ANALYSIS OF BEAM-COLUMN-GUSSET COMPONENTS IN 5-STORY VALUE-ADDED FRAME

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ABSTRACT:

This paper describes finite element analysis of subassemblies composed of beams, columns, and gusset plates in passively controlled buildings. Numerical analysis with consideration of geometrical and material nonlinearity is confirmed to have good performance for simulating degrading of frames due to local buckling of the bottom flange of a beam in cyclic response by comparison of test results. Yielding and buckling patterns of the frame members are summarized in subassemblies having various kinds of gusset connections. Stress profile around gusset connection is studied for design of gusset plate. A parametric study is also conducted to investigate sensitivity to frame stiffness by variation of gusset connections. Modeling techniques by using linear element for gusset connections is investigated for dynamic response analysis, referring a proposed equivalent strut model. Finally, a practical design procedure of thickness of gusset plate based on equivalent strut action is proposed for gusset plate subjected combined damper forces and frame forces.

KEYWORDS: braced frame, gusset plate, stiffener plate, subassembly, post-buckling analysis

1. INTORODUCTION

Passive control schemes, where dampers in frames absorb a part of vibration energy, are widely used in seismic design after the 1995 Kobe earthquake. A realistic shaking table test of a full-scaled 5-story passively controlled building will be conducted by utilizing E-Defense facility. Prior to the full-scaled test, static cyclic tests for subassembly specimens in the frame were conducted to investigate the structural performance before the shaking table test scheduled for 2009[1)].

The performance of passively-controlled buildings depends not only on damper but also frame members and connections. Premature failure or fracture of frames or connections results in poor performance of the system. Relatively large axial force produced by damper force develops in the beams in addition to bending moment and shear caused by story drift. The axial force can cause earlier yielding and possibly buckling in the elements. Stress profile in gusset plate is complex by damper force and frame shear. For stress occurring gusset plate due to damper force, the Whitmore's effective width concept[2)] is commonly used. However, components of stress in gusset plate produced by frame action are often neglected in design procedure although the stress along the gusset plate is relatively large and concentrates[3)].

This paper describes finite element analysis of subassemblies composed of beams, columns, and gusset plates in passively controlled buildings. The objective of this study is to investigate applicability of finite element analysis and enhance numerical simulation techniques through post analysis for the subassembly test. A parametric study is also conducted to investigate sensitivity to frame stiffness and plastic deformation capacity by gusset connections. In addition, a design procedure for determining thickness of gusset plate based on equivalent strut action for gusset plate is proposed.

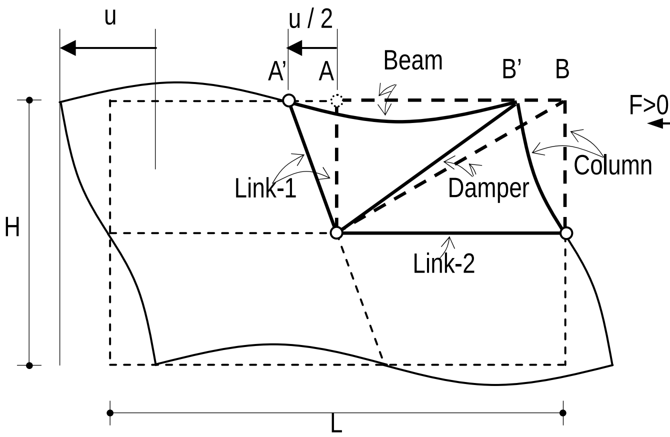


Figure 1 Schematic illustration of subassembly

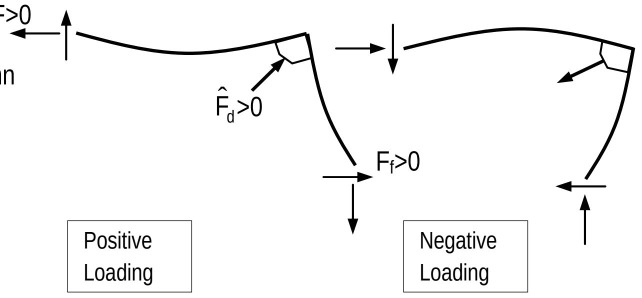


Figure 2 Loading pattern

2. FE ANALYSIS

Figure 1 shows the concept of subassembly consisting of beam, column, and damper. The subassembly has a configuration of L-shape, and it represents a quarter portion of the frame. Positive loading, where the beam is subjected to positive (tension) force and positive end moment, is defined as shown in Figure 2, and verse versa.
Figure 3 shows a typical specimen. Table 1 summarizes the specimen types. Specimen 1 has neither gusset plate nor stiffeners, and is not subjected to the damper force. Specimen 1 is to be compared with those having gusset plate. Specimen 3 refers to subassembly of the full-scaled 5-story frame specimen. Strong column-weak beam conditions are satisfied in all the specimens.

