Development of Asymmetric Bouc-Wen Model with Linear Strength-Degradation Functions

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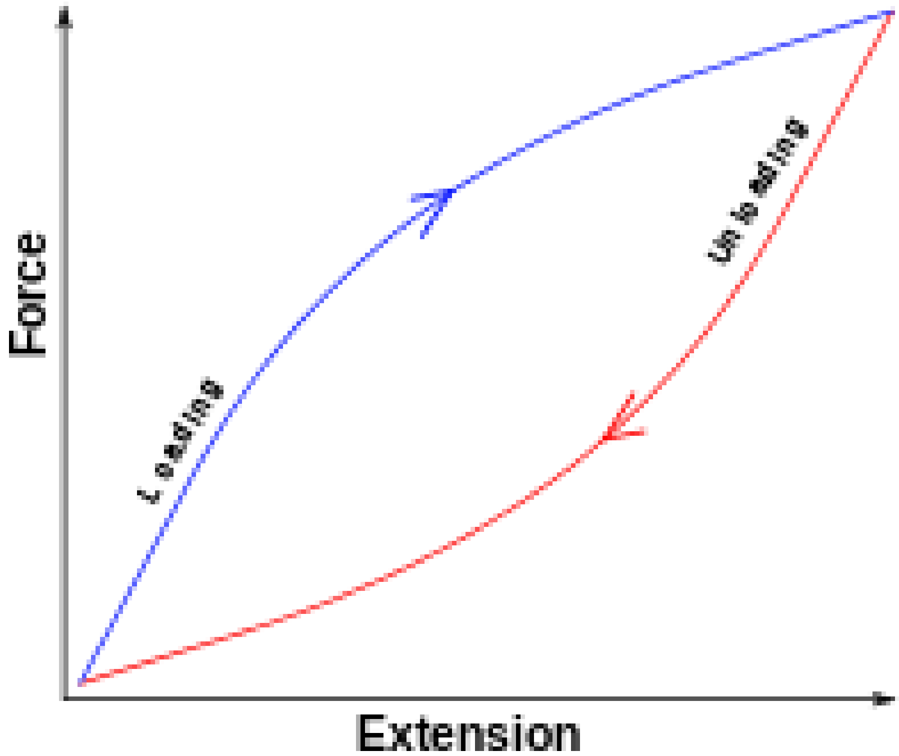
Asymmetric Bouc–Wen Model with Linear Strength–Degradation Functions

01. Introduction

Hysteresis refers to the dependence of the state of a system on its history.



Elastic hysteresis of an idealized rubber band. The area in the center of the hysteresis loop is the energy dissipated due to internal friction.

ref)
https://en.wikipedia.org/wiki/Hysteresis#In_mechanics

01. INTRODUCTION

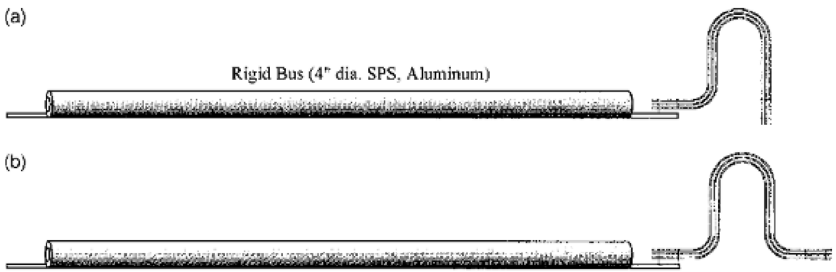


Fig. 4. Rigid bus conductors fitted with flexible strap connectors: (a) PG&E 30-2021; and (b) PG&E 30-2022

Typical assemblies of an RB and two FSCs: PG&E 30–2021 and PG&E 30–2022 of Pacific Gas & Electric Company. These connectors are made of three parallel straps, each strap consisting of a pair of copper bars.

ref) Song J, Der Kiureghian A. Generalized Bouc–Wen model for highly asymmetric hysteresis. J Eng Mech. 2006;132(6):610–8.

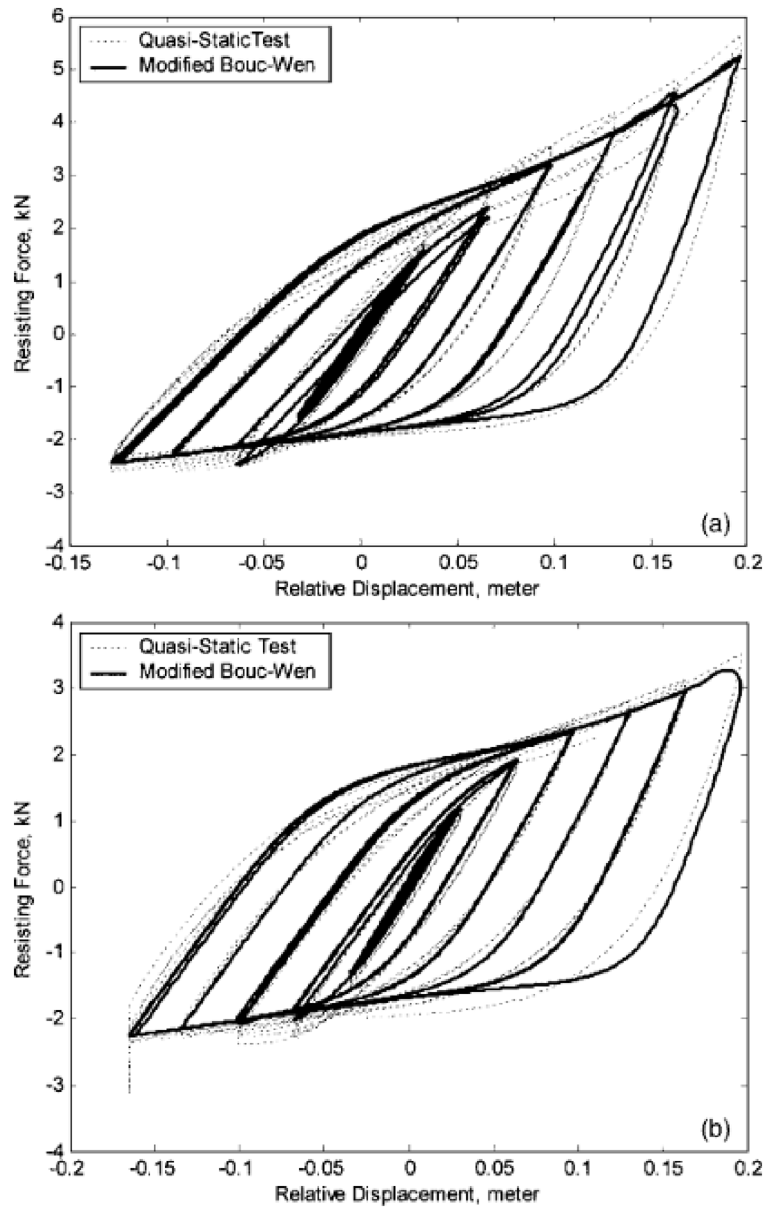
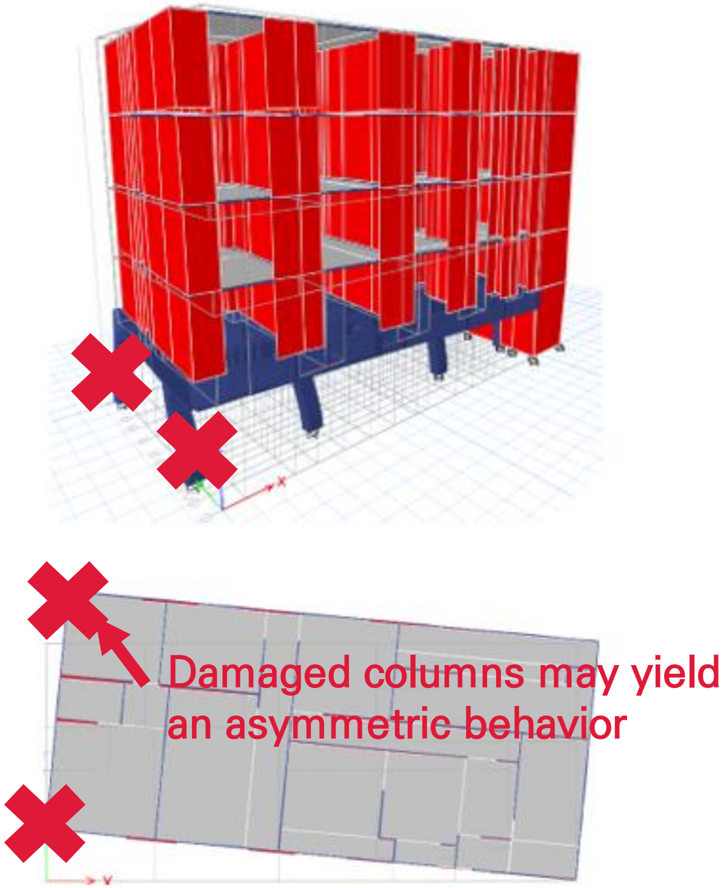
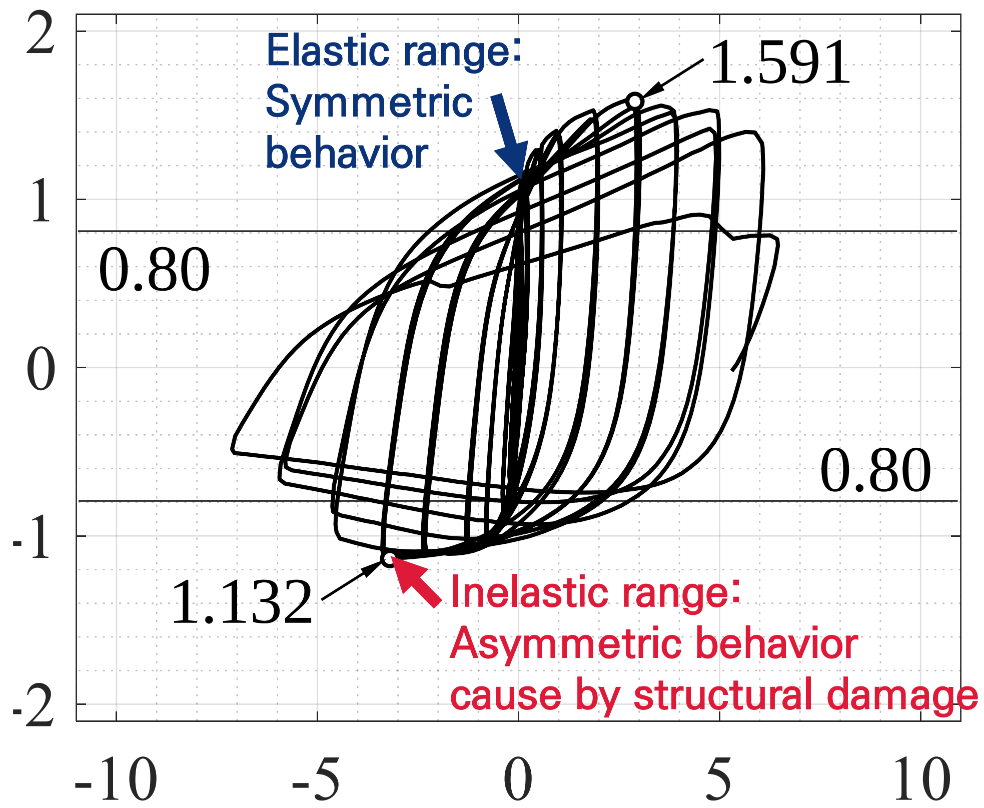


