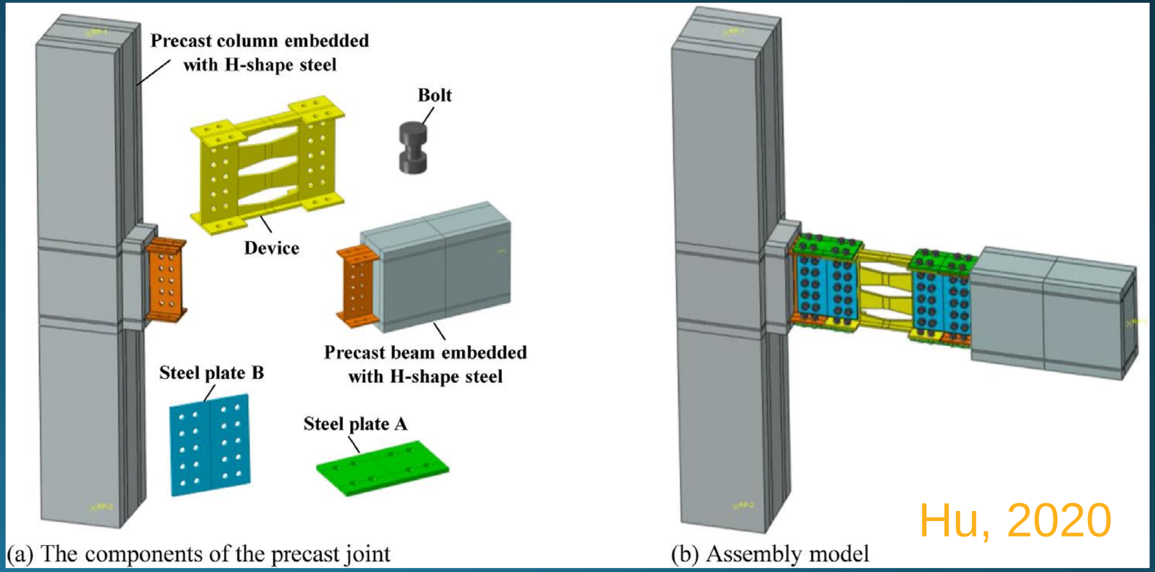


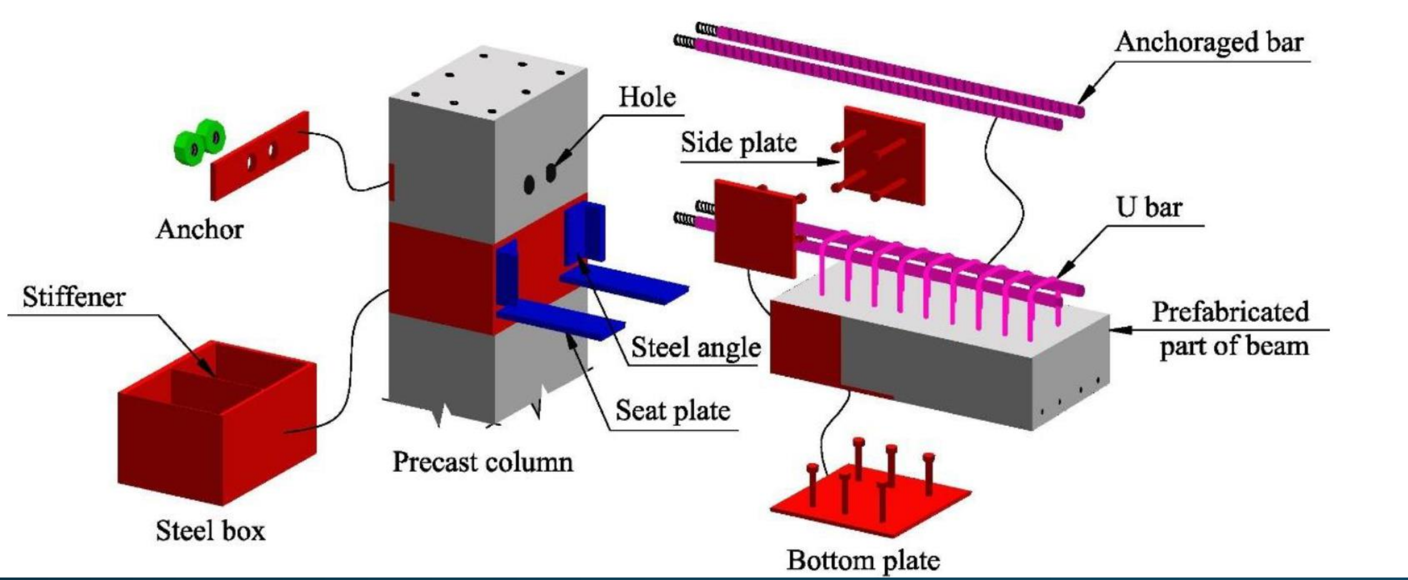


Feng, 2020

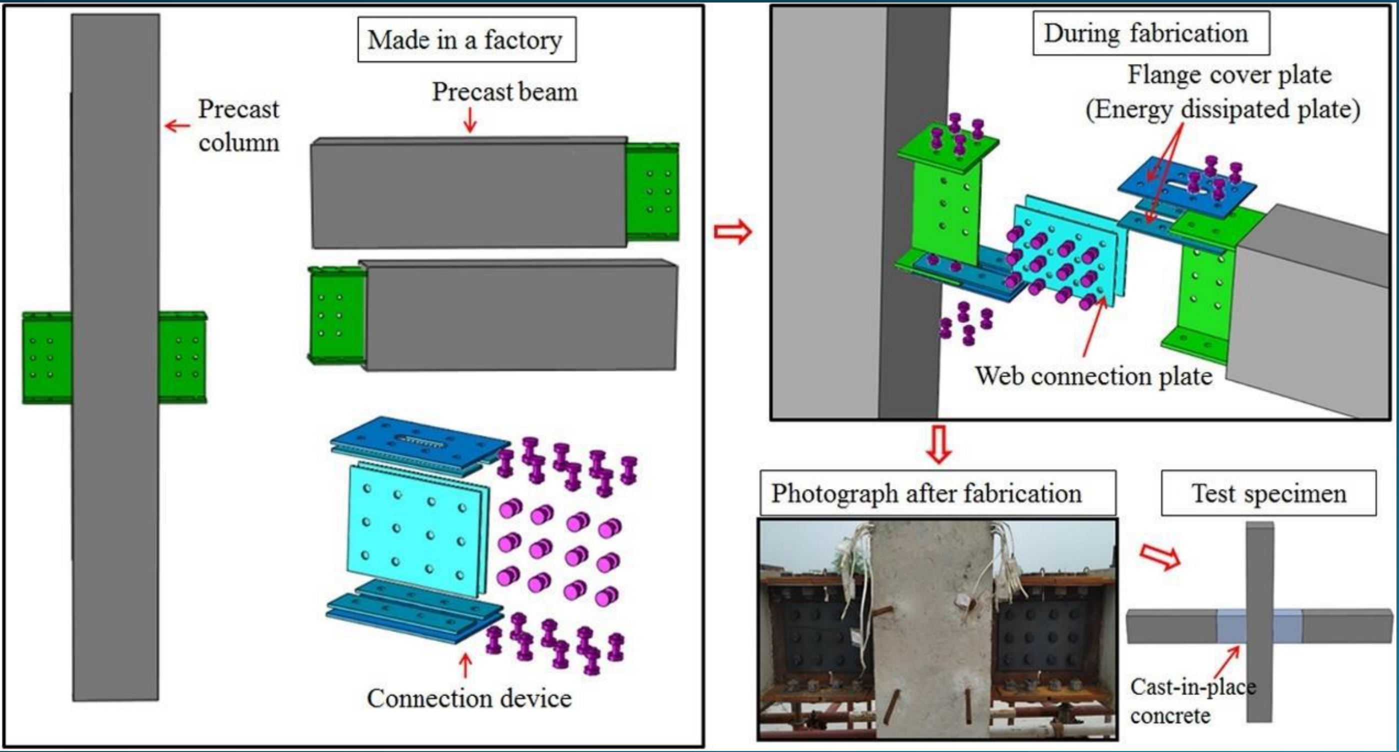


Gou, 2019

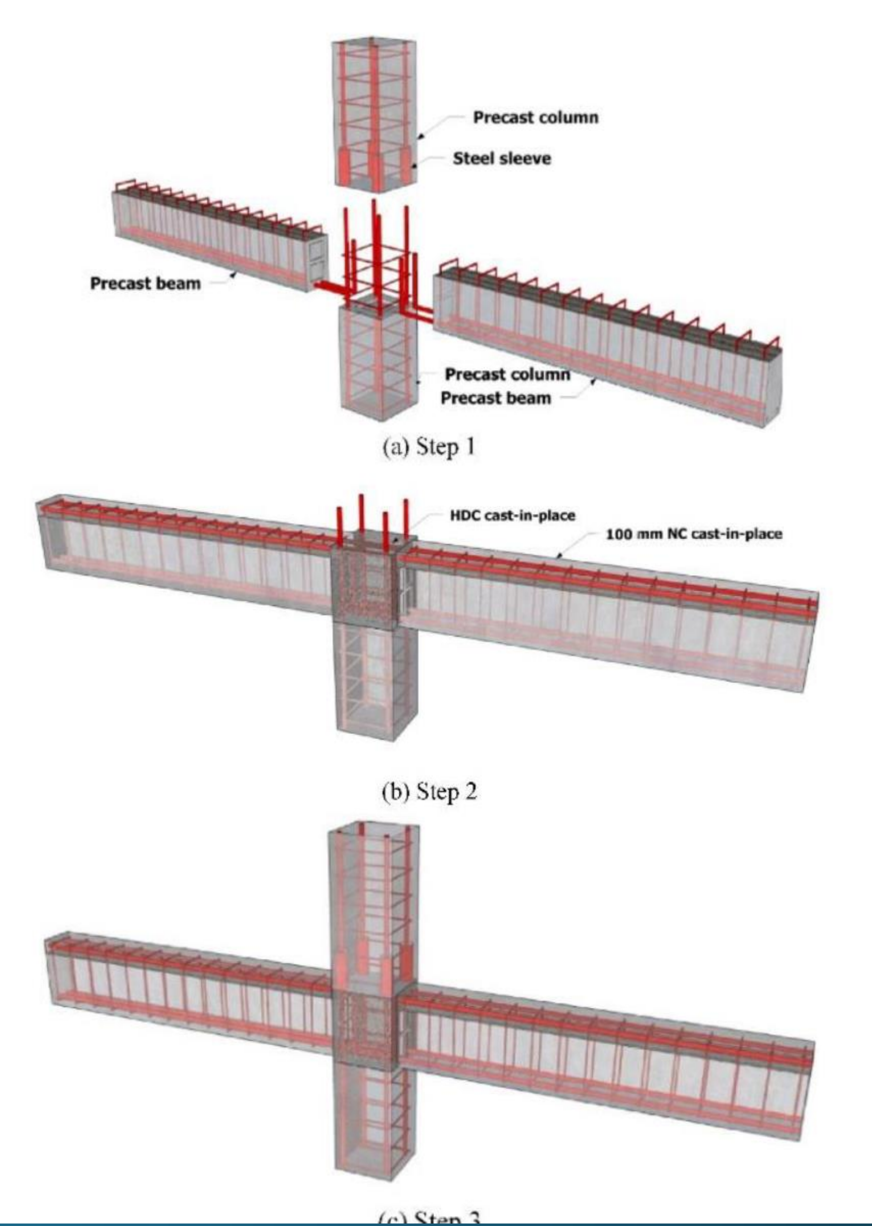




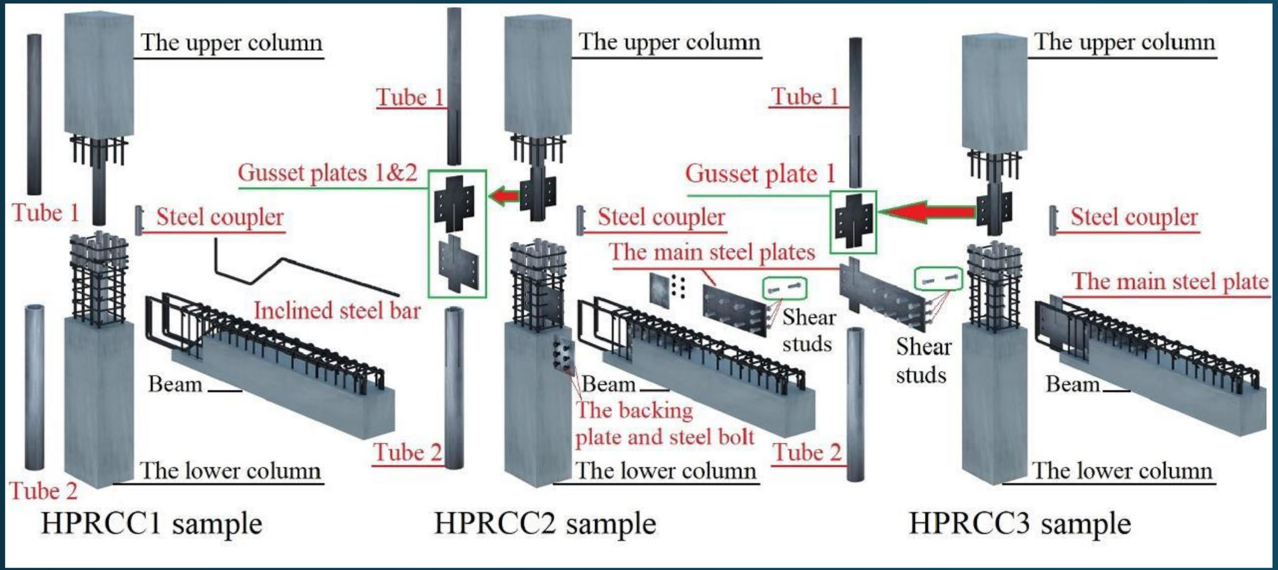
Ahooghalandary, 2020

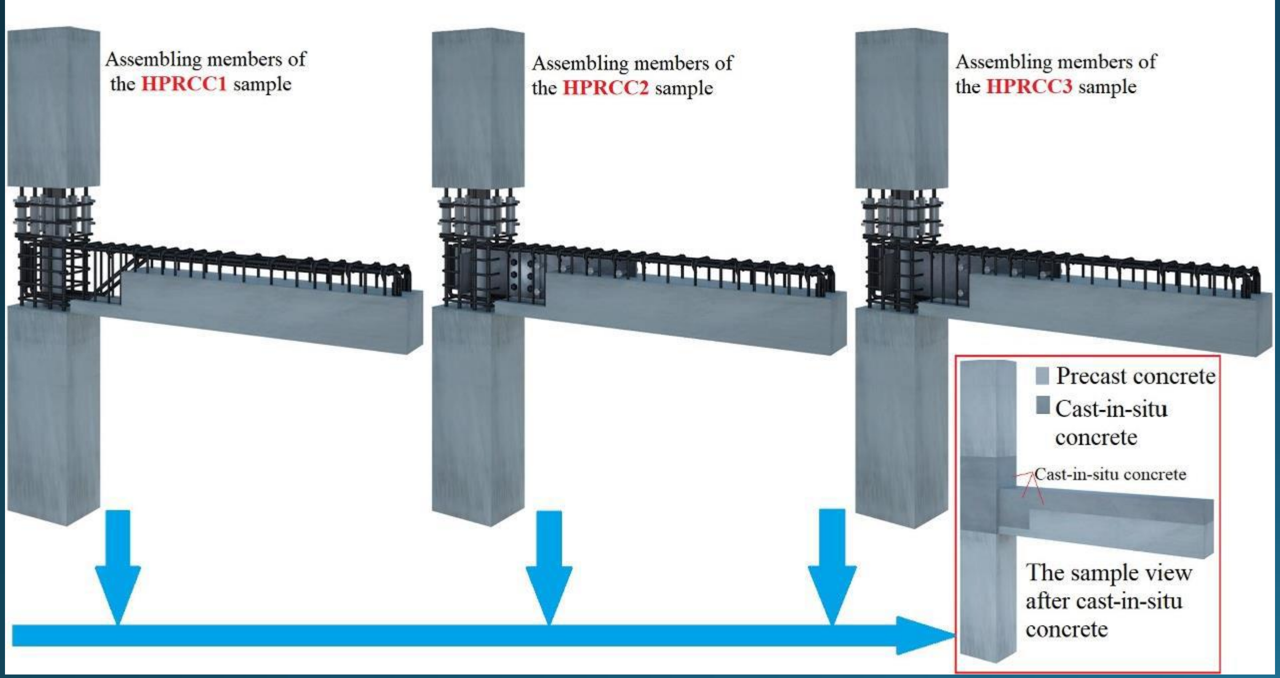


Zhang, 2020