2. 1. Analysis model

Finite element analysis is conducted to simulate test results[1)]. Both the material and geometric non-linearities are considered. 2nd Piola-Kirchhoff stress and Green strain are adopted. A four node quadrilateral shell element (Dvokin and Bathe 1984) is used to model the beam, the column, the gusset plate, and the stiffener. A rigid truss element is used to model the link element. The steel damper is idealized as beam elements. The damper force in the FE model is obtained from the inner fore of the damper, while the damper force is applied by control of an actuator force in the experiment. The bolts and the splice plates for connecting the dumper and the gusset plate are neglected for simplicity. Boundary conditions simulated the test restraints, including translational and rotational degrees of freedom shown in Figure 3.
Initial imperfection is added to the original geometry for post-buckling analysis. Buckling modes obtained by linear buckling analysis are used, and their values are one-hundredth of the flange thickness of the beam.

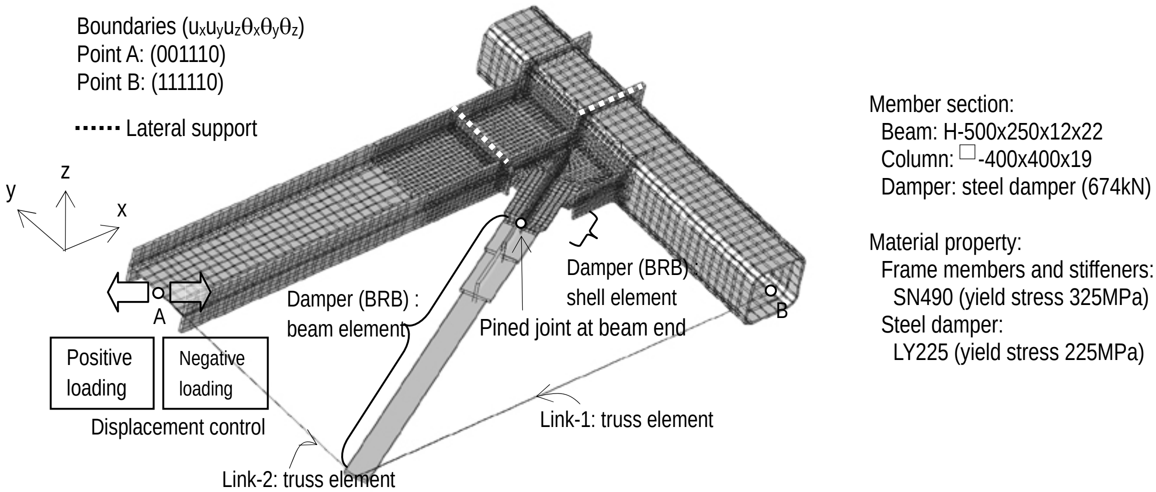


Figure 3 Analysis model for benchmark model

In the subassembly model, story drift θ, story shear F_f due to column shear and beam shear Q_b are calculated in the following relationship.

$$\theta = \frac{\Delta}{h\cos\alpha}, \quad F_f = P\cos\alpha, \quad Q_b = P\sin\alpha\left(1+\tfrac{1}{2}\theta\sin 2\alpha\right) \qquad (2.1)$$

where P is the force of the actuator and Δ is the corresponding displacement respectively. h and l are the half height of the story and half span respectively, that. α is the angle of the brace damper.

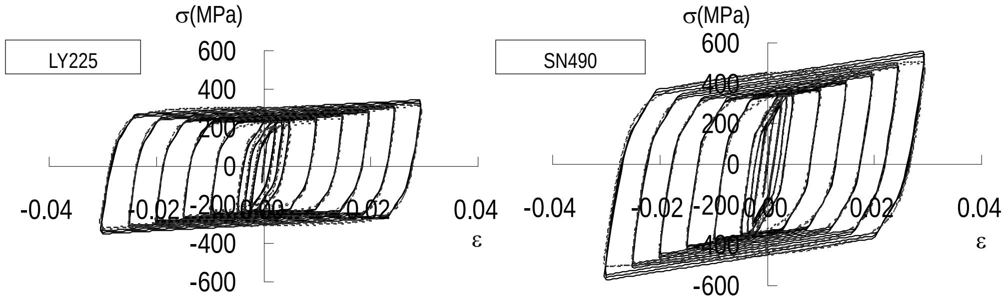
Table 1 Specimen type (analysis case)