Fig. 5. Hysteretic behavior of RB-FSC as observed by Filiatrault et al. (1999) and as predicted by fitted modified Bouc–Wen model with time varying parameters: (a) PG&E 30-2021; and (b) PG&E 30-2022

01. Introduction





The problem for the damage identification is that we do not have a model for describing asymmetric hysteresis yet.

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Asymmetric Bouc–Wen Model with Linear Strength-Degradation Functions

02. Bouc–Wen Model and Its Extensions

Original Bouc–Wen Model

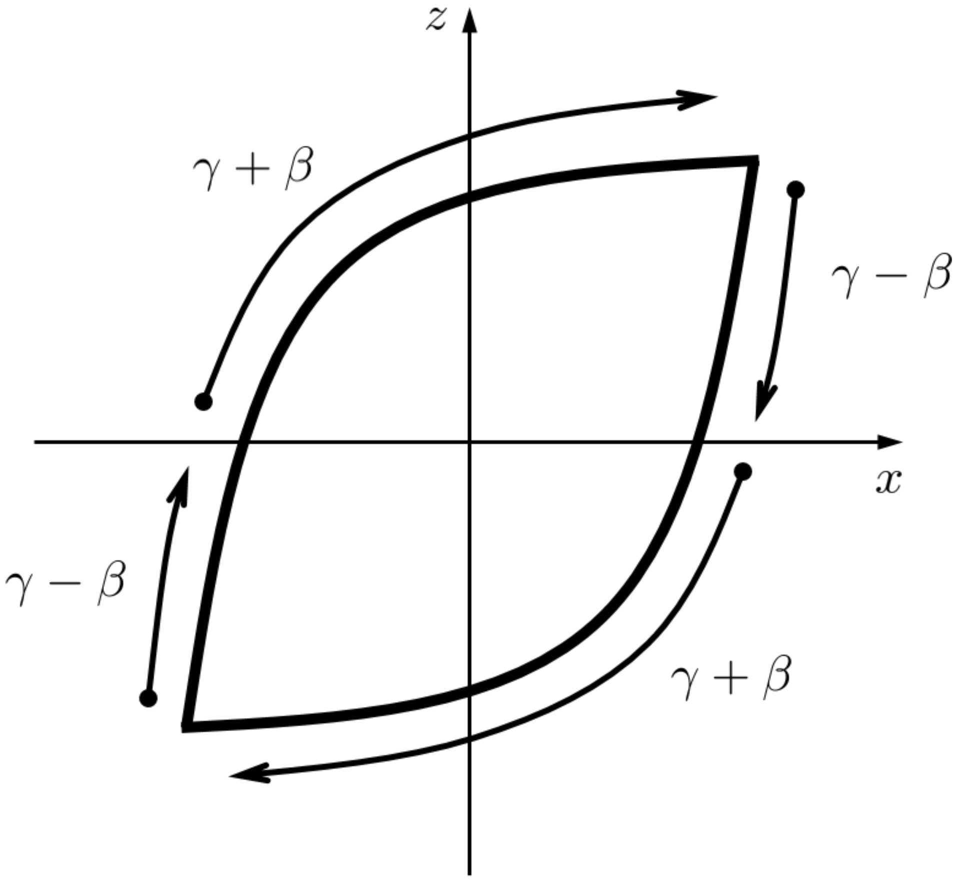
$$f = f^{\mathrm{PY}} + f^{\mathrm{H}} = \alpha k_i x + (1-\alpha) k_i z$$

where f^{PY} and f^{H} are the post-yielding and hysteretic forces, respectively; k_i is the elastic stiffness, α is the ratio of the post-yield stiffness to the elastic stiffness k_i; and z is an auxiliary variable introduced to simulate hysteretic behavior, which is controlled by the following nonlinear differential equation with a zero initial condition:

$$\dot{z} = \dot{x}(1 - |z|^n \psi)$$

where n is a parameter that controls the sharpness of the hysteresis loop and $\psi = \psi(x, \dot{x}, z)$ is a nonlinear function that controls the other shape characteristics of the hysteresis loop.

ORIGINAL BOUC–WEN MODEL



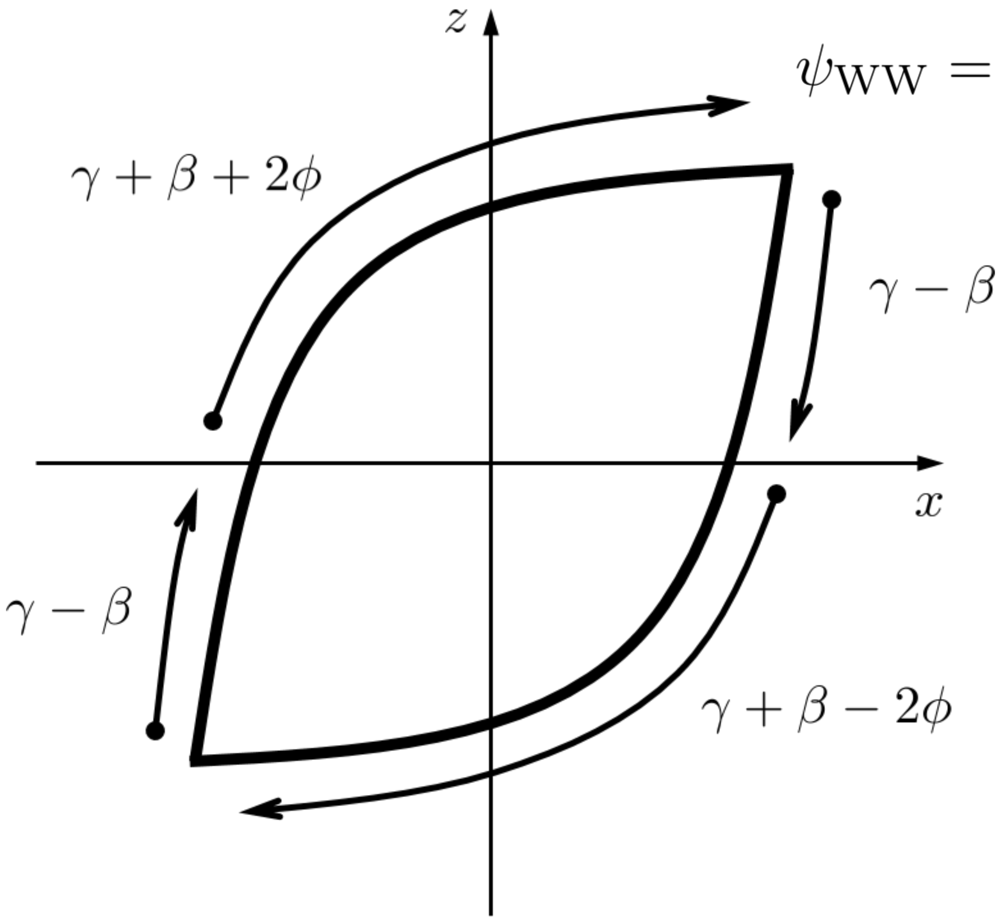
$$\psi_{\mathrm{BW}} = \psi_{\mathrm{BW}}(\dot{x}, z) = \gamma + \beta\, \mathrm{sgn}(\dot{x} z)$$

(1) $\gamma + \beta$
for $\dot{x} > 0$ (i.e., $\mathrm{d}x > 0$) and $z > 0$,
and for $\dot{x} < 0$ (i.e., $\mathrm{d}x < 0$) and $z < 0$
(2) $\gamma - \beta$
for $\dot{x} > 0$ and $z < 0$,
and for $\dot{x} < 0$ and $z > 0$.