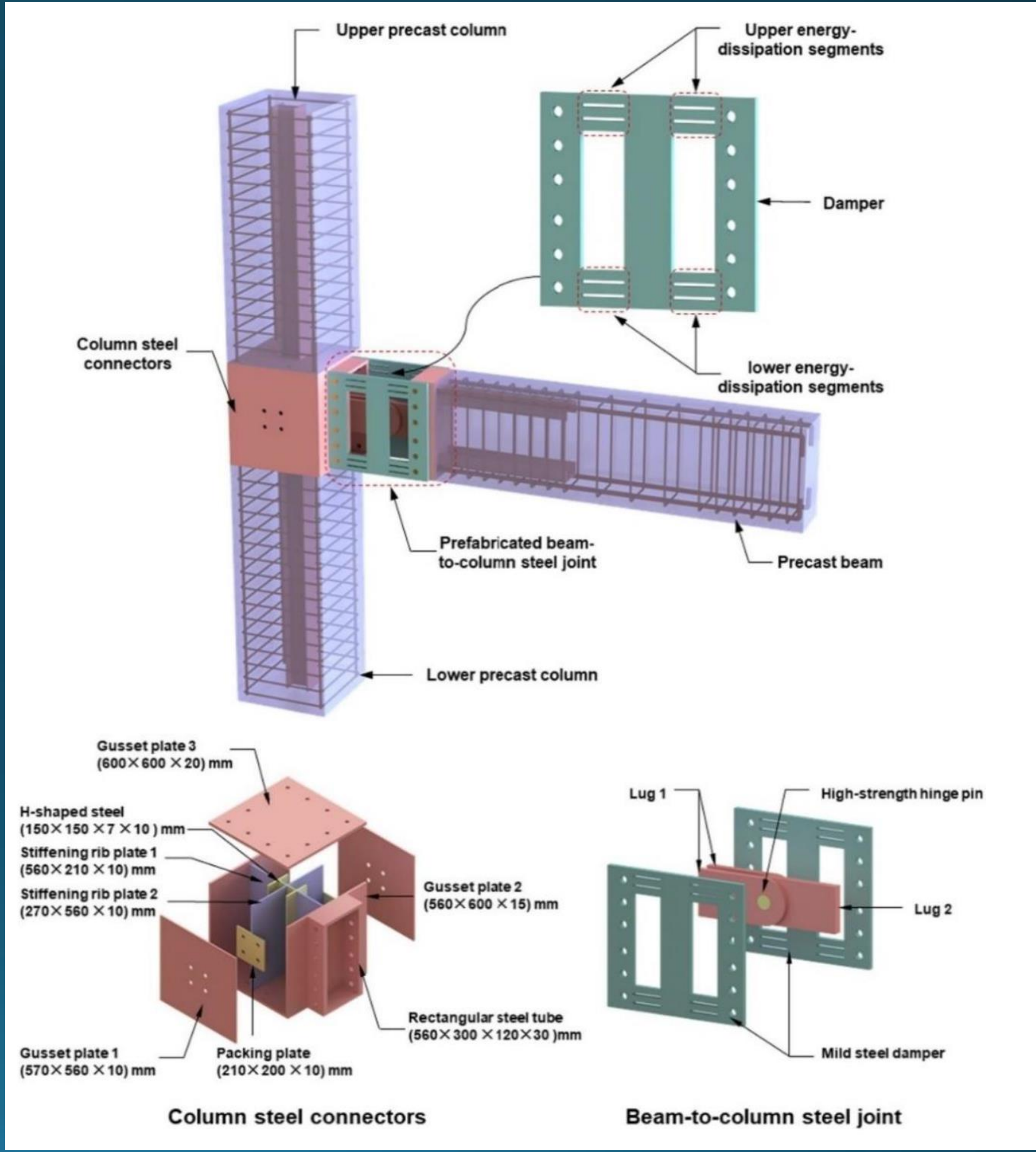


Deng, 2020

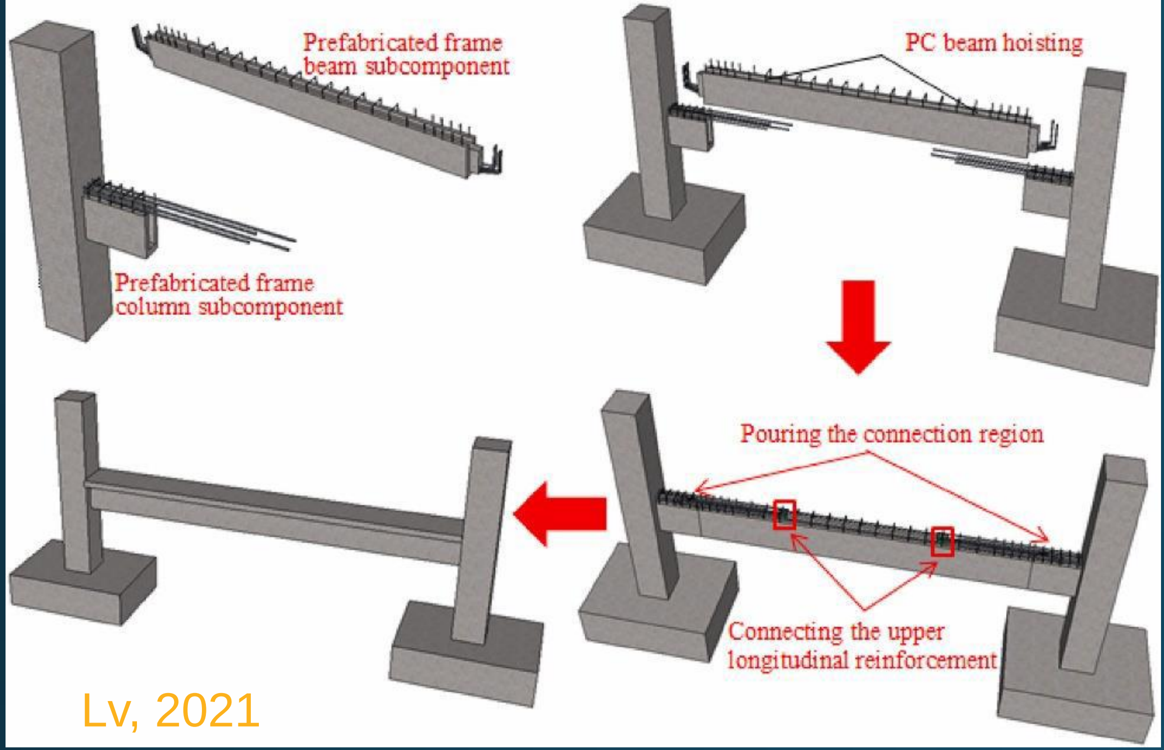


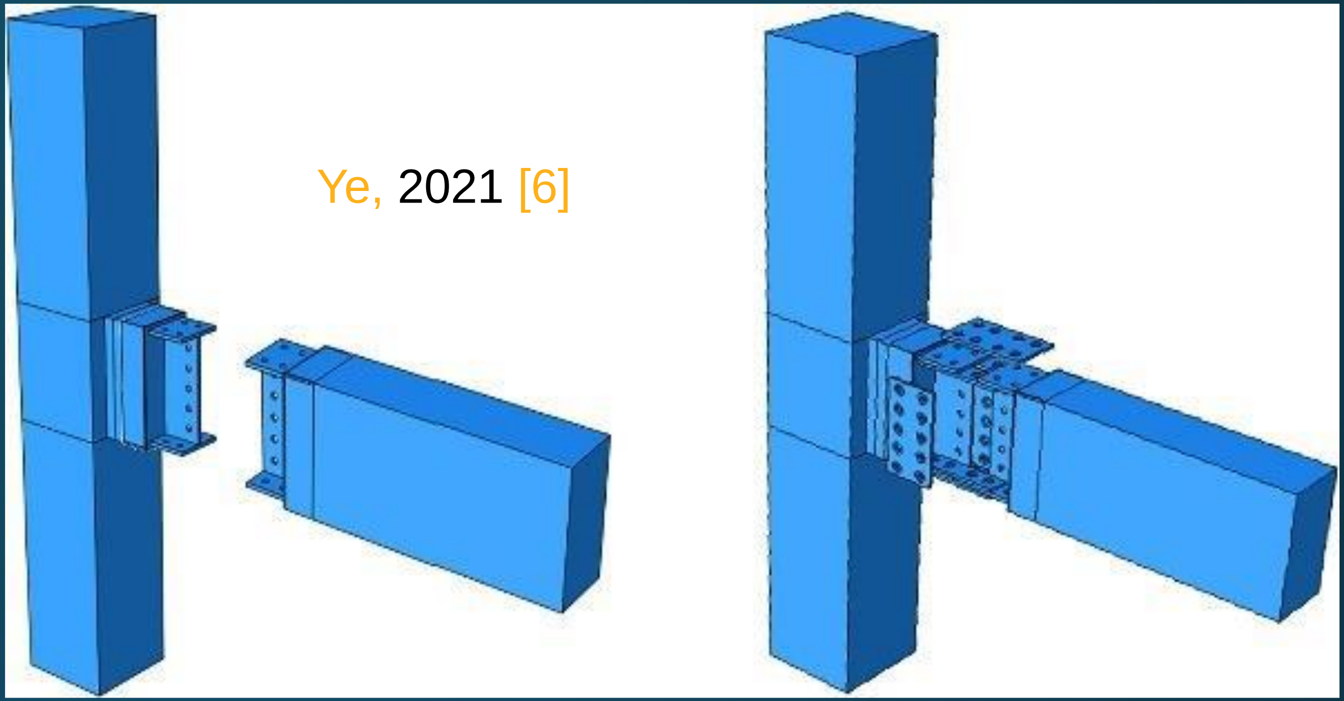


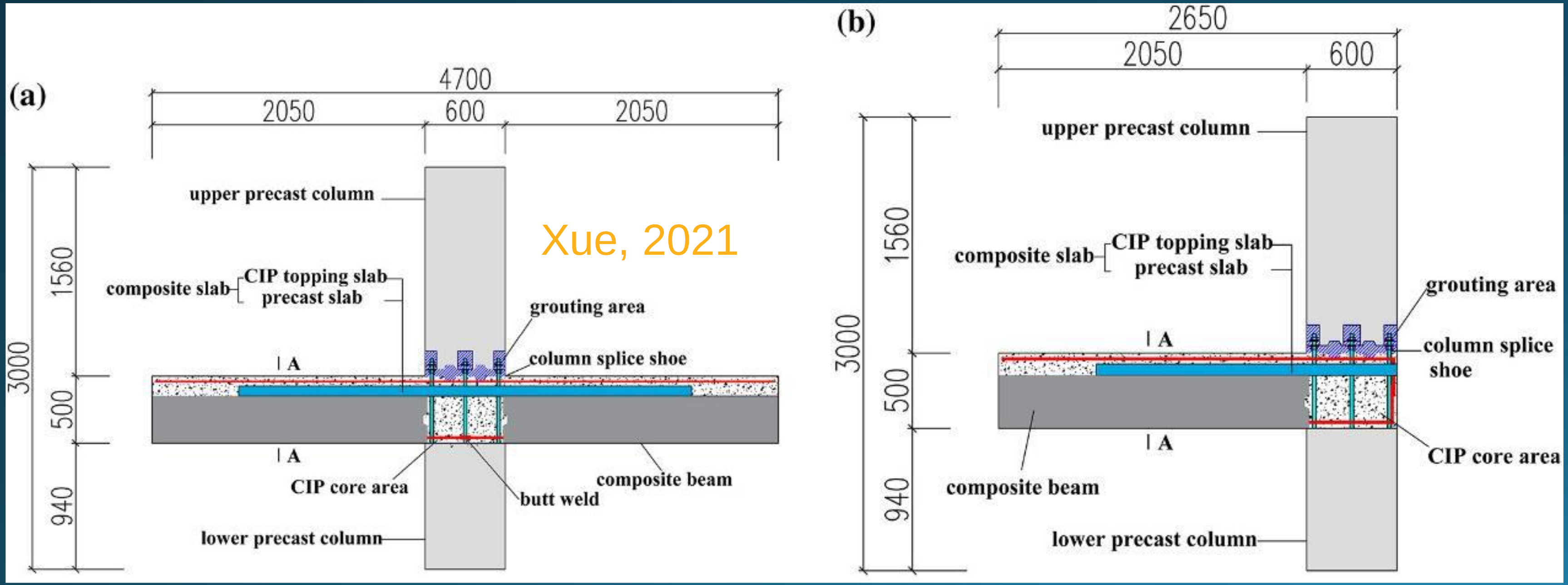
Ghayeb, 2020



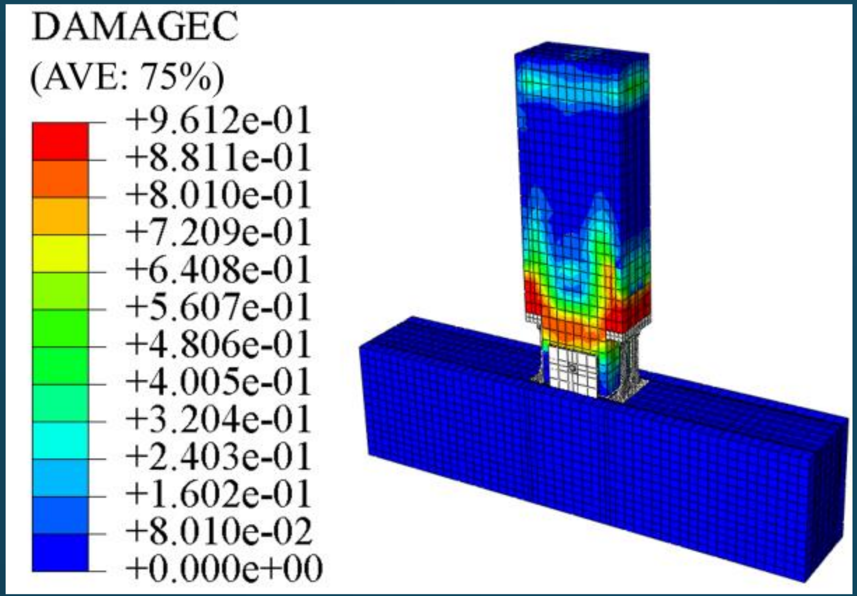
Li and Qi, 2020



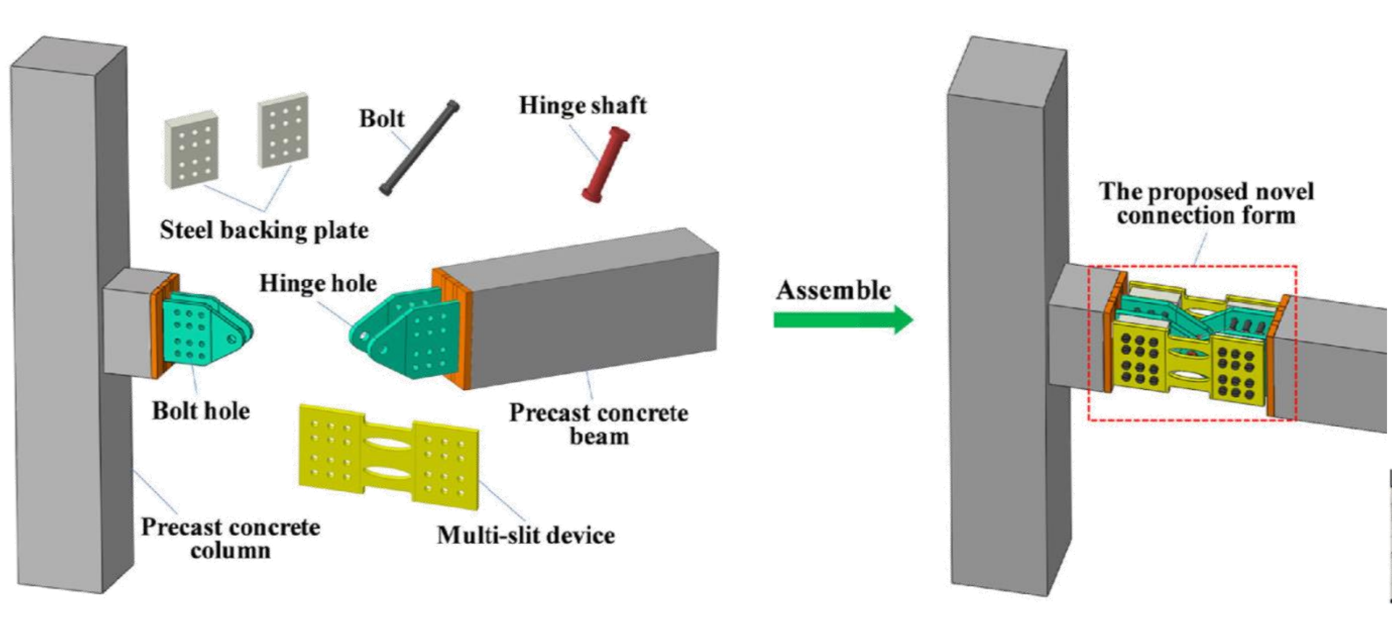