Specimen No.	Thicknes of web(W) and flange(F) in beam [mm]	Damper force	Thickness of stiffener [mm]				Thickness of gusset plate [mm]
			Beam	Column	Vertical side stiffener	Horizontal side stiffener	
1	W:12, F:22	None	None	None	None	None	None
2	W:12, F:22	None	16	16	16	16	19
3 (benchmark)	W:12, F:22	Steel	16	16	16	16	19
4*	W:12, F:22	VE	16	16	16	16	19
5	W:9, F:22	Steel	16	16	16	16	19
6	W:9, F:16	Steel	16	16	16	16	19
7	W:12, F:22	Steel	16	None	16	None	19
8	W:12, F:22	Steel	None	None	None	None	19
9	W:12, F:22	Steel	16	16	16	16	9

*Specimen 4 is out of target range in analysis because the damper is velocity-dependent

2. 2. Material constitutive law

For problems involving softening due to buckling in cyclic response, Baushinger effect of steel is critical to the system behavior. To take account of the effect, overlay model[4)] for material constitutive is adopted. Overlay model consist of multiple virtual layers with simple material nonlinearity to characterize complex stress-strain curve. The von Mises yield criterion with associated flow rule and combined hardening rule (kinematic and isotropic type) are employed for each layer. Yield stress obtained by coupon test of the beam, the column, the gusset plate, and the stiffener in the subassembly test specimen are used in the analysis. Figure 4 shows stress-strain curve by the overlay model with calibrated parameters for SN490 and LY225 steel.



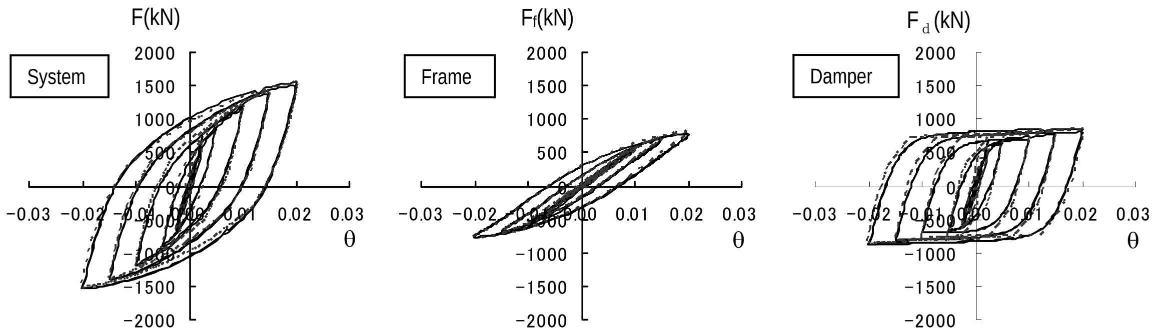
(solid line: simulated, broken line: experimental)