02. Bouc–Wen Model and Its Extensions

Wang–Wen Model

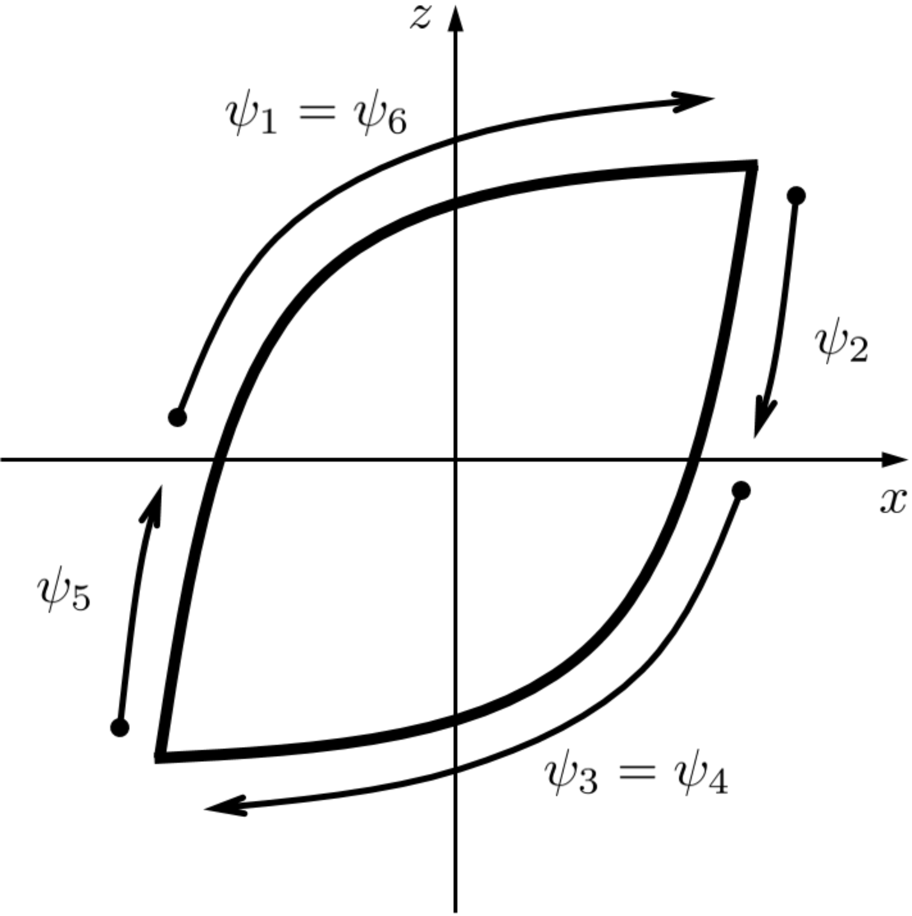
$$\psi_{\mathrm{WW}} = \gamma + \beta\,\mathrm{sgn}(\dot{x}z) + \phi[\mathrm{sgn}(\dot{x}) + \mathrm{sgn}(z)]$$



(1) $\gamma + \beta + 2\phi$
for $\dot{x} > 0$ (i.e., $\mathrm{d}x > 0$) and $z > 0$
(2) $\gamma - \beta$
for $\dot{x} > 0$ and $z < 0$,
and for $\mathrm{d}x < 0$ and $z > 0$
(3) $\gamma + \beta - 2\phi$
for $\dot{x} < 0$ (i.e., $\mathrm{d}x < 0$) and $z < 0$.

02. Bouc–Wen Model and Its Extensions

Generalized Bouc–Wen Model



$$\psi_{\mathrm{gBW}} = \psi_{\mathrm{gBW}}(x, \dot{x}, z)$$
$$= \beta_1 \mathrm{sgn}(\dot{x}z) + \beta_2 \mathrm{sgn}(x\dot{x}) + \beta_3 \mathrm{sgn}(xz)$$
$$+\beta_4 \mathrm{sgn}(\dot{x}) + \beta_5 \mathrm{sgn}(z) + \beta_6 \mathrm{sgn}(x)$$

The BW model can be characterized by using the parameters $\beta_1 = \gamma + \beta$, $\beta_2 = -\gamma$, $\beta_3 = \gamma$, and $\beta_4 = \beta_5 = \beta_6 = 0$. In a similar manner, the WW model can be obtained by taking the parameters $\beta_1 = \beta + \gamma$, $\beta_2 = -\gamma$, $\beta_3 = \gamma$, $\beta_4 = \phi$, $\beta_5 = \phi$, and $\beta_6 = 0$.

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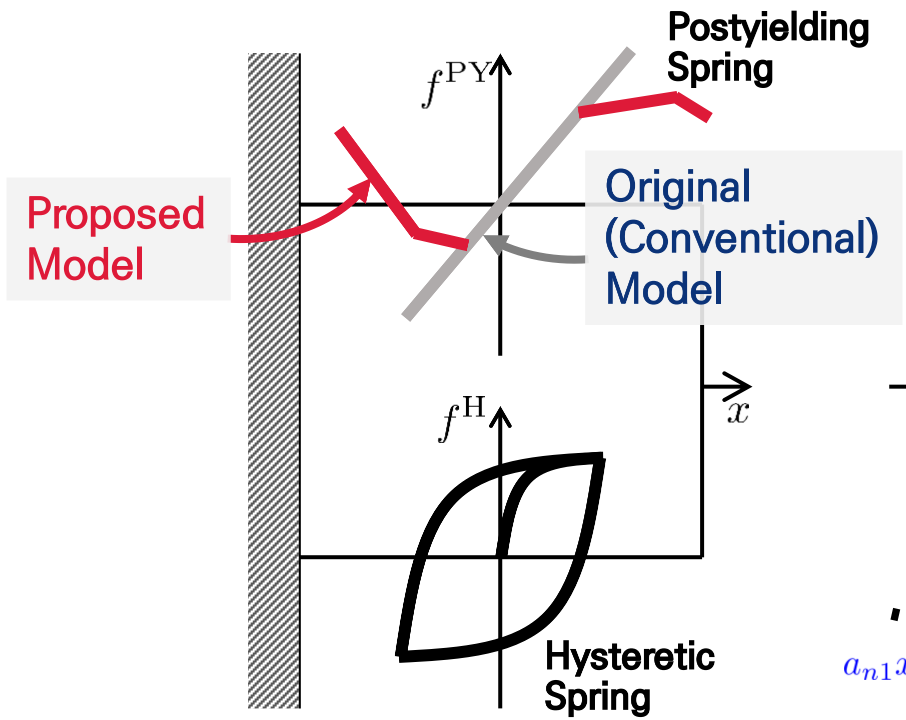
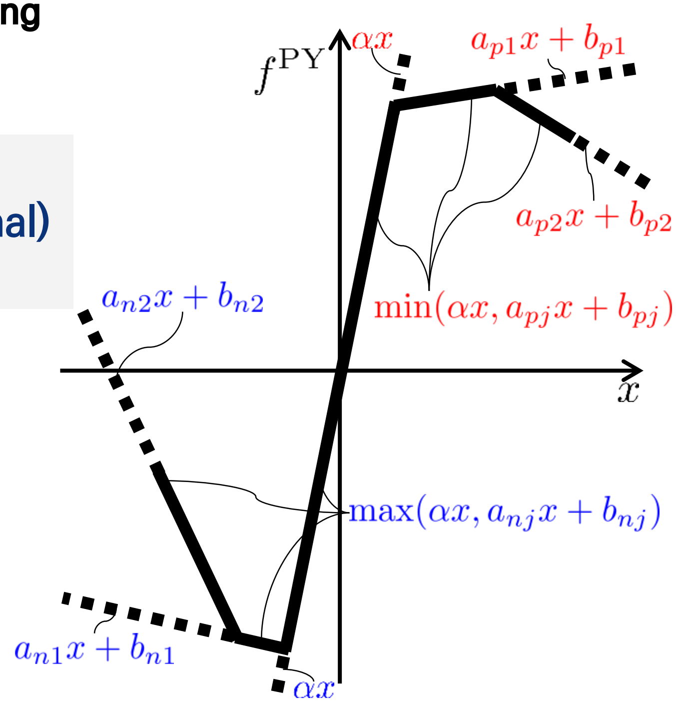
Asymmetric Bouc–Wen Model with Linear Strength–Degradation Functions

03. Asymmetric Bouc–Wen Model Proposed

Scheme of Proposed Model





Conventional BW Model: N+1 parameters

$$f = f^{\mathrm{PY}} + f^{\mathrm{H}} = \alpha x + (1-\alpha)z$$

Proposed Model: N+2n+1 parameters

Rather complex but accurate

$$f = \begin{cases} \min(\alpha x,\ a_{pj}x + b_{pj}) + (1-\alpha)z & x \geq 0 \\ \max(\alpha x,\ a_{nj}x + b_{nj}) + (1-\alpha)z & x < 0 \end{cases}$$

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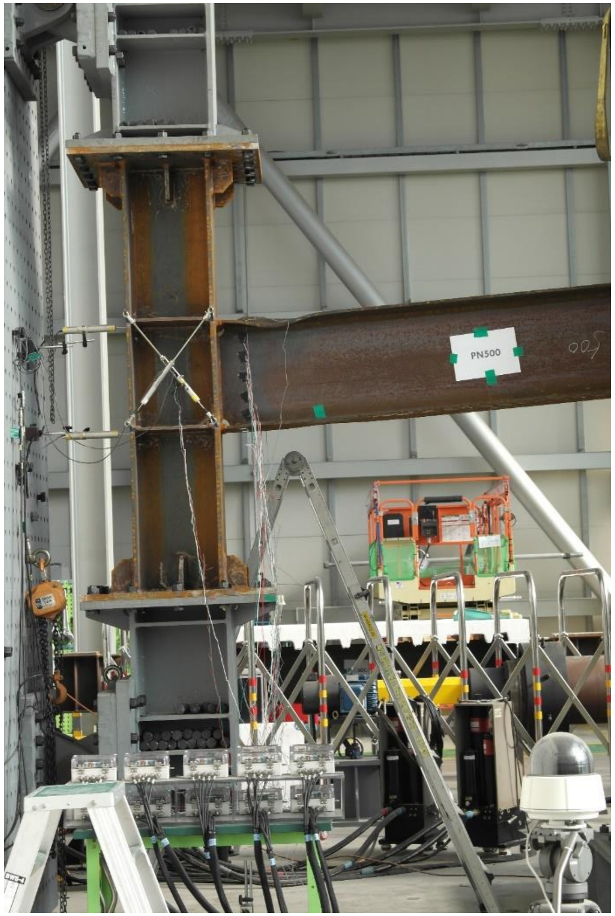
Asymmetric Bouc–Wen Model with Linear Strength-Degradation Functions

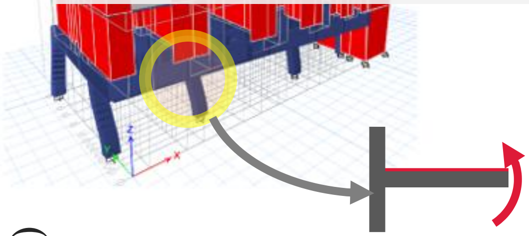
04. Model Validation
Composite Beam–Column Connections

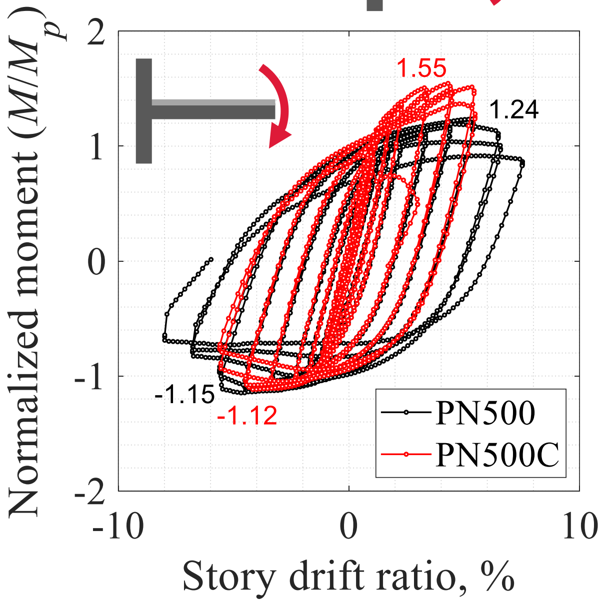


PN500:
Bare steel

PN500C:
Composite connection

In many cases, the beam is modeled with omitting the strength and stiffness of the slab.