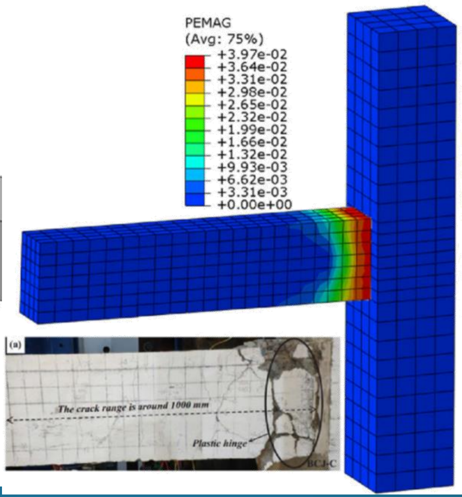


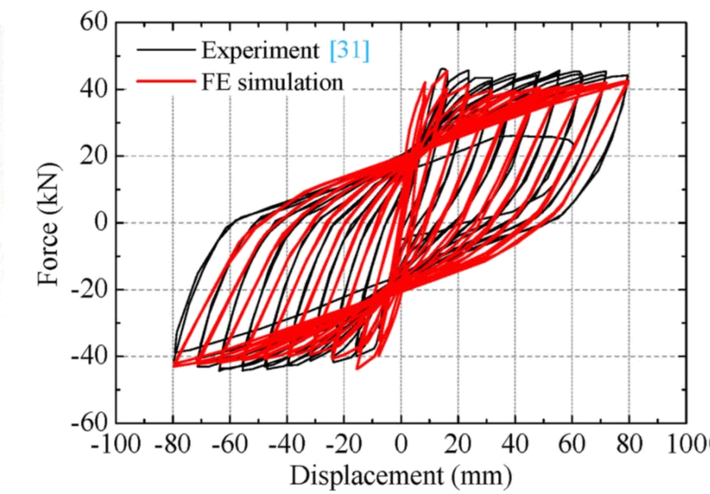
Breccolotti (2021) [18] used fiber-reinforced concrete to connect beams to columns.



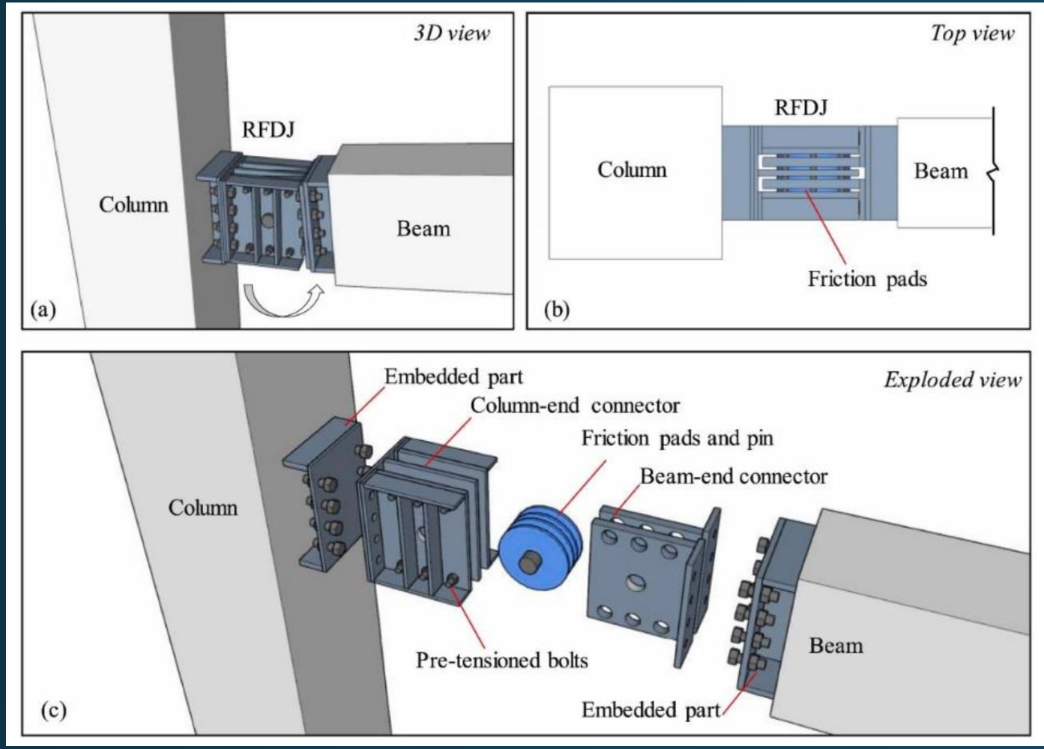
Qu, 2021



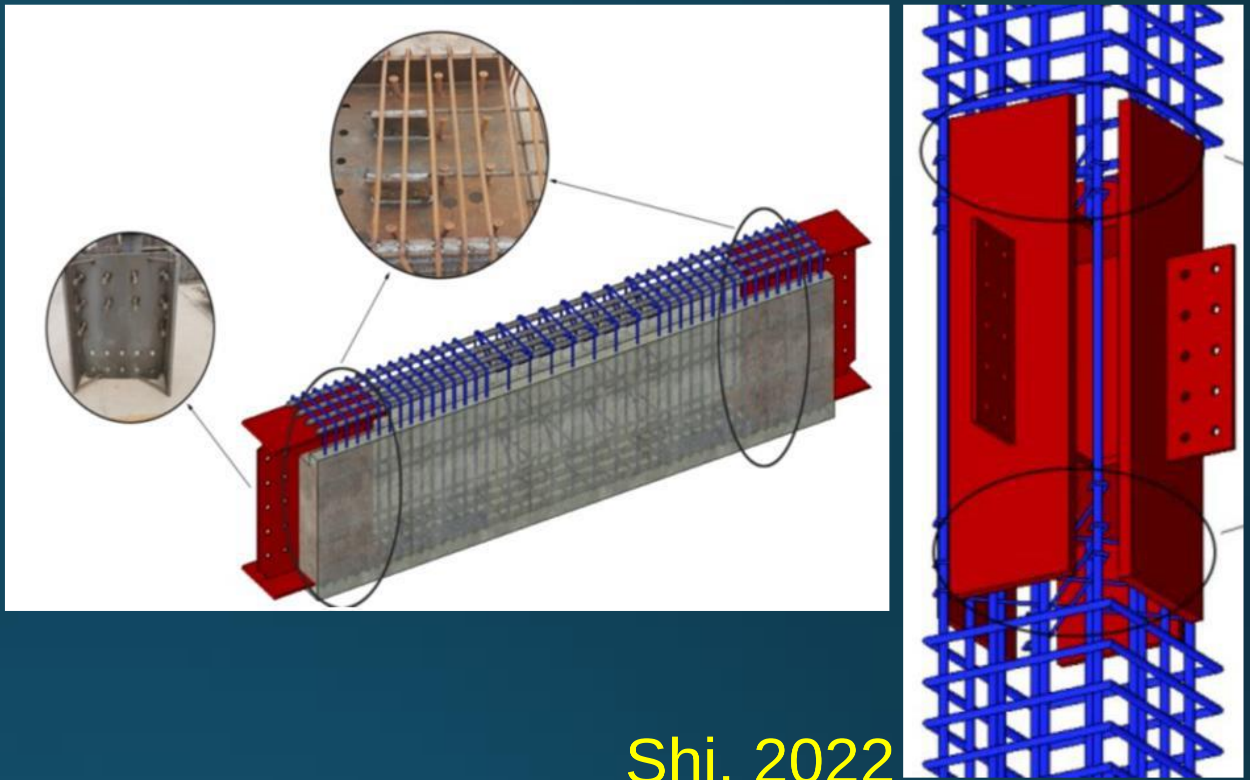




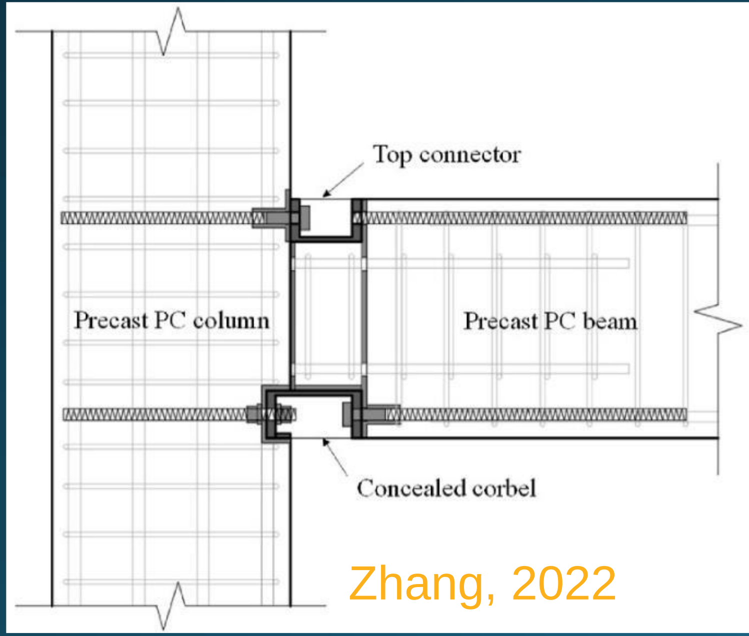
Huang, 2021 []