Figure 4 Simulated stress strain curve by overlay model with five layers

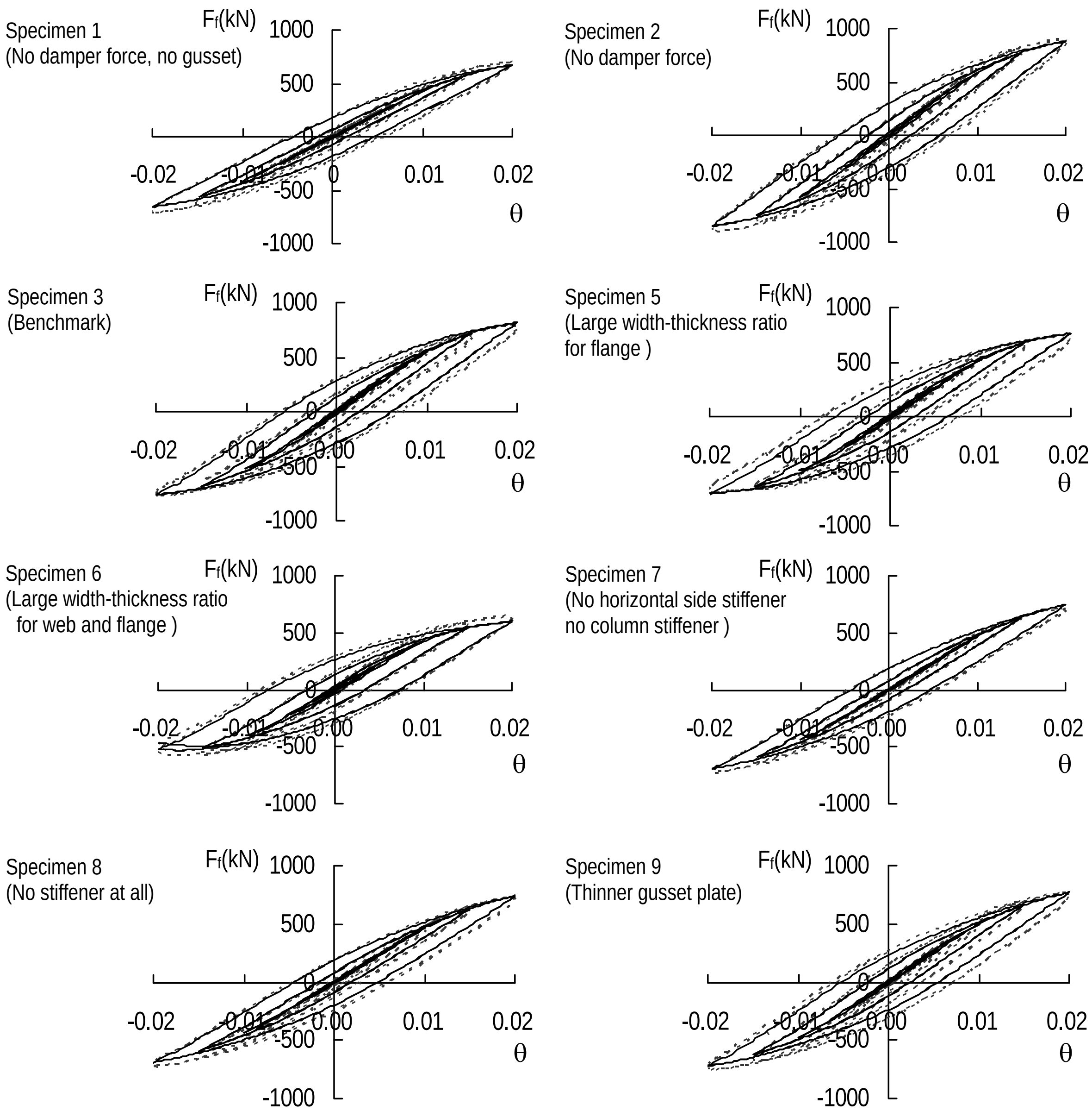
3. POST ANALYSIS FOR FULLSCALED-SUBASSEMBLY

3. 1. Macroscopic behavior

Figure 5 shows the forces of the system, the frame, and the damper with respect to drift angle. The results showed that resultant stress in the subassembly was well simulated in all the specimens. Significant damage was not observed at the beam-column interfaces up to 2% story drift in the benchmark model. The frame did not degrade after developing of local buckling in terms of relationships between story shear and story drift in the benchmark model. Stress reduction on the beam bending moment by gusset plate rigidity was not effective without proper stiffener details around the gusset plate.



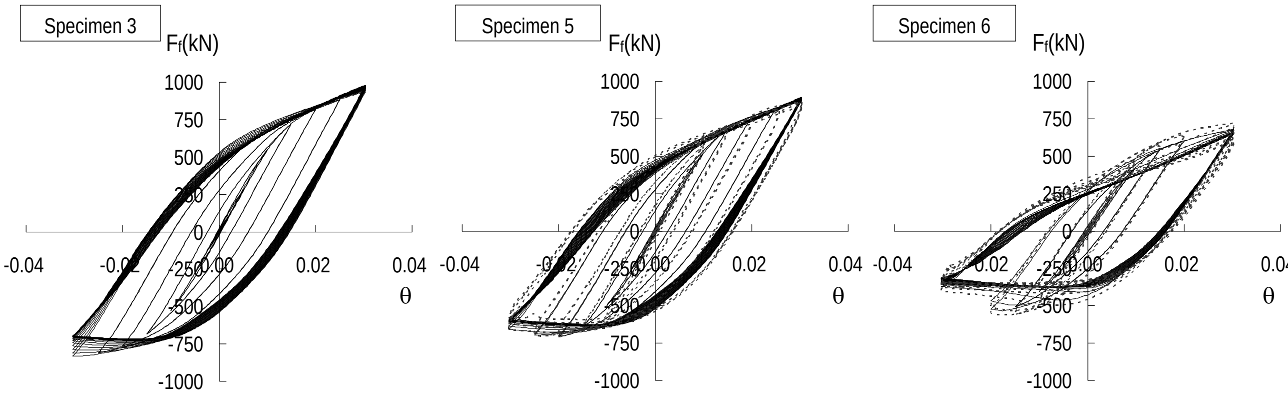
(broken line: experimental, solid line: numerica)
Figure 5 Forces with respect to drift angle