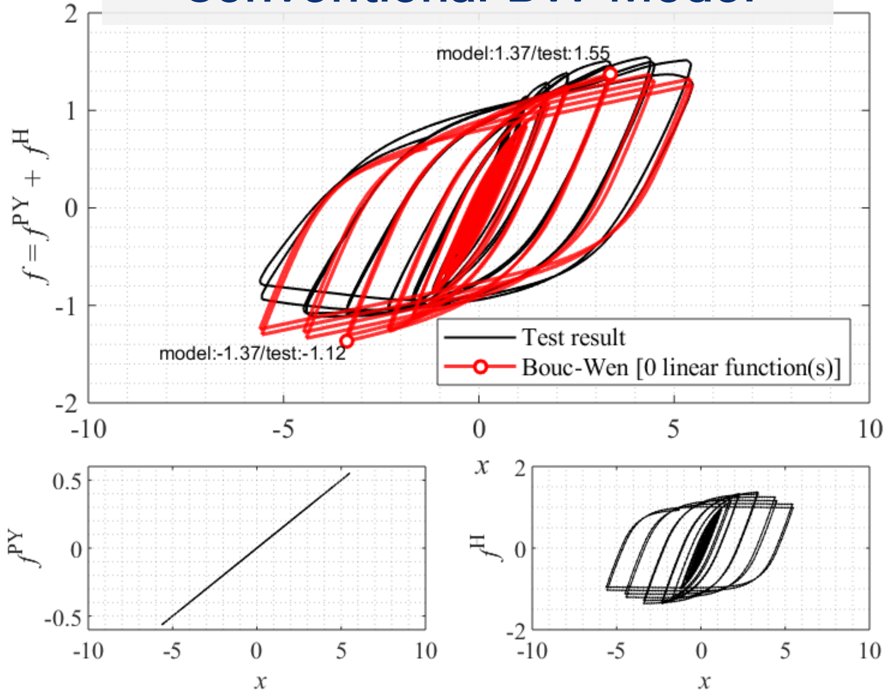


Reference (SCI): Kim S-Y, Lee C-H. Seismic retrofit of welded steel moment connections with highly composite floor slabs. *J Constr Steel Res*. 2017;139:62–8.

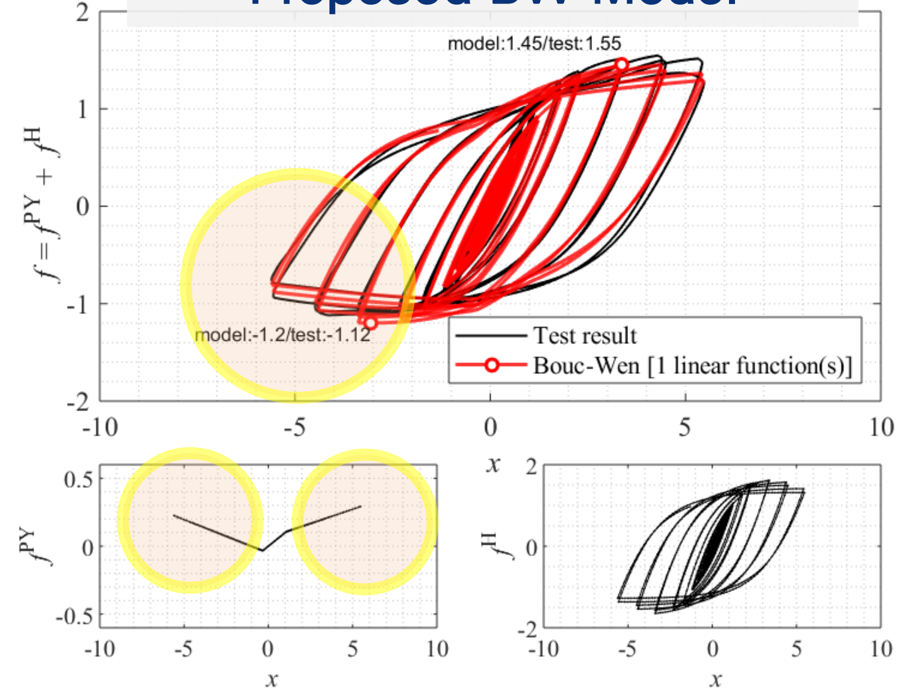
04. Model Validation

Composite Beam-Column Connections

Conventional BW Model



Proposed BW Model



Introducing linear functions enables the Bouc-Wen model to predict the asymmetric hysteresis more accurately.

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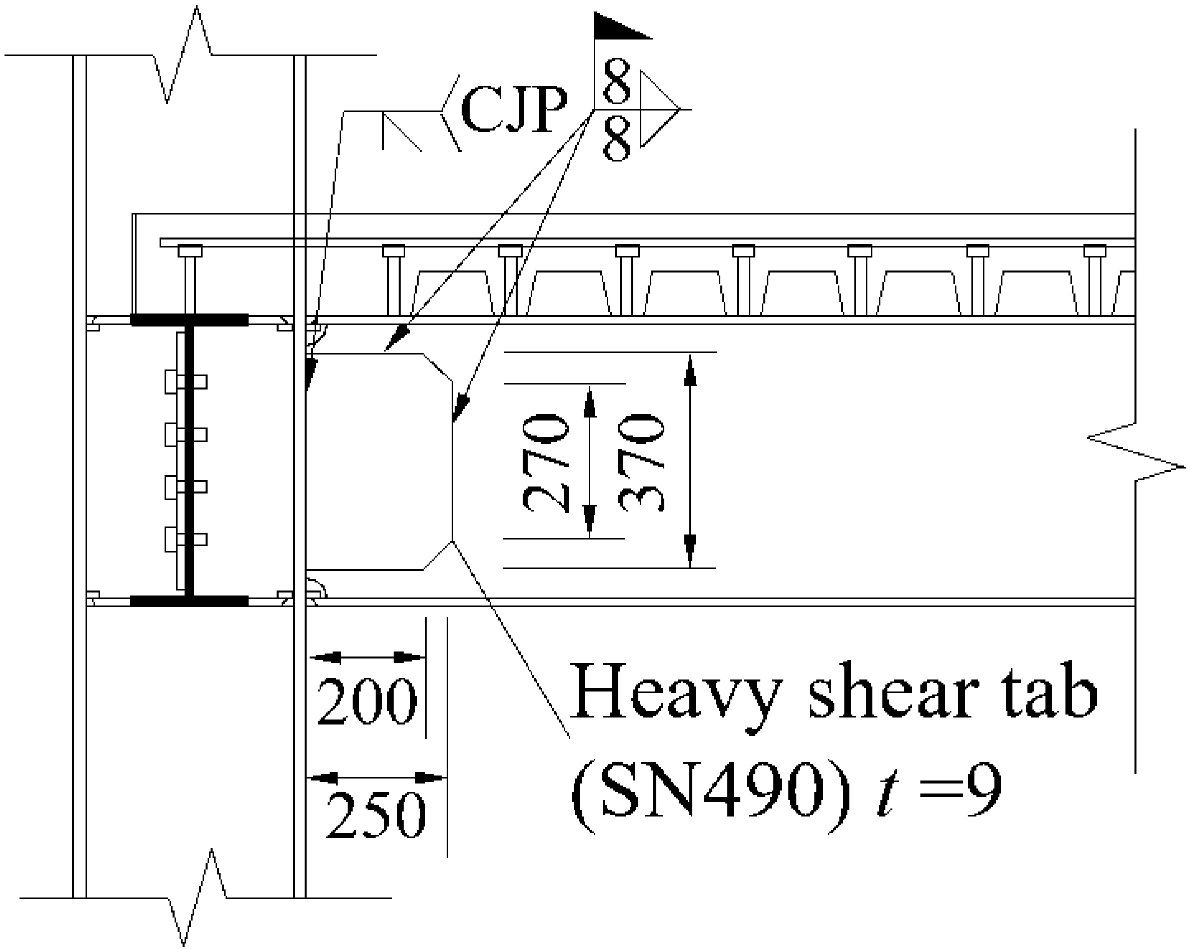
Connection Retrofitted with Heavy Shear Tab



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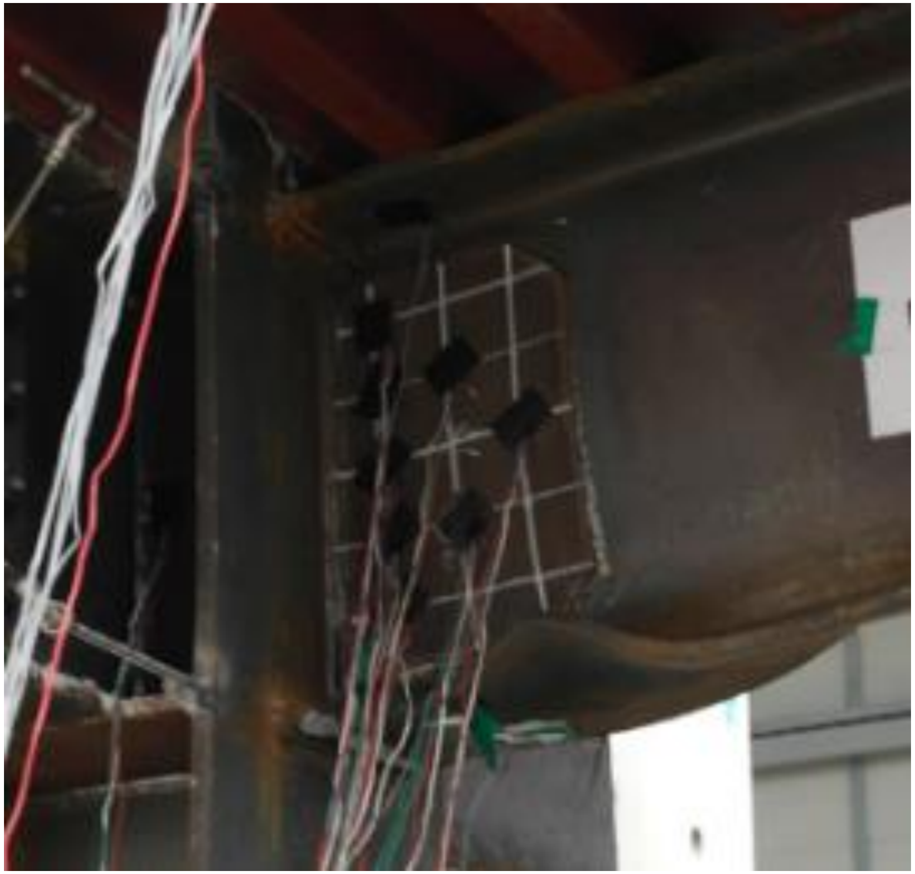