Yang, 2022



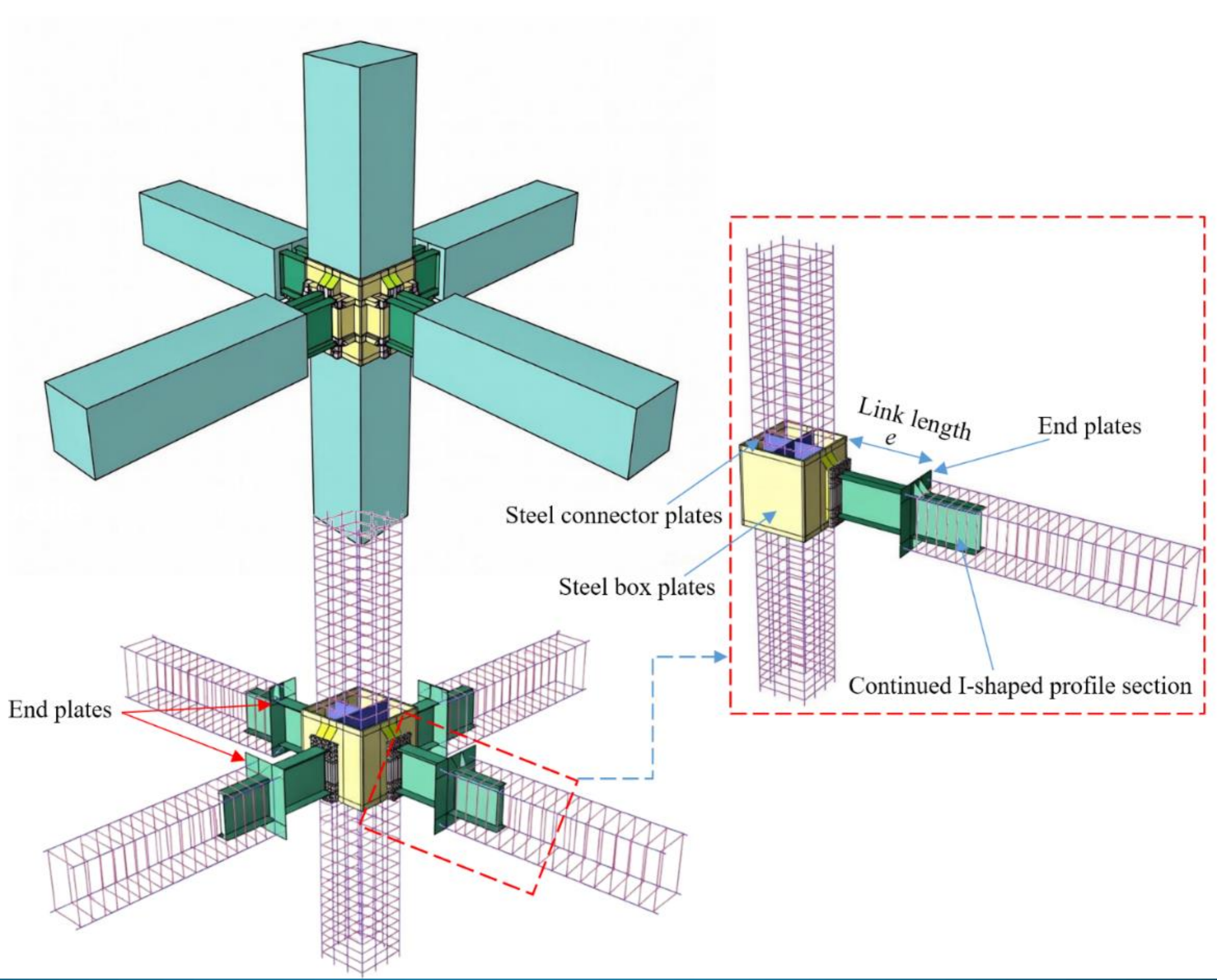
Shi, 2022

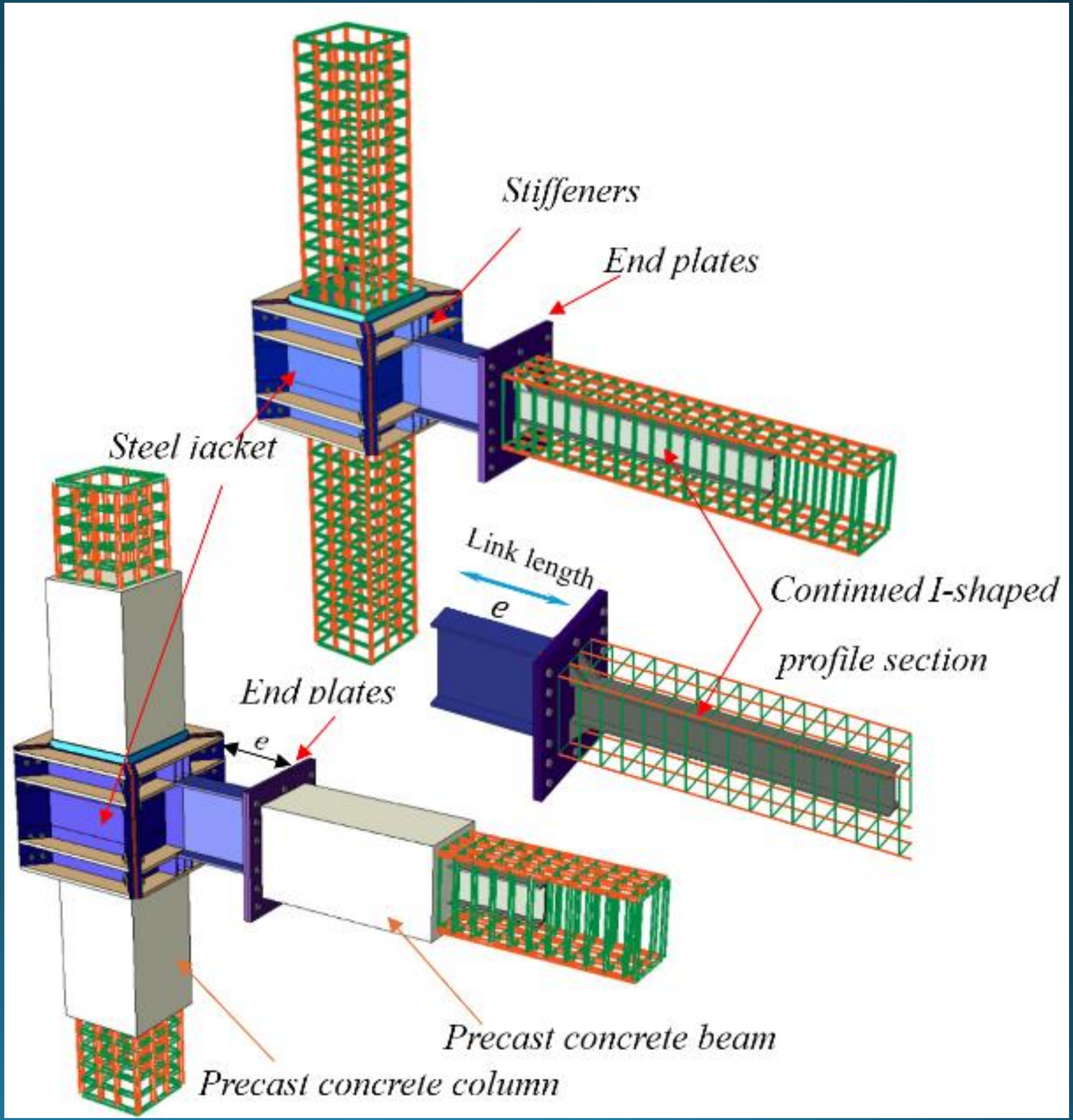


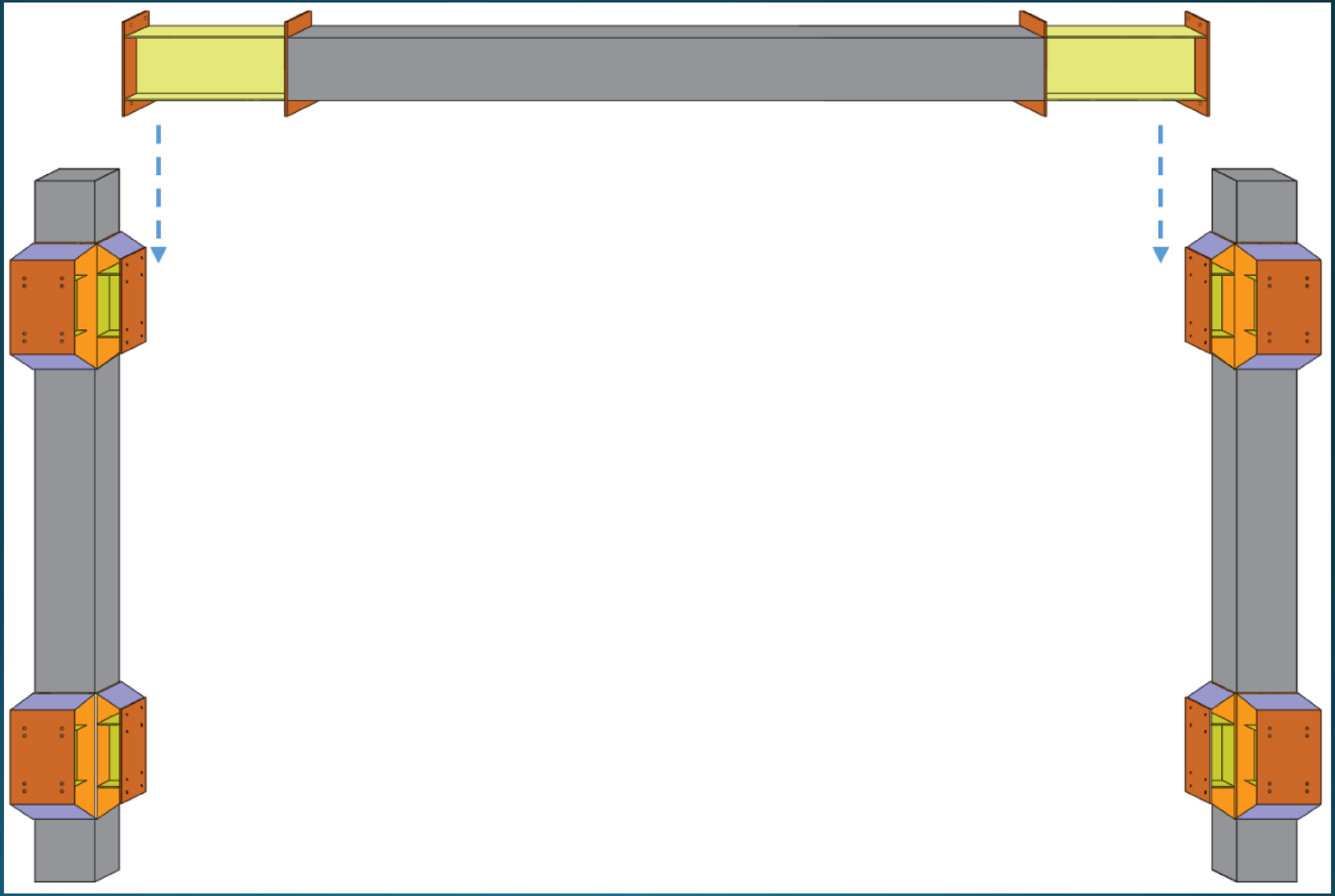
Zhang, 2022

Proposed system for PC frames

Precast concrete frame → replaceable d
steel fuse/link → controlled energy
dissipation → protected concrete memb
→ rapid post-earthquake repair




Stiffeners
End plates
Steel jacket
Link length
e
Continued I-shaped
profile section
End plates
e
Precast concrete beam
Precast concrete column



Conventional precast frame	Precast frame with replaceable steel fuse
Fast construction	Fast construction
Factory-controlled quality	Factory-controlled quality
Reduced site labor	Reduced site labor
Modular construction	Modular construction
Potential connection damage	Damage concentrated in replaceable fuse
Difficult repair after severe earthquake	Fuse can be replaced
Possible residual damage	Structural members can remain essentially elastic
Conventional energy dissipation	Controlled ductile energy dissipation

$$M_E \leq \emptyset_m M_p = 0.9 Z f_y$$

$$V_E \leq \emptyset_v V_p = 0.6 f_y d t_w$$

$$M_{uc} \geq \max \begin{cases} M_p \\ \frac{e}{2} V_p \end{cases}$$

$$V_{uc} \geq \max \begin{cases} \frac{2M_p}{e} \\ V_p \end{cases}$$

$$M_{nb} \geq M_p + V_p e$$

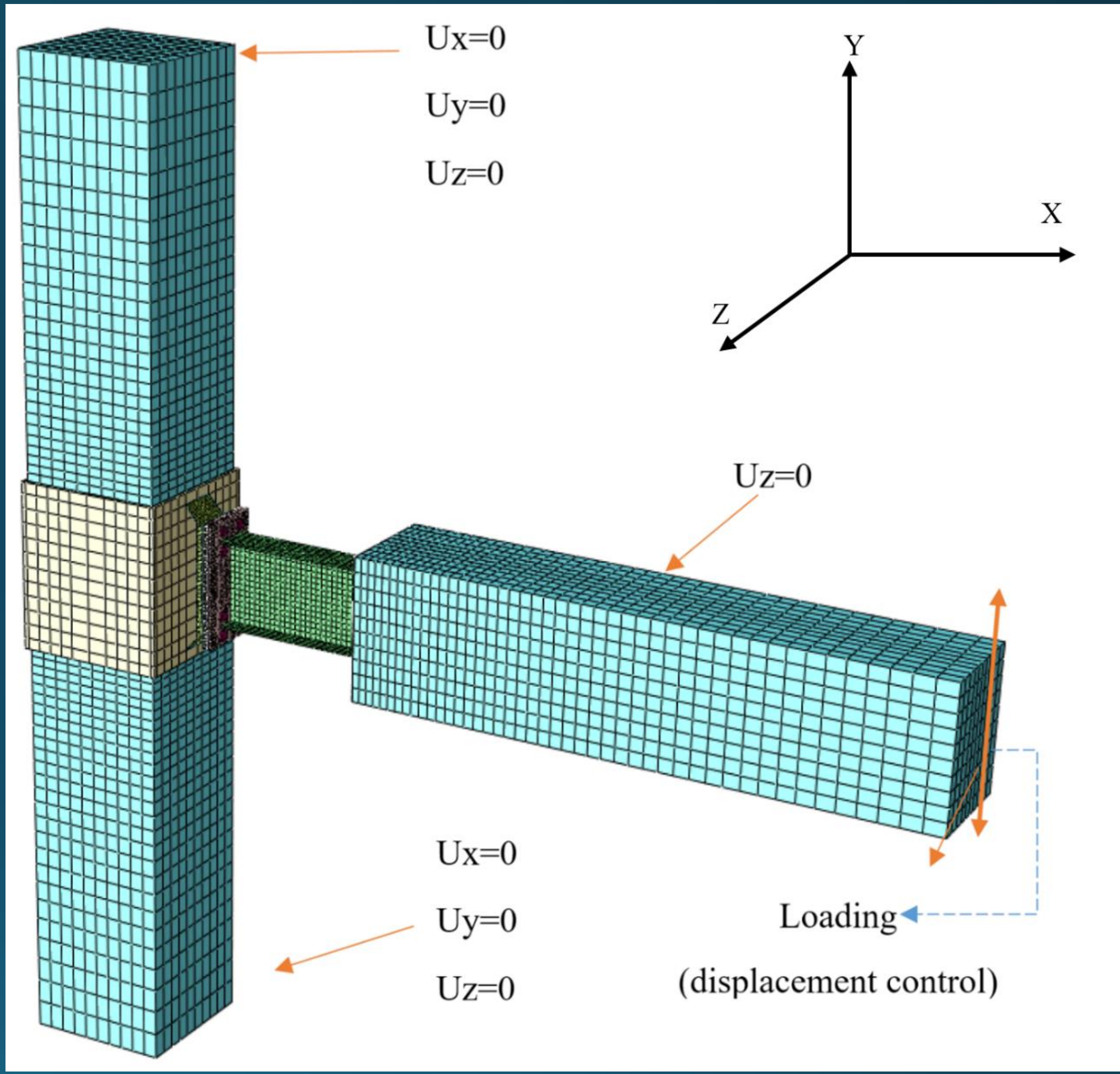
$$d - \frac{a}{2} \geq \left(\frac{Z_{sd}}{A_{sb}} + 0.6e \frac{A_w}{A_{sb}}\right) \frac{f_{yd}}{f_{yb}}$$