(solid line: numerical, broken line: experimental)
Figure 6 Forces of frame with respect to drift angle

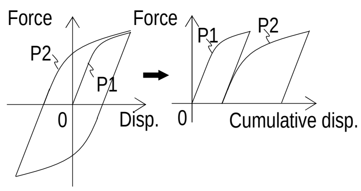
3.2. Deformation capacity of frame

Figure 6 shows the forces of the frame in large cyclic response (θ=1/33). The comparison with experimental results showed the finite element model accurately predicted the cyclic inelastic response of the test specimens. Degrading of the frame due to local buckling was well simulated in the fatigue experiment. The benchmark model (specimen 3) is relatively stable up to 1/33 radian of story drift angle. The hysteresis is asymmetry in terms of positive and negative loading directions. The shape of the load displacement curve in steady state response is similar to one in bending buckling of slender brace members subjected to repeated axial force.



(solid line: numerical, broken line: experimental)
Figure 7 Forces of frame with respect to drift angle for fatigue test

Figure 7 shows the envelope curve which represents deformation capacity of the frame in cyclic response. Horizontal axis is accumulated story drift angle calculated based on schematic illustration of Figure 8. The analysis result performed good results until fracture occurred in the beam flange in the experiment.



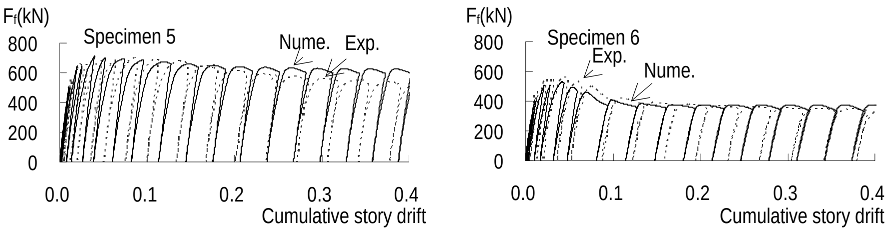
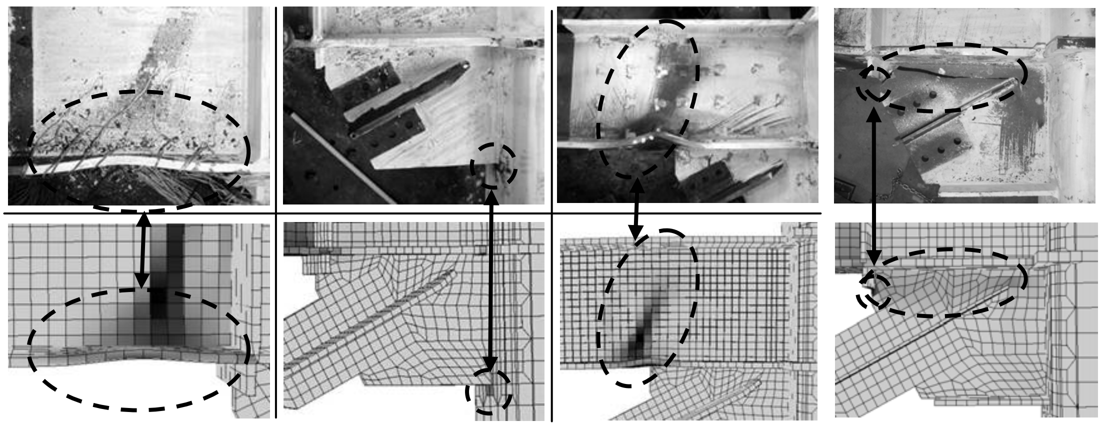


Figure 8 Composition of envelope curve Figure 9 Envelope curve in negative loading

3. 3. Plastic and buckling behavior



(a) buckled flange (b) stress concentration (c) buckle in shear (d) tear in gusset
*shading in analysis results represent propagation of equivalent plastic strain
Figure 10 Comparison of deformation between analysis and test results

Figure 10 shows failure modes of the frame. Specimen 3 showed the failure mode, where the bottom flange of the beam subjected to axial stress and bending stress buckled, as show in Figure 10(a). In specimen 7, plastic strain was concentrated on the corner of the gusset plate, as shown in Figure 10(b). In specimen 8, the web plate of the beam buckled in shear because of the concentrated shear force from the gusset plate, and tore in the orthogonal direction to buckling waves as shown in Figure 10(c). Specimen 9 showed that between gusset plate and vertical stiffener tends to fracture because of the high stress concentration.

