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*RESEARCH ARTICLE*

# STUDY ON SEISMIC BEHAVIOR OF STEEL BEAM-TO-COLUMN PANEL ZONES

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**ABSTRACT**

Beam-to-column panel zone behavior in a steel moment-frame is characterized by the surrounding acting forces and its rotating deformation. When subjected to lateral forces, panel zones are deformed in a parallelogram pattern that one side of its diagonal direction is in tension whereas the other side is in compression. Moreover, right angles at the joints between the beam, column ends and the panel remains right angles. Shear strain causes the panel to rotate at a finite angle characterizing its rotating deformation. Based on experimental results from a full scale steel building collapse test, this paper discusses the elastic and elasto-plastic behavior of some typical panel zones.

**KEYWORDS**

panel zone, steel structure, collapse experiment.

## 1. INTRODUCTION

A full-scale four-story steel building specimen was experimented to collapse using strong ground motions on the E-Defense shake-table in Miki city, Japan (Nam and Kasai, 2011). To expand the discussion on the building specimen performance, this paper addresses the behavior of beam-to-column panel zones. Six panel zones on the 2nd and 3rd floors in the open side of the building specimen were recorded in the experiment, as shown in Fig. 1. Several methods of obtaining forces acting on panel zones are presented and compared in details. The most appropriate method is employed to study the elastic and elasto-plastic behavior of typical panel zones recorded in the test.

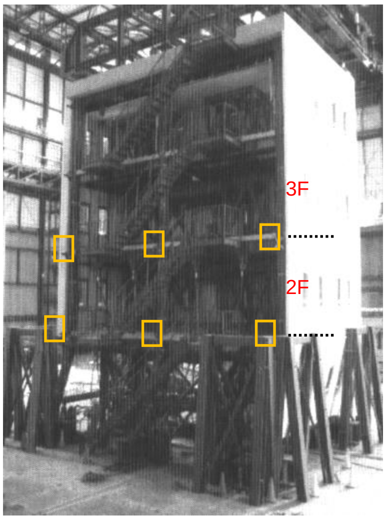


**Figure 1:** Panel zones in a full-scale steel building shaking experiment

## 2. MOMENT ACTING ON PANEL ZONES

Moment acting on the panel zone is computed by considering the equilibrium of two couples of vertical shear and horizontal shear forces around the edges of the free-body panel. Either of each equilibrated couple may be considered as the panel moment $_pM$. Assume column and beam internal forces, including moments and shear forces, are given, panel moment needs to be expressed in terms of those forces. In addition to this building specimen, composite effect of concrete slab to panel zones is supposed to take into account in case of positive bending moment. Followings are several methods to obtain panel moment:

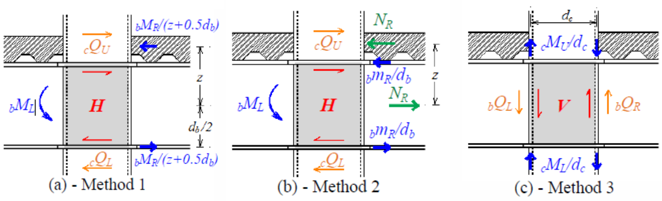


**Figure 2:** Different methods to obtain panel moment

**Method 1** (Fig. 2-a, based on (Kawano et al., 1993; Nakao and Osano; 1988; Yamada et al., 2009)): considering horizontal shear forces, this method increases the effective beam depth (originally $d_b$) to include slab thickness (latterly $z+d_b/2$, where $z$ is the distance between effective center lines of both concrete slab and bare steel beam section).

**Method 2** (Fig. 2-b, based on (Kishiki et al., 2010)): is also dealt with horizontal shears, but decomposes composite beam bending moment $_bM$ into partial moment $_bm$ carried by the bare steel beam section and partial moment $N.z$ caused by axial force $N$ at concrete slab. Axial forces in the beam and in the concrete slab are equilibrated. In case of no relative slip between steel beam ($E_S$, $A_S$, $I_S$) and concrete slab ($E_C$, $A_C$, $I_C$), one may obtain axial force using Newmark equation.