$$V_{nb} \geq V_p + \frac{M_p}{e}$$

$$V_{nb} \geq 0.6 A_w f_{yd} + \frac{Z f_{yd}}{e}$$

Model	h_w (mm)	t_f (mm)	λ_w	λ_f	Steel link		Concrete beam		ρ	Ψ	Φ
					M_p (kN.m)	V_{pb} (kN)	M_n (kN.m)	V_n (kN)			
1.34-1.02-0.81-15	400	15	50.0	4.7	286	460.8	213.71	450.2	0.81	1.34	1.02
1.00-1.02-1.07-10		10	50.0	7.0	214.6	460.8	213.71	450.2	1.07	1.00	1.02
0.68-1.02-1.59-5		5	50.0	14.0	144.8	460.8	213.71	450.2	1.59	0.68	1.02
0.52-1.02-2.08-2.5		2.5	50.0	28.0	110.6	460.8	213.71	450.2	2.08	0.52	1.02
0.95-0.77-0.86-15	300	15	37.5	4.7	202	345.6	213.71	450.2	0.86	0.95	0.77
0.69-0.77-1.17-10		10	37.5	7.0	147.4	345.6	213.71	450.2	1.17	0.69	0.77
0.44-0.77-1.83-5		5	37.5	14.0	94.44	345.6	213.71	450.2	1.83	0.44	0.77
0.32-0.77-2.52-2.5		2.5	37.5	28.0	68.61	345.6	213.71	450.2	2.52	0.32	0.77
0.60-0.51-0.90-15	200	15	25.0	4.7	127.6	230.4	213.71	450.2	0.90	0.60	0.51
0.42-0.51-1.28-10		10	25.0	7.0	89.76	230.4	213.71	450.2	1.28	0.42	0.51
0.25-0.51-2.15-5		5	25.0	14.0	53.64	230.4	213.71	450.2	2.15	0.25	0.51
0.17-0.51-3.18-2.5		2.5	25.0	28.0	36.21	230.4	213.71	450.2	3.18	0.17	0.51

$\lambda_w = \frac{h_w}{t_w}; \lambda_f = \frac{b_f}{t_f}; \Phi = \frac{V_p}{V_n}, \Psi = \frac{M_p}{M_n}$

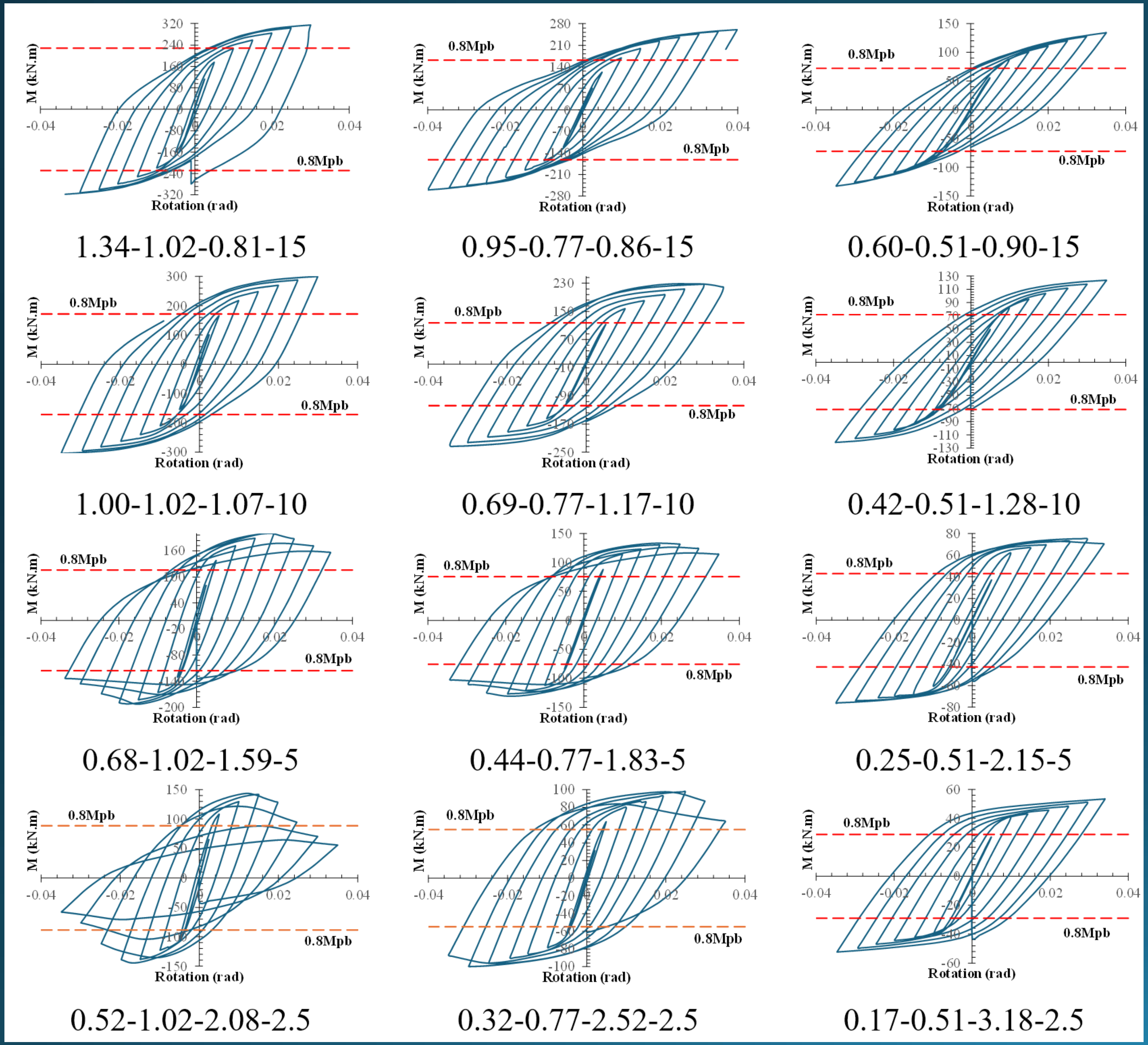


$\Psi - \Phi - \rho - t_f$

Ψ = Mp/ Mnb

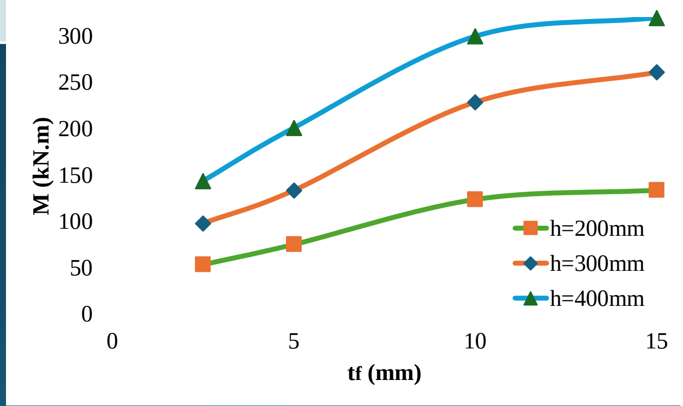
Φ = Vp /Vnb

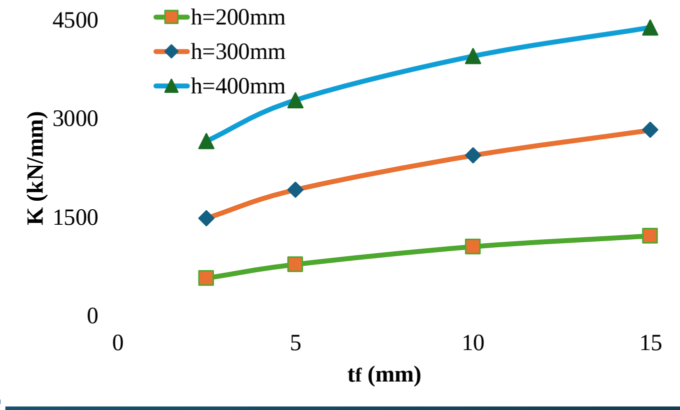
$\Psi - \Phi - \rho - t_f$

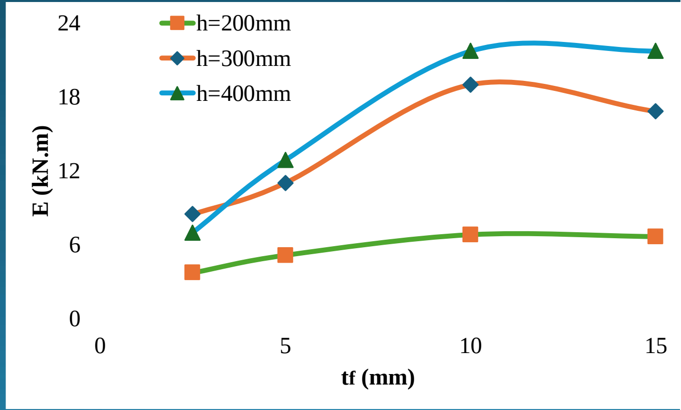


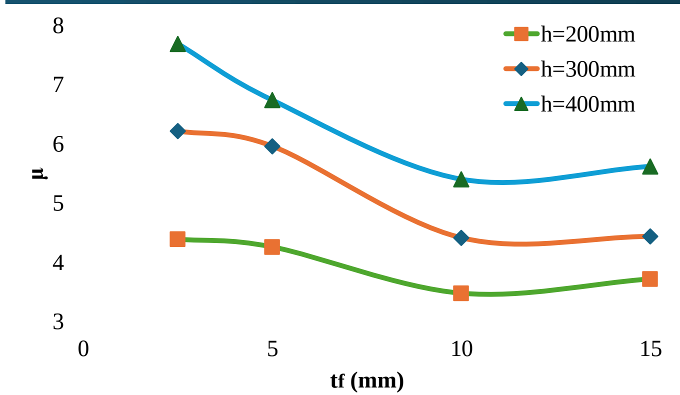
Model	h_w (mm)	t_f (mm)	Ψ	Φ	ρ	$\frac{models\ h = i}{model\ h = 200mm}$ M	K	E	θy	μ
1.34-1.02-0.81-15		15	1.34	1.02	0.81	2.39	1.07	2.39	3.617	3.27
1.00-1.02-1.07-10	400	10	1.00	1.02	1.07	2.42	1.01	2.42	3.765	3.20
0.68-1.02-1.59-5		5	0.68	1.02	1.59	2.67	0.99	2.67	4.213	2.51
0.52-1.02-2.08-2.5		2.5	0.52	1.02	2.08	2.69	0.88	2.69	4.663	1.88
0.95-0.77-0.86-15		15	0.95	0.77	0.86	1.95	1.23	1.95	2.330	2.53
0.69-0.77-1.17-10	300	10	0.69	0.77	1.17	1.85	1.13	1.85	2.326	2.79
0.44-0.77-1.83-5		5	0.44	0.77	1.83	1.78	1.01	1.78	2.461	2.15
0.32-0.77-2.52-2.5		2.5	0.32	0.77	2.52	1.84	0.97	1.84	2.601	2.28
0.60-0.51-0.90-15		15	0.60	0.51	0.90					
0.42-0.51-1.28-10	200	10	0.42	0.51	1.28					
0.25-0.51-2.15-5		5	0.25	0.51	2.15					
0.17-0.51-3.18-2.5		2.5	0.17	0.51	3.18					