4. LINEAR ELMENT MODELING WITH CONSIDERATION OF GUSSET RIGIDITY

4. 1. Equivalent strut model

A modeling method with linear element for frames having gusset connections is proposed to assess frame stiffness. As described in the previous chapter, gusset connections increase frame rigidity and often shift plastic hinge location from the face of a column to the tip of the gusset plate. However it is known that force transfer mechanism in the gusset connection cannot be reliably predicted by the conventional beam theory[3), 6)].

Figure 11 shows frame stiffness is insensitive to variation of horizontal stiffeners and vertical stiffeners. Stress flow along the diagonal line of the gusset plate and shear deformation is dominative compared to bending deformation. Accordingly, the horizontal stiffener is negligible in an analysis by using linear element. An equivalent strut model[6)], which considers the strut action in the gusset plate, is proposed for practical analysis as shown in Figure 12. Area of a truss element for the strut is expressed by gusset thickness multiplied by effective width of the gusset plate. The area identified by try and error analysis is shown in Figure 13(a), (b).

Based on the analysis results, effective width of the strut is sensitive to variation of the gusset thickness. An additional spring in series with the strut stiffness is added to take account of plate bending of rectangular steel column tube subjected to local bending. With the additional flexibility, effective width of the gusset is constant regardless of its boundaries as shown in Figure 13(c).

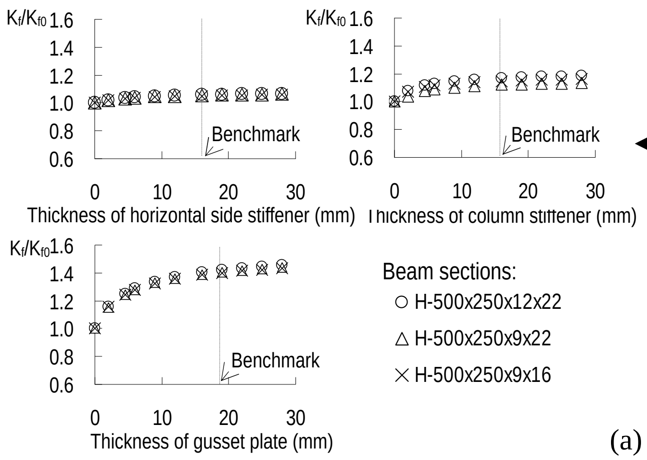
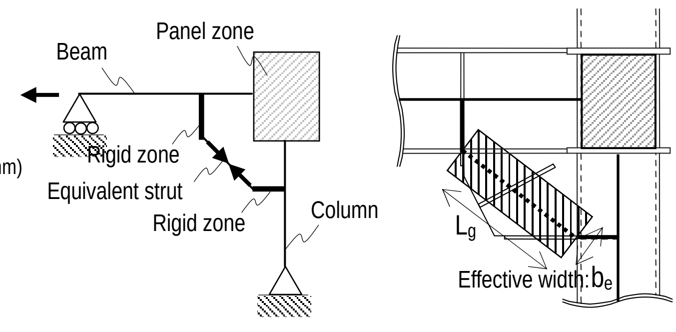
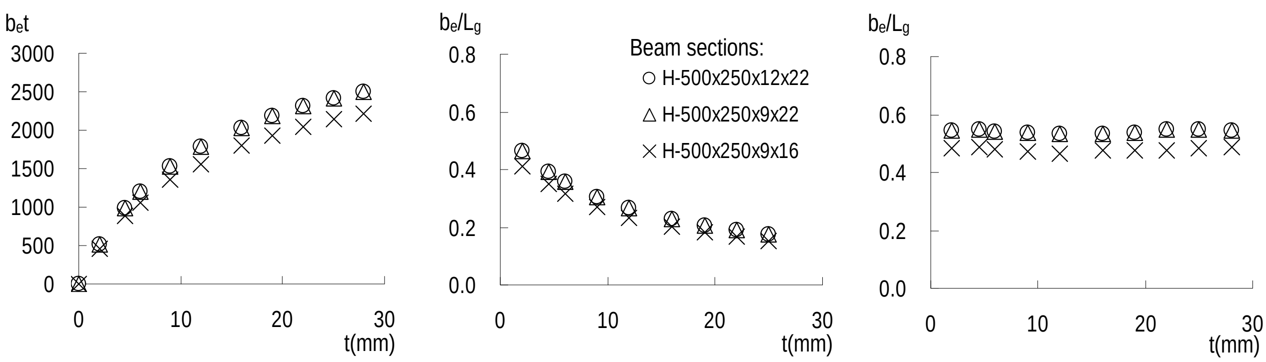