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$$N = \frac{z.\overline{EA}}{\overline{EI}}.M \tag{1}$$

where $\frac{1}{\overline{EA}} = \frac{1}{E_s A_s} + \frac{1}{E_c A_c}$ ; $\overline{EI} = E_s I_s + E_c I_c + \overline{EA}.z^2$ (2),(3)

**Method 3** (Fig. 2-c): unlike those above, this method counts for vertical shears. Column bending moment is decoupled by the effective column depth $d_c$. So that, axial force developed in the concrete slab is no need to concern. Followings are ${}_pM$ obtained by each method, respectively:

$${}_pM_1 = {}_bM_L + {}_bM_R \cdot \frac{d_b}{z + d_b/2} - \left({}_cQ_U + {}_cQ_L\right)\frac{d_b}{2} \tag{4}$$

$${}_pM_2 = {}_bM_L + {}_bM_R\left(1 - z.\frac{\overline{EA}}{\overline{EI}}\left(z - \frac{d_b}{2}\right)\right) - \left({}_cQ_U + {}_cQ_L\right)\frac{d_b}{2} \tag{5}$$

$${}_pM_3 = \left({}_cM_U + {}_cM_L\right) - \left({}_bQ_L + {}_bQ_R\right)\frac{d_c}{2} \tag{6}$$

However, due to the limit of strain data of concrete slab that could not be recorded in the experiment, the contribution of concrete slab to the gross composite beam moment is omitted. Therefore, the value of beam moment (${}_bM$) obtained from Eq.(7) is not exactly "composite beam moment" which is respect to the neutral axis, but means the moment with respect to the effective center line of concrete slab and carried by the beam. It can be found that **Method 1** appears to give unreasonable results when decomposing ${}_bM$ computed using Eq.(7) into such couple of forces with the arm length as shown in Fig. 2-a. An additional axial force, say N*, should be introduced to maintain the original stress diagram in the composite beam, as depicted in Fig. 4-b. At this point of view, **Method 2** is more reasonable than Method 1, because of including the equilibrated axial forces developed in the steel beam and concrete slab.

An example of hypothetic panel zone subassembly subject to unit loads as shown in Fig. 5 is used to access three methods. Loading ensures the moment equilibrium at the center of panel zone. The same size of columns, beams and panel zones with that used in the building specimen is employed. Concrete slab thickness is incrementally changed in order to get the trend curve as given in the figure. There is apparently a large difference between results obtained from **Method 1** and those computed from the other methods.

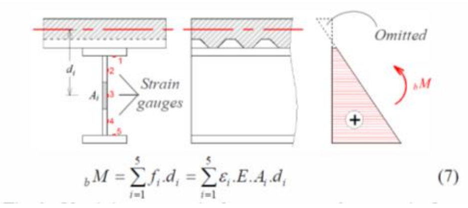



**Figure 3:** Obtaining composite beam moment from strain data

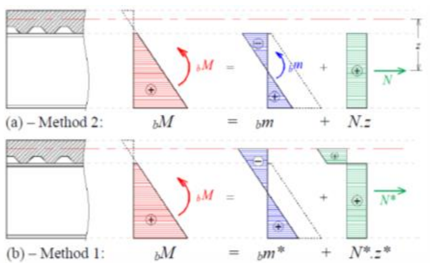



**Figure 4:** Decomposition of beam moment into partial moments

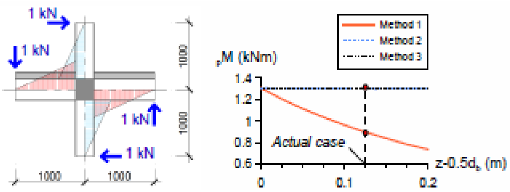
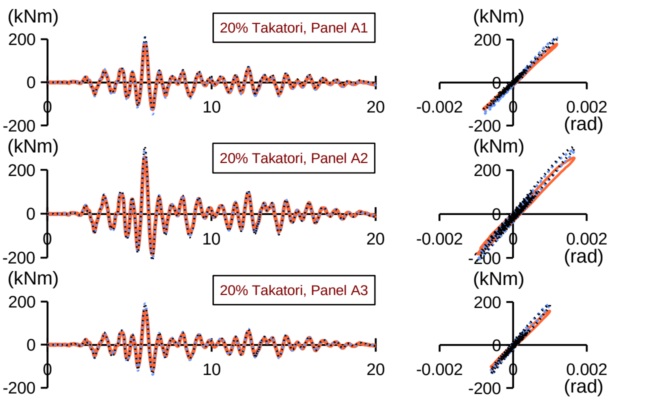