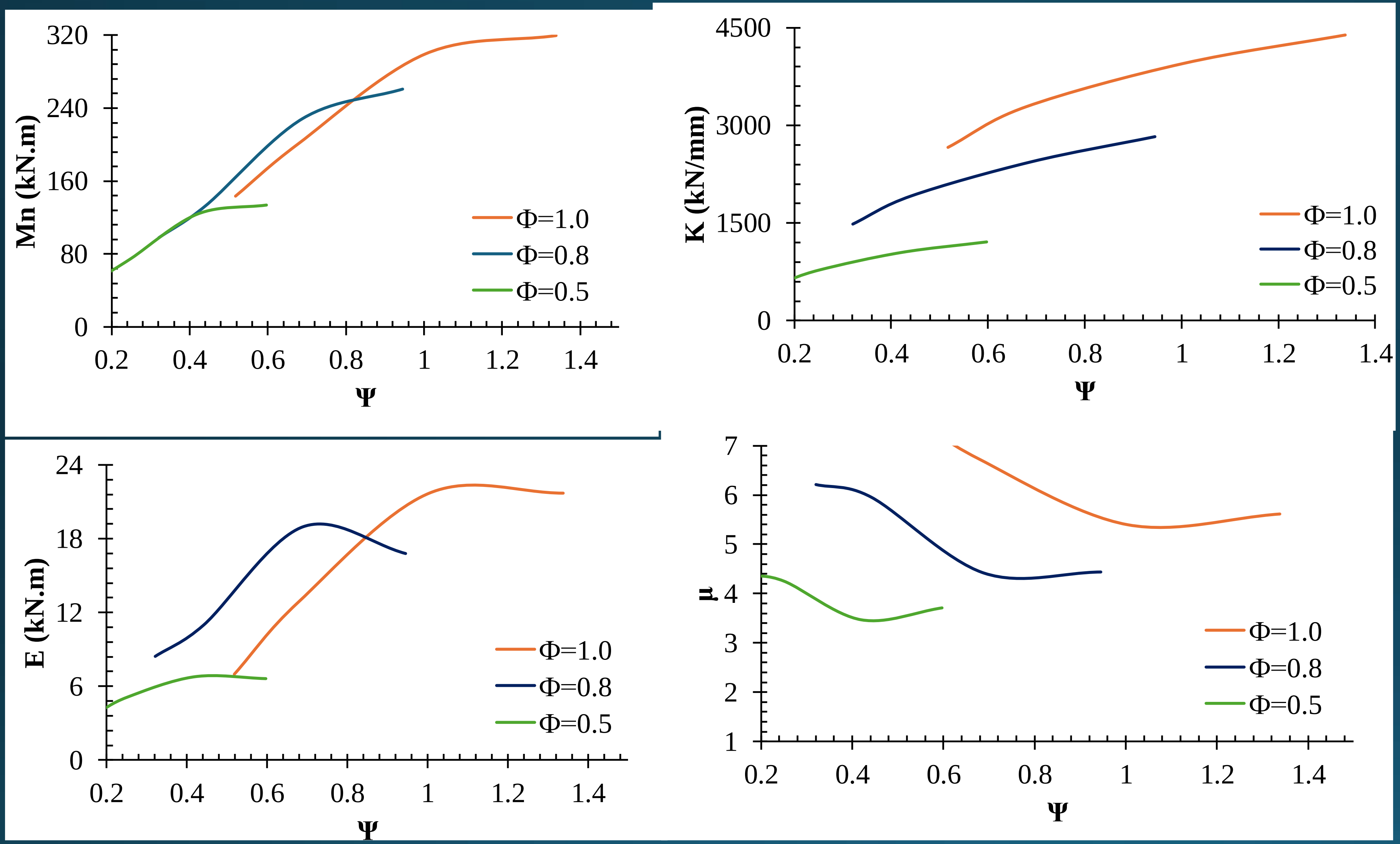
$\frac{t_f = i}{t_f = 2.5mm}$ M	K	E	θy	μ
2.23	1.09	2.23	1.65	3.12
2.09	1.08	2.09	1.48	3.12
1.40	1.07	1.40	1.23	1.84
2.67	0.91	2.67	1.90	1.99
2.34	1.09	2.34	1.64	2.25
1.36	0.99	1.36	1.29	1.30
2.51	0.71	2.51	2.13	1.79
2.32	0.94	2.32	1.84	1.83
1.41	0.95	1.41	1.37	1.38