Figure 11 Sensitivity of frame stiffness



(a) Equivalent strut action (b) Effective width of strut

Figure 12 Equivalent strut concept for gusset plate

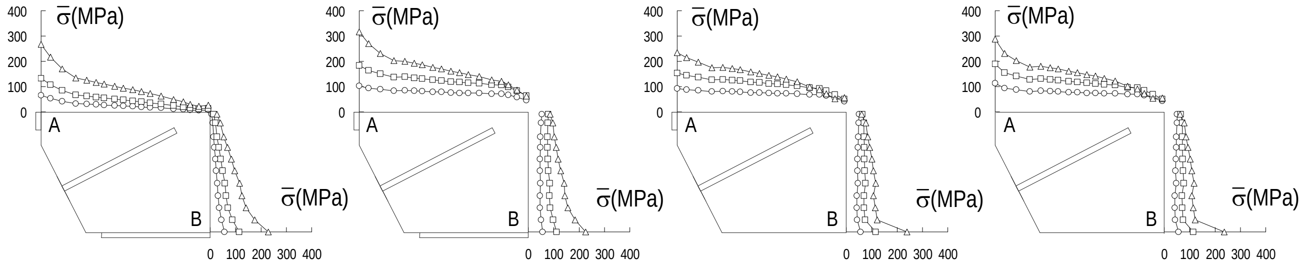


(a) Area of strut (b) Aspect ratio of strut (c) Aspect ratio of strut (improved)

Figure 13 Variation of equivalent strut property with respect to gusset thickness

4. 2. Idealized stress profile around gusset plate

Figure 14 shows equivalent stress profile around gusset plate at story drift $1/\theta$=800, 400, 200. In specimen 2 where no damper force work, the stress profile produced by frame action is approximated as triangular. In specimen 3, it is observed that stress shift compared to results in specimen 2 due to damper force. In specimen 7, having no horizontal side stiffener, stress is relieved at the corner with the vertical stiffener (point A), while stress locally increases at the corner without stiffener (point B). In all the case, the highest stress occurs in corners (point A, B) of the gusset. The results shows adding stiffener is effective to reduce stress concentration in the gusset plate.



(a) Specimen 2 (b) Specimen 3 (c) Specimen 7 (d) Specimen 8

Story drift: 1/800 1/400 1/200

Figure 14 Equivalent stress profile around gusset plate

4. 3. Design procedure of gusset plate under combined damper force and frame action force

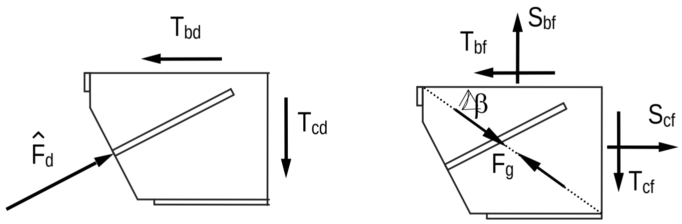
Design procedure of gusset plate is proposed by using reaction force of equivalent strut. Consider the free body of the gusset plate, subjected to damper and frame action, as shown in Figure 15.Using damper $\hat{F}_d$, reaction force of the strut F_g, resultant stresses along the gusset plate edge are computed in the following relationship.

$$T_{bd} = \hat{F}_d \cos\alpha\,,\ \ T_{bf} = F_g \cos\beta\,,\ \ S_{bf} = F_g \sin\beta \qquad \text{(for beam side)} \qquad (4.1a, b)$$

in which T_{bd} is the resultant shear stress due to damper force on beam side. T_{bf} is the resultant shear stresses produced by frame action. Similarly, S_{bf} are the resultant stresses. Based on the analysis results, the corresponding stress profiles are idealized as schematic diagram of Figure 16. Hence, the stresses are calculated in the following manner.