**Figure 5:** Hypothetical panel zone subassembly

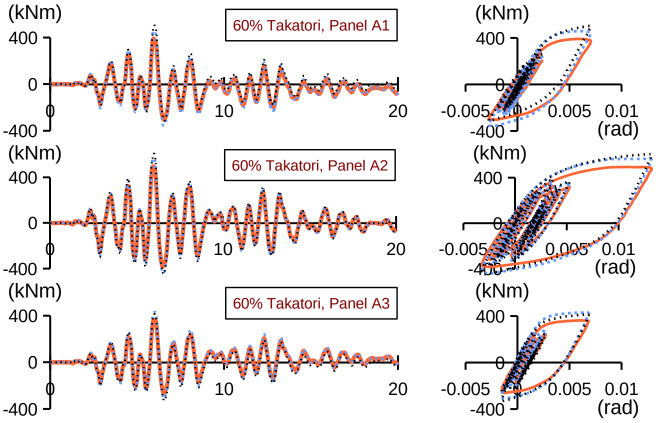
## 3. Panel Zone Behavior in The Test

Three panel zones of the 2nd floor, namely A1, A2 and A3 (see Fig. 1), are selected for practically examining the difference among panel moments obtained from three methods. *Panel moment time-history* curves, as well as *moment vs. shear angle* curves, under two load cases (i.e. 20% and 60% Takatori ground motion level) are plotted in Fig. 6. As aforementioned, results by **Method 1** show considerable difference with others, even in elastic load case (20% Takatori). The error is then improved by **Method 2**. However, in case of tension, the concrete slab tends to separate from the column, which means the tensile force must not logically involve in the equilibrium of the free-body panel. It is thus needed to determine whether in what case the axial force in concrete slab is included in the calculation, causing the discontinuous of the panel moment time-history curve.

**Panel moment time-history** **Moment vs. Shear angle**




(a) – 20% Takatori case




(b) – 60% Takatori case

**Figure 6:** Experimental elastic and elasto-plastic behavior of 2nd floor panel zones

This method is hence unpractical, especially for structures subject to seismic loadings. Under elasto-plastic case (60% Takatori), errors are found in panels A1 and A3, where the curve by Method 2 tends to shift a little rather than the curve by **Method 3**, showing the probable errors of beam strain data recorded in the test resulting in the inaccuracy of beam moment. Finally, by employing **Method 3** there is no need to concern about the contribution of concrete slab. This method which is the best of all is used hereafter for discussion on panel behavior. Superposition of panel moment - shear angle curves of those panels are shown in Fig. 7 (by panels) and Fig. 8 (by excitation levels). Fig. 7 shows stable behavior trend of all panels through load cases except small error in panel A1. Furthermore, though three panels have the same size and configuration as well as material property, the internal panel A2 tends to be stiffer than external panels that have nearly the same elastic stiffness as mathematically evaluation, characterized by the dashed line in Fig. 8. It may be explained due to the effect of internal panel induced by the combination of concrete slab on both sides.

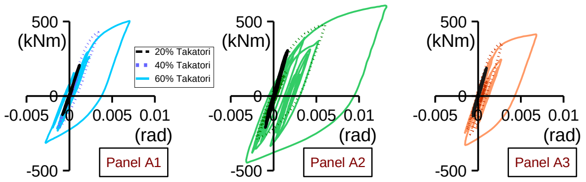



**Fig. 7:** Superposition of panel behaviors (by panels)

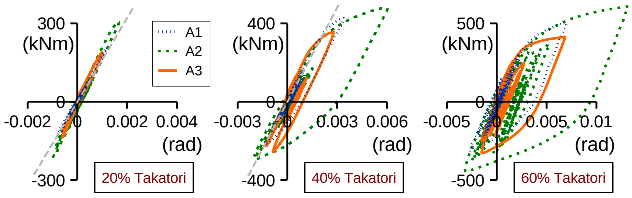



**Figure 8:** Superposition of panel behaviors (by excitation levels)

## 4. Conclusions

Different methods for obtaining panel zone moment of a full-scale steel building are systematically presented in this paper. From the comparison stated above, the method based on vertical shear forces appears to give the most trustful results. Elastic and elasto-plastic behaviors of panels obtained from this method are also discussed. Future study will examine panel behavior under collapse level, thereafter advance to establish a good numerical simulation of panel zones.

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