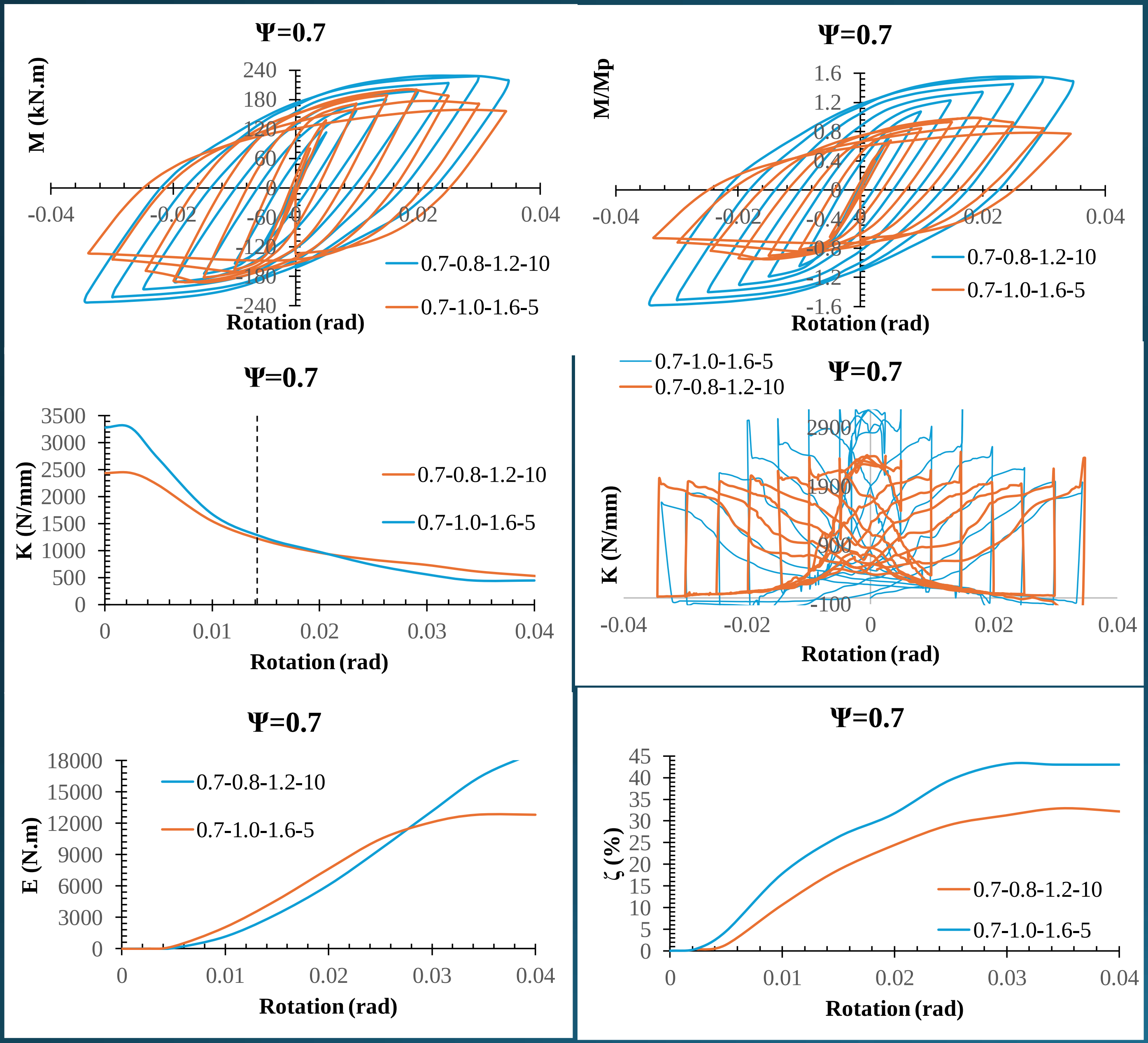


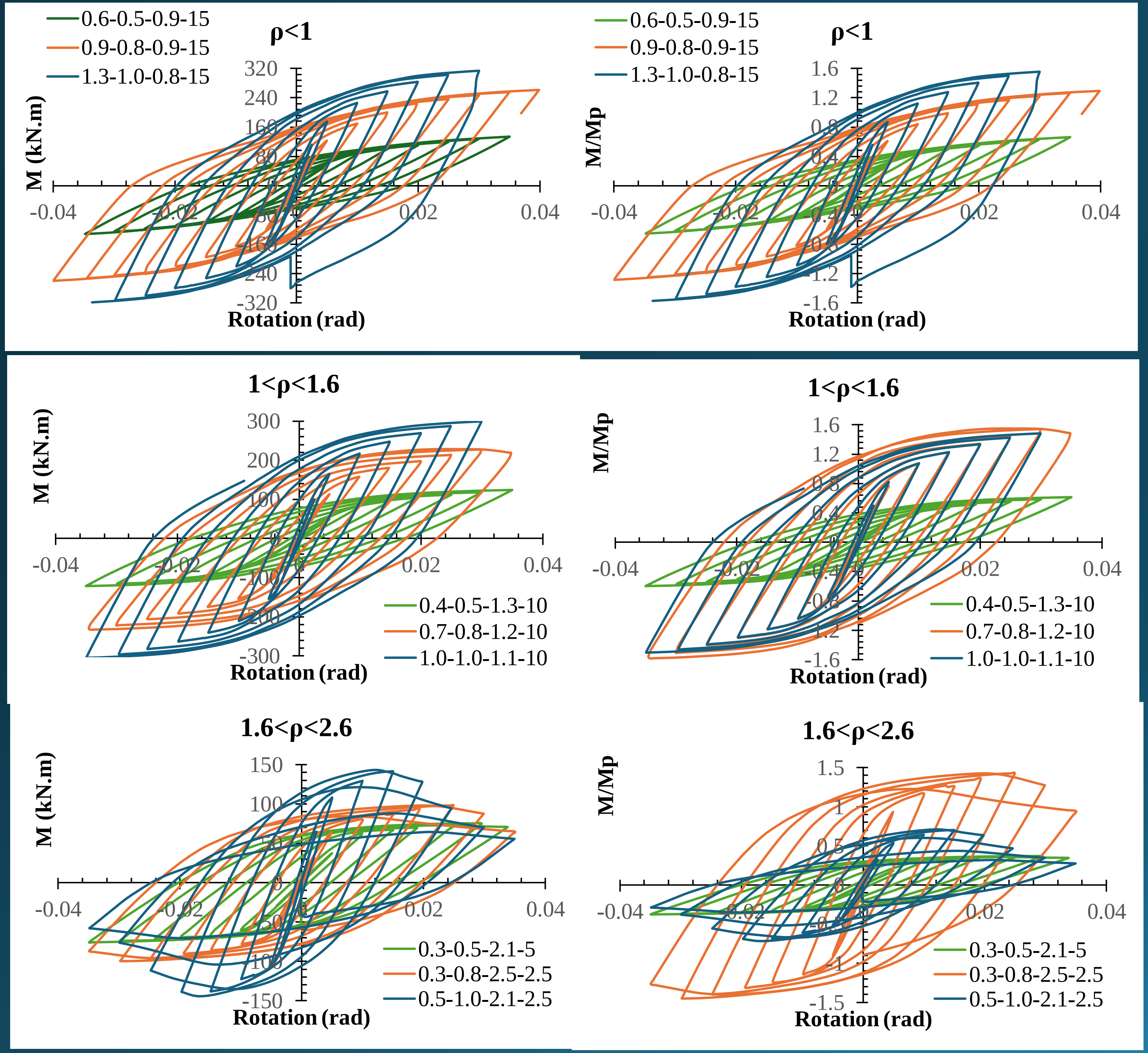


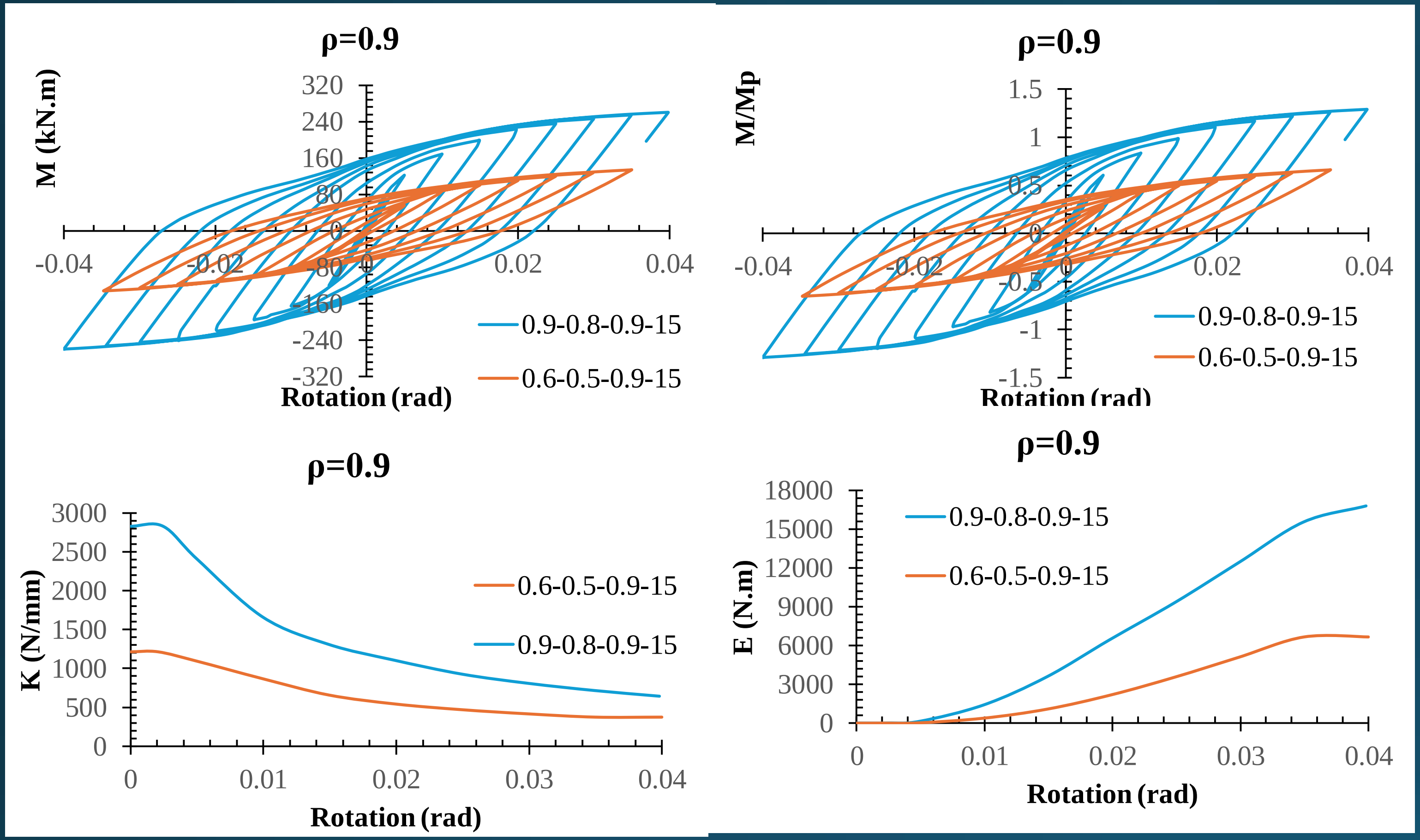


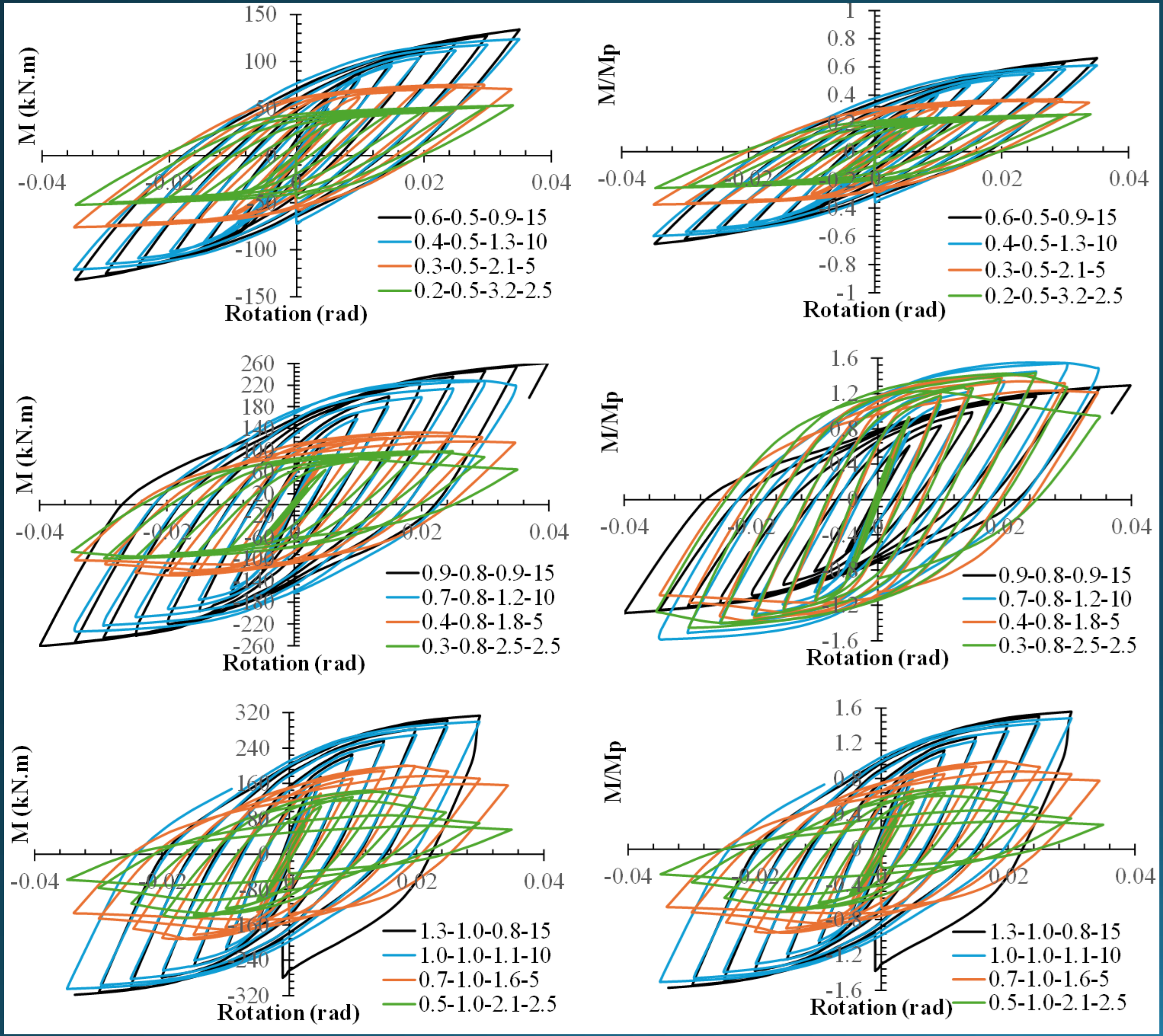


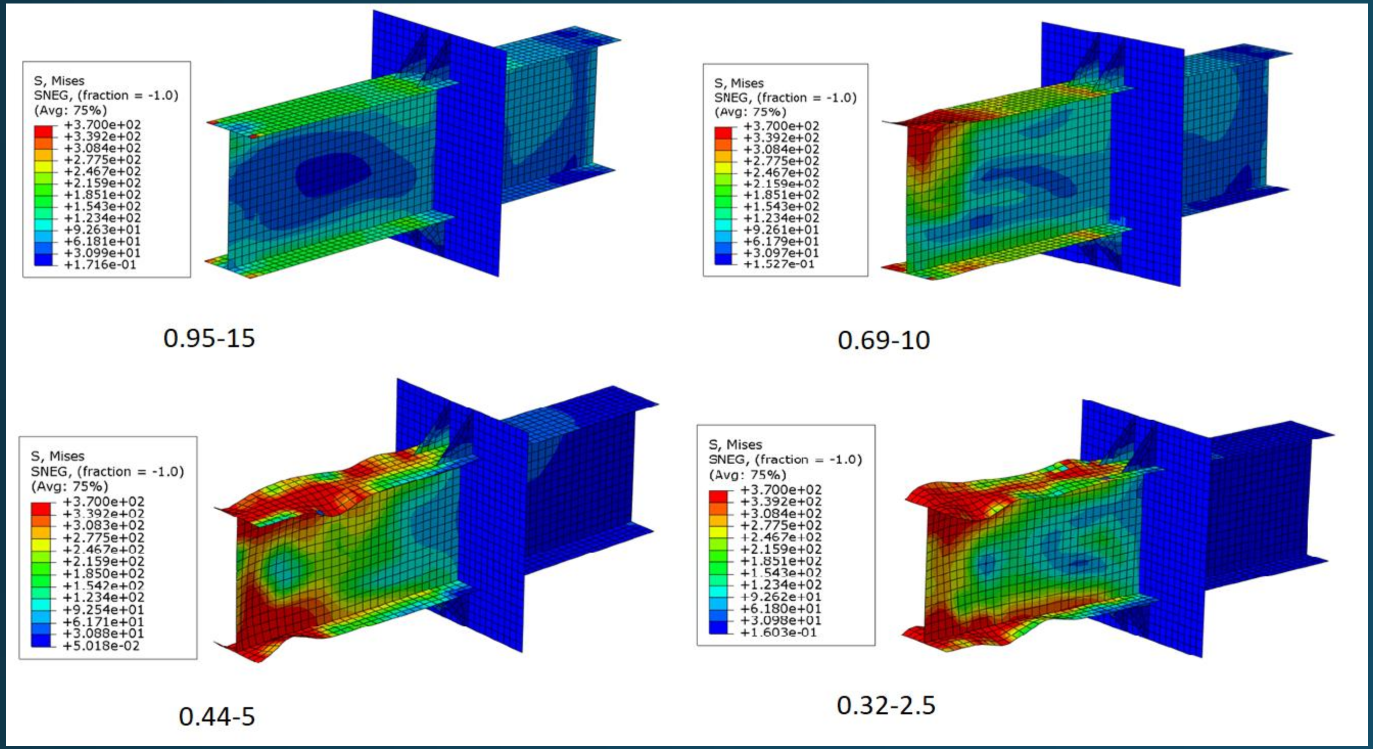

Mn (kN.m)
320
240
160
80
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Ψ
Φ=1.0
Φ=0.8
Φ=0.5
K (kN/mm)
4500
3000
1500
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Ψ
Φ=1.0
Φ=0.8
Φ=0.5
E (kN.m)
24
18
12
6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Ψ
Φ=1.0
Φ=0.8
Φ=0.5
μ
7
6
5
4
3
2
1
0.2
0.4
0.6
0.8
1
1.2
1.4
Ψ
Φ=1.0
Φ=0.8
Φ=0.5


Ψ=0.7
M (kN.m)
240
180
120
60
0
-60
-120
-180
-240
-0.04
-0.02
0
0.02
0.04
Rotation (rad)
0.7-0.8-1.2-10
0.7-1.0-1.6-5
Ψ=0.7
M/Mp
1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
-0.04
-0.02
0
0.02
0.04
Rotation (rad)
0.7-0.8-1.2-10
0.7-1.0-1.6-5
Ψ=0.7
K (N/mm)
3500
3000
2500
2000
1500
1000
500
0
0
0.01
0.02
0.03
0.04
Rotation (rad)
0.7-0.8-1.2-10
0.7-1.0-1.6-5
0.7-1.0-1.6-5
0.7-0.8-1.2-10
Ψ=0.7
K (N/mm)
2900
1900
900
-100
-0.04
-0.02
0
0.02
0.04
Rotation (rad)
Ψ=0.7
E (N.m)
18000
15000
12000
9000
6000
3000
0
0
0.01
0.02
0.03
0.04
Rotation (rad)
0.7-0.8-1.2-10
0.7-1.0-1.6-5
Ψ=0.7
ζ (%)
45
40
35
30
25
20
15
10
5
0
0
0.01
0.02
0.03
0.04
Rotation (rad)
0.7-0.8-1.2-10
0.7-1.0-1.6-5


ρ<1
0.6-0.5-0.9-15
0.9-0.8-0.9-15
1.3-1.0-0.8-15
M (kN.m)
M/Mp
Rotation (rad)
1<ρ<1.6
0.4-0.5-1.3-10
0.7-0.8-1.2-10
1.0-1.0-1.1-10
M (kN.m)
M/Mp
Rotation (rad)
1.6<ρ<2.6
0.3-0.5-2.1-5
0.3-0.8-2.5-2.5
0.5-1.0-2.1-2.5
M (kN.m)
M/Mp
Rotation (rad)


ρ=0.9
M (kN.m)
320
240
160
80
0
-80
-160
-240
-320
-0.04
-0.02
0
0.02
0.04
Rotation (rad)
0.9-0.8-0.9-15
0.6-0.5-0.9-15
ρ=0.9
M/Mp
1.5
1
0.5
0
-0.5
-1
-1.5
-0.04
-0.02
0
0.02
0.04
Rotation (rad)
0.9-0.8-0.9-15
0.6-0.5-0.9-15
ρ=0.9
K (N/mm)
3000
2500
2000
1500
1000
500
0
0
0.01
0.02
0.03
0.04
Rotation (rad)
0.6-0.5-0.9-15
0.9-0.8-0.9-15
ρ=0.9
E (N.m)
18000
15000
12000
9000
6000
3000
0
0
0.01
0.02
0.03
0.04
Rotation (rad)
0.9-0.8-0.9-15
0.6-0.5-0.9-15


M (kN.m)
M/Mp
Rotation (rad)
0.6-0.5-0.9-15
0.4-0.5-1.3-10
0.3-0.5-2.1-5
0.2-0.5-3.2-2.5
0.9-0.8-0.9-15
0.7-0.8-1.2-10
0.4-0.8-1.8-5
0.3-0.8-2.5-2.5
1.3-1.0-0.8-15
1.0-1.0-1.1-10
0.7-1.0-1.6-5
0.5-1.0-2.1-2.5


S, Mises
SNEG, (fraction = -1.0)
(Avg: 75%)
+3.700e+02
+3.392e+02
+3.084e+02
+2.775e+02
+2.467e+02
+2.159e+02
+1.851e+02
+1.543e+02
+1.234e+02
+9.263e+01
+6.181e+01
+3.099e+01
+1.716e-01
0.95-15
S, Mises
SNEG, (fraction = -1.0)
(Avg: 75%)
+3.700e+02
+3.392e+02
+3.084e+02
+2.775e+02
+2.467e+02
+2.159e+02
+1.851e+02
+1.543e+02
+1.234e+02
+9.261e+01
+6.179e+01
+3.097e+01
+1.527e-01
0.69-10
S, Mises
SNEG, (fraction = -1.0)
(Avg: 75%)
+3.700e+02
+3.392e+02
+3.083e+02
+2.775e+02
+2.467e+02
+2.159e+02
+1.850e+02
+1.542e+02
+1.234e+02
+9.254e+01
+6.171e+01
+3.088e+01
+5.018e-02
0.44-5
S, Mises
SNEG, (fraction = -1.0)
(Avg: 75%)
+3.700e+02
+3.392e+02
+3.084e+02
+2.775e+02
+2.467e+02
+2.159e+02
+1.851e+02
+1.543e+02
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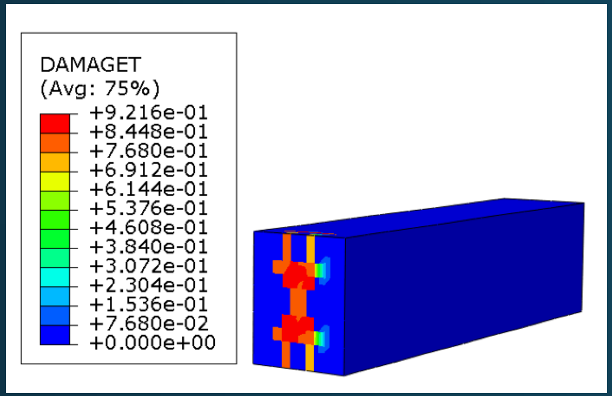
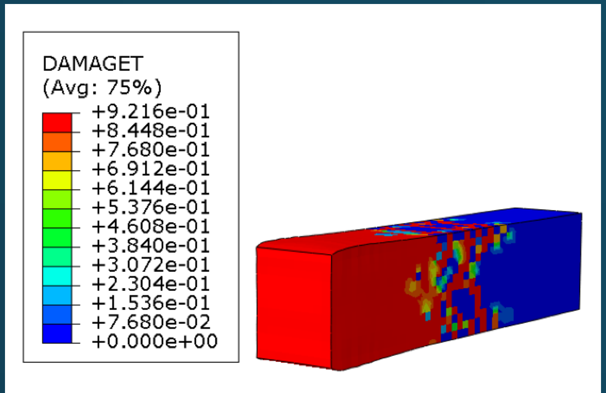
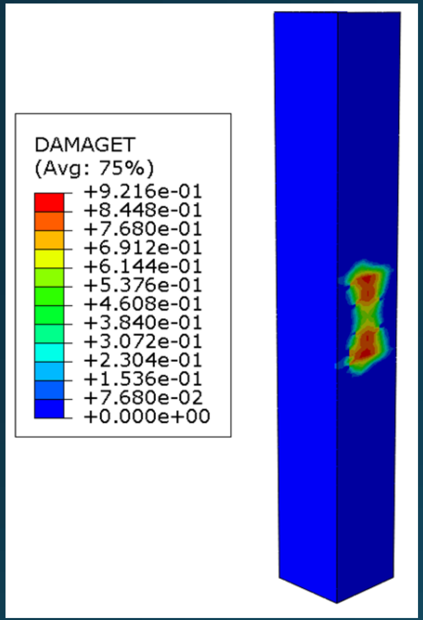
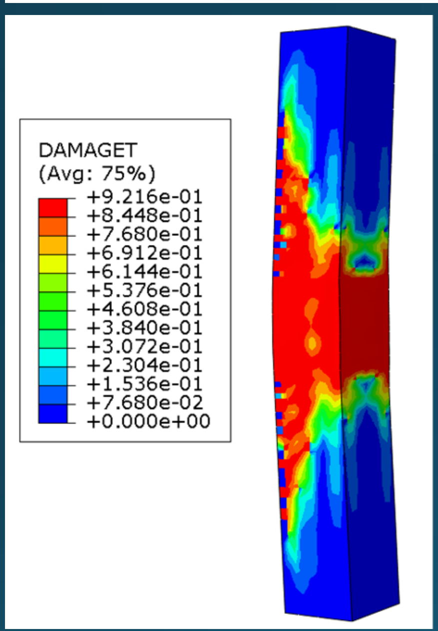
+1.603e-01
0.32-2.5