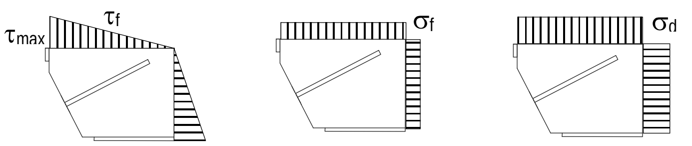
$$\sigma = \frac{S_{bf}}{bt}\,,\ \ \tau = \tau_f + \tau_d\,,\ \ \tau_d = \frac{T_{bd}}{bt}\,,\ \ \tau_f^{\mathrm{mean}} = \frac{1}{bt}T_{bf}\,,\ \ \tau_f^{\max} = \frac{2}{bt}T_{bf} \quad \text{(for beam side)} \qquad (4.2)$$

where b is the length of gusset plate in horizontal direction and t is the thickness of gusset plate.



(a) Damper force (b) Frame action force

Figure 15 Resultant stress profiles



(a) Shear stress (b) Normal stress (c) Normal stress

Figure 16 Idealized stress profile around gusset plate

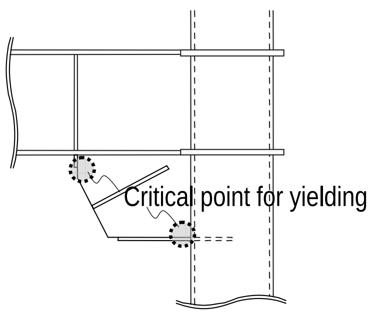


Figure 17 Critical point in gusset

Using the obtained equivalent stress $\overline{\sigma}$, we can determine thickness of gusset plate to meet the Mises yield criterion in plane stress field in the form of

$$\phi = |\overline{\sigma}| - \sigma_Y \leq 0, \quad \overline{\sigma} = \sqrt{\sigma^2 + 3\tau^2} \tag{4.3}$$

where σ_Y is the material yield stress. In Eqn. (4.3), shear is evaluated as τ^{max}, or τ^{mean} with expectation of stress redistribution along the gusset plate in partial yielding. The criterion for column side is exactly analogous. In addition to the above criterion, overall yielding and instability by compressive damper force should be checked through the other design method.

5. CONCLUSION

Numerical analysis was conducted to simulate test results of subassembly in passive-controlled buildings. Design procedure of gusset connection was discussed through parametric numerical analysis. Summary of conclusion is as follows.

1) Nonlinear finite element analysis with proper material modeling has good performance to simulate test results in cyclic response.
2) Significant damage was not observed at the beam-column interfaces up to 2% story drift for the subassembly specimen in a 5-story passively controlled building.
3) Gusset connection is idealized as an equivalent strut model, having equivalent width and gusset thickness for practical analysis.
4) Thickness of gusset plate subjected to frame action is designed by reaction force of a strut model.

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REFERENCES

1) Kasai, K., Ooki, Y., Motoyui S., Takeuchi T., Kajiwara, K. and Sato, E. (2008). Results of Recent E-Defense Tests on Full-Scale Steel Buildings, Part 3-Experiments on Dampers and Frame Subassemblies. *ASCE Struct. Congress*
2) Witmore RE. (1952). Experimental investigation of stresses in gusset plates. *Engineering Experiment Station, University of Tennessee, Vancouver, BC, Canada, Bulletin* No.16,24-26
3) Cheol-Ho Lee (2002). Seismic Design of Rib-Reinforced Steel Moment Connections based on Equivalent Strut Model, *J.Struct. of Eng., ASCE.*, Vol. 128, No. 9, 1121-1129
4) Zienkiewicz.O.C., Nayak, G.C. and Owen, D.R.J. (1972). Composite and Overlay Models in Numerical Analysis of Elasto-Plastic Continua, Symposium on Foundations of Plasticity, *Noordhoff International Publishing*, 703-123
5) N.Sheng, C.H.Yam, V.P.Iu (2002). Analytical investigation and the design of the compressive strength of steel gusset plate connections, *Journal of Constructional Steel Research* 58, 1473-1493
6) Cheol-Ho Lee, Chia-Ming Uang (2001). Analytical Modeling and Seismic Design of Steel Moment Connections with Welded Straight Haunch, *Journal of Structural Engineering, ASCE*, Vol. 127, No. 9, 1028-1035
7) Yam MCH, Sheng N, Iu VP, Cheng JJR. (1998). Analytical study of the compressive behavior and strength of steel gusset plate connections, *Proceedings of the CSCE 1998 Annual Conference*