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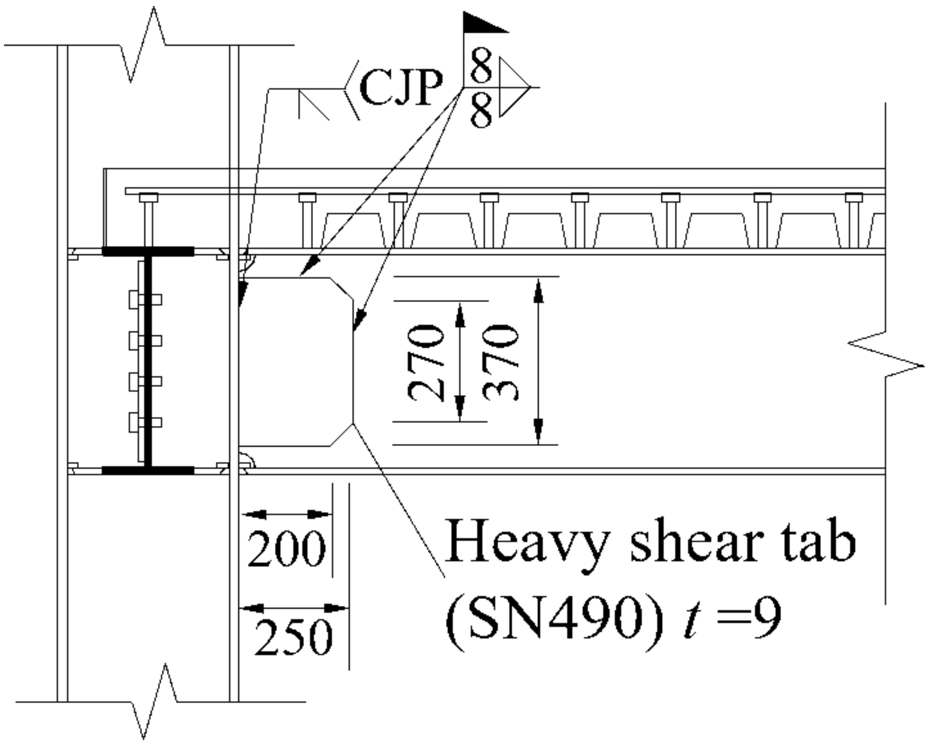

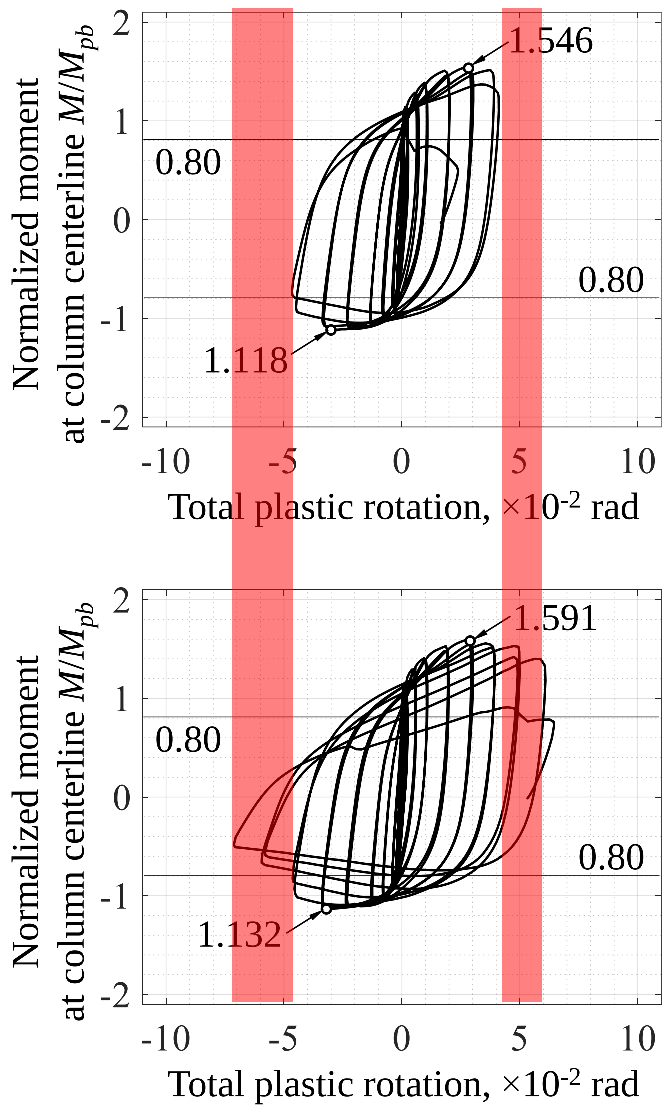

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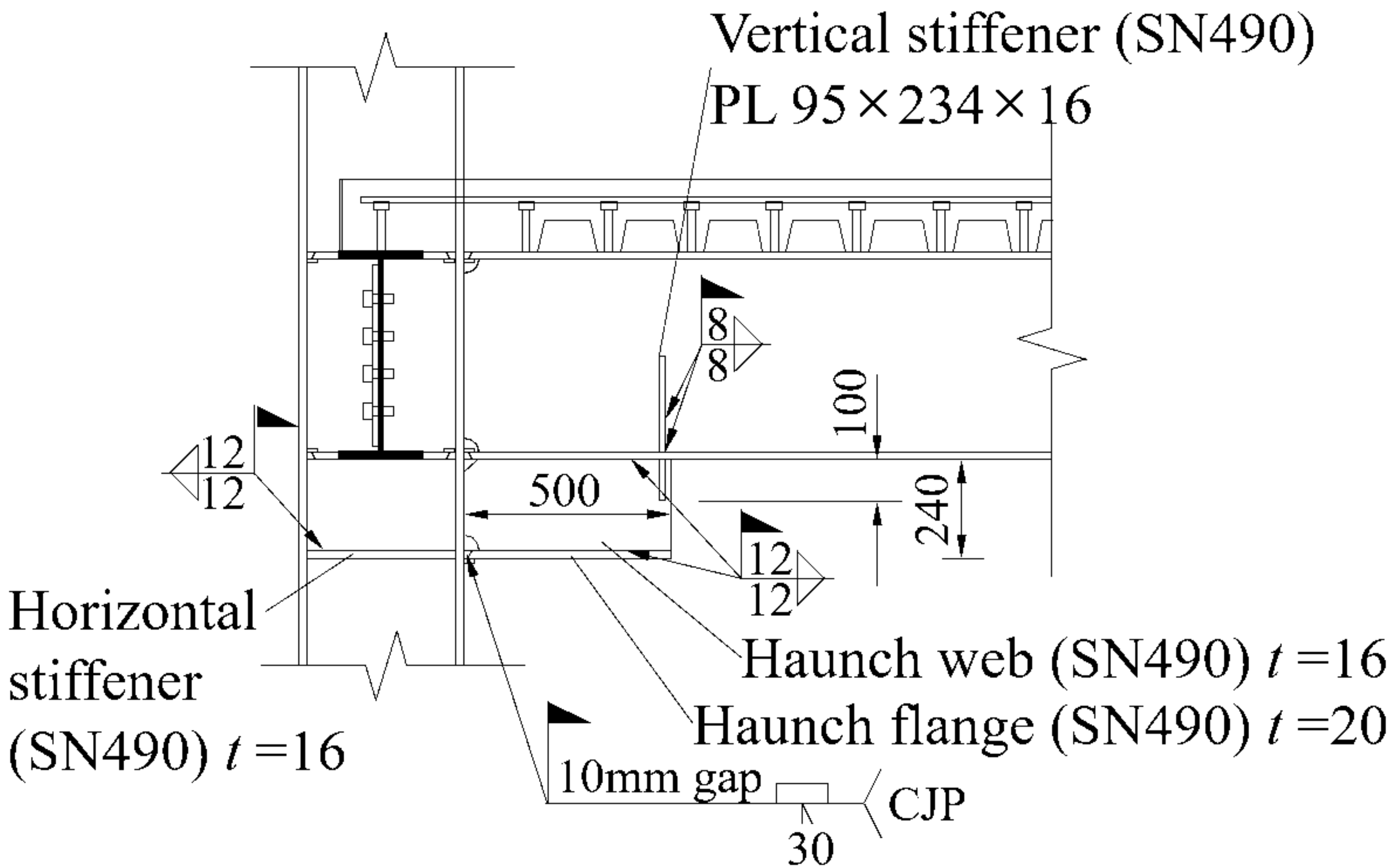