DAMAGET
(Avg: 75%)
+9.216e-01
+8.448e-01
+7.680e-01
+6.912e-01
+6.144e-01
+5.376e-01
+4.608e-01
+3.840e-01
+3.072e-01
+2.304e-01
+1.536e-01
+7.680e-02
+0.000e+00


DAMAGET
(Avg: 75%)
+9.216e-01
+8.448e-01
+7.680e-01
+6.912e-01
+6.144e-01
+5.376e-01
+4.608e-01
+3.840e-01
+3.072e-01
+2.304e-01
+1.536e-01
+7.680e-02
+0.000e+00


DAMAGET
(Avg: 75%)
+9.216e-01
+8.448e-01
+7.680e-01
+6.912e-01
+6.144e-01
+5.376e-01
+4.608e-01
+3.840e-01
+3.072e-01
+2.304e-01
+1.536e-01
+7.680e-02
+0.000e+00


DAMAGET
(Avg: 75%)
+9.216e-01
+8.448e-01
+7.680e-01
+6.912e-01
+6.144e-01
+5.376e-01
+4.608e-01
+3.840e-01
+3.072e-01
+2.304e-01
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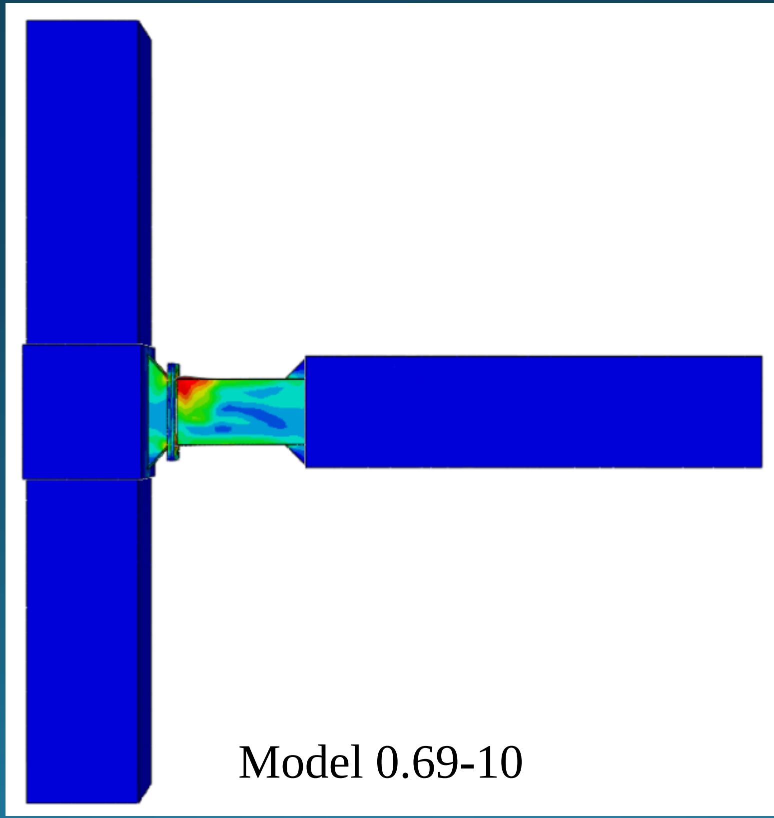
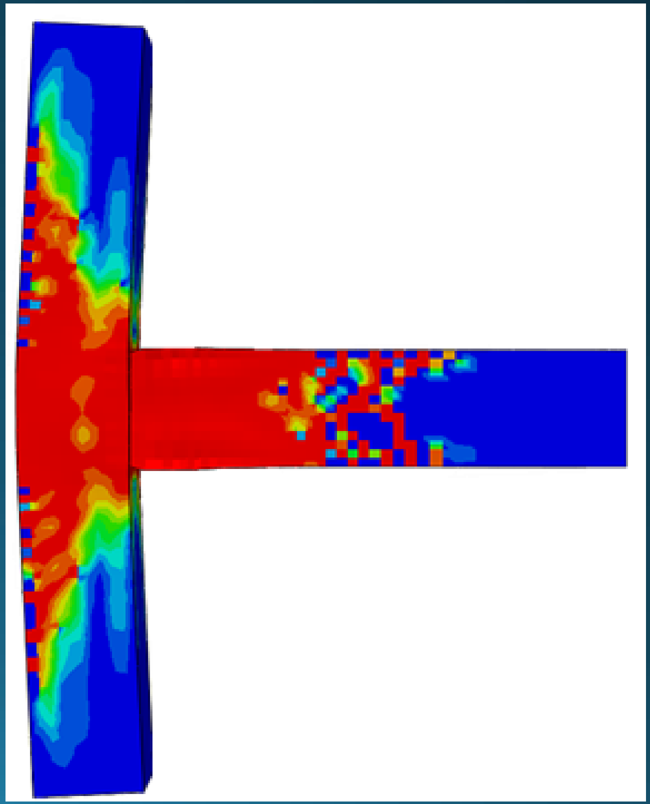
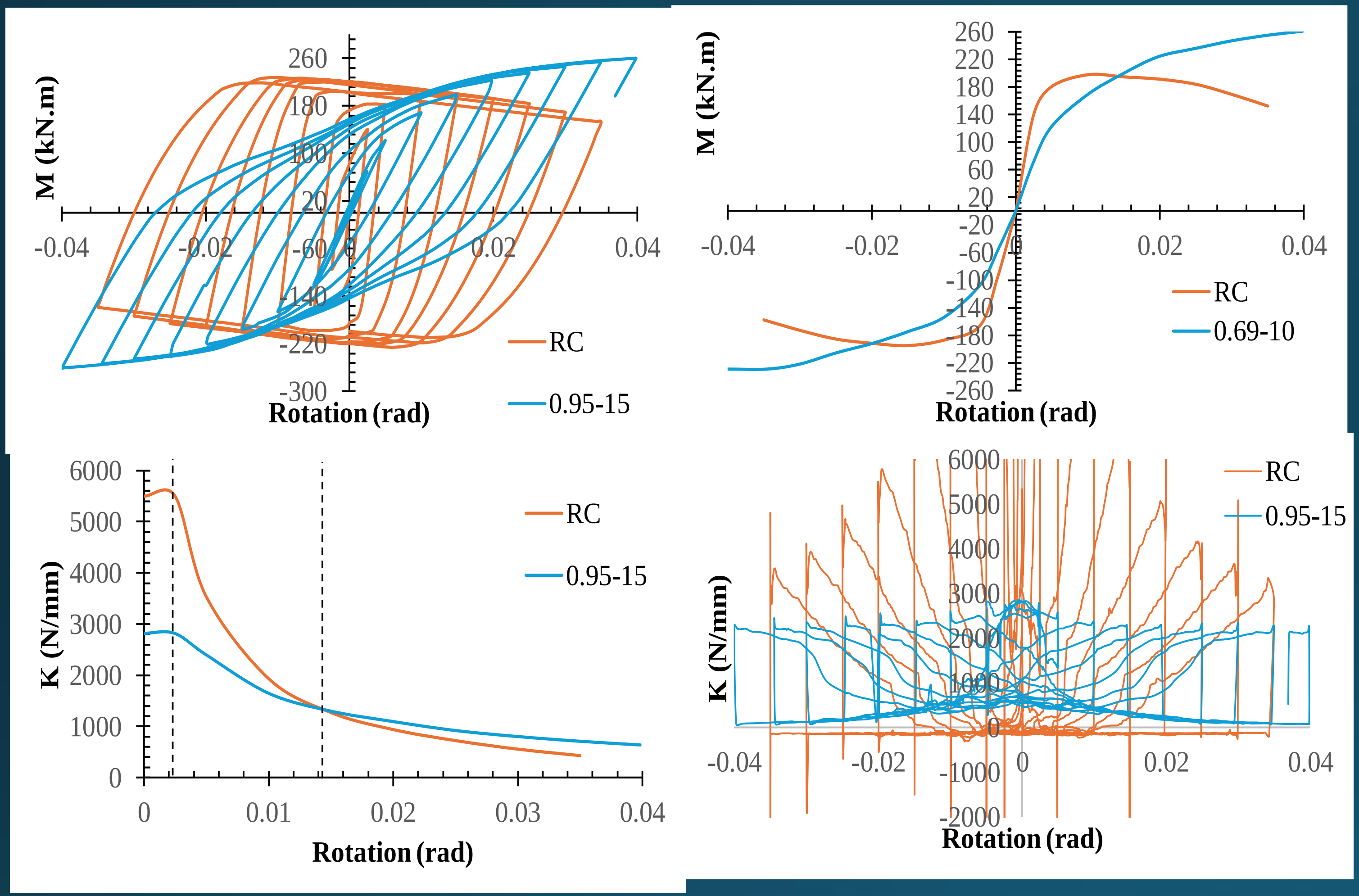
+7.680e-02
+0.000e+00


Model 0.69-10




M (kN.m)
Rotation (rad)
RC
0.95-15
M (kN.m)
Rotation (rad)
RC
0.69-10
K (N/mm)
Rotation (rad)
RC
0.95-15
K (N/mm)
Rotation (rad)
RC
0.95-15

Story No	Flexural reinforcement (kg)		Shear reinforcement (kg)		RC/Proposed system	
	RC	Proposed	RC	Proposed	Flexural	Shear
4	626.05	434.21	45.43	33.22	1.44	1.37
3	799.62	567.84	65.92	53.36	1.41	1.24
2	863.44	603.15	70.01	57.83	1.43	1.21
1	853.92	594.22	69.38	56.73	1.44	1.22

Story No	Flexural reinforcement (kg)		Shear reinforcement (kg)		RC/Proposed system	
	RC	Proposed	RC	Proposed	Flexural	Shear
8	185.68	117.71	13.33	9.13	1.58	1.46
7	279.18	164.34	27.77	18.31	1.70	1.52
6	253.87	157.55	20.61	13.30	1.61	1.55
5	263.71	165.32	21.31	14.42	1.60	1.48
4	248.31	166.47	16.65	10.86	1.49	1.53
3	250.79	170.61	17.45	11.42	1.47	1.53
2	244.54	170.97	16.89	11.57	1.43	1.46
1	229.57	153.40	15.75	9.76	1.50	1.61

Story No	Flexural reinforcement (kg)		Shear reinforcement (kg)		RC/Proposed system	
	RC	Proposed	RC	Proposed	Flexural	Shear
12	642.63	413.02	56.73	38.01	1.56	1.49
11	642.63	413.02	56.73	38.01	1.56	1.49
10	697.13	472.08	46.70	36.74	1.48	1.27
9	793.26	576.79	65.35	49.74	1.38	1.31
8	839.51	626.34	89.64	71.71	1.34	1.25
7	803.62	625.02	116.96	95.87	1.29	1.22
6	795.90	647.95	120.24	98.56	1.23	1.22
5	812.66	664.72	104.03	86.69	1.22	1.20
4	807.11	676.17	104.03	86.69	1.19	1.20
3	806.82	692.70	102.03	90.29	1.16	1.13
2	805.93	693.59	98.85	89.87	1.16	1.10
1	770.98	668.91	94.11	85.56	1.15	1.10

Conclusions

- The proposed hybrid system, comprising an RC frame with replaceable ductile steel links, exhibits excellent seismic performance characterized by stable hysteresis curves without stiffness or strength degradation throughout the applied loading. Damage is intentionally confined to the link, which serves as a ductile fuse, effectively dissipating seismic energy while protecting the primary structural elements.
- Parametric studies reveal that the link β ratio has the most significant influence on key seismic parameters. Increasing β from 0.32 to 0.95 (a 2.97times increase) enhances the ultimate moment capacity (M) by 2.66 times, initial stiffness (K) by 1.90 times, and cumulative energy dissipation (E) by 1.98 times, while reducing ductility (μ) by 1.40 times. Conversely, reducing beam flange thickness from 15 mm (β = 0.95) to 10 mm (β = 0.69), 5 mm (β = 0.44), and 2.5 mm (β = 0.32) decreases flexural capacity by 12%, 49%, and 63%, respectively. Notably, a 50% reduction in flange thickness (15 mm to 10 mm) corresponds to only a 37% drop in β and a mere 12% loss in capacity, demonstrating high efficiency in material utilization.
- By reducing the beam flange thickness from 15mm ($\beta = 0.95$) to 10 ($\beta = 0.69$), 5 ($\beta = 0.44$), and 2.5mm ($\beta = 0.32$), the flexural capacity of the models is reduced by 12%, 49%, and 63%, respectively. So, it confirms that although the beam flange thickness is changed 15mm to 10mm, give 50% reduction in thickness and 37% in β, only 12% reduction in capacity is realized.
- The β containing the most impact on the M, E, K, and μ. Except for the K, other structural parameters have a response in three segments as $\beta < 0.4$, $0.4 \leq \beta \leq 0.7$, and $\beta > 0.7$. For optimal balance of strength, energy dissipation, stiffness, and ductility, links should be designed within 0.4 ≤ β ≤ 0.7, with β ≈ 0.5 identified as the optimum value.

- Stiffness degradation with increasing connection rotation θ follows three clear phases: (i) $\theta < 0.0025$ rad (elastic range, no degradation), (ii) $0.0025 \leq \theta \leq 0.01$ rad (sharp stiffness drop), and (iii) $\theta > 0.01$ rad (gradual reduction approaching zero). A critical observation is that models with $\beta = 0.32$ and $\beta = 0.44$ reach near-zero stiffness at $\theta = 0.04$ rad, highlighting the importance of adequate β to maintain residual stiffness under extreme drifts.
- Equivalent damping ratio (ζ) analyses show strong pairwise similarities up to $\theta = 0.02$ rad: the 0.44-5 model closely matches the 0.32-2.5 model, while the 0.95-15 model aligns with the 0.69-10 model. These pairings persist beyond 0.02 rad, indicating comparable damping performance under large deformations. To achieve the best combination of high energy absorption and sufficient damping (ζ), the model with $\beta = 0.69$ is recommended.

• Compared to conventional RC moment frames, incorporating ductile steel links reduces the required beam flexural reinforcement by 50–70% and shear reinforcement by approximately 60%. This substantial decrease in steel rebar consumption not only enhances seismic resilience but also delivers significant economic benefits through reduced material costs and simpler detailing, making the proposed system a highly efficient and practical solution for earthquake-resistant design.

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Any Question?