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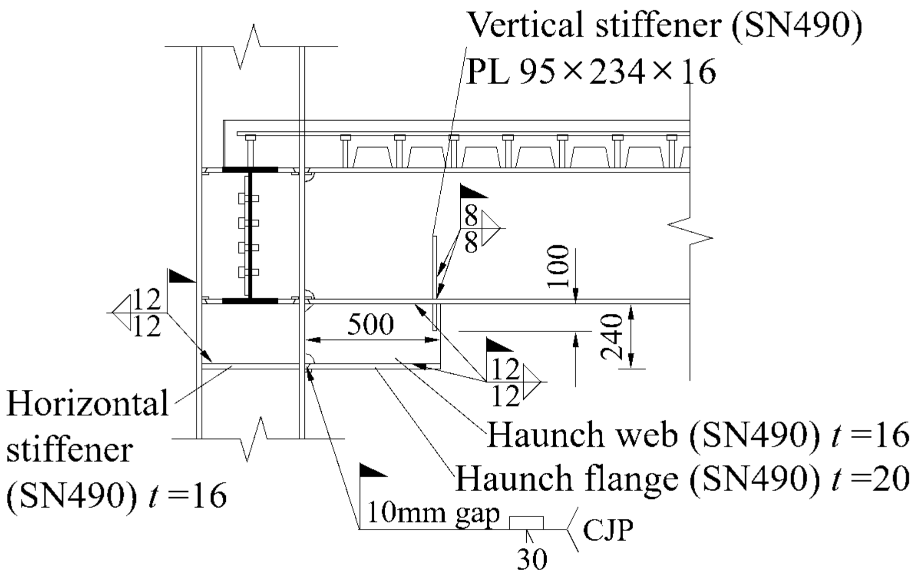

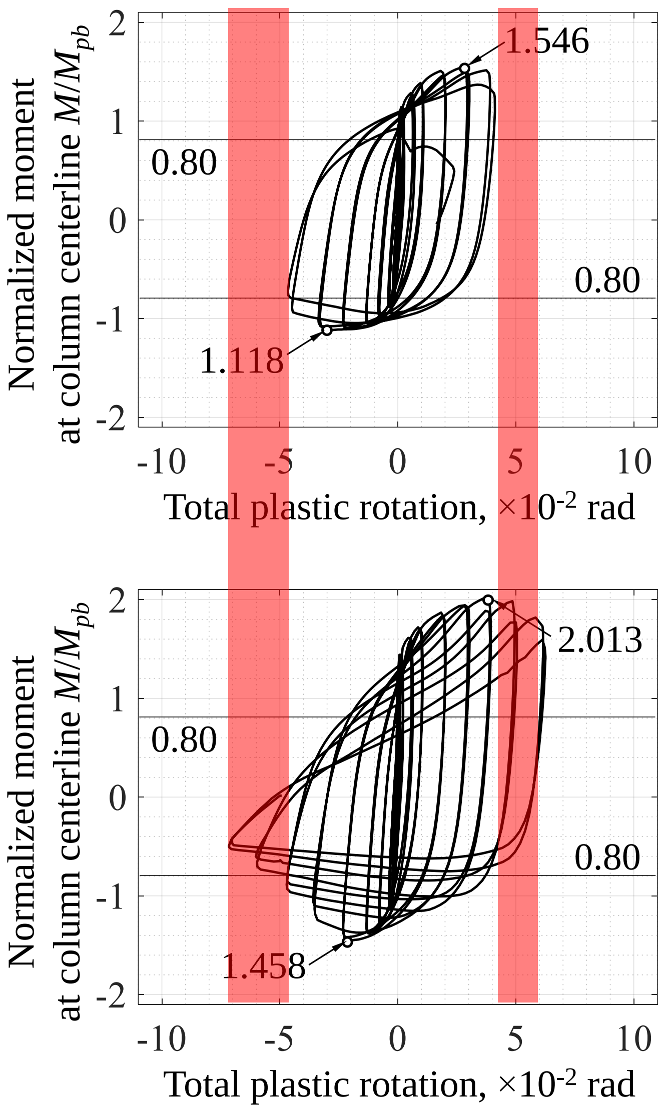

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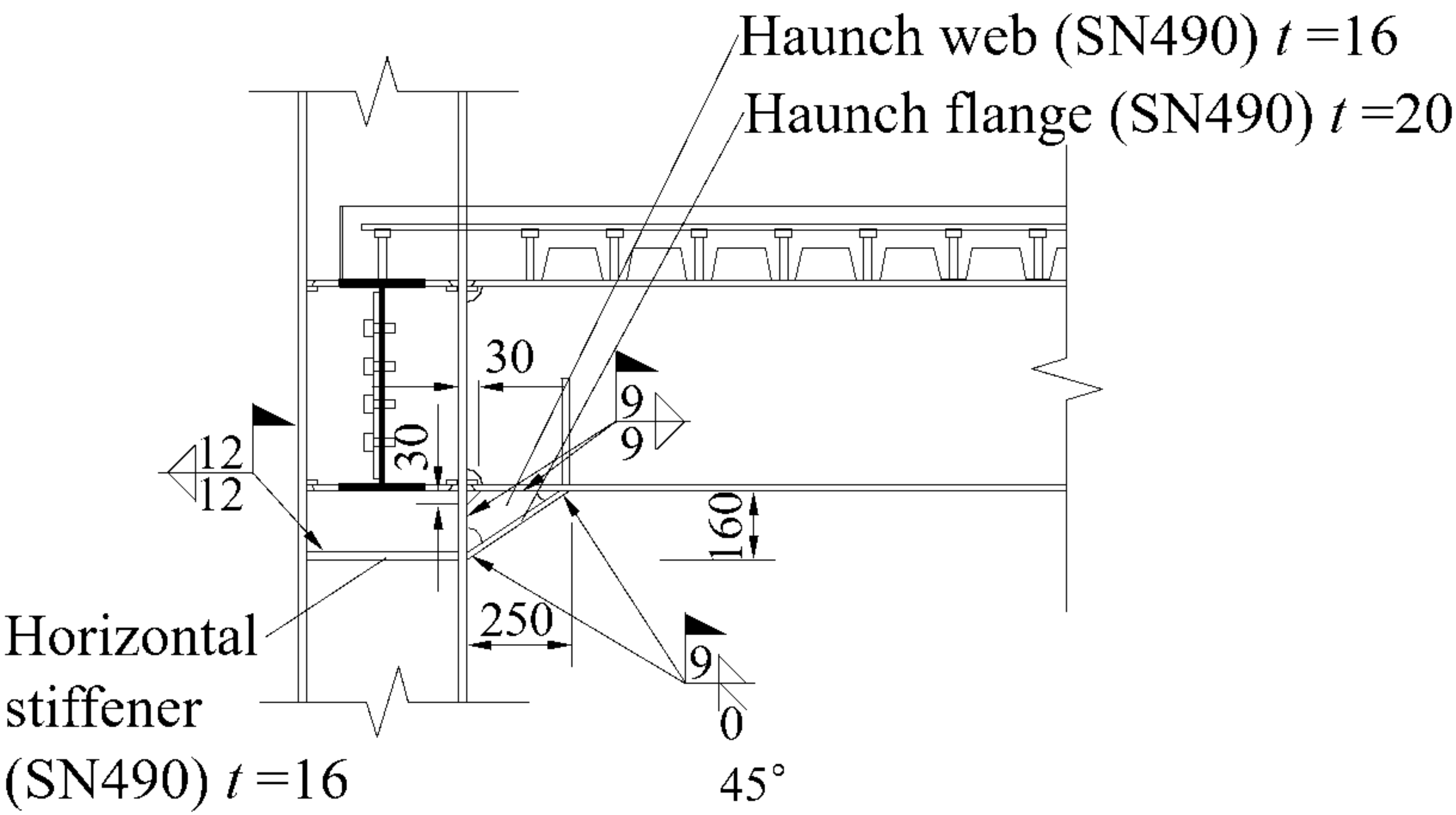

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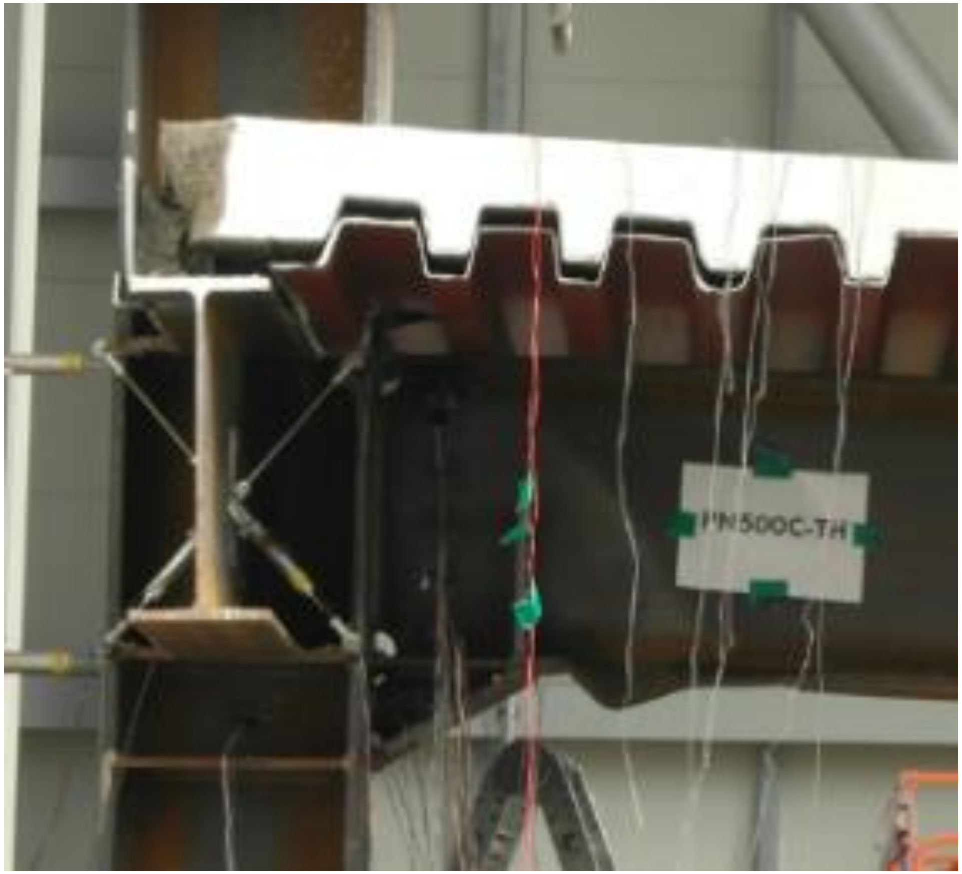

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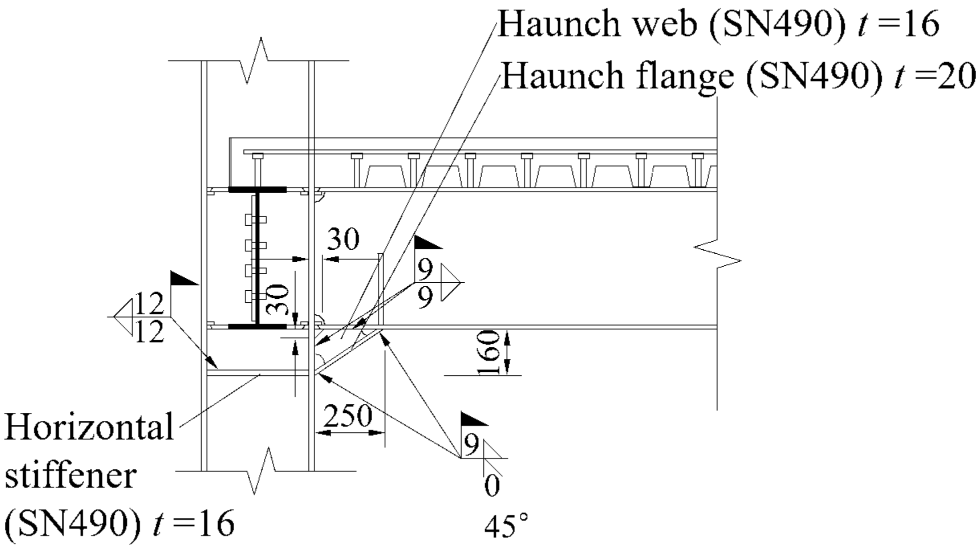

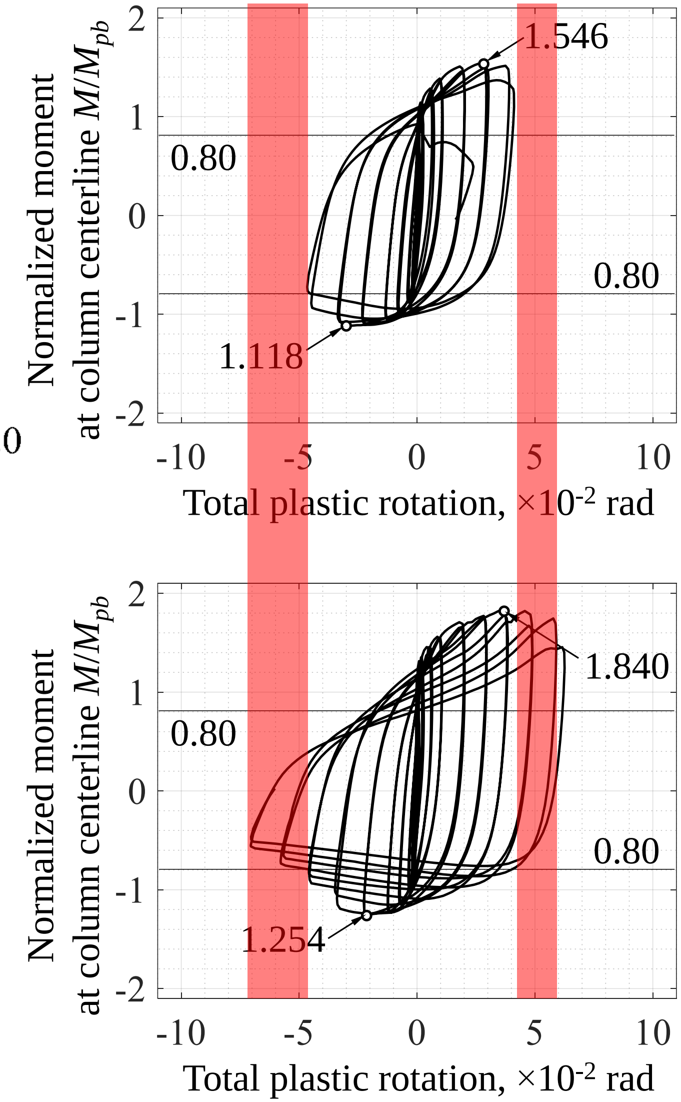

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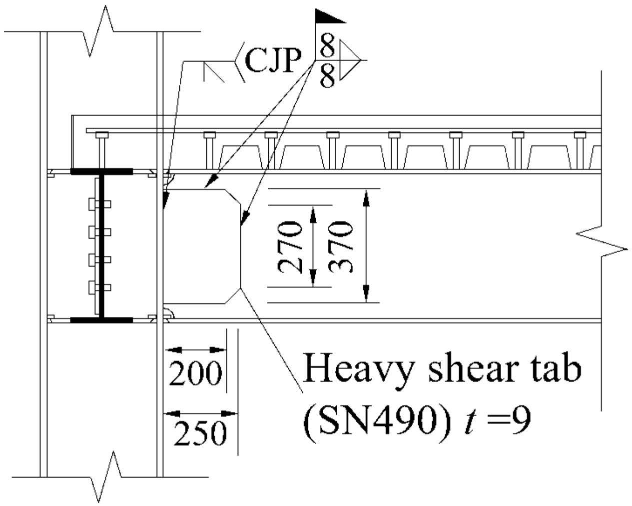

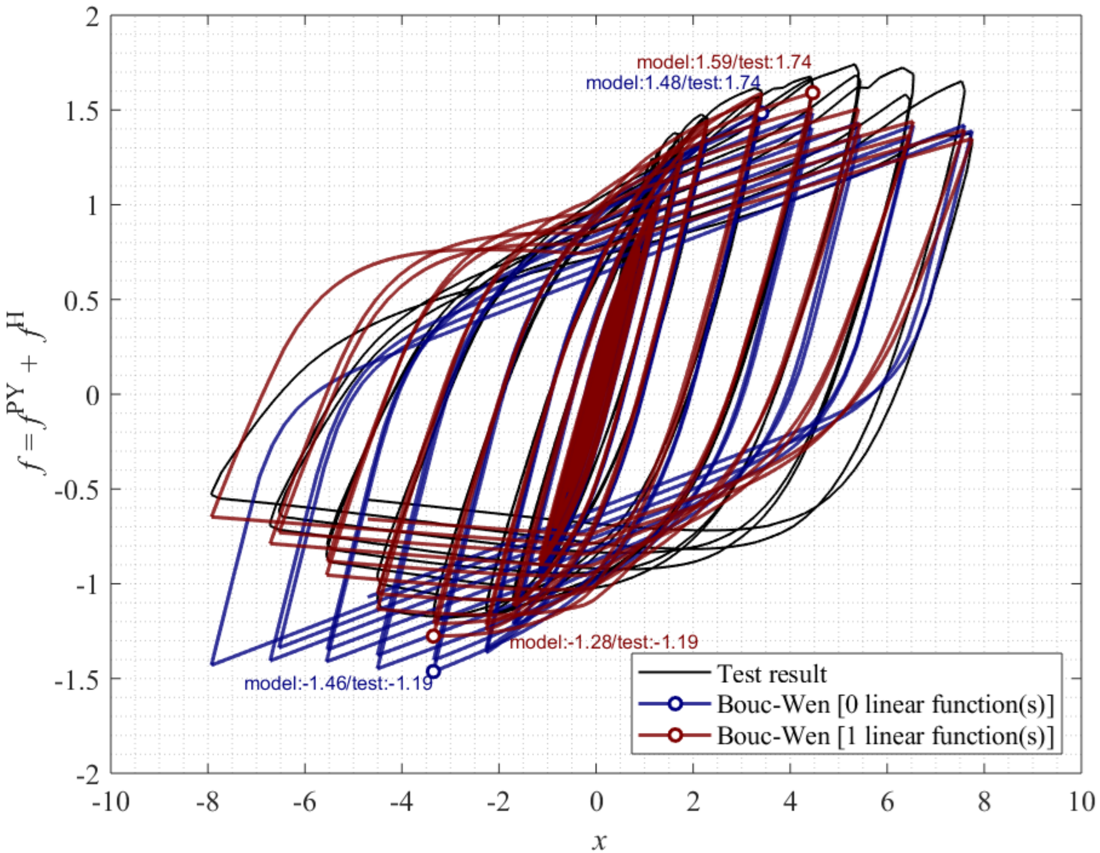

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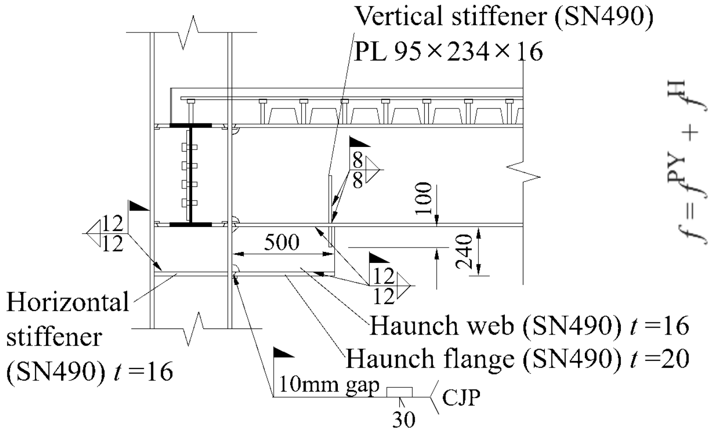

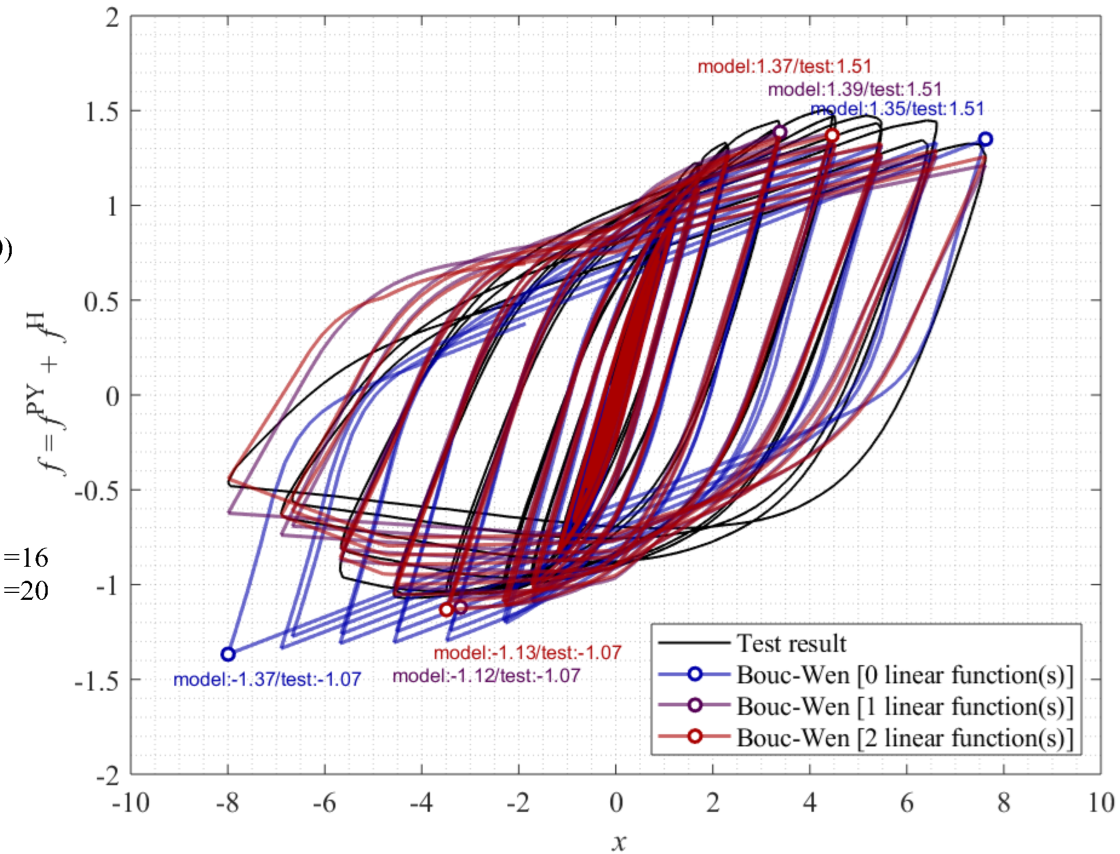

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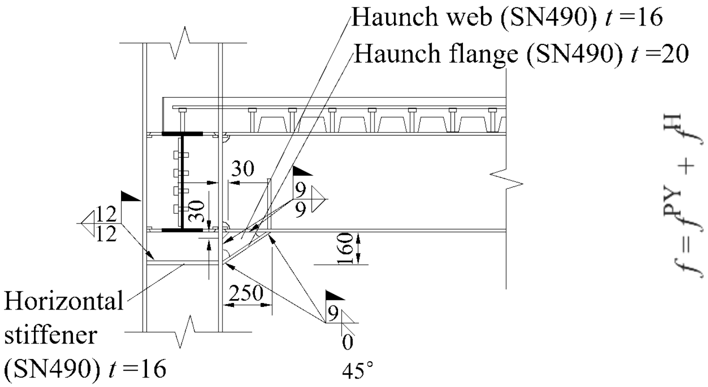

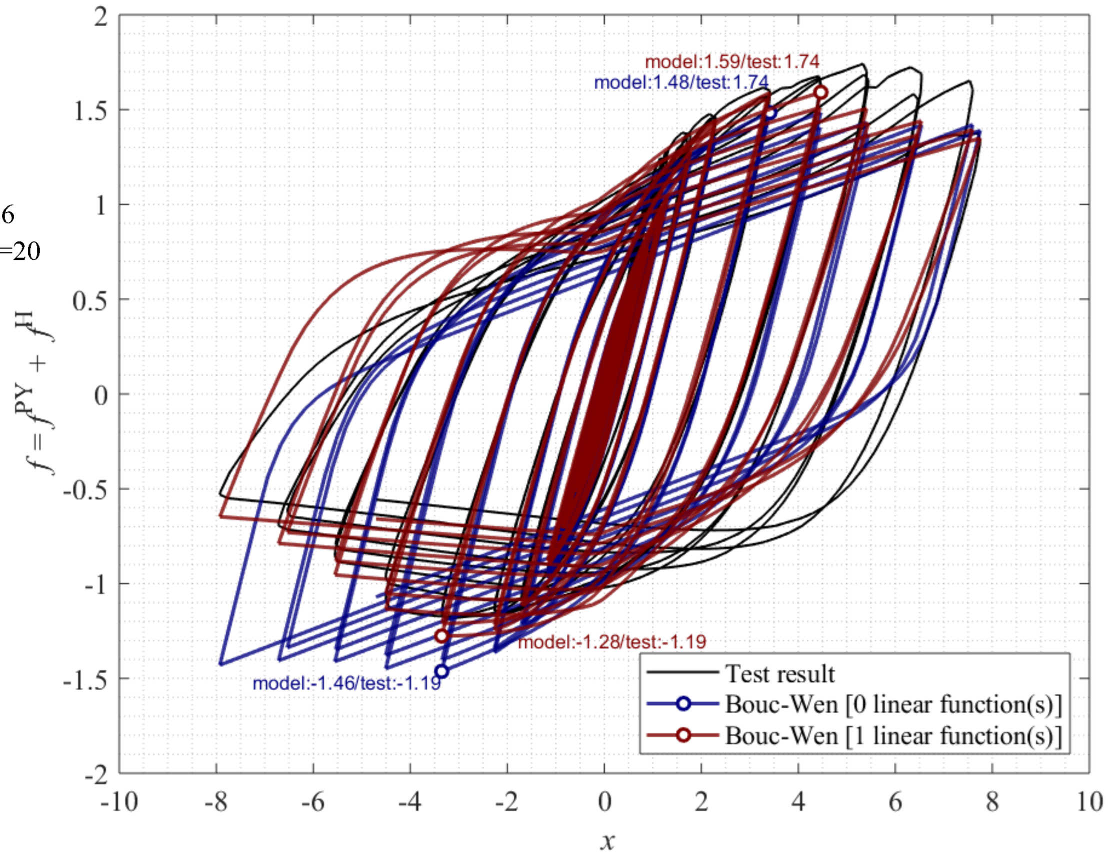

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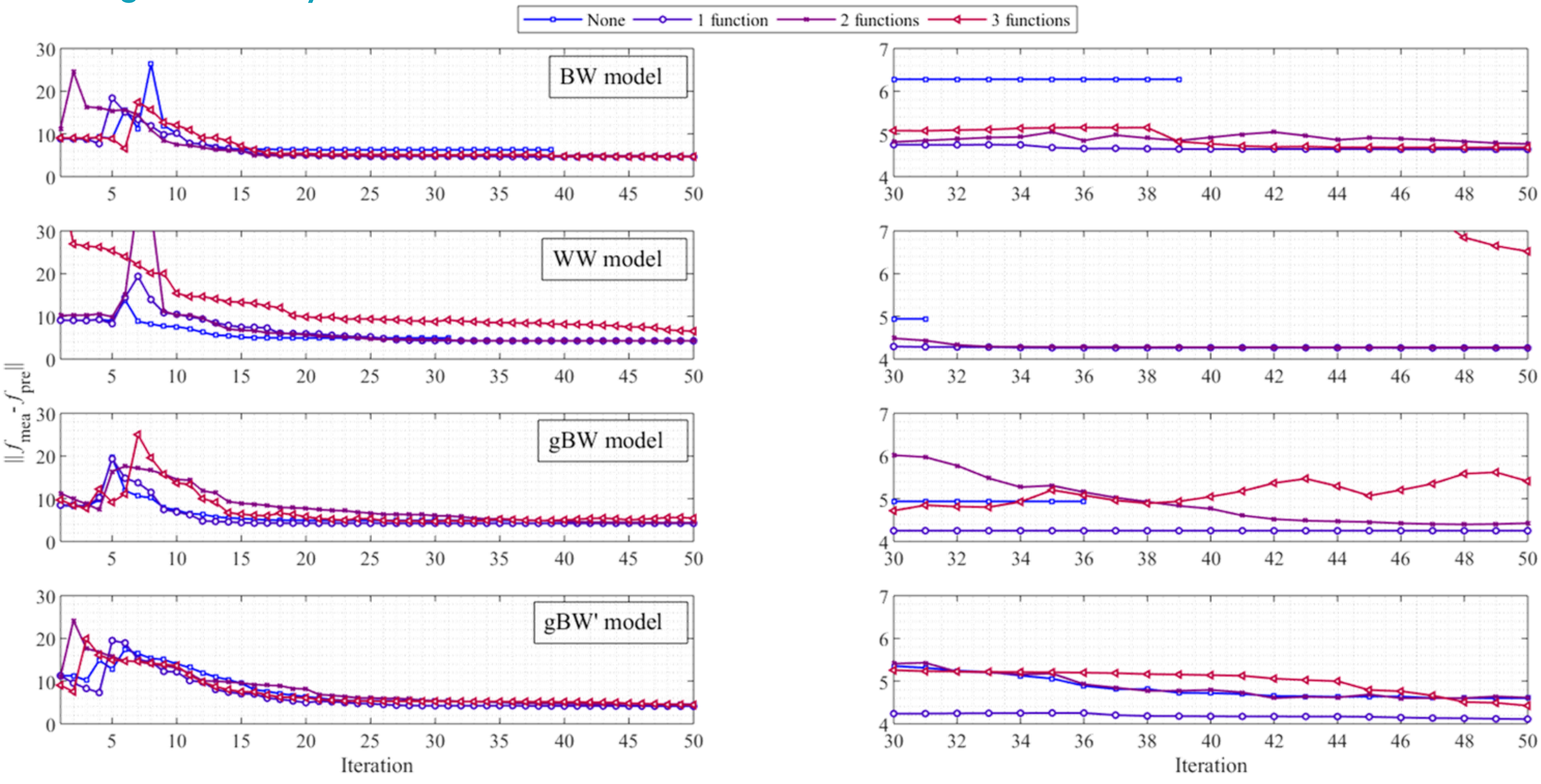
04. Model Validation

Convergence Study



Inclusion of one or two linear functions in the original BW or Wang–Wen model is recommended for better accuracy and more optimal numerical performance.

05. Summary and Conclusions

1. A new hysteresis model was proposed by combining the BW class hysteresis models with a post-yielding convex function composed of piecewise linear functions.

2. The proposed model and its parameter identification procedure could simulate the asymmetric hysteresis well compared to the existing BW class models.

3. The convergence of the proposed model was also examined. Inclusion of one or two linear functions in the original BW or Wang-Wen model is recommended for better accuracy and more optimal numerical performance.

Any Questions?